Analysis of Coupling Coordination between Resource Environment and Economic Development in Anhui Province

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Abstract: In order to facilitate the balanced advancement of regional economic systems and natural resource-ecological systems in Anhui Province, a multi-dimensional indicator dataset spanning 2009 to 2021 was compiled. Data standardization techniques were employed to preprocess the dataset, an information weight quantification approach was utilized to compute indicator weights, and a synergistic harmonization assessment framework was applied to dissect the interconnected dynamics between regional economic systems and natural resource-ecological systems. The key findings are outlined as follows: (1) The integrated assessment metric of natural resource-ecological systems in Anhui Province exhibited an oscillating ascending trajectory over the 2009–2021 study period. (2) The integrated assessment metric of regional economic advancement in Anhui Province demonstrated a pronounced linear expansion trajectory from 2009 to 2021, signifying that the provincial economy has remained in a phase of accelerated advancement. (3) A robust synergistic harmonization interconnection exists between regional economic systems and natural resource-ecological systems in Anhui Province.

Keywords: Coupling Coordination Degree; Economic Development; Resources and Environment; Anhui Province

1. Introduction

The progress of economic systems and ecological systems are inherently interdependent. Systematic investigations into the interactive synergies between regional economic advancement and ecological systems can yield insightful references for regional long-term balanced advancement [1]. At present, researchers across the globe have carried out extensive inquiries into the interconnected dynamics of regional economic advancement and ecological systems, employing a diverse array of methodological approaches including the enhanced TOPSIS technique [2], rank-sum ratio approach, entropy weighting technique [3], and synergistic coordination evaluation framework [4] for analytical purposes. Among these endeavors, research teams led by Bian Shiyu and Su Sheng-liang et al. [5-7] have applied the synergistic coordination evaluation framework to dissect the synergistic coordination levels between regional economic advancement and ecological systems in the northern prefectures of Anhui Province and the Liupan Mountains area of Ningxia.

Amid the continuous deepening of national reform initiatives and the implementation of regional developmental strategies, the province of Anhui has encountered mounting pressures concerning its natural resources and ecological systems, and the tensions between natural resource constraints, ecological challenges, and regional economic advancement have grown progressively pronounced. In this study, data pertaining to a diverse set of metrics across the province of Anhui from 2000 to 2021 were gathered, and the synergistic coordination evaluation framework was employed to examine the integrated systems of regional economic advancement, natural resources, and ecological conditions, with the aim of exploring the synergistic advancement status between regional economic advancement and natural resource-ecological constraints, as well as their evolutionary trajectories over the study period.

2. Regional Context and Geographical Profile

The study region spans a total land extent of 140,100 km² and lies within a climatic gradient bridging the warm-temperate and subtropical biomes. Mean annual thermal conditions oscillate between 14°C and 16°C, while annual mean rainfall amounts range from 700 mm to

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2,000 mm, endowing the territory with abundant freshwater endowments, encompassing more than 2,000 rivers and over 110 lacustrine bodies. Geologically, the region hosts substantial mineral deposits, with 128 documented mineral categories and 110 varieties with verified reserves. By the conclusion of 2022, the region was home to a resident populace of 61.27 million individuals, and had attained a gross regional product (GRP) of 4.5045 trillion yuan, solidifying its status as a pivotal hub for agrarian output, energy provision, primary material supply, and advanced manufacturing and processing sectors.

3. Research Data and Methods

3.1 Index Selection and Data Source

Following the basic principles of index selection [8,9] and in consideration of the actual situation in the study area, a set of 14 indexes was selected for the coupling coordination evaluation system (Table 1). The index data was sourced from the *Anhui Statistical Yearbook* and relevant departments such as the Anhui Provincial Department of Ecology and Environment.

Table 1. Evaluation Index System and Index Weights

Objective layer	Criterion layer	Index layer	Index weight
Research on the coupling of resources, environment and economic development	Resources and environment g(y)	Forest coverage (+)y_1	0.0443
		Cultivated area (+)y_2	0.1214
		Per capita water resources (+)y_3	0.0665
		Per capita residential energy consumption intensity (-)y_4	0.0801
		Holistic Resource Recovery Efficiency for Non-Hazardous Manufacturing Solid-State Residues (+)y_5	0.0686
		Municipal wastewater treatment efficiency (+)y_6	0.0286
		Industrial sulfur dioxide emissions (-)y_7	0.1361
	Economic development f(x)	Per capita gross regional product (GRP) (+)x_1	0.0628
		Per capita disposable income of urban households (+)x_2	0.0663
		Share of secondary sector in gross regional product (GRP) (+)x_3	0.082
		Share of tertiary sector in gross regional product (GRP) (+)x_4	0.0918
		Rural Engel coefficient (-)x_5	0.0717
		Total industrial output value (+)x_6	0.0452
		Energy consumptions per GDP (-)x_7	0.0346

(+) denotes a beneficial indicator, and (-) denotes a detrimental indicator.

3.2 Index Weight Determination

3.2.1 Data standardization

Due to differences in the attributes and units of measurement of various indicator data, they are not comparable with each other. Therefore, it is necessary to standardize the indicator data to obtain relatively objective indicator weights. This paper adopts the normalization theory for data standardization. And the calculation formulas are (1) and (2).

Positive index:

$$Y_{ij} = \frac{x_{ij}-x_{jmin}}{x_{jmax}-x_{jmin}} \quad (1)$$

Negative index:

$$Y_{ij} = \frac{x_{jmax}-x_{ij}}{x_{jmax}-x_{jmin}} \quad (2)$$

Where

Y_{ij} =the normalized value;

x_{ij}=the original value;

x_{jmax} represents the upper bound value of the j-th indicator across all observations, and x_{jmin} represents the lower bound value of the j-th indicator across all observations.

3.2.2 Quantification of indicator weighting

The information entropy weighting approach was employed to quantify the indicator weights, which reflect the differential contribution of each indicator within the assessment framework [10]. The computational procedure is outlined as follows:

Calculate the proportional share p_{ij} of the standardized indicator value for the i-th observation under the j-th indicator:

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

Calculate the information entropy of each indicator, derive the information entropy e_j corresponding to the j-th indicator:

$$e_j = -k\sum_{i=1}^{m} \cdot \ln p_{ij}, \text{ in which } k=\frac{1}{\ln m} \quad (4)$$

Derive the weight of each indicator, compute the final weight ω_j assigned to the j-th indicator:

$$\omega_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (5)$$

Where

y_{ij}: The standardized value of the j-th indicator for the i-th observation;

e_j: The information entropy value associated

with the j-th indicator;
ω_j: The quantified weight value of the j-th indicator within the assessment framework.

3.3 Synergistic Harmonization Magnitude Framework

Systemic synergy encapsulates the dynamic evolution of reciprocal shifts from chaotic to ordered states among distinct subsystems [11], whereas harmonization quantifies the equilibrium state and intensity of alignment between or within subsystems throughout their evolutionary trajectory. Synergistic harmonization can elucidate the magnitude of interlinkages across distinct subsystems [12]. Leveraging the synergistic interconnection between the integrated assessment metric for regional economic advancement f(x) and the integrated assessment metric for natural resource-ecological conditions g(y), the assessment of synergistic interactions between these two entities can be implemented, with categorization criteria and evolutionary phases segmented into six distinct tiers (Table 2) [13]. The intensity of synergistic harmonization between the two entities can be evaluated and categorized, further stratified into five distinct tiers (Table 3). The detailed computational expression is presented as follows:

$$D = \sqrt{C \times T} \quad (6)$$

$$T = \alpha f(x) + \beta g(y) \quad (7)$$

$$C = \left\{\frac{f(x)\times g(y)}{[f(x)+g(y)]^2}\right\}^{\frac{1}{2}} \quad (8)$$

$$f(x) = \sum_{i=1}^{m} a_i x'_i \quad (9)$$

$$g(y) = \sum_{j=1}^{n} b_j y'_j \quad (10)$$

Where

D: The synergistic harmonization magnitude (the core metric quantifying the level of coordination between subsystems); C: The synergistic interconnection index (measuring the strength of interaction between the two subsystems);
T: The integrated assessment score (reflecting the overall developmental level of both subsystems);
α, β: Pre-specified weighting coefficients, set to $\alpha=\beta=0.5$ to assign equal importance to both subsystems;
f(x): The integrated assessment function for the regional economic-social subsystem;
g(y): The integrated assessment function for the natural resource-ecological subsystem;
a_i: The quantified weight of the i-th indicator within the regional economic-social subsystem;
b_j: The quantified weight of the j-th indicator within the natural resource-ecological subsystem;
x'_i: The normalized value of the i-th indicator in the regional economic-social subsystem;
y'_j: The normalized value of the j-th indicator in the natural resource-ecological subsystem.

Table 2. Coupling Degree Grading Standards and Action Stages

Coupling degree	Coupling action stages
C=0	Disordered developmental phase
0＜C＜0.3	Incipient synergistic interconnection phase
0.3≤C＜0.5	Antagonistic interaction phase
0.5≤C＜0.8	Transitional adjustment phase
0.8≤C＜1	Advanced synergistic interconnection phase
C=1	Benign resonant synergistic phase

Table 3. Typology and Discriminatory Criteria for Synergistic Harmonization Magnitude

Synergistic Harmonization Magnitude (D)	Harmonization Level
0＜D≤0.2	Minimal synergistic harmonization
0.2＜D≤0.4	Incipient synergistic harmonization
0.4＜D≤0.6	Moderate synergistic harmonization
0.6＜D≤0.8	Advanced synergistic harmonization
0.8＜D≤1	Optimal synergistic harmonization

4. Results and Analysis

4.1 Analysis on Evolution of Resources and Environment System

According to Table 1, it can be inferred that within the natural resource-ecological systems, industrial SO_2 discharge levels (0.1361), arable land extent (0.1214), and per capita residential energy use (0.0801) exhibit relatively elevated indicator weights.
Assessment grounded in the time-series variations of the integrated assessment metric for natural resource-ecological systems in Anhui Province (Fig. 1) demonstrates that this metric has followed a general ascending trajectory with periodic oscillations from 2009 to 2021, rising

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from 0.2276031 in 2009 to 0.7364297 in 2021, corresponding to an expansion rate of 223.56%.

During 2009–2010, the integrated assessment metric for natural resource-ecological systems displayed an ascending trajectory with an expansion rate of 38.49%. This can be attributed to the sustained reduction in per capita residential energy use, alongside increments in freshwater endowments, forestry resource stocks, and other related factors. Furthermore, technological investment has driven continuous improvements in the resource recovery efficiency of non-hazardous manufacturing solid residues and municipal wastewater treatment efficiency, thereby alleviating pressures on natural resource-ecological systems.

In the period 2010–2011, the integrated assessment metric for natural resource-ecological systems contracted by 39.10%, primarily stemming from abrupt declines in the resource recovery efficiency of non-hazardous manufacturing solid residues and per capita freshwater endowments.

From 2011 to 2013, the expansion rate remained sluggish at merely 33.14%. Despite notable improvements in municipal wastewater treatment efficiency and the resource recovery efficiency of non-hazardous manufacturing solid residues, the enhancement of freshwater endowments and forestry resource stocks was inconspicuous, and industrial SO_2 discharge levels escalated. Consequently, industrial development exerted a relatively pronounced adverse influence on natural resource-ecological systems.

Between 2013 and 2014, the expansion rate rose sharply to 105.51%, mainly driven by substantial increases in freshwater endowments, forestry resource stocks, and particularly arable land extent.

From 2014 to 2018, the expansion rate stabilized at 30.97%. This stability arose from the consistent performance of municipal wastewater treatment efficiency and arable land extent, resulting in a gradual increment in the integrated assessment metric for natural resource-ecological systems.

During 2018–2019, the integrated assessment metric for natural resource-ecological systems experienced an abrupt contraction of 21.77%, potentially linked to rapid industrial expansion, a notable decline in the resource recovery efficiency of non-hazardous manufacturing solid residues, and detrimental effects on freshwater endowments, leading to worsening conditions within natural resource-ecological systems in Anhui Province.

From 2019 to 2020, the integrated assessment metric for natural resource-ecological systems expanded rapidly, with an expansion rate of 39.27%. This may reflect responses to national strategic policies, as 2019 marked a pivotal year for attaining comprehensive moderate prosperity. Anhui Province implemented a suite of pollution abatement and control initiatives, effectively advancing ecological stewardship. From2020 to 2021, the integrated assessment metric for natural resource-ecological systems exhibited a minor contraction of 1.75%. Over this timespan, accelerated regional economic advancement exerted amplified strains on natural resource-ecological systems.

The peak magnitude of the integrated assessment metric for natural resource-ecological systems in Anhui Province was documented at 0.7495428 in 2020, which can be ascribed to the effective rollout of ecological stewardship initiatives formulated in alignment with the national strategic objective of attaining comprehensive moderate prosperity. Conversely, the trough magnitude of the integrated assessment metric was recorded at 0.1919711 in 2011, primarily driven by the manufacturing expansion phase prevailing during this era, which precipitated manufacturing-related pollution and suboptimal utilization of freshwater endowments and other natural resources, compounded by restricted technical innovations in the treatment of manufacturing residues, thereby imposing substantial pressures on natural resource-ecological systems.

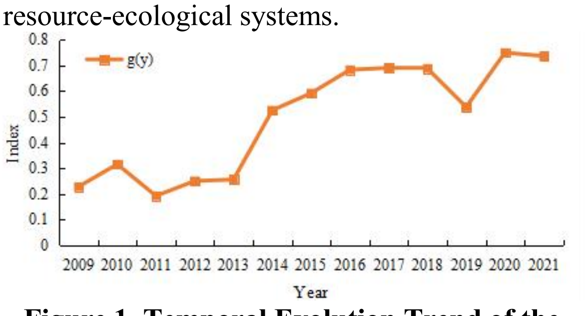

Figure 1. Temporal Evolution Trend of the Integrated Assessment Metric for Natural Resource-Ecological Systems

Of particular note, the integrated assessment metric for natural resource-ecological systems in Anhui Province contracted by 21.77% in 2019, registering a value of 0.538183, whereas the metric expanded by 39.27% in 2020 relative to 2019. This abrupt contraction was preceded by a

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pronounced reduction in the resource recovery efficiency of non-hazardous manufacturing solid residues, which induced degradation of freshwater endowments and a concomitant downturn in the integrated assessment metric.

4.2 Temporal Evolution Assessment of Regional Economic Advancement Systems

Table 1 reveals that within the framework of regional economic advancement systems, the indicators bearing relatively prominent weights include the share of tertiary sector in gross regional product (GRP) (0.0918), the share of secondary sector in GRP (0.082), and the rural household Engel's coefficient (0.0717).

Drawing on time-series variations in the integrated assessment metric for regional economic advancement in Anhui Province (Fig. 2), it is apparent that this metric has followed a linear ascending trajectory from 2009 to 2021, rising from 0.1297428 in 2009 to 0.8452676 in 2021, corresponding to a notable expansion rate of 551.49%. This trajectory signifies that Anhui Province has entered a stage of accelerated regional economic advancement. From 2009 to 2019, the integrated assessment metric for regional economic advancement displayed an ascending trajectory with an expansion rate of 488.62%. Nevertheless, a minor contraction of 1.47% in the metric was observed from 2019 to 2020. Notably, the integrated assessment metric for regional economic advancement in Anhui Province registered a substantial expansion rate of 12.34% from 2020 to 2021.

The peak magnitude of the integrated assessment metric for regional economic advancement in Anhui Province was documented at 0.8452676 in 2021, which can be ascribed to the consistent enhancement in regional economic advancement within Anhui Province. Conversely, the trough magnitude of the integrated assessment metric was recorded at 0.1297428 in 2009, which stemmed from the nascent level of regional economic advancement in Anhui Province during this interval, as it remained in the incipient developmental stage. Notably, the integrated assessment metric for regional economic advancement in Anhui Province contracted by 1.47% in 2020, registering a value of 0.752438 relative to 2019. However, the metric expanded by 12.34% in 2021 relative to 2020. This trajectory may be attributed to the reduction in the share of secondary sector in GRP, which reached its nadir from 2019 to 2020, resulting in impediments to industrial advancement.

Throughout the research interval, per capita gross regional product (GRP) in Anhui Province escalated from 17,715 yuan in 2009 to 70,321 yuan in 2021, corresponding to an approximate fourfold expansion rate. Per capita disposable income of urban households rose from 14,085.74 yuan in 2009 to 43,008.7 yuan in 2021, corresponding to a threefold expansion rate. The rural household Engel's coefficient diminished from 40.9% in 2009 to 33.6% in 2021. These trajectories signify that the regional economy of Anhui Province has sustained a steady expansion trajectory.

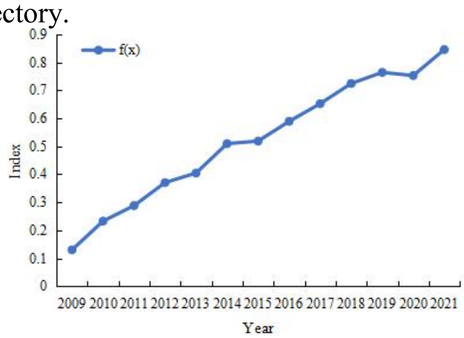

Figure 2. Temporal Evolution Trend of the Integrated Assessment Metric for Regional Economic-Social Systems

4.3 Assessment of Synergistic Harmonization Magnitude across Regional Economic Advancement, Natural Resource Endowments, and Ecological Systems

In accordance with Equations (6), (7), (8), (9), and (10) of the synergistic harmonization assessment framework, the synergistic harmonization magnitude across regional economic advancement, natural resource endowments, and ecological systems in Anhui Province was computed, as illustrated in Figures 3 and 4.

As depicted in Figure 3, the synergistic harmonization magnitude among regional economic advancement, natural resource endowments, and ecological systems in Anhui Province has demonstrated a general ascending trajectory, accompanied by intermittent oscillations. The magnitudes of synergistic harmonization among these three systems in Anhui Province from 2009 to 2021 have fluctuated within the range of 0.480 to 0.5, falling within the antagonistic phase, which signifies that the interconnection between the regional economic advancement system and the natural resource-ecological system remains relatively tenuous. The synergistic harmonization magnitude among these three systems has undergone cyclical oscillations, typified by a sequential pattern of "ascension-decline-ascension-decline-ascension-decline" over the 2009–2021 study interval.

As illustrated in Figure 4, the synergistic harmonization magnitude among regional economic advancement, natural resource endowments, and ecological systems in Anhui Province has exhibited a fluctuating ascending trajectory, marked by a pronounced incremental shift. According to Table 2, the synergistic harmonization magnitude in Anhui Province ranges from 0.2931 to 0.6280, with corresponding tiers encompassing incipient synergistic harmonization, moderate synergistic harmonization, and advanced synergistic harmonization.

During 2009–2012, the synergistic harmonization magnitude expanded from 0.2931 to 0.3899, corresponding to an expansion rate of 33.05%, and was characterized by an incipient level of synergistic harmonization. Throughout this phase, Anhui Province underwent accelerated regional economic advancement, yet diverse natural resource endowments were not sufficiently safeguarded, and the ecological ramifications of manufacturing development were inadequately regulated, culminating in natural resource depletion and ecological degradation, as well as a diminished synergistic harmonization magnitude between regional economic advancement and natural resource-ecological systems.

Between 2013 and 2019, the synergistic harmonization magnitude in Anhui Province expanded from 0.4009 to 0.5661, representing an expansion rate of 41.22%. This moderate level of synergistic harmonization was ascribed to the ascending trajectory of the province's economic indicators during this interval, alongside augmented investment in scientific and technological R&D, which fostered enhanced efficiency in manufacturing residue recovery and a concomitant amelioration of ecological conditions.

In the ensuing 2020–2021 interval, the synergistic harmonization magnitude expanded from 0.6128 to 0.6281, corresponding to an expansion rate of 2.50%. This relatively advanced level of synergistic harmonization encapsulates a notable milestone in the province's endeavors to advance balanced regional economic and ecological sustainability. Notwithstanding the incremental elevation in the synergistic harmonization magnitude across regional economic advancement, natural resource endowments, and ecological systems in Anhui Province, to attain an advanced degree of synergistic harmonization among these three domains, Anhui Province ought to sustain the balanced development of regional economic advancement, natural resource endowments, and ecological systems, prioritize the sustainable utilization of natural resources, enhance the efficacy of natural resource utilization, intensify ecological conservation initiatives, and proactively foster the growth of eco-friendly industries.

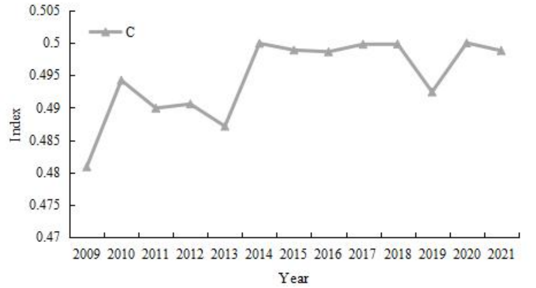

Figure 3. Economic Resource Environment Coupling Degree

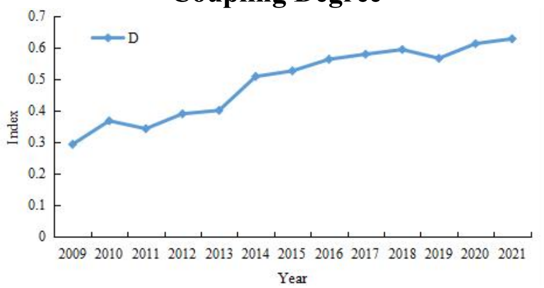

Figure 4. Synergistic Harmonization Magnitude between Regional Economic-Social Systems and Natural Resource-Ecological Systems

5. Conclusions

Between 2009 and 2021, the integrated assessment metric of natural resource endowments and ecological systems in Anhui Province demonstrated an oscillating ascending trajectory, accompanied by a pronounced linear expansion trajectory in the integrated assessment metric of regional economic advancement. The synergistic harmonization magnitude between the regional economic advancement system and the natural resource-ecological systems in Anhui Province exhibited a time-varying oscillating growth trajectory, characterized by notable incremental shifts and distinct developmental phases. From 2009 to 2012, the synergistic harmonization magnitude remained at a relatively incipient level. From 2013 to 2019, it was categorized as moderate synergistic harmonization, and from 2020 to 2021, it was classified as advanced synergistic harmonization.

In the pursuit of regional economic advancement, Anhui Province must prioritize the sustainable utilization of natural resources and ecological conservation, especially in ecologically vulnerable regions, including the safeguarding of water resources, water quality remediation, and the enhancement of per capita freshwater endowments. To address these interconnected challenges, Anhui Province needs to formulate and implement more targeted policy instruments to secure the sustainable supply of water resources and reinforce ecological resilience.

Acknowledgments

This article was funded by the Suzhou University Surplus Fund Sponsored Project (Online Course of Solid Waste Treatment and Disposal, Exploration on Teaching Reform of the Course Solid Waste Treatment and Disposal) (szxy2025jyjf53), College Student Research Project of Suzhou University (KYLXYBXM22-027).

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