

A Study on the Coupling and Coordination of Provincial-Level Digital Finance and Green Innovation, and Pathways for Improvement, in the Context of the "Dual Carbon" Goals

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Abstract: Focusing on the problem of the co-evolution of provincial-level digital finance and green innovation in the context of the "Dual Carbon" target, this paper constructs a multi-dimension index system that includes input, output, and development potential. Using the entropy method to measure the level of development of the subsystems, the interaction of the two systems is analyzed by the coupling coordination model. The results show that the two systems show an upward trend, although the pace of their development is different; the degree of coupling and coordination is characterised by a gradual and fluctuating pattern. Spatially, they display the features of core agglomeration and gradient distribution, with significant regional differences. Further, the research identifies constraining factors and suggests pathways for structural optimization.

Keywords: Digital Finance; Green Innovation; Coupling Coordination; Regional Disparities

1. Introduction

Constrained by the "double carbon" objectives, the region's economy is moving away from factor-driven growth towards a combination of low carbon and efficiency. Digital finance intervenes in the process of green innovation by allocating data and allocating funds, creating a multi-dimensional interaction structure [1]. There are considerable differences between provinces in terms of development bases, technical capacities, and factor endowments, resulting in different pathways for their co-evolution. In this paper, we build a multi-level indicator system, which is centered on digital finance and green innovation. Through the combination of Entropy and Coupling Coordination Model, the Temporal Evolution Model and Spatial Structure Variation can be identified.

2. Indicator System and Research Methods

2.1 Construction of the Indicator System

On the basis of the provincial level, the assessment framework of the dual e-finance and green-innovation systems has been developed [2]. The Green Innovation System consists of "Input — Output — Environment." On the input side, the ratio of research and development staff, R&D spending, and capital stock; on the output side, the key indicators are green patents, revenue from new products, and output per employee, and also includes environmental pressures and environmental improvements; on the environmental side, GDP, education spending, and environmental regulation intensity are used to describe supporting conditions[3]. The digital financial system is based on a "basic-scale-potential" structure, choosing indicators like the number of mobile Internet users, the size of third party payments, the number of fintech firms, and the balance of green loans.

2.2 Entropy Method Measurement

Each indicator is standardized, with positive and negative indicators standardized using the range method, respectively:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

Calculate the proportion of the th indicator J in the th sample i :

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \quad (3)$$

The information entropy is:

$$e_j = -k \sum_{i=1}^n p_{ij} \ln p_{ij} \tag{4}$$

The coefficient of variation and weight are respectively:

$$d_j = 1 - e_j, \quad w_j = \frac{d_j}{\sum_{j=1}^m d_j} \tag{5}$$

where x_{ij} represents the original data, \hat{x}_{ij} represents the standardized values, p_{ij} represents the proportion, e_j represents the entropy value, and w_j represents the weight.

2.3 Coupling Coordination Model

Based on the digital financial development level U_1 and the green innovation development level U_2 , a coupling degree model is constructed:

$$C = \frac{2\sqrt{U_1 \times U_2}}{U_1 + U_2} \tag{6}$$

The comprehensive development index is expressed as:

$$T = \alpha U_1 + \beta U_2 \tag{7}$$

The coordination function is:

$$D = \sqrt{C \times T} \tag{8}$$

where D represents the system coupling strength, T represents the comprehensive development level, C represents the coupling coordination degree, and α and β are weight coefficients, typically set to $\alpha = \beta = 0.5$.

3. Empirical Analysis of the Coupling and Coordination Between Digital Finance and Green Innovation

3.1 Measurement of Subsystem Development Levels

On the basis of entropy-weighted measure, the level of green innovation and digital finance was standardized to form the annual time series. In order to show the differences between the subsystems visually, the data for the key years are summarised in Table 1.

Table 1. Development Levels of Subsystems in Typical Cities, 2015–2023

City	Green Innovation (2015)	Green Innovation (2023)	Digital Finance (2015)	Digital Finance (2023)
Wuhan	0.4504	0.8153	0.2342	0.9719
Yichang	0.1992	0.3566	0.0802	0.3042
Xiangyang	0.2095	0.3748	0.0781	0.2925
Huanggang	0.0977	0.1399	0.0214	0.1118

In Wuhan, as shown in Table 1, the levels of development of both subsystems show a continuous upward trend. Green innovation rose from 0.4504 to 0.8153, while digital finance rose more sharply from 0.2342 to 0.9719, suggesting that the difference between the two dimensions is growing. This model indicates that the speed of digital finance has exceeded the capacity of absorbing and transforming of green innovation. By contrast, Yichang and Xiangyang show relatively balanced growth trends, with the two subsystems steadily improving and converging in the 0.30-0.37 range by 2023, reflecting a more synchronous evolution of financial support and innovation output. Absolute levels, however, remain modest, suggesting limited scope effects. In Huang Gang, the level of green innovation and digital finance is still relatively low, rising from 0.0977 to 0.1399, and from 0.0214 to 0.1118. This suggests a lack of capacity to pool innovative inputs and a weak digital finance infrastructure. There is a clear hierarchical structure between the cities, in which the high level cities show strong growth and structural expansion, whereas the lower level cities are constrained by the limited resources and the slower development of the system.

3.2 Analysis of the Evolution of Coupling Coordination

The coupling coordination degree time series was calculated based on the annual values of U_1 and U_2 , as shown in Figure 1.

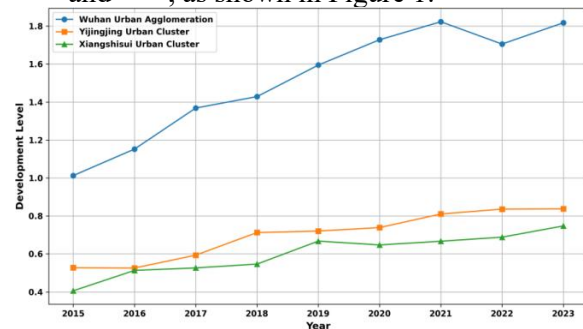


Figure 1. Multi-Regional Time Series Line Chart

The coupling coordination index of each region shows a phase change with time. From 2015 to 2017, it remained generally at a low level, with values rising slowly in tandem with the growth of the subsystems; between 2018 and 2020, the expansion of digital finance accelerated, resulting in a significant increase in the coupling, although there has been a lag; since 2021, there have been fluctuations in some cities: the slope

of the Wuhan Metropolitan Area has decreased, whereas the Yichang-Jingzhou-Jingmen and Xiangyang-Shiyan areas have shown a gradual upward trend, reflecting how the difference in the rate of growth of the subsystems results in the divergence of the coordination curves.

3.3 Analysis of Regional Differences and Constraining Factors

Based on the calculated coupling and coordination indices at the urban level, a spatial distribution is constructed, as illustrated in Figure 2.

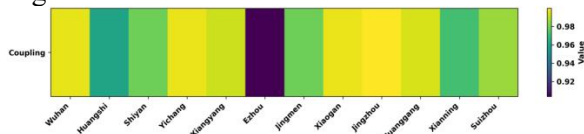


Figure 2. Heatmap of Coupling and Coordination Indices for Various Cities

The coupling coordination shows a distinct spatial gradient distribution, with high values concentrated in Wuhan and its vicinity, forming a continuous high value belt; moderate concentration in Yichang, Xiangyang, and other node cities; low value is concentrated in Huanggang, Xianning, and other areas, showing scattered distribution. In addition to the dispersion of indicators, the number of fintech firms, green patents, and R&D capital stock dominate the spatial distribution, which results in a stratification of coupling coordination between different cities.

4. Pathways for Enhanced Coordination and Synergy

4.1 Strengthening Digital Finance Support

Addressing differences in the internal structure of digital finance, implementing tiered optimization across three dimensions: foundation, scale, and potential [4]. Given the high concentration of fintech firms and the amount of third party payments — which are disproportionately concentrated in specific areas — the establishment of fintech clusters in the core cities will enhance research, development and application capabilities [5]. Increase the penetration of digital financial infrastructure by integrating green credit balances and digital bonds, and implement targeted lending to projects with green patents and high R&D capital, and reduce funding obstacles by means of on-line validation procedures and data-driven risk management mechanisms [6].

Meanwhile, we can make use of nonbank payment and Internet insurance to expand the business scenario, increase the efficiency of the digital payment and settlement, and realize the goal of allocating digital finance to green innovation [7].

4.2 Enhancing the Synergy Efficiency of Green Innovation

Dealing with the features of the GI system — where capital and technology outputs are concentrated in specific areas, and there is considerable variation in the conversion efficiency — we will optimize the internal links in the "input-output environment" chain. Focusing on the spatial differences between R&D capital and the share of R&D staff, we will encourage the diffusion of technology from highly invested cities to surrounding areas, and to share resources by means of joint research and development platforms and interregional research projects [8].

In the output stage, we set up a link mechanism between the results of the patent and the income of the new products, so as to shorten the period of technology commercialization, and make use of the industrial platform for the adoption of high technology productions. Addressing of the ecological pressure index and the difference of the investment in environmental regulation, we will regulate the intensity of the investment and the enforcement of the environmental rules, so as to establish a stable green limit. At the same time, the combination of financial education spending and the participation of enterprises in research and development will improve the matching of the supply of talent with the enterprise's innovation activities, thus reducing the links in the innovation chain.

4.3 Optimizing Regional Coordination Mechanisms

On the basis of the gradient distribution of inter-city coupling and coordination, a tiered linkage structure is built. With Wuhan as a key node, it will make use of its high value agglomeration advantage in the area of digital finance and green innovation to create trans-regional flow channels, which will lead to Yichang, Xiangyang, Yichang, Xiangyang, and other medium-sized cities [9]. For low value areas like Huanggang and Xianning, priority should be given to strengthening infrastructure and introducing innovative elements.

Based on the Wuhan Metropolitan Area, Yichang-Jingmen-Jingzhou, and Xiangyang-Shiyan-Suizhou as the core, a unified data sharing and project coordination mechanism is needed to facilitate interregional allocation of financial, technical and environmental resources[10]. Differentiation of functions and collaborative work can reduce the homogeneity of competition, and foster a multi-tiered cooperative structure.

5. Conclusion

Digital finance and green innovation are characterized by asynchronous evolution and structure differentiation. The combination of technology factor clustering and capital allocation differences results in a gradient distribution of coupling coordination levels, with transmission paths from core to peripheral diffusion in different regions. Through the integration of micro-level entity data, we can improve the accuracy and explanation of the co-evolution process.

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