

Article

Accelerating Transition to a Low-Carbon Economy: A Coupling Analysis of Agricultural Products and Resource Environment

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Abstract: This study examines the low-carbon economy, agricultural products, and the resource environment as three interconnected subsystems, establishing an evaluation framework for their coordinated growth across eight regions of China. The results highlight significant regional imbalances, particularly in North China, Northwest China, and Northeast China. Principal component analysis (PCA) shows that the agricultural product system captures 99.502% of its information, while the resource-environment system accounts for 84.823%, demonstrating robust explanatory power. The national Economic–Agricultural–Resource–Environment (EARE) system progressed from sub-coordinated growth (2010–2014) to coordinated growth (2019–2020), moving from mild imbalance to high-quality growth. Initially, resource growth lagged behind economic development (2010–2015), which then shifted to economic growth lagging behind resource and environmental growth (2015–2020). This study underscores the need for targeted policies to enhance regional sustainability and balanced development.

Keywords: low-carbon economy; agricultural products; resource–environment coupling; coordinated growth; regional analysis



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1. Introduction

This study explores the human low-carbon economy [1], a model of green economic growth characterized by low energy consumption, low emissions, low pollution, and high efficiency. It emphasizes the development of clean energy and the pursuit of green GDP. At the 2009 Copenhagen World Climate Conference, nations universally agreed to curb greenhouse gas emissions, actively promoting energy conservation and emission reduction [2] and advocating for a low-carbon economy. With “low carbon” now a leading trend in global economic growth, the agricultural product industry has emerged as a vital sector in sustainable management [3]. The essence of fostering a low-carbon economy involves transforming human development and survival strategies to guide low-carbon lifestyles and green consumption towards achieving sustainable development [4]. However, the interplay between economic and social growth systems—which include economic performance, social progress, population dynamics, and urbanization levels—and the resource environment system, comprising resource endowment, pollution output, and ecological conditions, is complex. These systems are coupled through mutual influence and constraints.

Currently, the challenges of resource shortages and environmental degradation in the agricultural sector are becoming increasingly critical. The industry, now the largest non-point source polluter, faces ecological limits due to the excessive use of chemicals and waste in production, severely impacting water, soil, and air quality. Resource environments are essential for human survival and socio-economic development. Yet, the rapid advancements of human civilization often overlook the finite and non-renewable nature of these resources,

leading to their unchecked exploitation and the reckless discharge of pollutants [5]. This has resulted in significant resource depletion and ecological damage, manifesting in water scarcity, reduced forest areas, land subsidence, and severe air pollution, which not only impede socio-economic growth but also pose severe threats to human survival. Addressing these issues requires rethinking the growth models to emphasize resource and environmental factors within the low-carbon framework. Achieving sustainable growth in a low-carbon economy means harmonizing productivity growth with increasing human needs, fostering social sustainability through fairness and justice, and enhancing resource utilization alongside environmental quality. Coordinated growth [6]—balancing social justice with economic growth within the limits of environmental and resource capacities—is pivotal for achieving regional sustainability. This research will investigate the coupling of agricultural products with resources and the environment in a low-carbon context, aiming to enhance environmental protection in agriculture and improve governance transformation in line with modernization goals during the “13th Five-Year Plan.” It provides crucial technical support and theoretical references for local and regional planning, fundamentally impacting practical approaches to agricultural and environmental policy.

This study addresses the significant impact of resource endowment and environmental conditions on socio-economic growth within a low-carbon economy framework [7]. Resource endowment is fundamental to economic and social development, population growth, and urbanization. However, excessive pollutant discharges that surpass environmental self-purification capacities can disrupt ecosystems and degrade the quality of the ecological environment, imposing a serious constraint on economic and social progress due to diminishing resource availability and reduced environmental capacity [8]. Therefore, the interaction between agricultural products and the resources and environment system is crucial, as it enables the rational allocation of economic resources and the harmonious coexistence between humanity and nature through the application of natural laws and ecological civilization principles [9].

The concept of coupling, originating in physics, describes the phenomenon where multiple systems exhibit interconnectedness, interaction, and interdependence, significantly influencing each other's outputs through energy transmission [10]. This paper employs the coupling coordination degree model, derived from capacity coupling theory, which quantitatively assesses the level of harmony and consistency between subsystems [11]. Notable research in this field includes proposals by Wang et al. [12], who suggest environmental impact reduction through limits on population growth, material consumption, and enhancements in technology. Meanwhile, Li et al. [13] argue for the effective management of resource utilization conflicts through coordinated approaches, suggesting that alternative resources will eventually replace non-renewable ones. Zhan et al. [14] discuss a coordinated growth theory that adapts economic processes to environmental changes, promoting symbiosis between ecological and social systems. Further, Li et al. [15] emphasize that resource utilization efficiency hinges on technological advancements, which can mitigate resource waste and address environmental challenges inherent to socio-economic development. This approach has been supported by prior studies (e.g., Higgins, 2017) [16]. Moreover, the adoption of an input–output model by Singh et al. [17] introduces resource and environmental considerations into economic studies, demonstrating a new pathway for studying the interrelations between economic behavior and environmental impacts. Similar methodologies have been applied in regional sustainable strategies (Fu and Lin, 2010) [18]. Meng et al. [19] provide a comprehensive analysis of regional coordination. Urban and rural development evaluations have also used these criteria (Zhu, 2013) [20]. Lastly, Hao et al. [21] utilize RS technology to assess urbanization and its ecological impacts in the Lake Aibi basin, employing the coupling coordination model to forecast future growth trends and develop strategic recommendations. This body of research collectively underscores the critical role of coordinated growth in achieving sustainable regional development.

This paper utilizes RS technology to explore the relationship between agricultural product growth and environmental resources within a low-carbon economy, providing

quantitative analysis and algorithmic support. Innovatively, this study discusses the coupling coordination evaluation model, which is applied nationwide and divided into eight regions, predominantly using mathematical models with RS technology. This paper is structured into five chapters, starting with an introduction that sets the research background and objectives, followed by a literature review, a detailed methodology section, an experimental analysis, and concluding with a summary of findings and future research directions. This approach highlights the study's contributions to sustainable agricultural practices and regional growth coordination.

2. Methodology

In this study, the low-carbon economy, agricultural products, resources, and environment are treated as three complex yet inseparable subsystems within the broader framework of regional growth. These systems are interconnected, each exerting both promotional and restrictive influences on the others. The interactions among them significantly impact the overall regional growth system. If a problem arises in one subsystem, it can adversely affect the others, potentially leading to disorder and significant changes in the overall system, which may disrupt the coordinated growth of the region. An interesting imbalance index of economic factors affecting agricultural products, resources, and the environment (I) is also introduced to measure the degree of difference between these factors and their regional distribution.

2.1. RS Technology

Remote sensing (RS) technology, a cutting-edge high-tech tool, utilizes spacecraft to collect electromagnetic radiation information from ground objects, providing critical insights into the Earth's environment and resources. The fundamental principle behind RS technology is its ability to discern and identify terrestrial objects based on the differential electromagnetic reflection characteristics exhibited by various materials. This capability makes RS technology invaluable for a wide range of applications, including resource surveys, vegetation classification, land use planning, environmental planning, and pollution monitoring. Its broad sensing range, advanced technological capabilities, rapid information acquisition, frequent update cycles, and the facility for dynamic and real-time monitoring amplify its utility across these domains.

In the context of coupled and coordinated evaluation, RS technology plays a pivotal role by offering a vital data source for land resource assessment. The remote sensing data undergo several preprocessing and classification steps to prepare it for analysis. Preprocessing involves data acquisition, band data fusion, geometric correction, and image registration. The classification process typically includes supervised classification and visual correction. These steps culminate in the accurate classification of land use, which establishes a solid foundation for subsequent land resource evaluations. The data processing workflow, depicted in Figure 1, illustrates these sequential steps, showcasing how remote sensing data are transformed into actionable environmental intelligence. The values and repositories used in this workflow include datasets from Landsat and Sentinel satellites, with specific bands such as Band 1 (Coastal/Aerosol), Band 2 (Blue), Band 3 (Green), Band 4 (Red), Band 5 (Near Infrared—NIR), Band 6 (Shortwave Infrared—SWIR 1), Band 7 (Shortwave Infrared—SWIR 2), Band 10 (Thermal Infrared—TIRS 1), and Band 11 (Thermal Infrared—TIRS 2). These datasets are publicly available and provide consistent and reliable data for our analysis.

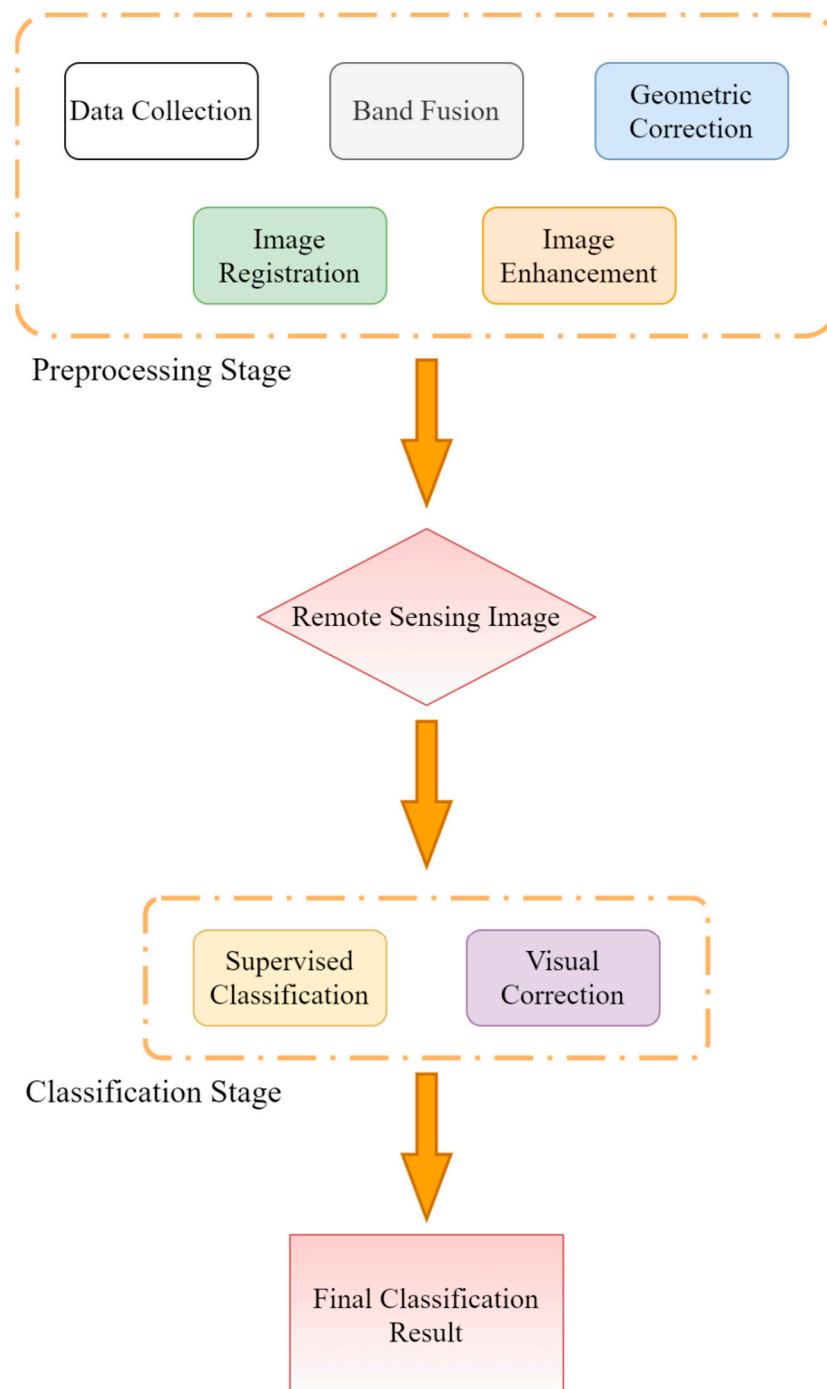


Figure 1. Data processing flow chart.

2.2. Coupling Mechanisms of Agricultural Products, Resources, and Environment

The regional dynamics of the low-carbon economy, agricultural products, resources, and environment are intricately interconnected, shaping the trajectory of social and economic growth. In the early stages, when economic activities are minimal, the ecological environment experiences little disturbance, and resource exploitation is low. However, as development progresses, the demand for resource utilization intensifies, leading to significant environmental degradation and more robust interactions among these systems. This initiates a cycle that can oscillate between phases of primary coordination, high-quality coordination, and low-level coordination, reflecting the evolving nature of mutual coupling and coordination within the region.

On the one hand, the advancement of society and technology enhances resource utilization by increasing the efficiency of material and energy flows, which supports human survival and growth. On the other hand, factors such as population growth, economic expansion, and intensified human activities place considerable pressure on regional resources and the environment. This dual-natured interaction results in ecological degradation and resource depletion that severely impair the quality of life and hinder social and economic progress. Consequently, the relationship between regional growth and its resources and environment is characterized by both mutual promotion and restriction.

To address these challenges, a coordinated approach is necessary. The growth of the social economy can lead to increased investments in environmental protection and improved utilization rates of ecological resources, thereby reducing environmental damage. Enhancing man-made purification processes and adopting practices such as energy conservation, emission reductions, and the implementation of new technologies help alleviate resource pressures and reduce the environmental impact of socio-economic activities. Additionally, improving the ecological environment and promoting sustainable resource use not only enhances the environmental competitiveness of the region but also attracts foreign investments, boosting economic strength and promoting sustainable regional development. This research establishes an evaluation index system that integrates indicators from the subsystems of the low-carbon economy, agricultural products, resources, and environment, creating a comprehensive framework for studying their coupling and coordination (Figure 2).

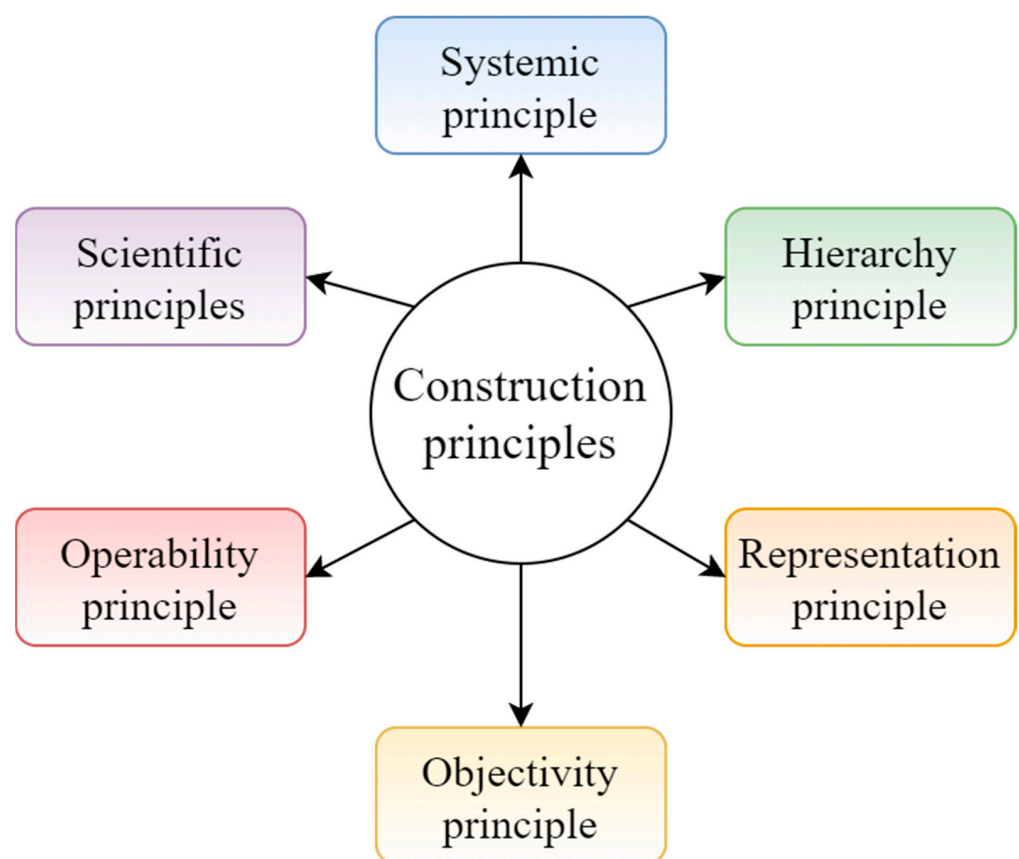


Figure 2. Construction principles of the indicator system.

2.3. Coupling Coordination Evaluation Index System

Under the framework of a low-carbon economy, both the agricultural product system and the resource and environment system are complex entities, exhibiting various stages, dynamics, and levels of complexity in their growth. The term ‘low-carbon economy’ in this paper encompasses broader economic activities aimed at reducing carbon emissions, includ-

ing but not limited to the agricultural sector. The evaluation of growth levels within these systems transcends simple index parameters, necessitating a comprehensive assessment that integrates multiple indicators such as GDP per capita, energy consumption per unit of GDP, carbon emissions per unit of GDP, agricultural productivity, and resource use efficiency. These specific indicators were used to establish the regional coupling coordination evaluation index system, as illustrated in Figure 3.

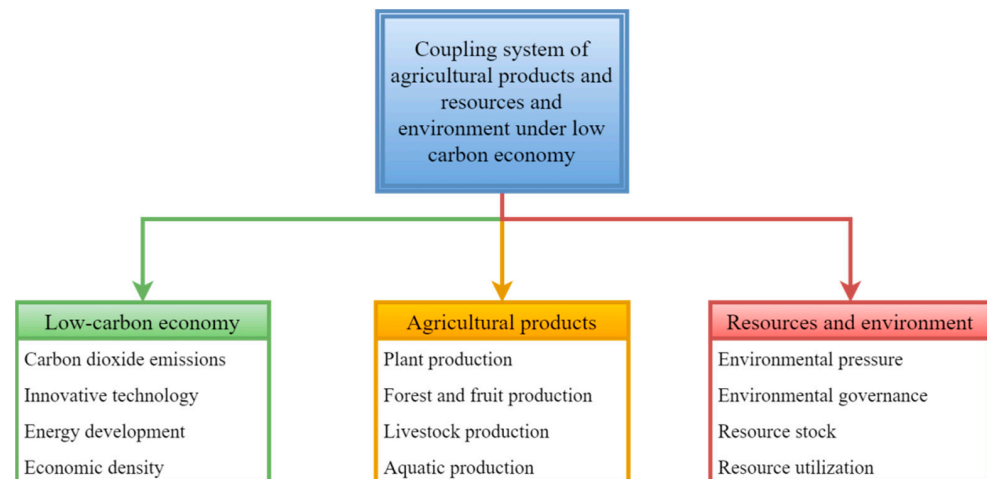


Figure 3. The established regional coupling coordination evaluation index system.

2.3.1. Data Collection and Preparation

The data for this study were collected from various authoritative sources, including national statistical yearbooks, environmental reports, and agricultural databases covering the period from 2010 to 2020. These datasets include economic indicators, environmental metrics, and agricultural production statistics for the eight regions of China.

2.3.2. Software and Tools

The statistical analysis was conducted using SPSS version 17.0. Remote sensing (RS) technology was employed to collect and preprocess environmental data, including land use and resource distribution. The data preprocessing steps included acquisition, band data fusion, geometric correction, and image registration, followed by supervised classification and visual correction.

2.3.3. Statistical Analysis

We utilized the coupling coordination degree model to evaluate the interaction and growth levels of the three subsystems—the low-carbon economy, agricultural products, and resources environment. Principal component analysis (PCA) was performed using SPSS to reduce dimensionality and extract the most significant components representing the data. The coupling degree and coordination degree models were then applied to quantify the interactions and coordination among the subsystems.

The imbalance index (I) was calculated to measure the disparity between agricultural products, resources, and economic factors across the regions. The standardized data were analyzed using a linear scale transformation to ensure comparability across different indicators.

By providing these additional details, we aim to clarify the methodology and enhance the transparency of our experimental and statistical analysis processes.

The imbalance index (I) is introduced to quantify the degree of imbalance between agricultural products, resources, and economic factors in different regions. The calculation formula for the imbalance index is as follows:

$$I = \sum_{i=1}^n |x_i - y_i| \quad (1)$$

where x_i and y_i represent the proportions of agricultural products and various resources, environmental, and economic factors in region i , respectively. A smaller difference between x_i and y_i indicates a more balanced distribution, while a larger difference indicates greater imbalance.

To address this issue, this study establishes a regional coupling coordination evaluation index system, as illustrated in Figure 3. The weighting of these indices is determined through methods such as data standardization and the coupling coordination degree model, enabling a detailed analysis of the interactions and growth patterns within these systems.

First, the imbalance index of economic factors of agricultural products, resources, and environment (I) is introduced to measure the degree of difference between agricultural products, resources, and environment and the economic growth level of a country or region. The calculation formula is as follows:

$$I = \sqrt{\frac{\sum_{i=1}^n \frac{\sqrt{2}/2(x_i - y_i)^2}{n}}{n}} \quad (2)$$

where n is the number of regions; x_i and y_i represent the proportions of agricultural products and various resources and environmental and economic factors in region i , respectively. When x_i is plotted on the x -axis and y_i on the y -axis, a smaller difference between x_i and y_i places the point (x_i, y_i) closer to the line $y = x$, indicating a relative balance. Conversely, a larger difference between x_i and y_i moves the point (x_i, y_i) farther from the line $y = x$, signifying an imbalance in the regional distribution of agricultural products and this indicator.

(1) Standardization of data

Different data dimensions will make the indicators not fall under the same reference system. To eliminate the dimensional differences in indicators, it is necessary to standardize the original data of the indicator system. There are many ways to standardize data, and the effects of each have their advantages and disadvantages. Commonly used methods include the range transformation method, linear scale transformation method, standard sample change method, normalization method, etc., and the less commonly used method is the Log function. Standard method, Arctan function standard method, Logistic/Softmax transformation, etc., as well as some methods improved from the above methods, will not be introduced in detail here. After screening and experiments, this paper uses the linear scale transformation method to standardize the data. The process is as follows:

In the matrix $X = (x_{ij})_{m \times n}$ formed by the index system, take $x_j^* = \max_{1 \leq i \leq m} (x_{ij}) \neq 0$ for the positive index f_j ,

$$y_{ij} = \frac{x_{ij}}{x_j^*}, 1 \leq i \leq m, 1 \leq j \leq n \quad (3)$$

For the positive indicator f_j , take $x_j^* = \max_{1 \leq i \leq m} (x_{ij}) \neq 0$,

$$y_{ij} = \frac{x_j^*}{x_{ij}}, 1 \leq i \leq m, 1 \leq j \leq n \quad (4)$$

Then, for the matrix $Y = (y_{ij})_{m \times n}$ formed by y , it is referred to as a linear scaling normalization matrix. The advantage of this type of data standardization is that, by considering the data variances, after linear scaling transformation, the positive and negative values are averaged into positive values.

(2) Coupling Coordination Degree Model

Coupling degree refers to the degree of close relationship between systems and is used to measure the strength of the interaction between systems or elements. Coordination, on the other hand, is the state of proper coordination and coordinated growth between systems. Coupling coordination involves mutual influence, cooperation, and cooperation between systems. The coupling coordination degree serves as an indicator to measure the

degree of this state. A coupling coordination degree model has been established to study the coupling and coordinated growth of agricultural products, resources, and environment systems in the country from 2010 to 2020 under a low-carbon economy. The process has been improved, and the specific operation process is as follows:

First, establish the coupling function as follows:

$$C_i = \left\{ \frac{E_i \times S_i \times R_i}{\left[\frac{1}{3}(E_i + S_i + R_i) \right]^3} \right\}^{\frac{1}{3}} \quad (5)$$

Among them, C_i ($0 \leq C_i \leq 1$) represents the coupling degree, with values ranging from 0 to 1. When $C_i = 0$, it indicates the three subsystems of the economy (E), agricultural products (A), and resources and environment (R) in the EARE system. Conversely, during the disorderly growth of the system, the three subsystems are highly interconnected; they are in the optional coupling state. Based on the pertinent research findings, the EARE system is categorized into six growth stages based on the value of C_i (Tables 1 and 2).

Table 1. C_i value and the stage division and standard of the EARE system.

C_i Value	EARE Stage
$C_i = 0$	Irrelevant
$0 < C_i < 0.3$	Low level
$0.3 \leq C_i < 0.5$	Antagonism
$0.5 \leq C_i < 0.8$	Running-in
$0.8 \leq C_i < 1$	High level
$C_i = 1$	Optimal

Table 2. Classification of coupling evaluation criteria.

Coupling C	Coupling Class
(0, 0.50]	Uncoupled
(0.50, 0.60]	Barely coupled
(0.60, 0.70]	Primary coupling
(0.70, 0.80]	Intermediate coupling
(0.80, 0.90]	Well coupled
(0.90, 1.00]	Premium Coupling

Table 1 outlines the specific values and their corresponding stages in the EARE system's growth phases. Table 2 further elaborates on these stages, providing detailed descriptions and criteria for each phase.

E_i , A_i , and R_i are the growth level indices of the three subsystems: economy, society, resources, and environment. These values are determined based on their respective efficacy functions. The function formula is as follows:

$$E_i = \sum_{j=1}^P \alpha_j \times y_{ij} \quad (6)$$

$$s_i = \sum_{j=1}^P \beta_j \times y_{ij} \quad (7)$$

$$R_i = \sum_{j=1}^P \gamma_j \times y_{ij} \quad (8)$$

$$\sum_{j=1}^P \alpha_j = 1, \sum_{j=1}^P \beta_j = 1, \sum_{j=1}^P \gamma_j = 1, 1 \leq i \leq m, 1 \leq j \leq p < n \quad (9)$$

Among them: p is the number of data indicators of the three subsystems in the EARE system; α , β , and γ are the weights of the indicators of each subsystem, that is, the contribution of each indicator to each subsystem, and the entropy method will be used to calculate α , β , and the value of γ .

Second, establish a coupling coordination function as follows:

$$M_i = (C_i F_i)^{\frac{1}{2}} \quad (10)$$

$$F_i = a \times E_i + b \times S_i + c \times R_i \quad (11)$$

Coupling coordination degree M_i can reflect the level of coordinated growth of the three subsystems of low-carbon economy, agricultural products, and resource environment, while coupling degree C_i only reflects the degree of mutual influence between the three subsystems. F_i is the comprehensive coordination evaluation index of the three subsystems of the EARE system. The geometric mean method is used to determine the value of F_i , where a , b , and c are the weights of each subsystem ($a + b + c = 1$). The three subsystems of resources and environment are equally important in the growth of the economy; thus, $a = b = c = 1/3$. Referring to the research results of related scholars, the coupling and coordinated growth of the EARE system are divided into three categories and nine subcategories (Figure 4).

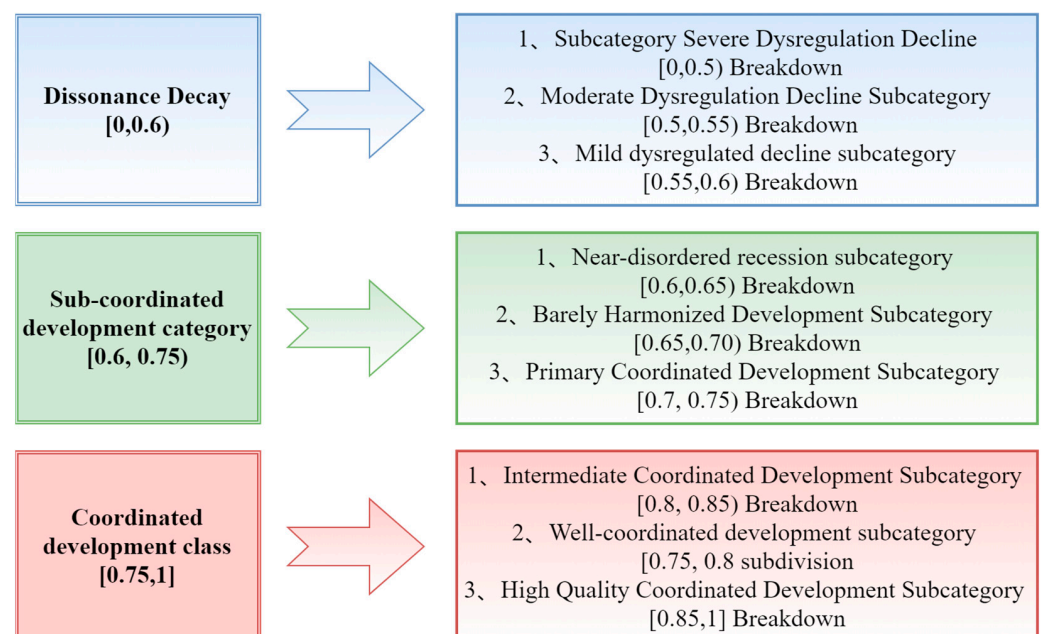


Figure 4. Type division and standard of EARE system coupling and coordinated growth. Note: Each subcategory can be subdivided into the following six types: resource–environmental balance, social lag type ($R_i > E_i > A_i$); resource–environmental balance, economic lag type ($R_i > A_i > E_i$); economic growth, social lag type ($E_i > R_i > A_i$); economic growth, resources, and environment lag type ($E_i > A_i > R_i$); social progress, economic lag type ($A_i > R_i > E_i$); social progress, resources, and environment lag type ($A_i > E_i > R_i$).

2.4. Coupling Coordination Evaluation Model

This paper establishes a mathematical model of the coupling degree of three subsystems, including the low-carbon economy, agricultural products and resources, and environment, based on relevant domestic and foreign literature, as shown in Equation (11):

$$C = 3 \left\{ (U_1 \times U_2 \times U_3) / \left[(U_1 + U_2 + U_3)^3 \right] \right\}^{\frac{1}{3}} \quad (12)$$

where C is the system coupling degree, $C \in (0, 1)$.

The larger the value of C , the better the coupling between the subsystems, indicating a stronger interaction between them. However, the degree of coupling only signifies the strength of interaction among the three subsystems, not the level of coordination within the system. A high value of C could represent either high-level or low-level coupling. Based on system coupling, in order to intuitively reflect the degree of coordinated growth of each subsystem, a model of coordinated growth is established with reference to relevant literature. The coordinated growth model is developed based on the existing literature. This model can effectively assess the coordinated growth of the three subsystems related to agricultural product growth, resource use, and environmental significance under low-carbon conditions. Its calculation formula is as follows:

$$D = (C \times T)^{1/2} \quad (13)$$

$$T = \alpha \times U_1 + \beta \times U_2 + \gamma \times U_3 \quad (14)$$

In the formula: D represents the degree of coordinated growth of the system; T stands for the comprehensive coordination index of the α , β , γ subsystem; is the undetermined coefficient of the contribution degree of the subsystem, $\alpha + \beta + \gamma = 1$. This study considers that the low-carbon economy, agricultural products, resources, and the environment play equally important roles in regional coordinated growth.

To sum up, the Coordinated Growth Degree Model D combines the System Coupling Degree Model C and the Growth Level T of each subsystem. The Coordinated Growth Degree has a broader research scope than the Coupling Degree on the coordinated growth of the region and can provide a more comprehensive reflection. The coordinated growth of subsystems in a region can be compared and analyzed not only between different regions in the same period but also between subsystems in the same region in different periods, and it has strong operability. The evaluation criteria for Coupling Degree C and Coordinated Growth Degree D are divided as follows:

3. Result Analysis and Discussion

The coupling relationship between the resource environment system and the population economic system arises from their intricate connections and interactions. The intricate comparison of the evolution of the three interconnected subsystems—low-carbon economy, agricultural products, and resource environment—across the eight regions of China adds a layer of complexity to the study. This comparative analysis not only highlights regional disparities but also provides insights into region-specific challenges and opportunities, making the study intellectually stimulating and thought-provoking. The resource environment system furnishes essential resources and ecological services while also processing the waste generated by human activities. Conversely, the population consumes these resources and ecological services to drive economic development and enhance welfare. This interdependence prompts continuous improvements in resource efficiency and waste management practices aimed at bolstering the carrying capacity of the ecological environment. Reflecting this dynamic, the degree of influence of various factors on the spatial differentiation of agricultural products, resources, and environment is illustrated in the accompanying figure, where X represents agricultural products and Y denotes resources and environment. This visualization helps clarify the complex interplay between these elements, highlighting the interconnected nature of agricultural productivity and environmental sustainability.

Figure 5 illustrates the degree of effect of various factors affecting the spatial differentiation of agricultural products and resource–environment systems. The data include several key variables represented by different lines and colors. The Y Standardization Coefficient (Beta), shown by the blue line, indicates the standardized impact of independent variables on the dependent variable Y in standardized units, with values such as $Y1$ (1.073), $Y2$ (1.191), and $Y3$ (1.496). The Y Variance Inflation Factor (VIF), represented by the orange line, measures the degree of multicollinearity among the independent variables for Y , with

values including Y1 (1.029), Y2 (1.063), and Y3 (1.433). The Y Significance (p -value), shown by the green line, indicates the statistical significance of the relationships for Y, with key values such as Y1 (0.443), Y2 (0.724), and Y3 (0.729). Similarly, the X Standardization Coefficient (Beta), represented by the yellow line, measures the standardized impact of independent variables on the dependent variable X, with values like X1 (0.102), X2 (0.083), and X3 (0.138). The X Variance Inflation Factor (VIF), shown by the red line, measures the degree of multicollinearity among the independent variables for X, with values including X1 (1.073), X2 (1.191), and X3 (1.496). The X Significance (p -value), indicated by the gray line, shows the statistical significance of the relationships for X, with values such as X1 (0.047), X2 (0.053), and X3 (0.062). This figure provides insights into the relative importance and significance of these factors in driving the spatial differentiation of agricultural products and resource–environment systems, aiding in the identification of key drivers and potential areas for intervention.

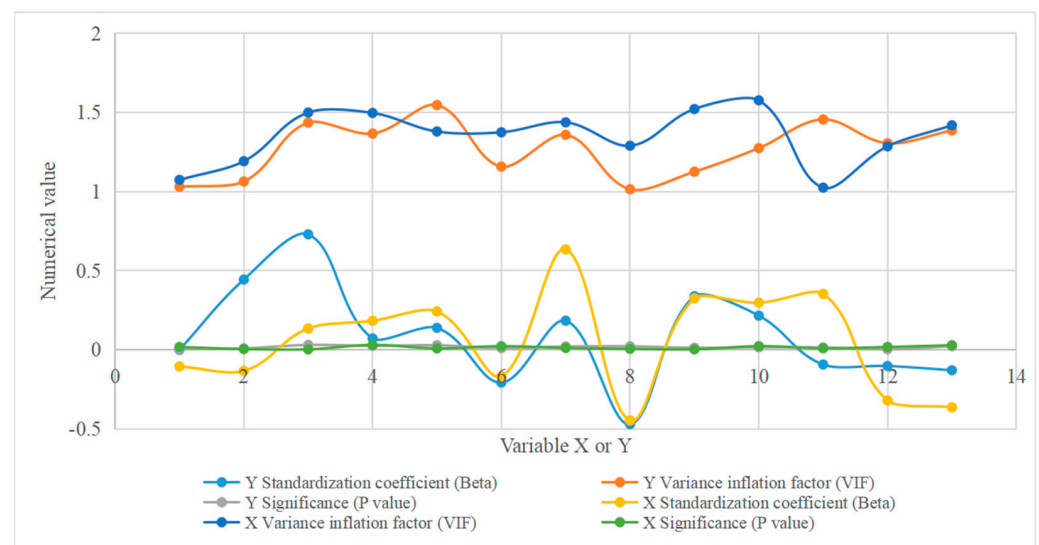


Figure 5. The effect degree of the factors affecting the spatial differentiation of agricultural products, resources, and environment.

It can be seen from the figure that the Beta values of the two fluctuate significantly, which will have a substantial impact later on, while the p values of the two fluctuate very little, almost close to 0, indicating a minor impact.

China's 31 provinces (autonomous regions and municipalities) are divided into eight regions. The imbalance index is introduced to analyze and compare these regions, aiming to clarify the spatial matching degree of agricultural products and related factors such as resources, environment, and economic growth in China. By using formula (1), the imbalance indices of agricultural products to population, cultivated land area, water resources, soil erosion control area, and GDP can be obtained as I_p , I_c , I_w , I_e , and I_g , respectively.

Figure 6 shows the unbalanced index of agricultural products and the associated resources, environment, and economic factors across eight major regions in China. The lines in the graph represent the indices for five factors: I_p (blue), I_c (orange), I_w (green), I_e (yellow), and I_g (red). Each line represents how unbalanced each factor is within the specified regions: Northeast, North China, Huang Huaihai, Northwest, Southeast, Yangtze River, South China, and Southwest. For example, the I_e factor (yellow line) has its highest imbalance in the Huang Huaihai region with a value of 0.241, while the I_c factor (orange line) shows a significant imbalance in the Northwest region with a value of 0.1483. The table below the graph provides specific numerical values for each factor in each region, highlighting areas with a higher or lower imbalance. These data help identify regions where agricultural production and related factors are most out of balance,

indicating where targeted policy interventions might be needed to improve sustainability and resource management.

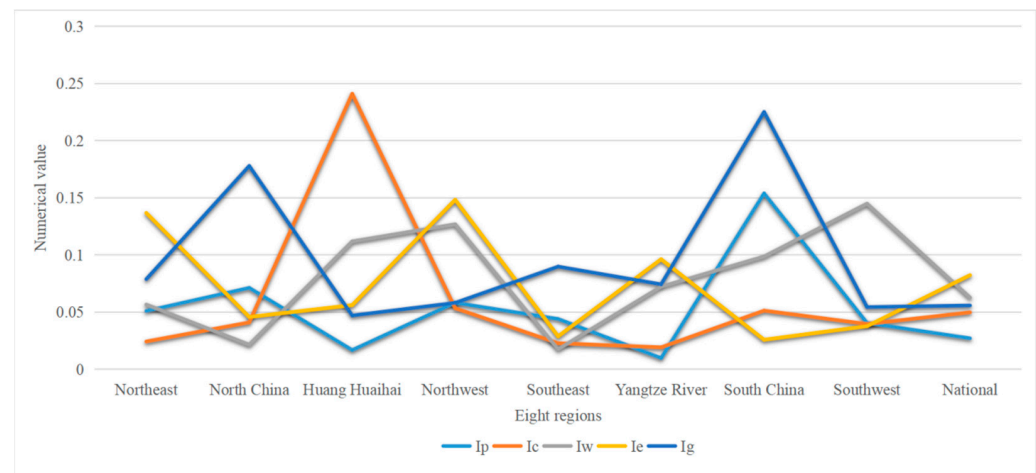


Figure 6. Unbalanced index of agricultural products and agricultural products—resources, environment, and economic factors—in eight major regions of China.

It can be seen from Figure 6 that the imbalance index of agricultural products, resources, and the environment in the country is the smallest, indicating that the spatial matching degree of agricultural products, resources, and the environment is the highest. The regions with larger imbalance indices are North China, Northwest China, and Northeast China.

After standardizing the evaluation index values of the agricultural trade system and the economic coordination degree, this paper uses SPSS 17.0 to process the data using the standardization method. Subsequently, it conducts principal component analysis and generates the variance decomposition principal component analysis diagram of the two systems, as shown in Figure 7.

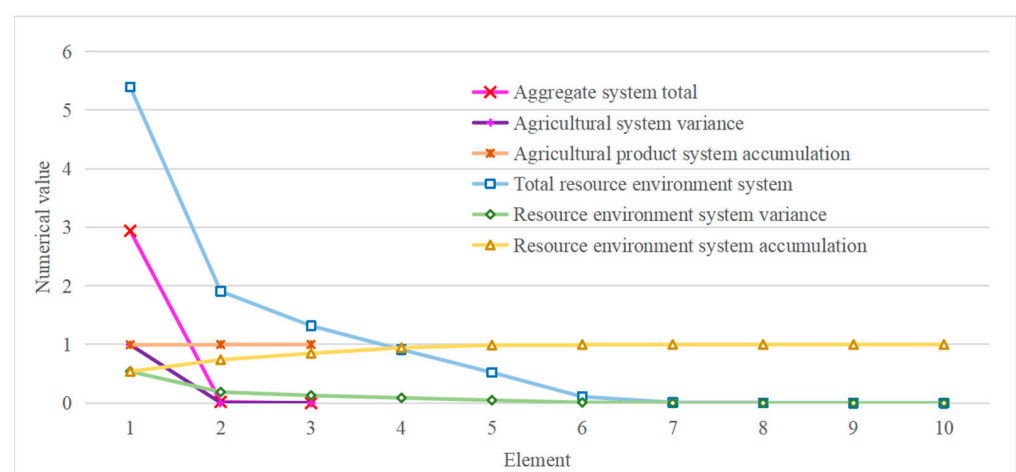


Figure 7. Variance decomposition principal component analysis diagram of agricultural products, resources, and environment system.

Figure 7 depicts the variance decomposition principal component analysis of the agricultural products, resources, and environment systems. The graph illustrates the variance contributions of different principal components to the overall system variance. The blue line represents the aggregate system total, while the orange line shows the total resource environment system variance. The green line indicates the agricultural product system accumulation, and the pink line represents the resource environment

system accumulation. The table below the graph provides numerical values for each component across different variances and accumulations. For example, the aggregate system total variance for the first principal component is 2.94, while the total resource environment system variance for the same component is 5.393. These values demonstrate the significant contribution of the first few principal components to the overall variance, highlighting key factors that influence agricultural products, resources, and environmental systems. This analysis helps in understanding the primary drivers of variability within the system, aiding in more targeted and effective resource management strategies.

According to the principle that the initial characteristic root is greater than 1, this paper extracts the principal components for the two systems of agricultural products, resources, and environment, respectively. It can be seen from the figure that a principal component extracted by the agricultural product system reflects 99.502% of the information in the system, demonstrating the method's strong explanatory power. The three principal components extracted by the environmental system reflect 84.823% of the information in the system, indicating that the explanatory power of the principal component method is very good. PCA is a statistical technique that transforms the original variables into a new set of uncorrelated variables (principal components) that capture the maximum variance in the data. The steps involved in the PCA process in our study are as follows: First, the original data for agricultural products and resource–environment systems were standardized to ensure comparability, transforming the data to have a mean of zero and a standard deviation of one. Next, a covariance matrix was calculated to understand the relationships between the variables. Eigenvalues and eigenvectors were then computed from the covariance matrix, where the eigenvalues represent the amount of variance captured by each principal component, and the eigenvectors indicate the direction of the principal components. Principal components were selected based on the criterion that their eigenvalues are greater than one, capturing the most significant variance in the data. Finally, the original data were transformed into a new set of principal components. For the resource–environment system, three principal components were extracted, accounting for 84.823% of its total information, further underscoring the robustness of the principal component analysis.

Figure 8 shows the comprehensive scores of the low-carbon economy, agricultural products, and resource and environmental systems over time. The blue line represents the composite score of the economic system, the green line represents the composite score of the agricultural system, and the orange line represents the comprehensive score of the resource and environmental systems. The table below the graph provides specific numerical values for each system's score across different time periods. For example, the economic system composite score starts at -4.56762 and gradually increases to 5.97583 , indicating significant growth over time. Similarly, the agricultural system composite score starts at -3.16701 and rises to 5.42576 , while the resource and environmental system score improves from -5.47457 to 5.976445 . This figure highlights the trends and progress in these systems, showcasing how they evolve and interact, ultimately reflecting the effectiveness of policies and practices aimed at promoting sustainability and balanced development.

In this paper, the principle component analysis method is used to calculate the comprehensive scores of agricultural products, resources, and environmental systems. The scores are illustrated in the figure below (the x -axis numbers 1–11 correspond to the years 2010–2020, respectively):

It can be seen from Figure 8 that the comprehensive scores of the low-carbon economy, agricultural products, resources, and environmental systems all show a growing trend over time. This growth is not linear but rather tortuous. Initially, the effect was not good; however, negative numbers are followed by continuous improvement.

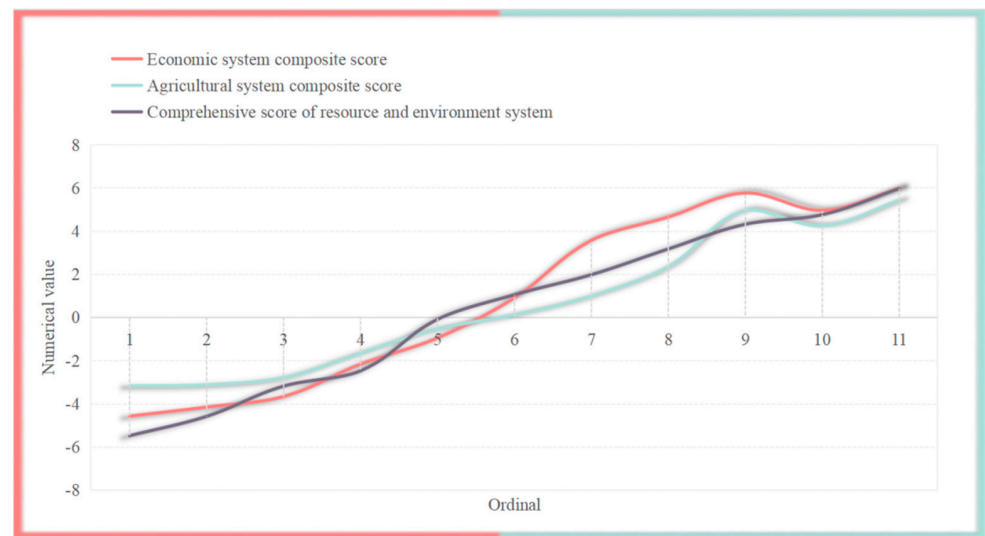


Figure 8. Comprehensive scores of low-carbon economies, agricultural products, resources, and environmental systems.

According to the coupling coordination method, the growth level index (E_i , A_i , and R_i) of the national low-carbon economy, agricultural products, resources, and environment subsystems from 2010 to 2020 is obtained. This paper asserts that the three subsystems are equally vital for regional growth. Therefore, E_i and A_i are assigned the same weight as R_i , which is $1/3$ of the total weight. This calculation yields the comprehensive growth index of the EARE system (Figure 9; the X-ray numbers 1–11 in the figure correspond to 2010–2020, respectively).

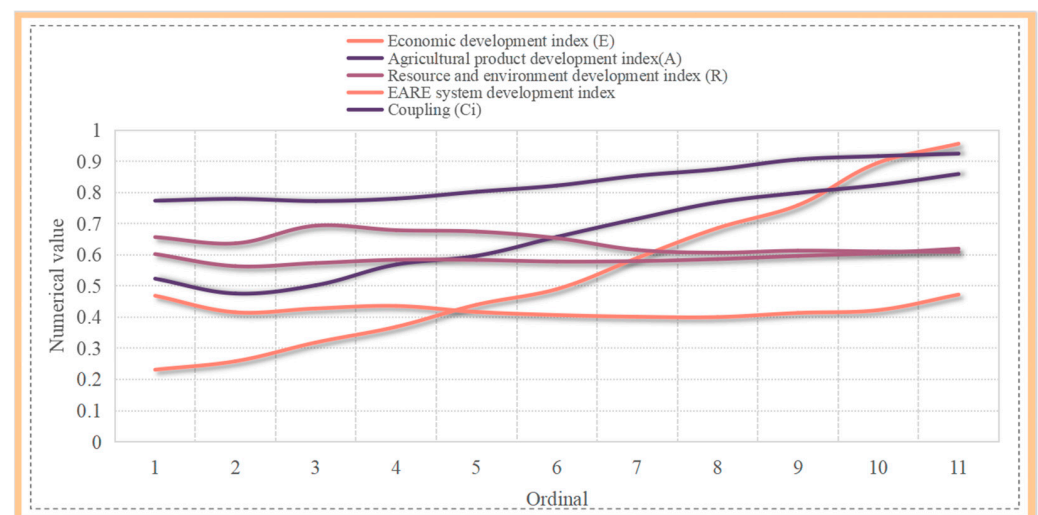


Figure 9. EARE System Comprehensive Development Index Chart.

Figure 9 illustrates the comprehensive development indices of the EARE system, which includes the economic, agricultural, resource, and environmental sectors. The chart tracks the Economic Development Index (E, blue line), Agricultural Product Development Index (A, green line), Resource and Environment Development Index (R, orange line), EARE System Development Index (red line), Coupling Index (C_i , yellow line), and Coupling Coordination Degree (M_i , pink line) over time. The indices show a general upward trend, with the Economic Development Index rising from 0.2314 to 0.9563 and the Agricultural Product Development Index increasing from 0.5234 to 0.8592. The Resource and Environment Development Index remains relatively stable. The Coupling Index and Coupling

Coordination Degree also improve, indicating enhanced integration and coordination among the economic, agricultural, and environmental systems. This figure highlights the progress and interplay between these systems, emphasizing the advancements in achieving balanced and sustainable development.

Observing Figure 9 reveals the growth trends from 2010 to 2020 across different subsystems of the low-carbon economy, agricultural products, resources, and the environment. Firstly, the economic subsystem exhibits a clear overall upward trajectory: slow growth between 2010 and 2014, rapid growth from 2015 to 2019, and stable growth in 2020. Secondly, the agricultural product system curve displays a pattern of initial decline followed by a rise, with a slow decrease from 2010 to 2013 and a rapid increase from 2014 to 2020. Thirdly, the growth trend in the resource and environmental systems is relatively stable, though it shows some fluctuations in certain years. Lastly, the EARE system curve also follows a pattern of initial decline and subsequent rise, with a slight decrease from 2010 to 2012 and a steady growth from 2013 to 2020, reflecting the combined effects of the individual subsystems.

The analysis of the coupling degree shows that from 2010 to 2020, the national EARE system was consistently in a high-level coupling stage. According to the classification criteria in Table 2, the system was in the run-in growth stage from 2010 to 2015, shifting to a high-level growth stage from 2016 to 2020, marking the transition from a run-in phase to a more advanced stage.

In terms of the coupling coordination degree, the national EARE system evolved from a low level to a medium and high level over the same period. According to the criteria in Table 2, the system was overall in a stage of imbalance and recession from 2010 to 2014, transitioned to a sub-coordinated growth stage from 2015 to 2018, and entered a coordinated growth stage from 2019 to 2020. This progression signifies a gradual shift from a mild disorder decline phase to a high-quality, coordinated growth stage. Additionally, the analysis indicates that from 2010 to 2015, the country experienced balanced resource growth with lagging economic development, which then transitioned to balanced economic growth with lagging resource and environmental growth from 2015 to 2020.

4. Conclusions

This paper investigates the coupling of agricultural products with resources and the environment within a low-carbon economy framework, yielding several key conclusions. First, given the dual objectives of ensuring national food security and promoting the sustainable growth of regional resources, environment, and economy, specific actions are recommended for various regions. For example, in areas like Huanghuaihai, Northeast China, and the middle and lower reaches of the Yangtze River, there is a critical need to enhance the efficiency of water resource utilization. Additionally, regions such as Northeast China should focus on intensifying the utilization of agricultural land. Furthermore, areas like Huanghuaihai and the middle and lower reaches of the Yangtze River are advised to bolster the construction of agricultural ecological environmental protections, including soil erosion control.

The policy implications of this research are significant, providing valuable insights into how regional resource, environmental, and economic sustainability can be balanced with the goal of maintaining food security in China. This study offers practical recommendations that can guide policy formulation and strategic planning.

The relationship between agricultural products and resource and environmental systems has emerged as a critical area of study both domestically and internationally. Investigating the alignment of these systems within the context of a low-carbon economy, particularly from a temporal and spatial perspective, is essential for understanding and optimizing their interaction.

Additionally, the growth of agricultural free trade should focus on adjusting the internal structure of agricultural products, emphasizing the expansion of agricultural product processing, local specialty product processing, and the rural tertiary industry. This

approach aims to promote large-scale processing of agricultural products and develop a number of agricultural trade systems enriched with scientific and technological content. Concurrently, efforts should be made to accelerate the enhancement of China's agricultural free trade infrastructure and deepen the reform of the agricultural free trade system. Such measures are crucial for ensuring that China's agricultural free trade efforts effectively support resource conservation and environmental protection.

These conclusions are based on a comprehensive analysis using principal component analysis (PCA) and the coupling coordination degree model. The PCA results indicated that a single principal component extracted for the agricultural product system explained 99.502% of the variance, and three principal components for the resource-environment system explained 84.823% of the variance. The coupling coordination degree model revealed significant variations in the coupling degree and coordinated growth degree across different regions and time periods. These findings support our recommendations and underscore the need for targeted regional strategies to achieve balanced and sustainable development.

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References

1. Panitchpakdi, S. World Investment Report 2010: Investing in a low-carbon economy (overview): Key messages: FDI trends and prospects. *Transnatl. Corp.* **2010**, *19*, 63–106.
2. Wen, Z.; Li, H. Analysis of potential energy conservation and CO₂ emissions reduction in China's non-ferrous metals industry from a technology perspective. *Int. J. Greenh. Gas Control* **2014**, *28*, 45–56. [\[CrossRef\]](#)
3. Cui, Y. Special reports on the development of artificial intelligence and the rule of law. In *Blue Book on AI and Rule of Law in the World (2020)*; Springer Nature Singapore: Singapore, 2022; pp. 129–206.
4. Vargas-Hernández, J.G.; Vargas-González, O.C.; González-Ávila, F.J. Sustainable development and its implications in the green economy concept. In *Circular Economy and Manufacturing*; Woodhead Publishing: Sutton, UK, 2024; pp. 197–216.
5. Ullah, S. A sociological study of environmental pollution and its effects on the public health Faisalabad city. *Int. J. Educ. Res.* **2013**, *1*, 2.
6. Chen, A.; Gao, J. Urbanization in China and the coordinated development model—The case of Chengdu. *Soc. Sci. J.* **2011**, *48*, 500–513. [\[CrossRef\]](#)
7. Negash, M.; Kelboro, G. Effects of socio-economic status and food consumption pattern on household energy uses: Implications for forest resource degradation and reforestation around Wondo Genet Catchments, South-Central Ethiopia. *East. Afr. Soc. Sci. Res. Rev.* **2014**, *30*, 27–46. [\[CrossRef\]](#)
8. Kun, Y.; Peng, Z. Characteristics of China's Development in the New Era Explained in Light of Economic Principles. *China Econ.* **2018**, *13*, 2–13.
9. Ruili, G.; Linlin, W. Evaluation of Coordinated Development of Urbanization and Ecological Environment in the Efficient Ecological Economic Zone of the Yellow River Delta. *Meteorol. Environ. Res.* **2018**, *9*, 48–51.
10. Mitchell, P. Chemiosmotic coupling in oxidative and photosynthetic phosphorylation. *Biochim. Biophys. Acta (BBA) Bioenerg.* **2011**, *1807*, 1507–1538. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Tang, Z. An integrated approach to evaluating the coupling coordination between tourism and the environment. *Tour. Manag.* **2015**, *46*, 11–19. [\[CrossRef\]](#)
12. Wang, J.; Zhai, Z.J.; Jing, Y.; Zhang, C. Optimization design of BHP system to maximize to save energy and reduce environmental impact. *Energy* **2010**, *35*, 3388–3398. [\[CrossRef\]](#)

13. Li, J.; Akdeniz, N.; Kim HH, M.; Gates, R.S.; Wang, X.; Wang, K. Optimal manure utilization chain for distributed animal farms: Model development and a case study from Hangzhou, China. *Agric. Syst.* **2021**, *187*, 102996. [[CrossRef](#)]
14. Zhan, Q.; Li, G.; Zhan, W. Measurement of the coupling coordination relationship between the structures of secondary vocational school programs and industries in China. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 1–10. [[CrossRef](#)]
15. Li, X.; Qian, Z.; Lu, S.; Wu, J. Energy efficient virtual machine placement algorithm with balanced and improved resource utilization in a data center. *Math. Comput. Model.* **2013**, *58*, 1222–1235. [[CrossRef](#)]
16. Higgins, S.I. Ecosystem assembly: A mission for terrestrial earth system science. *Ecosystems* **2017**, *20*, 69–77. [[CrossRef](#)]
17. Singh, S.; Bakshi, B.R. Accounting for emissions and sinks from the biogeochemical cycle of carbon in the US economic input-output model. *J. Ind. Ecol.* **2014**, *18*, 818–828. [[CrossRef](#)]
18. Fu, W.; Lin, T. Comparison of models for coupled relation between regional social-economic development and ecological environment. *Sichuan Environ.* **2010**, *29*, 102–109.
19. Meng, L.; Yang, R.; Sun, M.; Zhang, L.; Li, X. Regional sustainable strategy based on the coordination of ecological security and economic development in Yunnan Province, China. *Sustainability* **2023**, *15*, 7540. [[CrossRef](#)]
20. Zhu, X.Q. Construction and Application of Urban and Rural Coordinated Development Evaluation Index System of Xinxiang City. *J. Henan Agric. Sci.* **2013**, *49*, 109–113.
21. Hao, Y. Dynamic Study on Urban Development and Ecological Efficiency in Northern Xinjiang-Take urumqi, hami and turpan for Example. In Proceedings of the 2018 2nd International Conference on Management, Education and Social Science (ICMESS 2018), Qingdao, China, 23–24 June 2018; pp. 1278–1283.

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