An Empirical Study on the Impact of Urban Digital Level on Regional Innovation Ecology in the Yangtze River Delta

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Abstract. This paper conducts an empirical analysis based on the regional innovation ecological index and digital index of cities from 2020 to 2022 in the Yangtze River Delta jointly issued by the Institutes of Science and Development, Chinese Academy of Sciences and other research institutes. The research finds that the digital level has significantly improved the regional innovation ecological level. The promotion effect of digital level on different indicators to measure regional innovation ecology is different, and the promotion effect on innovation resources is the best. The multiple regression results show that the financial environment, social security environment, and ecological environment will affect the ecological level of regional innovation. Heterogeneity analysis shows that there are significant regional differences in the innovation ecological spillover effects at the digital level. The calculation results of the Moran's I further verify that the digital level has a promoting effect on the regional innovation ecology. Based on the above research, this article suggests that the country should formulate relevant policies to effectively improve the digital level of cities, mobilize the enthusiasm of investors and financiers, increase environmental supervision, increase investment in social security environments, fully utilize the leading role of advanced cities to improve the ecological level of regional innovation.

Keywords: Yangtze River Delta Region; Regional Innovation Ecology; Digital Level; Aggregation Effect.

1. Introduction

1.1 Research Background and Significance

1.1.1 Research Background

Innovation and development are the theme of today's era. In recent years, with the deepening of globalization, innovation has shown a regional development. The innovation ecosystem is an economic community with symbiotic relationships, as well as a loose and interconnected network formed based on long-term trust relationships.[14] In October 2020, the "2020 Yangtze River Delta 41 Urban Innovation Ecological Index Report" was released at the opening ceremony of the Third Yangtze River Delta Science and Technology Achievements Trade Expo. The report includes detailed data of all cities at or above the prefecture level in the Yangtze River Delta region, and comprehensively measures the regional innovation practice level in the Yangtze River Delta region using four indicators: innovation resources, innovation output, industrial potential, and environmental support, which provides a factual basis for strengthening the construction of innovative ecosystems in urban agglomerations in the Yangtze River Delta. In recent years, China's digital economy has flourished, enabling the real economy to improve its quality and efficiency, and becoming a new driving force for economic growth. [13] The digital level is a symbol of the comprehensive strength of a region. There is no doubt that under the innovation-driven development strategy, the improvement of digital level will become a new driving force for the improvement of China's comprehensive strength.

1.1.2 Research Significance and Innovation

As an economically developed region in China, the Yangtze River Delta region ranks among the top in terms of its digital level and regional innovation ecology. Choosing this region as the research object is very representative. In addition, research over the years has simply focused on "regional innovation capabilities", and the concept of "regional innovation ecology" includes "regional innovation capabilities" making the research results more scientific.

1.2 Literature Review

Reviewing relevant literatures, we can find that there has been relatively detailed and complete research on the factors affecting regional innovation capacity. The academic research has explored factors that can potentially improve regional innovation capacity from qualitative to quantitative aspects, while there has been less research on the concept of "regional innovation ecology". At present, the main domestic studies includes: Meng Xiaoqian and Wu Chuanqing (2022) explored the impact of digital finance on regional innovation ecology through panel regression, instrumental variable regression and other methods. The results show that digital finance can significantly promote the regional innovation ecology. Through regional heterogeneity analysis, it is proved that there are significant regional differences in the innovation ecological spillover effect of digital finance. [1] Zhou Qing, Wang Yanling, et al. (2020) showed in their research report through panel data from 73 counties in Zhejiang that the improvement of regional digital access level is conducive to improving innovation performance, and the impact of regional digital equipment, platform construction, and application level on innovation performance presents an inverted U-shaped relationship.[3] Liu Jie et al. (2022) used the VIKOR method to evaluate the regional innovation capability of Beijing. Their research shows that the overall regional innovation capability of Beijing has shown a trend of increasing year by year from 2010 to 2019, with the innovation environment, innovation resources, and innovation performance playing an important role in improving the regional innovation capability. [2] Xiao Jing and Zeng Ping (2022) took the data of listed companies as a sample, and found that digitalization promotes the development of green innovation in enterprises. Innovation human resources investment and financial resources investment play an important role in digitalization and the development of green innovation in enterprises. [4] Foreign research on regional innovation ecosystems mainly focuses on topics such as firm, organization innovation, and prosumer (producer and consumer). Adner. R pointed out that common value creation can be achieved through the complementary collaboration of a series of entities within the system, thereby forming the connotation of the enterprise innovation ecosystem; [6] Zhang et al. believe that the innovation ecosystem requires groups such as suppliers, customers, and partners to achieve value creation and co evolution through self-organization models.[12] On this basis, Autio pointed out that the innovation ecosystem is an organizational network composed of key enterprises or platforms, and the innovation ecosystem requires assistance from producers and users to innovate and develop new value for enterprises. [7] At the stage when "production and consumption" has become a research hotspot, contents such as "digital ecosystem" and "digital healthcare" have also become key research objects.

2. Research Methods and Variable Descriptions

2.1 Explained Variables

The explanatory variable used in this article is the regional innovation ecological level (RIL). The calculation was completed by the 114 industry-university-research collaborative innovation service platform and *East China Science* and *Technology*, and officially released at the Yangtze River Delta Science and Technology Achievements Trading Expo. The calculation basis is shown in Table 1 below:

Table 1. Measurement Indicators of Regional Innovation Ecosystem

Level 1 indicator	Level 2 indicator	Level 3 indicator
Innovation resources	Innovative talents	Ratio of R&D personnel/10000 persons
		Employment in information transmission, computer services, and software industries/10000 persons

		Employment in scientific research, technical services, and geological exploration/10000 persons
	Innovation capital	R&D expenditure/GDP
		(New OTC Market + The Science and Technology Innovation Board) Market Value/GDP
	Innovation platform	Number of national high-tech zones
		Proportion of high-tech enterprises
Innovation industry	Innovation achievements	Number of international scientific and technological papers/10000 persons
		Number of valid invention patents/10000 persons
		Average wage growth rate
	Achievement transformation	Total technical input and technical output/GDP
		Cooperative application for domestic invention patents/10000 persons
		Revenue from sales of new products
Industrial potential	Industrial structure	Growth rate of added value of high-tech industry
		Added value of tertiary industry/GDP
		Proportion of foreign invested industrial enterprises
	Incremental potential	Number of national level maker spaces
		Innovation Challenge
		Profit growth rate of industrial enterprises above designated size
	Efficiency potential	Actual amount of foreign capital used/export amount
		GDP/(total social electricity consumption - residential electricity consumption)
Environmental support	Policy support	Government science and technology expenditure/total budget expenditure
		Frequency of scientific and technological innovation words in government work reports
	Talent support	Number of undergraduate students/10000 people
		Number of higher education teachers/10000 persons
		Local government education expenditure/total budget expenditure
	Technical support	Number of local higher education institutions
		Number of state key laboratory
		Number of national science and technology enterprise incubators
	Innovation foundation	Passenger volume/10000 persons
		Number of Internet broadband access users/10000 persons
		Greening coverage

2.2 Main Explanatory Variables

In this paper, the comprehensive digital level index (DIL) of 41 Yangtze River Delta cities in the 2020-2022 "*Urban Digital Development Index - Cities*" released by the Digital China Research Institute of Xinhua Third Group is selected as the main explanatory variable. The calculation basis is shown in Table 2 below:

Table 2. Index System of *Urban Digital Development Index (2022)*

Level 1 indicator	Weight	Level 2 indicator	Weight
Digital infrastructure	15%	Information infrastructure	40%
		Platform infrastructure	40%

		Operational infrastructure	20%
Digital economy	25%	Digital technology innovation	30%
		Digital industrialization	30%
		Industry digitization	40%
Digital society	25%	public service	40%
		Smart city and digital village	30%
		Digital life	30%
Digital government	25%	Open data sharing	20%
		Government informatization	50%
		Service effectiveness	30%
Digital ecology	10%	Data element market	40%
		Data policy environment	30%
		Network security protection	30%

2.3 Control Variables and Reasons for Selection

To reduce endogenous errors, the following control variables that may affect the regional innovation ecosystem are selected:

(1)Social Security Environment

A sound social security system helps ensure and improve people's livelihood, maintain social equity, and enhance people's well-being. There have also been studies indicating that social security contributions can force enterprises to increase innovation investment and strengthen employee training, thereby promoting innovation.[14] Based on the criteria given by the National Bureau of Statistics, this article selects the number of employees covered by basic medical insurance (SG) and the actual road area (TA) of each region at the end of the year to measure the social security environment.

(2) Financial environment

Zhao Siqi, Zhao Yuting, et al. (2021)[8] demonstrated through empirical research that the financial ecological environment is a key factor affecting regional innovation capabilities. Increasing investment in science and technology and developing Internet finance can help improve the development of innovative industries and enhance industrial potential. This article selects year-end loan balances (SRDs) of financial institutions in various provinces and cities to measure local financial risks and explore the impact of the entire financial environment on regional innovation ecology.

(3) Ecological environment

This article refers to the calculation of the environmental pollution index (EQ) by Wang Yun and Sun Xiaohua (2017), which includes three indicators: industrial wastewater emissions, industrial sulfur dioxide emissions, and industrial smoke and dust emissions. According to the entropy method, the "three wastes" are dimensionless treated, and their respective weight coefficients are calculated for each year. Then, the weighted sum is obtained to obtain the comprehensive pollution emission index for each industry [10] to explore the impact of the ecological environment on regional innovation ecology.

The control variable data are all from the *China Urban Statistical Yearbook*.

2.4 Descriptive Analysis

Table 3. Descriptive Statistics of Main Variables

Variables	Name	Minimum	Maximum	Mean	Standard Deviation
DIL	Digital index	35.8	92.3	59.221	14.6842

RIL	Regional innovation ecological index	8.82	122.05	27.2563	17.59832
RS	Innovation resources	0.75	163.62	23.2628	24.00444
RP	Innovation output	3.31	134.11	20.7687	18.46527
RT	Innovation output	15.30	503.00	39.0911	54.41709
RST	Environmental support	10.35	66.89	25.8055	12.80521
SRD	Balance of loans from financial institutions at the end of the year (unit: 10000 yuan)	6097439.00	779910285.00	83368959.5618	147077718.33782
SG	Number of employees participating in basic medical insurance	174376.00	15882500.00	1813685.1610	3117176.36500
EQ	Environmental pollution index	0.01	0.33	0.0875	0.70370
TA	Actual urban road area at the end of the year (unit: 10000 square meters)	765.00	31012.00	4295.2258	5995.43468

3. Analysis of Empirical Results

3.1 Correlation Analysis

Table 4. Correlation between Digital and Regional Innovation Ecology Level I Indicators

	Regional Innovation Ecological Index	Innovation Resources	Innovation Output	Industry Potential	Environmental Support
Pearson correlation	0.754**	0.747**	0.692**	0.318**	0.735**
Sig (Double tailed)	0.000	0.000	0.000	0.004	0.000

(Note: * * indicates a significant correlation at 0.01 level (double tailed))

Through correlation analysis, it can be seen that the digital level of a city in the Yangtze River Delta is highly correlated with its regional innovation ecology, innovation resources, innovation output, and environmental support, while it is moderately correlated with its industrial potential. The digital level has improved the allocation efficiency of innovative resources such as talent and knowledge, enhanced the agglomeration effect of innovative resources throughout the region, and thus promoted the flow of innovative resource elements and the construction of a regional innovation ecosystem. However, due to the fact that many enterprises in China are still in the traditional manufacturing industry and are in the upward phase of digital transformation, it is unrealistic to achieve qualitative growth through the promotion of industrial potential in the short term. In the indicator system for measuring industrial potential, the development of foreign-funded enterprises in China accounts for a large proportion, while China has been hit by the COVID-19 in recent three years, and the reduction of foreign trade in various countries has impacted China's international market. Therefore, even though the digital level in the Yangtze River Delta has increased rapidly in the past three years, the industrial potential has not been greatly improved.

3.2 Analysis of Regression Results

Based on the previously set control variables, we build the following basic model:

$$RIL_{it} = \alpha_1 + \alpha_2 DIL_{it} + \alpha_3 Control + \mu_i + \varepsilon_{it} \tag{1}$$

In formula (1), RIL_{it} represents the innovation ecological level indicator of province i during the t period; DIL_{it} represents the digital level indicator of province i during the t period; μ_i represents unobservable individual fixed effects in province i; ε_{it} is a random perturbation term; coefficient α_2 represents the impact of digital level on the regional innovation ecosystem. In order to narrow the magnitude gap between the numbers, logarithmic processing is performed on the balance of loans from financial institutions and Number of employees participating in basic medical insurance. The output result is as follows:

Table 5. Multiple Regression Results

Name	Variable	Coefficient	Tolerance	VIF	R Squared
/	(Constant)	-37.697(-0.848)	/	/	0.891
DIL	Digital level	0.354**(2.213)	0.218	4.583	
EQ	Pollution index	61.941*(1.804)	0.300	3.330	
TA	Road area	0.001**(2.159)	0.309	3.232	
Ln(SG)	The logarithm of the number of employees insured	-12.973***(-4.612)	0.195	5.126	
Ln(SRD)	The logarithm of loan balance	12.050***(5.293)	0.223	4.479	

Finally, the regression equation can be obtained:

$$RIL = 0.354 * DIL + 12.050 * ln(SRD) + 0.001 * TA + 61.941 * EQ - 12.973 * ln(SG) - 37.697$$

From the output results, there is no multicollinearity problem among the variables, and the model has a good goodness of fit for the observed values. Further analysis of the regression results showed that the promotion effect of digitization on regional innovation ecology decreased significantly after adding control variables; The higher the total amount of loans, the higher the regional innovation ecosystem. We speculate that the reason behind this may be that the active trading activities of investors and financiers in the financial market will instead promote the reform and technological upgrading of enterprises. Only with high risks can there be high returns, and enterprises can increase capital investment, forming a virtuous cycle; the empirical results show that environmental pollution will reverse the development of regional innovation ecology; the impact of the social security environment on the regional innovation ecology is diverse. The actual urban road area is positively correlated with the regional innovation ecology, while the number of employees participating in insurance is negatively correlated with the regional innovation ecology, reflecting the different effects of governments and individuals on the development of regional innovation ecology.

3.3 Heterogeneity Analysis

In order to deeply investigate the regional differences in the impact of digital level on regional innovation ecology, the entire sample was divided into three sub samples, namely, near, medium, and far from Shanghai, with Shanghai as the center. The impact coefficient of digital level on regional innovation ecology is significantly positive in the regression of each region, consistent with the promotion effect of the full sample test. From the perspective of spillover intensity, there are significant regional differences in the spillover intensity of digital innovation ecology, with a coefficient of "near>far>medium".

Table 6. Analysis of the Heterogeneity of Innovation Ecological Regions

	Near	Medium	Far
R Square	0.660	0.329	0.374
Coefficient	0.030***(8.239)	0.013**(3.323)	0.016***(5.298)

As a developed city in the Yangtze River Delta region, Shanghai has played an advanced and leading role. Several cities far from Shanghai are relatively low in terms of digital level and regional innovation ecological level, so the improvement of digital level has played a significant role in promoting development. The distribution of cities in the region with a medium distance from Shanghai is relatively scattered, with no leadership support from large cities such as Shanghai, and the economic development level is at a medium level. Therefore, the ecological driving effect of digital innovation is poor.

3.4 Spatial Correlation Analysis - Moran's I

Based on the regional differences reflected in the heterogeneity analysis, the Moran's I is used to conduct a specific analysis of the spatial agglomeration effect. The Moran's I exponential formula for global spatial correlation testing is shown in Equation (2):

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

Where: ***n*** refers to the 41 cities in the Yangtze River Delta in ecology included in the sample; W_{ij} is the spatial weight matrix; x_i and x_j refer to the innovation ecology and digital level of region i and region j respectively; $\bar{x}$ is the average value of provinces in the same year.

The mathematical expression of the spatial adjacency weight matrix (**W**) is:

$$W_{ij} = \begin{cases} 1, \text{Area i and area j are adjacent} \\ 0, \text{Region i and region j are not adjacent} \end{cases} \quad (i \neq j) \tag{3}$$

The output result of GeoDa software is shown in Figure 1. From the z and p values, the result is significant, and the observed spatial model is unlikely to generate a random process, rejecting the zero hypothesis. This indicates that there is a significant high degree of aggregation of innovation ecology and digital levels in the Yangtze River Delta region, which means that objects with similar attributes are spatially clustered together. That is, cities with good ecological level of regional innovation and good digital level gather together, while cities with poor ecological level of regional innovation and poor digital level gather together.[5]

Figure 1. 2022 Innovation Ecology and Digitalization Global Moran's I

Table 7. Global Moran's I Output Results

Variable	Year	Moran's I	Z Value
Regional innovation ecological level	2020	0.225***	2.7524
	2021	0.209***	2.5463
	2022	0.175***	2.3339
Digital level	2020	0.293***	3.3568
	2021	0.293***	3.3630
	2022	0.279***	3.1060

In order to investigate the spatial aggregation around a certain region i, we use the local Moran's I, with the formula:

$$I_i = \frac{(x_i - \overline{X})}{S^2} \sum_{j=1}^{n} w_{ij}(x_j - \overline{X})$$

Where: $S^2 = \frac{\sum(x_i - \overline{x})^2}{n}$. W_{ij} is the spatial weight value, x_j is the regional innovation ecological level and digital level of region ***j***, and $\overline{x}$ is the average value of provinces in the same year.

The meaning of the local Moran' I is similar to that of the global Moran' I. A positive value I_i indicates that the high value of the region *i* is surrounded by the surrounding high value or the low value is surrounded by the surrounding low value; A negative value I_i indicates that the high value of region i is surrounded by surrounding low values or that the low value is surrounded by surrounding high values. [10] The output results are shown below:

Figure 2. Local Moran's I for Regional Innovation and Digitalization in 2022 (Note 1: Dark blue indicates low-low, light blue indicates low-high, dark red indicates high-high, light red indicates high-low, and gray indicates insignificant.)

Figure 3. Significance Test of Regional Innovation and Digitalization l Moran's I in 2022(Note 2: The color from dark to light indicates that there is statistical significance when p<0.01, p<0.05, and p<0.1, respectively, while gray indicates that there is no significant difference.)

The four types of Moran's I are listed below:

Table 8. High - high regional innovation ecology and digital cities under spatial weight

Year	Indicator	Prefecture-level City
2020	RIL	Shanghai, Suzhou, Jiaxing, Nantong, Huzhou
	DIL	Taizhou, Suzhou, Nantong, Shaoxing, Huzhou
2021	RIL	Nantong, Suzhou, Jiaxing, Huzhou
	DIL	Nantong, Suzhou, Jiaxing, Taizhou, Shaoxing, Hefei
2022	RIL	Shanghai, Suzhou, Jiaxing
	DIL	Shanghai, Suzhou, Jiaxing, Shaoxing, Changzhou

Table 9. Low-low regional innovation ecology and digital cities under spatial weight

Year	Indicator	City
2020	RIL	Xuzhou, Bengbu, Suqian, Huaibei
	DIL	Huainan, Bengbu, Fuyang, Bozhou, Huaibei
2021	RIL	Xuzhou, Bengbu, Fuyang, Suqian
	DIL	Huainan, Bengbu, Fuyang, Bozhou, Huaibei
2022	RIL	Xuzhou, Bengbu, Fuyang, Bozhou
	DIL	Huainan, Bengbu, Fuyang, Bozhou

Table 10. Low-High and High-Low Regional Innovation Ecology and Digital cites under Spatial Weights

Year	Indicator	Cities (low-high anomaly type)	Cities (high-low anomaly type)
2020	RIL	Xuancheng	/
	DIL	/	/
2021	RIL	Xuancheng	/
	DIL	/	Hefei
2022	RIL	Huzhou, Nantong	/
	DIL	Huzhou	Hefei

From the perspective of regional interaction, the higher of the digital level of cities, the higher their regional innovation ecological level is indeed, and there is an agglomeration effect between cities, confirming the above regression output results. For low-high and high-low abnormal cities, the following is a simple analysis:

Xuancheng and Hefei both belong to Anhui Province, but they exhibit two distinct states: low high and high low. Considering their geographical location, Xuancheng is characterized by mountainous areas in the south and plains in the north, with seasonal rivers in the north. This geographical condition hinders their communication with the outside world. Xuancheng is far away from the provincial capital and has no obvious resource advantages, so it belongs to the marginal zone of key development areas in the province. In addition, the late construction of Xuancheng City has resulted in limited time for its urban planning and economic and social development, resulting in a serious lag in the urbanization process and a disadvantage of latecomers. As the capital city of Anhui Province, Hefei has the power to mobilize all resources, including human, material, and policy resources. With the growth of Hefei, the resources in the province tend to be here. In recent years, Hefei has vigorously developed the economic zone along the Yangtze River. Anhui Province has issued many preferential policies, paying special attention to Hefei City, making Hefei a "peak area". Huzhou City is surrounded by first-tier and second-tier cities. High-end technical talents have been attracted by the Shanghai, Hangzhou, and Nanjing circles, with a small migrant population and a lack of attraction for enterprises. Therefore, the development level of Huzhou is relatively backward.

3.5 Robustness Test

Table 11. Robustness Test

Name	Variable	Coefficient	Tolerance	VIF	R Squared
/	(Constant)	-106.311(-2.292)	/	/	0.884
Ln(TQ)	The logarithm of the number of mobile phone users	21.506*(1.744)	0.532	1.881	
EQ	pollution index	89.649**(2.746)	0.305	3.277	
TA	Road area	0.001*(1.960)	0.184	5.436	
Ln(SG)	The logarithm of the number of	-15.665***(-5.237)	0.557	1.795	

	employees insured				
Ln(SRD)	The logarithm of loan balance	15.946***(10.715)	0.354	2.826	

Referring to previous research, this article replaces the explained variable digitization level with the number of mobile phone users at the end of the year (unit: 10000 households). The output coefficient is still significantly positive. Through the robustness test, it is shown that the digital level is positively promoting the regional innovation ecosystem, with fewer endogenous issues, and the regression results are robust.

4. Conclusion and Suggestion

4.1 Research Conclusion

This article conducts empirical research on the innovation ecology and digital level index of 41 urban areas in the Yangtze River Delta and draws the following conclusions:

(1) The improvement of digital level will promote the development of regional innovation ecology in the Yangtze River Delta cities. Among them, the promotion effect of digitalization level on innovation resources in the regional innovation ecology is the best.

(2) Using a fixed effect model, the regression results show that increasing financial risks, worsening environmental pollution, and municipal government investment in public utilities will promote the development of regional innovation ecology, while increasing the number of employees participating in insurance will have a blocking effect on regional innovation ecology.

(3) Heterogeneity analysis: According to the distance from Shanghai, cities in the Yangtze River Delta are divided into three regions, namely, near, middle, and far regions. The heterogeneity test found that the level of digitalization in the urban area closest to Shanghai has the strongest promotion effect on the regional innovation ecology.

(4) The Moran’s I test shows that both the regional innovation ecology and the digital level do have spatial spillover effects, and further confirms the driving effect of digitalization on the regional innovation ecology in the Yangtze River Delta.

4.2 Suggestions

Based on the conclusions of this study, the following suggestions are proposed: cities in the Yangtze River Delta should make full use of their geographical advantages, formulate long-term digital development strategies, actively improve the level of digitization, and provide a foundation for regional innovation resources, innovation expenditures, industrial potential, and environmental support; Cities should strengthen exchanges and communication, especially leading cities such as Shanghai, to play a leading role in driving the development of surrounding cities; The government should increase investment in infrastructure and public utilities, formulate strict policies and systems, encourage people to actively participate in financial market activities, encourage investment and financing behavior, improve the financial environment and social security environment for enterprises, and achieve a "qualitative change" in the role of digital technology in promoting regional innovation ecology as soon as possible.

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