Study on Coupling Coordination Relationship and Interaction Effect Between Digital Economy and Agricultural Modernization in Heilongjiang Province

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Abstract: Utilizing panel data (2013-2023) from Heilongjiang's 12 prefecture-level cities, this study established a comprehensive evaluation index system for a composite system (DE-AM). Methods including comprehensive evaluation, coupling coordination degree (CCD), spatial autocorrelation, and obstacle degree models were employed to analyze CCD, interaction effects, and influencing factors. Key findings are:1. Provincial AM and DE levels showed upward trends, with CCD improving annually. Most cities exhibited DE lag (optimizing), exceptHarbin.2. DE is the Granger cause of AM;AM's positive impact on DE was statistically insignificant.3. Major obstacle factors: Labor productivity, S&T expenditure, telecom business volume, granted invention patents. Key external factors: Economic development level, regional population size, transportation infrastructure level.

Keywords: Digital Economy; Agricultural Modernization; Heilongjiang Province; Coupling and Coordination

As a major agricultural province in China, Heilongjiang's integration of agricultural and digital economies is crucial for its high-quality agricultural development. Existing research primarily focuses on national-level studies, lacking provincial empirical analysis of their coupling. Therefore, this study utilizes panel data from Heilongjiang's prefecture-level cities (2013-2023) and employs comprehensive evaluation, coupling coordination, and PVAR models to analyze their spatiotemporal evolution characteristics. The findings aim to offer scientific guidance for integrated digital-agricultural development in Heilongjiang.

1. Theoretical analysis and Index System Construction

Referring to the coupling coordination mechanism of digital economy and agricultural modernization system proposed by Xu Hui et[1] al., and combined with the problems of agricultural modernization in Heilongjiang Province under the digital background pointed out by Bu Lijun et[2] al., this paper makes the following coupling coordination mechanism of digital economy and agricultural modernization system .

1.1 The Development of Digital Economy has a Great Role in Promoting Agricultural Modernization

The digital economy exhibits an inclusive growth effect. Inclusive finance mitigates information asymmetry, unlocking agricultural market potential and enhancing the market system. It also facilitates agricultural financing, strengthening enterprise viability and thereby increasing farmers' income. Integrating digital technologies with production drives agricultural mechanization and digitization, reducing labor/resource inputs while boosting output and income. Furthermore, digital expansion broadens agricultural sales platforms, enabling participants to access buyer demand information. This optimizes agricultural structures and lowers transaction costs. Additionally, the digital economy enhances sustainable agricultural practices.

1.2 Agricultural Modernization Has a Positive but Insignificant Reaction on Digital Economy

The digital transformation of agricultural enterprises, extending to inputs, production, operations, and economic structure, signifies optimization and expansion of the digital economy. Concurrently, agricultural modernization substantially boosts farmers' incomes and consumption. This increased consumption expands demand in the digital economy market, stimulating supply-side development—meaning agricultural

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modernization feeds back into the digital economy. Additionally, agricultural modernization requires substantial specialized digital talent. However, due to Heilongjiang's relatively low agricultural modernization level, its feedback effect on the digital economy is expected to be insignificant.

2. Research design and Data Sources

2.1 Research Methods

2.1.1 Comprehensive evaluation model

Firstly, this paper uses the entropy method to calculate the weight of each three-level index in the agricultural modernization index system and the digital economy index system. In order to standardize the data, we first use the extreme value standardization method to normalize the data to a unified scale. Then, we use the entropy method to determine the weight of each index to ensure the objectivity and accuracy of the weight. Finally, through the linear weighting method, we calculate the specific value of the first-level index comprehensively.

In this paper, the comprehensive evaluation model is used to calculate the comprehensive development index of digital economy and agricultural modernization in each prefecture-level city in Heilongjiang province, which is based on the weighted sum of weights and indicators. This index aims to comprehensively evaluate the comprehensive development level of digital economy and agricultural modernization. The specific calculation formula is as follows:

$$U = \sum_{j=1}^{m} W_j * x_{ij}^{'}$$

W_j index weight; $x_{ij}^{'}$ Is the value of j in the ith year of a city after standardization.

2.1.2 Coupling coordination model

Coupling coordination model is an effective tool to evaluate the synergy effect and overall efficiency of interaction development between different systems. This model can make up for the mutual influence between relying solely on coupling analysis system of shortcomings. Through the application of coupling coordination model, we can understand the complex interaction between systems more comprehensively, and then provide strong support for relevant decision-making. This paper refers to the research of Fang Shiqiao et[4]] al., and constructs the modified and optimized coupling coordination model of digital economy and agricultural modernization development. The calculation formula is as follows:

$$C = \sqrt{[1-(U_2-U_1)*\frac{U_1}{U_2}]}$$

$$T = \alpha * U_1 + \beta * U_2$$

$$D = \sqrt{C * T}$$

The coupling coordination degree C, coupling, D, and U_1 and U_2 are respectively used to measure the digital economy and the modernization of agriculture comprehensive development index. Alpha and beta are two undetermined coefficients, they are endowed with specific values in this study. T stands for the comprehensive coordination index, which reflects the mutual influence and promotion between digital economy and agricultural modernization. Given their equal importance in driving overall development, we set both α and βat 0.5. In addition, in order to more accurately quantify the development gap between the two, we introduce the concept of relative development and calculate it by the following formula:

$$E = U_1 / U_2$$

According to the characteristics of the digital economy and agricultural modernization, based on the scientific nature of the study, this article refer to the division standard[1] of rogam im.arthroscopic debridement, etc, the coupling coordination degree is divided into 12 types of differences (table 1).

Table 1. Classification and Discrimination Criteria of Coupling Coordination Degree Between Digital Economy and Agricultural Modernization

Types of coupling coordination	Range of coordinated development	Relative degree of development	Type	Level of coordination
Dissonance	0 < D≤0.3	0 < β≤0.8	I	Dissonant digital economy lag type
		0.8 < β≤1.2	II	Dissonant synchronous development type
		1.2 < β	III	Unbalanced agricultural modernization lag type
Antagonism	0.3 < D≤0.5	0 < β≤0.8	IV	Antagonize the lagging type of digital economy
		0.8 < β≤1.2	V	Antagonistic synchronous developmental type
		1.2 < β	VI	Antagonize the lagging type of agricultural modernization

Running-in	0.5 < D≤0.7	0 < β≤0.8	VII	Running-in digital economy lag type
		0.8 < β≤1.2	VIII	Run-in synchronous development type
		1.2 < β	IX	Running-in agricultural modernization lag type
Coordination	0.7 < D≤1	0 < β≤0.8	X	Coordinate the lagged type of digital economy
		0.8 < β≤1.2	XI	Coordinated and synchronous development type
		1.2 < β	XII	Coordinate the lagged type of agricultural modernization

2.1.3 Spatial autocorrelation test

The spatial autocorrelation model can further observe whether the coupling coordination between digital economy and agricultural modernization has spatial aggregation characteristics, and whether there is spatial spillover effect[3] in the coupling coordination degree of each province. The global Moran index and the local Moran index were used to verify the spatial autocorrelation and spatial aggregation.

Global moran index:

$$I=\frac{n*\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2*(\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij})}$$

Local Moran Index: $I_{\mathrm{i}}=x_i\sum_{j\neq1}^{n}W_{ij}x_{ij}$

n is the number of prefecture-level cities is 12; W_{ij} is the adjacency spatial weight matrix, W_{ij}=0 if region i is adjacent to region j, and xi and xj are the coupling coordination degree values of region i and j. Moran's I values between [1, 1], as for the positive correlation, negative negative correlation.

2.1.4 PVAR model

The PVAR model is the panel vector autoregressive model. Through the PVAR model, the direction and degree of influence of digital economy and agricultural modernization can be calculated. The basic calculation formula of the model is as follows:

$$y_{it}=\alpha_0+\sum_{j=1}^{p}\alpha_{i,j}y_{i,t-j}+\gamma_i+\theta_t+\varepsilon_{i.t}$$

In this article, we use to represent different provinces, I t on behalf of the research. α_0 is the intercept term in our model. p represents the lag order we consider.$\alpha_{i,j}$ is a matrix to be estimated, which reflects the impact of fixed effects.$y_{i,t-j}$ denotes the column vector of endogenous variables, which plays an important role in the model.θ_t represents the time effect, which captures the influencing factors that change over time. Finally,$\varepsilon_{i,t}$ represents the regression residual of the model, which reflects the part that the model fails to explain.

2.1.5 Obstacle degree model

The obstacle degree model is used to find out the main obstacle factors that hinder the coupling and coordination of digital economy and agricultural modernization development in Heilongjiang cities. The calculation formula is as follows:

$$A_{ij}=\frac{W_j*I_i}{\sum_{j=1}^{n}(W_j*I_i)}*100\%$$

A_{ij} is the obstacle degree of the JTH index to the coupling coordination degree of agricultural modernization and digital economy in the ith year. The higher the value is, the higher the obstacle degree is. Ii is the deviation degree of indicator; W_j is the weight of each index.

2.1.6 Panel Tobit model

In order to more accurately explore the key external influencing factors of the development of digital economy and agricultural modernization, and accurately identify the external factors affecting the coupling and coordination degree, this paper uses the maximum likelihood method to construct the Tobit regression model of ground random effect. The specific form of the model is as follows:

$$Y=\begin{cases}Y_i=\alpha_0+\beta_0+\beta_t*X_i+\varepsilon_i, Y^*>0\\ 0, Y^*\geq 0\end{cases}$$

Y represents the vector of restricted dependent variables, which is the core object of our analysis;αis the vector of intercept terms, which provides the basic reference point of the model;βis the parameter vector, which reflects the degree of influence of independent variables on dependent variables; X_i represents the vector of independent variables, which is the key explanatory variable in our study; Finally,ε_i represents the random disturbance term, which captures the part of the model that is not explicitly explained.

2.2 Indicator System

Referring to Xu Hui et[1] al. 's construction of digital economy index system, this paper adds the two indexes of digital infrastructure and digital industrialization, as well as his construction of agricultural modernization index system, and selects the modernization of agricultural investment and agricultural development. At the same time, according to the research of Bu Lijun et[2] al., the index of digital innovation ability is added. In addition, according to the selection of agricultural modernization index by Guo Xiuqi et[11] al., the indexes of agricultural production modernization and agricultural economy modernization are added. At the same time, combining with the current level of agricultural modernization in Heilongjiang and the availability of data, eight three-level indicators of agricultural modernization and six three-level indicators of digital economy are selected (Table 2).

Table 2. Evaluation Index System of Digital Economy and Agricultural Modernization and Their Weights

Target layer	Dimensions	Indicator layer	Units	Attributes	Weight
Comprehensive evaluation system of agricultural modernization	Agricultural Modernization Inputs	Electrification of agriculture x_1	10,000 kW/h	+	0.1714
		Financial expenditure x_2	%	+	0.1148
	Agricultural Modernization of Production	Labor productivityx_3	%	+	0.37
		Agricultural mechanization x_4	Kw/ha	+	0.0571
	Modernization of the agricultural economy	Per capita disposable income of rural residents x_5	yuan	+	0.0595
		Rural per capita agricultural outputx_6	yuan	+	0.1321
	Modernization of agricultural development	Urbanization ratex_7	%	+	0.0524
		The net amount of chemical fertilizer applied x_8	Tons of	-	0.0428
Comprehensive evaluation system of digital economy	Digital infrastructure	Internet broadband access user x_9	Ten thousand households	+	0.1107
		Mobile phone penetration rate x_{10}	%	+	0.0309
	Digital industrialization	ITS Employmentx_{11}	Ten thousand	+	0.1897
		Total amount of telecom business x_{12}	One hundred million yuan	+	0.15
	Digital innovation capability	Science and technology expenditure x_{13}	RMB '000	+	0.3349
		Number of authorized invention patents x_{14}	a	+	0.1838

2.3 Data Sources

Considering the availability of data and research is scientific, this article selects the period from 2013 to 2023 panel data of heilongjiang province are 12 district cities as the research object. These data mainly are from heilongjiang statistical yearbook "Chinese city statistics yearbook and the urban statistical yearbook and bulletin. For a small number of missing data, we used the linear interpolation method to supplement the data reasonably.

3. The Empirical Results and Analysis

3.1 Evolution Analysis of Comprehensive Development Level

Computed indices for digital economy and agricultural modernization across Heilongjiang's cities (2013-2023)， The average agricultural modernization index rose from 0.153 to 0.322 during this period, indicating moderate yet still low provincial progress. Daqing achieved significant improvement through its "crop-to-livestock transition" strategy. Qitaihe remains in early development due to economic constraints and limited agricultural foundations. Other cities showed modest advancement.

The digital economy index increased marginally from 0.087 to 0.1436, reflecting minimal annual growth (0.6%) and underdeveloped digitalization. While most cities saw gradual pre-2021 improvement (except Harbin), the province retains significant untapped digital growth potential.

3.2 Analysis of Coupling Coordination Degree and Relative Development Degree

Table 3 presents the coupling coordination degree (D values) for DE-AM development across Heilongjiang's cities from 2013 to 2023. Temporally, the provincial D values show an upward trend: the mean rose from 0.322 to 0.508 , indicating a shift from dysfunctional to running-in coupling overall. All cities exhibited improvement. Harbin and Daqing saw the largest gains: Harbin progressed from running-in (2013) to coordinated (2023), while Daqing advanced from dysfunctional to running-in. Other cities, though still predominantly dysfunctional, also improved. This demonstrates a progressively synergistic and mutually reinforcing dynamic between DE and AM in Heilongjiang during this period.

Spatially, the highest coordination occurred in southern cities, Harbin and Daqing, strongly

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correlating with their superior DE levels. This highlights DE's substantial influence on DE-AM coupling coordination.

Table 3. 2013-2023 Digital Economy - Coupling Coordination Degree of Agricultural Modernization

region	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Daqing	0.34	0.377	0.405	0.405	0.407	0.436	0.444	0.429	0.642	0.614	0.628
Harbin	0.574	0.607	0.649	0.67	0.704	0.717	0.719	0.766	0.799	0.807	0.803
Hegang	0.254	0.256	0.283	0.3	0.297	0.293	0.303	0.329	0.345	0.366	0.372
Heihe	0.186	0.212	0.256	0.272	0.317	0.314	0.335	0.346	0.353	0.398	0.407
Chicken West	0.239	0.279	0.299	0.32	0.324	0.323	0.331	0.359	0.375	0.407	0.401
Jiamusi	0.276	0.295	0.332	0.328	0.36	0.377	0.39	0.424	0.433	0.474	0.48
Mudanjiang	0.284	0.309	0.319	0.348	0.356	0.35	0.371	0.36	0.391	0.396	0.412
Qitai River	0.1	0.145	0.163	0.181	0.206	0.206	0.236	0.232	0.25	0.334	0.326
qiqihar	0.268	0.301	0.314	0.333	0.365	0.371	0.392	0.416	0.431	0.462	0.453
Shuangyashan	0.249	0.265	0.29	0.295	0.271	0.277	0.301	0.314	0.337	0.363	0.377
That is suihua	0.315	0.327	0.345	0.364	0.388	0.398	0.4	0.4	0.42	0.489	0.465
Yichun	0.25	0.261	0.276	0.295	0.217	0.235	0.284	0.299	0.314	0.36	0.373
Mean	0.322	0.35	0.376	0.392	0.399	0.409	0.427	0.444	0.488	0.508	0.508

Temporally, all Heilongjiang cities except Daqing and Harbin entered Phase IV successively. Daqing transitioned from Phase IV to Phase VII in 2021, indicating that while the digital economy lag improved over time in most cities, they remain in a digital economy lag phase. Conversely, Harbin progressed to Phase XII in 2017 but persists in an agricultural modernization lag phase. This demonstrates that digital economy lag primarily constrains their coupling coordination.

Spatially, cities remain predominantly in Phase IV except Daqing and Harbin. Harbin exhibits agricultural modernization lag despite being in optimal coupling Phase XII, while Daqing in Phase VII still experiences digital economy lag. Overall, Heilongjiang's digital economy lags behind its agricultural modernization.

Table 4, 2013-2023 in heilongjiang province cities digital economy and agricultural modernization coupled development stage

Region	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Daqing	IV	IV	IV	IV	IV	IV	IV	IV	VII	VII	VII
Harbin	IX	IX	IX	IX	XII	XII	XII	XII	XII	XII	XII
Hegang	I	I	I	IV	I	I	IV	IV	IV	IV	IV
Heihe	I	I	I	I	IV	IV	IV	IV	IV	IV	IV
Chicken West	I	I	I	IV	IV	IV	IV	IV	IV	IV	IV
Jiamusi	I	I	IV	IV	IV	IV	IV	IV	IV	IV	IV
Mudanjiang	I	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV
Qitai River	I	I	I	I	I	I	I	I	I	IV	IV
Qiqihar	I	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV
Shuangyashan	I	I	I	I	I	I	IV	IV	IV	IV	IV
suihua	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV
Yichun	I	I	I	I	I	I	I	I	IV	IV	IV
Mean	IV	IV	IV	IV	IV	IV	IV	IV	IV	VII	VII

3.3 Spatial Autocorrelation Analysis of Coupling Coordination Degree

To analyze the spatial association and agglomeration changes in DE-AM coupling coordination within Heilongjiang, this study employs the Moran's I index. Global spatial autocorrelation results (Table 5) show the Moran's I shifted from negative to positive overall, but remained statistically insignificant. This indicates no significant spatial relationship between the cities' DE-AM composite systems, attributable to their currently low coupling and development levels. However, the decreasing P-values and positive shift in Moran's I suggest an emerging tendency towards positive spatial autocorrelation.

Table 5. Global Moran Index of Coupling Coordination Degree of Digital Economy-Agricultural Modernization from 2013 to 2023

Year	Moran Index	Z-score	P-value
2013	-0.007	0.488	0.313
2014	0.006	0.560	0.288
2015	-0.013	0.453	0.325
2016	-0.015	0.439	0.330

2017	-0.030	0.351	0.363
2018	0.002	0.537	0.296
2019	0.014	0.608	0.271
2020	-0.069	0.125	0.450
2021	0.098	1.096	0.137
2022	0.102	1.117	0.132
2023	0.094	1.076	0.141

4. Conclusions and Suggestions

4.1 Conclusion

This study examines 12 prefecture-level cities in Heilongjiang Province, constructing a comprehensive evaluation index system based on data from 2013 to 2023 to assess their digital economy and agricultural modernization levels. It analyzes the coupling coordination status between these two systems, yielding the following key findings:

From 2013 to 2023, the digital economy in Heilongjiang's cities showed continuous yet insignificant growth. Except for Harbin, other cities started from a low base and remain at a relatively underdeveloped level. In contrast, agricultural modernization demonstrated a pronounced upward trend, with Daqing exhibiting particularly significant progress in recent years.

Regarding spatial effects, the generally low levels across most cities resulted in negligible spatial spillover and agglomeration effects on neighboring areas.

The coupling coordination degree (CCD) improved annually across all cities, yet significant inter-city disparities exist. Daqing and Harbin achieved relatively higher CCD, strongly correlated with their superior digital economy and economic development levels, reflecting a distinct Matthew effect. All cities except Harbin remain in a digital economy lag phase, highlighting an urgent need to accelerate digital economic development to match agricultural modernization progress. Furthermore, economic development level, transportation accessibility, and regional population size significantly influenced the overall CCD.

4.2 Suggest

The specific interaction mechanisms between the digital economy and agricultural modernization are complex. Due to variations in development starting points and local conditions across prefecture-level cities, the influencing factors and their impact on this interaction differ significantly. As a provincial capital and higher education hub, Harbin possesses a far more developed digital economy than other cities, leading to a high coupling coordination degree between its digital and agricultural sectors. However, this also results in agricultural modernization lagging relatively behind its digital economy. Therefore, Harbin can advance the application and integration of digital technologies in agriculture. Given the currently weak spatial spillover effects, efforts should focus on extending Harbin's digital advantages to surrounding cities.

Excluding Harbin and Daqing, most prefecture-level cities in Heilongjiang exhibit low coupling coordination between the digital economy and agricultural modernization, predominantly remaining in dysfunctional or antagonistic coupling stages. To address this, rural infrastructure—particularly digital infrastructure—requires substantial strengthening. The government should increase investment in agricultural digital technologies to inject vitality into digital agriculture. Actively cultivating interdisciplinary talent proficient in both digital and agricultural fields is crucial, alongside intensifying digital guidance and awareness among farmers. Comprehensively advancing digital technology is essential to achieve both digital industrialization and industrial digitalization, leveraging the inclusive growth effect to alleviate agricultural financing constraints. These measures are vital for achieving coordinated coupling development of the digital economy and agricultural modernization in Heilongjiang.

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