A Study on the coupling and Coordination Between the Digital Economy and Low-Carbon Development

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Abstract. This paper focuses on the five provinces in Northwest China and employs the entropy-based weighting technique to quantify digitalization and decarbonization indicators spanning the years 2011 through 2023. By establishing a coupling coordination model, the study identifies trends in the interplay between them and categorizes the stages of synergistic integration. The study found that the low-carbon and digital economy indices in the five northwestern provinces rose overall. Significant development disparities existed among the five provinces, with regional gaps initially widening before narrowing. Qinghai and Xinjiang led in low-carbon development, while Gansu lagged behind; Shaanxi and Gansu led in the digital economy, with Ningxia and Qinghai catching up. The synergistic integration of green and digital sectors across the five northwestern provinces improved substantially, with Xinjiang showing the largest increase in 2023. The timing of achieving coupling coordination varied across the five provinces Qinghai the latest among them. This paper aims to offer recommendations to promote he coordinated progress of digitalization and decarbonization across the five northwestern provinces.

Keywords: Digital economy; Low-carbon development; Entropy-weighted method; Synergistic integration metric; Five provinces in Northwest China

1 Introduction

Rapid technological advancements and the promotion of low-carbon governance principles are continuously driving the economy and society toward a new phase of synergistic advancement linking a green, low-carbon economy and the digital sector. In terms of low-carbon development governance, the Chinese government has set the goal of "reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060"which is fully demonstrates China's commitment as a major power to proactively shoulder its responsibilities in addressing global climate change[1].Not only that, but digital transformation has emerged as an irreversible trajectory. According to the Digital China Development Report (2024), China's digital economy reached 53.9 trillion yuan in 2023, accounting for 42.8% of GDP. Data from the Global Climate Action Summit also indicates that the application of digital solutions in sectors such as energy,

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manufacturing, and agriculture could reduce global carbon emissions by 15%[2].Against this backdrop, how to coordinate the development of the digital transformation coupled with decarbonization and promote their synergistic advancement has become a key issue in current research on sustainable development.

Northwest regions as the core area of the Silk Road Economic Belt, the synergistic advancement of its low-carbon transition and high-quality economic development carries significant strategic importance[3].However, the five provinces of Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang exhibit significant differences in terms of resource endowments, industrial structure, urbanization levels, and digital infrastructure development [3].On the one hand，The Northwest region generally faces practical constraints such as heavy reliance on energy, a fragile ecological environment, and an industrial structure that is overly heavy on resource-intensive sectors, making the task of low-carbon transition particularly challenging. On the other hand, with the continued advancement of strategies such as the “West-to-East Gas Pipeline,” “East Data, West Computing,” and the Digital Silk Road, the digital economy in the Northwest region has ushered in new opportunities.

2 Literature Review

2.1 Research on the Digital Economy

There has been a wealth of research on the digital economy in recent years. Wang Li and Wang Yifeng (2026) selected digital infrastructure and the industrialization of the digital economy to establish an indicator system for the digital economy across China’s 30 provinces[4]; Xue Lina, Zhang Xuefeng, and Qi Hongmei (2025) collected data on inputs, outputs, and environmental factors related to the manufacturing and digital economy sectors, and developed a system of evaluation indicators and a framework for assessing the level of coordinated development of the digital economy across cities in Hebei Province[5]; Zhu Shujin and Li Xiaoxiao (2025) used panel data from 284 prefecture-level cities in China to systematically analyze the impact of the digital economy on the efficiency of green development and its underlying mechanisms from the perspective of reducing capital misallocation[6]; YuanWang et al. (2026) developed an assessment framework for digitalization and carbon emissions spanning 30 Chinese provinces developed by applying the theory of coupling and coordination[7].

2.2 Research on Low-Carbon Development

Research on low-carbon development has primarily focused on index calculation, regional disparities, and spatial econometrics. Zhao Ling and Feng Bowen (2026) developed a Drivers-Pressures-State-Response (DPSR) theoretical framework to establish a comprehensive evaluation index system that integrates the synergistic concepts of green development and low-carbon transition[8]; Yu Xiaoping et al. (2024) developed a methodology for measuring low-carbon development efficiency to assess the level of low-carbon development efficiency across multiple dimensions in the Yangtze River Delta urban agglomeration from 2005 to 2020, and conducted a zoning analysis of low-carbon development in the region[9]; Ding Tao et al. (2023) employed methods such as the "tiered horizontal and vertical" classification approach and the "entropy value" nonlinear programming method to analyze the degree of low-carbon economic progress through the lens of the eight primary economic regions, revealing regional disparities and spatial convergence characteristics in the development of low-carbon economies across these zones[10]; Cuixia Gao et al. (2026) collected and established a foundational database on urban low-carbon development in the pre-dual-carbon era. They developed a comprehensive evaluation index system for the quality of low-carbon urban development based on the "drivers-pressures-state-impacts-responses" framework[11].

In summary, existing research provides an important theoretical foundation for this study, but there remains room for further exploration. Therefore, this study takes the five provinces of the Northwest as its research subjects, constructs a comprehensive evaluation system for the digital economy and low-carbon development, and employs a coupling coordination model and spatiotemporal analysis methods to systematically investigate the level of coordinated development between the two and their spatiotemporal differentiation characteristics, with the aim of addressing the shortcomings of existing research.

3 Research Methods and Data Sources

3.1 Establishment of an Indicator System

Digital Economy Indicator System: Building upon the work of researchers such as Shao Yingying[12], Wu Jianhui[13], and Pan Kai[14], the digital economy is categorized into digital economic infrastructure, digital industrialization, and industrial digitalization. Indicators such as internet broadband penetration rate, internet penetration rate, and the scale of mobile phone infrastructure were selected as third-level indicators.

Low-Carbon Development Indicator System: Drawing on the research by Shi Dandan[15] low-carbon development is categorized into economic development level, population and urbanization, energy consumption and efficiency, resource utilization, and environmental emissions. Two systems are presented in Table 1.

Table 1. Digital Economy Indicator System and Low-Carbon Development Indicator System.

Primary Indicator	Secondary indicator	Third-level indicator	Properties
Digital Economy	Digital Foundational Facilities	Broadband subscription coverage	+
		Internet penetration rate	+
		Scale of mobile telephone infrastructure	+
		Fiber-optic backbone extent	+
		Number of web pages	+
		Number of domain names	+

	Digital Industrialization	Total telecommunications service volume per capita	+
		Mobile phone penetration rate	+
		Number of legal entities in the information transmission, software, and information technology services sector	+
		Proportion of employment in the information software industry	+
		Number of domestic patent applications granted	+
		Number of domestic patent applications filed	+
	Sectoral Digital Integration	Digital Inclusive Finance	+
		Proportion of enterprises engaged in e-commerce activities	+
		E-commerce sales	+
		Number of websites per 100 enterprises	+
		Value added in the secondary and tertiary industries	+
		Investment in science and technology innovation	+
		Express delivery volume	+
Low-carbon development	Level of Economic	Per capita GDP	+
	Population and Urban	Number of registered unemployed in urban areas	-
	Energy Consumption and Efficiency	Energy consumption elasticity coefficient	-
		Total energy consumption	-
	Resource Utilization	Per capita water consumption	-
	Environmental Emissions	Ammonia nitrogen emissions in wastewater	-

3.2 Entropy-weighted method

The entropy technique assigns objective weights to metrics according to their informational content; smaller entropy values signify richer information and consequently yield larger weightings. This paperapplies this entropy-based scheme to assign objective weights to each metric, thereby enabling a robust assessment of digitalization advancement and low-emission transition

To eliminate the influence of different indicators, the raw data was processed using the range-standardization method:

$$Z_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \tag{1}$$

In the formula, Z_{ij} represents the standardized value of metric j in province I, X_{ij} denotes the original observation, while X_{max} and X_{min} indicate the highest and lowest recorded values for index j, respectively.

Calculate the weight of the ith province for the jth indicator:

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} \tag{2}$$

Next, calculate the information entropy of the jth metric:

$$e_j = \frac{1}{ln\,n} \sum_{i=0}^{n} P_{ij}\, ln\, P_{ij} \tag{3}$$

Next, calculate the weight of the jth indicator:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m} (1-e_j)} \tag{4}$$

In the formula, n represents the number of provinces, m represents the number of indicators, and w_j represents the entropy-weighted weight of the jth indicator, satisfying$\sum_{j=1}^{m} w_j = 1$

The final result is the Comprehensive Digital Economy Development Index:

$$Y = \sum_{i=1}^{n} w_j \times Z_{ij} \tag{5}$$

In the formula, Y represents the composite index of digitalization and decarbonization, w_j denotes the entropy-derived weight for metric j,n represents the sum of the indicators.

3.3 Coupling Coordination Model

The calculation of coupling and coordination includes three levels: coupling degree, coordination degree, and coupling-coordination degree. The coupling degree reflects the intensity of interaction between two systems.

$$C = 2 \times \sqrt{\frac{DE \times GLC}{(DE+GLC)^2}} \tag{6}$$

In the equation, C represents the coupling coefficient, which takes values in the range [0, 1]; a larger value of C indicates a stronger interaction between the two systems.

The degree of coordination reflects the synchrony of the two systems' development:

$$T = \alpha \times DE + \beta \times GLC \tag{7}$$

In the formula, T represents the coordinated development index, and α and β are undetermined weights; given that the two systems are of equal importance, let α=β=0.5.

The coupling coordination index comprehensively reflects the level of synergistic development between the two systems:

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

In this equation, D represents the coupling coordination index, with values ranging from 0 to 1; a higher value of D indicates a higher level of coordinated development between the two systems.

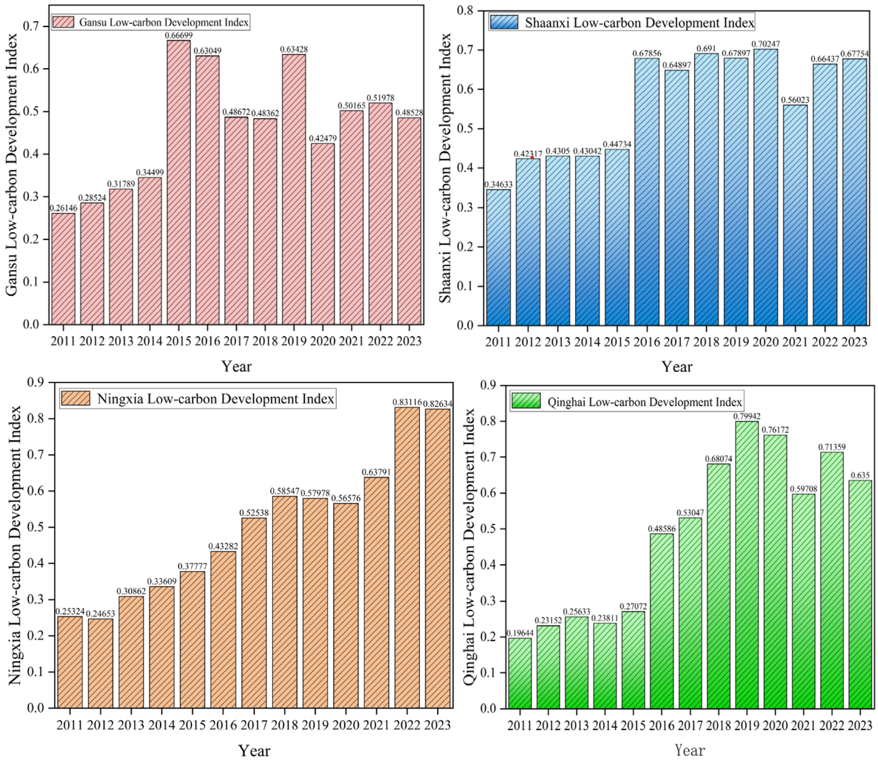
3.4 Data Source

This research draws on a panel dataset covering the five northwestern provinces of China from 2011 through 2023. The data were predominantly extracted from provincial statistical compendia and environmental bulletins, including the Shaanxi Statistical Yearbook and the Ningxia Statistical Yearbook.

4 Empirical findings

4.1 Trends in the Low-Carbon Development Index

The low-carbon development index for the five northwestern provinces has shown an overall upward trend. Shaanxi has continued to improve, demonstrating a relatively stable development trajectory. Gansu has shown an overall upward trend, but with significant fluctuations. Ningxia has improved year by year. Qinghai has remained at a relatively high level. Xinjiang first declined and then rebounded, showing an overall trend of gradual improvement. As shown in Figure 1.



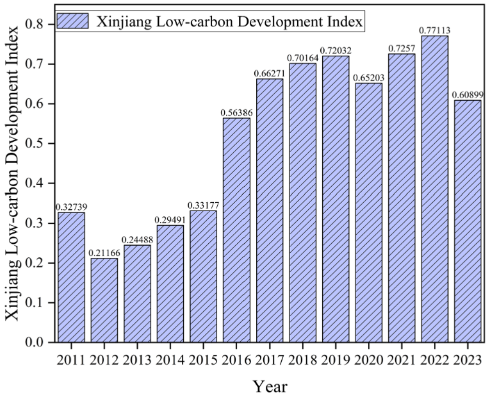
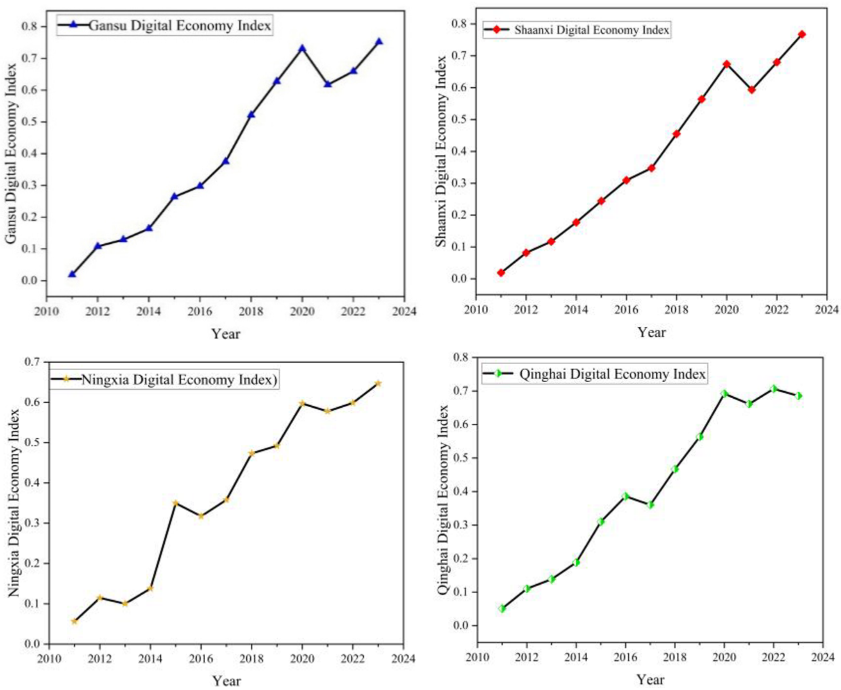


Fig. 1. Trends in the Low-Carbon Development Index for the Five Northwestern Provinces.

4.2 Trends in the Digital Economy Index

The indices of five northwestern provinces are on an upward trajectory, though the patterns of change vary across provinces, as shown in Figure 2. Shaanxi has generally shown a sustained upward trend. Gansu generally exhibits a fluctuating upward trend. Ningxia shows a steady upward trend. Qinghai exhibits a marked upward trend. Xinjiang shows a fluctuating upward trend.



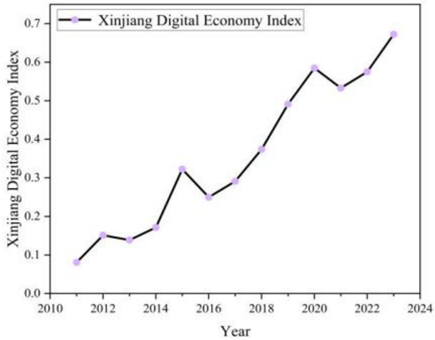


Fig. 2. Trends in the Digital Economy Index for the Five Northwestern Provinces.

4.3 Comparative Analysis of the Five Northwestern Provinces

Comparison of Decarbonization progress Indices: The indices of five northwestern provinces all show an overall upward trend, but there are significant differences in their levels of development. Qinghai and Xinjiang consistently ranked among the top in the later stages; Shaanxi's index remained relatively stable; Ningxia's index fluctuated significantly; and Gansu's index remained relatively low. The low-carbon development indices of the five northwestern provinces exhibit a pattern where disparities first widened and then narrowed.

Comparison of Digital Economy Indices: The digital economy indices of the five northwestern provinces all show an overall upward trend, but there are certain disparities in their levels of development. Shaanxi and Gansu have higher indices in the later stages; Xinjiang's index fluctuates significantly; while Ningxia and Qinghai remain relatively low. The digital economy indices exhibit a pattern where disparities first widen and then narrow. As shown in Figure 3.

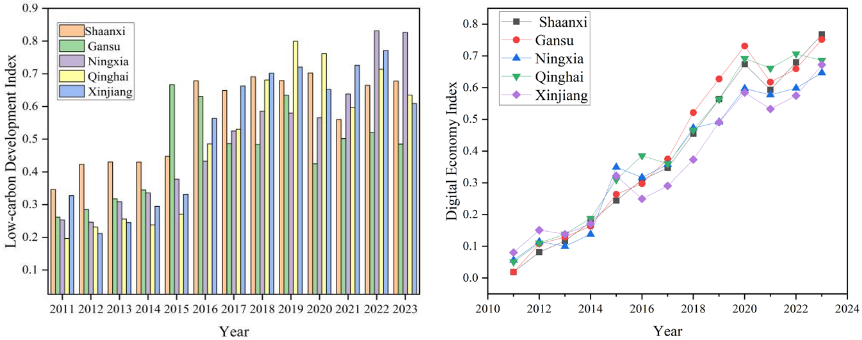


Fig. 3. Trends in the Low-Carbon Development and Digital Economy Index for the Five Northwestern Provinces

4.4 Examining the Synergistic Integration of Decarbonization and Digitalization Across Northwest China's Five Provinces

Analysis of Coupling Coordination: Overall, the degree of coupling and coordination across the five provinces shows a significant upward trend. As shown in Figure 4.

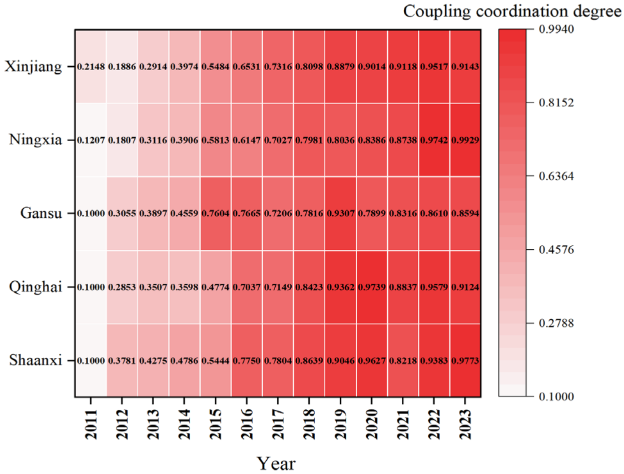


Fig. 4. Degree of Coupling and Coordination Between Low-Carbon Development and the Digital Economy

Analysis of Coupling and Coordination Types: As shown in Table 2, the number of coupling and coordination types experienced by the five northwestern provinces varies. Shaanxi and Gansu experienced six types of coupling coordination, while Ningxia, Qinghai, and Xinjiang experienced seven types. The provinces that achieved coordination earliest were Shaanxi, Gansu, Ningxia, and Xinjiang, all of which entered a coordinated state for the first time in 2015, achieving coordination simultaneously. Qinghai was the last to achieve coordination, entering the "intermediate coordination" state for the first time in 2016.

Table 2. Table of Coupling and Coordination Levels Between Low-Carbon Development and the Digital Economy

Year	Shaanxi	Gansu	Ningxia	Qinghai	Xinjiang
2011	Severe disequilibrium	Severe disequilibrium	Severe disequilibrium	Severe disequilibrium	Moderate imbalance
2012	Mild disequilibrium	Mild disequilibrium	Severe disequilibrium	Moderate disequilibrium	Severe disequilibrium
2013	On the verge of a breakdown	Mild disequilibrium	Mild disequilibrium	Mild disequilibrium	Moderate disequilibrium
2014	On the verge of a breakdown	On the verge of a breakdown	Mild disequilibrium	Mild imbalance	Mild imbalance

2015	a tenuous compromise	Intermediate Coordination	a tenuous compromise	On the verge of a breakdown	a tenuous compromise
2016	Intermediate Coordination	Intermediate Coordination	Basic Coordination	Intermediate Coordination	Basic Coordination
2017	Intermediate Coordination	Intermediate Coordination	Intermediate Coordination	Intermediate Coordination	Intermediate Coordination
2018	Good coordination	Intermediate Coordination	Intermediate Coordination	Good coordination	Good coordination
2019	High-quality coordination	High-quality coordination	Good coordination	High-quality coordination	Good coordination
2020	High-quality coordination	Intermediate Coordination	Good coordination	High-quality coordination	High-quality coordination
2021	Good coordination	Good coordination	Good coordination	Good coordination	High-quality coordination
2022	High-quality coordination	Good coordination	High-quality coordination	High-quality coordination	High-quality coordination
2023	High-quality coordination	Good coordination	High-quality coordination	High-quality coordination	High-quality coordination

5 Conclusions and Recommendations

5.1 Conclusion

Based on the results of the measurement of the digital economy and low-carbon development indices for the five northwestern provinces from 2011 to 2023, as well as the analysis of coupling coordination and coordination types, the following conclusions were drawn: (1) Overall Trends: Both the digital economy and low-carbon development indices for the five northwestern provinces show an overall upward trend, though their development characteristics exhibit significant differences. (2) Regional Disparities: Regional disparities in both indices first widened and then narrowed; since 2020, provinces that were previously lagging have accelerated their catch-up, and regional synergy has gradually strengthened. (3) Coupling and Coordination: The degree of coupling and coordination among the five provinces has significantly improved, with Xinjiang showing the largest increase and Shaanxi the smallest. The rankings were reshuffled in 2023, highlighting the catch-up effect of the less developed provinces. (4) Evolutionary Pathways: Shaanxi and Gansu followed stable evolutionary pathways, while Ningxia, Qinghai, and Xinjiang experienced more fluctuations; Shaanxi, Gansu, Ningxia, and Xinjiang entered the coordination phase simultaneously in 2015, with Qinghai achieving coordination last in 2016.

5.2 Policy Recommendations

(1) Establish a regional coordination mechanism to centrally manage the allocation of resources and factors of production, set up special funds to provide targeted support to

less developed provinces, and gradually narrow the development gap between provinces. (2) Implement targeted policies based on each province's resource endowments, facilitate the deep-seated synergy of digital and green sectors through context-specific, differentiated policy measures, and create distinctive development models (3) Establish a dynamic monitoring system for coordination and synergy, improve mechanisms to ensure policy implementation, and incorporate the outcomes of integrated development into local development evaluation systems.

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