

Research on the Role of Digital Economy in Driving Green Eco-efficiency of Cities

-- The Case of Yangtze River Delta Urban Agglomeration

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Abstract

This paper combs the mechanism of digital economy driving urban green eco-efficiency from five perspectives: marginal cost, technological innovation, industrial transformation and upgrading, environmental regulation, and spatial spillover effect, and establishes the green eco-efficiency index based on the DEA analytical framework of global parametrics, taking into account the Super-SBM model of non-desired outputs and the influencing factors of the Malmquist Productivity Index. Next, the impact of digital economy on urban green eco-efficiency is examined at the empirical level with the data of the Yangtze River Delta urban agglomeration from 2011 to 2019. The results show that the development of digital economy can drive the improvement of urban green ecological efficiency, but the spatial spillover effect is not yet significant. Therefore, in order to deeply implement the new development concept and promote the high-quality growth of China's economy, functional industrial policies such as digital infrastructure construction, support for R&D investment and talents training should be actively promoted, and global thinking should be established to unleash the spatial effects of the digital economy.

Keywords

Digital Economy; Green Eco-efficiency; Yangtze River Delta; Spatial Spillover Effects.

1. Introduction

At present, resource and environmental problems have become one of the centralized manifestations of China's "unbalanced and inadequate" development, and one of the important factors restricting China's high-quality development. The report of the 19th CPC National Congress puts forward that "Clear waters and green mountains are as good as mountains of gold and silver" ; in 2020, General Secretary Xi Jinping promised at the 75th United Nations General Assembly to realize the strategic goal of carbon peaking in 2030 and carbon neutrality in 2060, which shows the unswerving determination and confidence of taking the green development road of our country. Adhering to the vision of green development and improving eco-efficiency has become a must for China's high-quality development. At the same time, in recent years, the digital economy represented by digital technology and information technology has been developing rapidly, greatly changing the traditional mode of production, consumption and distribution, and providing a new power and a new engine for the high-quality development of China's economy, with huge social benefits and broad prospects for development. According to the White Paper on the Development of China's Digital Economy (2021) released by the China Academy of Information and Communications Technology, the total value added of China's digital economy in 2020 has reached 39.2 trillion yuan, accounting for 38.6% of GDP. The deep integration of digital economy with other fields will also become a trend of future development, playing an important role in China's industrial upgrading and

green development. Therefore, it is of great significance to study the driving role of digital economy on green development. Based on this, this paper starts from the concept of digital economy, summarizes the relationship between digital economy and green ecological efficiency by sorting out the mechanism of digital economy driving green ecological efficiency and constructing the evaluation indexes of digital economy and green ecological efficiency, and conducts empirical tests with the panel data of 26 prefectural-level cities in the Yangtze River Delta from 2011-2019. Finally, we will combine the Chinese economic development with the reality, and put forward sufficiently rational policy recommendations.

2. Literature Review

2.1. Concept and Measurement of the Digital Economy

In the new era of global technological revolution and industrial change, the new economic formations generated by the flourishing development of digital technology have become a key force in reshaping the global economic landscape. Subsequently, studies on the digital economy have begun to appear. The concept of digital economy was first proposed in the book *Digital Economy: Opportunities and Challenges in the Age of Networked Intelligence*. Tapscott (1996) argued that digital economy is an economic system that makes extensive use of information and communication technologies based on the Internet and other technologies. In the G20 Initiative on Digital Economy Development and Cooperation released by China in 2016, it is stated that the digital economy is "the sum of economic activities that use digitized information and knowledge as the factors of production, the information network as the carrier, and the use of ICT to promote the improvement of efficiency and the optimization of macroeconomic structure".

Most studies on digital economy measurement are qualitative (Goldfarb & Tucker, 2019); the few quantitative measures can generally be categorized as direct way (Chihiro et al., 2018) and comparative way (Sidorov & Senchenko, 2020), and are mainly limited to the provincial and national levels (Pan et al., 2022). However, because the digital economy is still in continuous development, the connotation, definition and components of the digital economy are still being enriched, the dynamic development and rapid evolution of the characteristics of the digital economy makes it more difficult to define the connotation of the digital economy, and the methods and results of the academics on the measurement of the size of the digital economy have been different so far. For example, Xu Xianchun and Zhang Meihui (2020) measure the level of the digital economy from the digital empowerment infrastructure, digital media, digital transactions, and digital economy transaction products, while Zhao Tao et al. (2020) measure the level of digital economy development from two aspects, namely, Internet development and financial inclusion. The lack of a recognized production accounting system for the digital economy is a bottleneck in current digital economy research.

2.2. Digital Economy and Green Eco-efficiency

The concept of eco-efficiency was first proposed by Schaltegger, and then several international organizations have their own definitions of eco-efficiency. For example, the World Organization for Economic Cooperation and Development (OECD) believes that "eco-efficiency refers to the efficiency of ecological resources to meet the needs of human beings". Although there are many academic studies on digital economy-driven green development, most of them are based on the impact of digital economy on carbon emissions (Guo Yueqin et al., 2022), green total factor productivity (Cheng Wenxian and Qian Xuefeng, 2021), and green innovation (Han Feng and Mao Xin, 2022), and few scholars have measured the impact of the digital economy on green eco-efficiency.

Therefore, on the basis of existing research, this paper tries to establish green eco-efficiency indicators based on the global parametric DEA analysis framework, integrating the influence factors of Super-SBM model of non-expected output and Malmquist productivity index, and take the Yangtze River Delta urban agglomeration as a sample to test the impact of digital economy on green eco-efficiency.

3. Mechanisms and Research Hypotheses

This part clarifies the mechanism of digital economy on green ecological efficiency from five aspects: marginal cost, technological innovation, industrial transformation and upgrading, environmental regulation, and spatial spillover effect:

3.1. Marginal Cost

The digital economy can reduce resource waste and marginal costs, thereby improving green ecological efficiency. First, as a new production factor, big data resources have the characteristics of reproducibility and sharing, with obvious incremental marginal benefits and almost zero marginal costs; second, the degree of data fusion, analysis and sharing in the era of the digital economy is higher, and big data can break the information silos and enhance the flow of information through the collection, collation and analysis of data resources in all aspects, so that the market entities can better grasp the market trends, identify market demand and reduce the waste of resources caused by information asymmetry and information fragmentation of market players (Xu Xianchun, 2019), and promote the improvement of green eco-efficiency by reducing transaction costs.

3.2. Technological innovation

The digital economy can enhance the spillover of knowledge, thereby improving green ecological efficiency by facilitating technological innovation. Digital technologies such as communication technologies and Internet platforms facilitate knowledge sharing and break the barrier of geospatial access to knowledge, resulting in the enhance of knowledge spillover and diffusion, whereby workers can break through traditional education and training methods and use digital media and platforms for training and learning to enhance their knowledge reserve and improve their innovative thinking and capabilities. In fact, technological innovation is the cornerstone of green development (Koo et al., 2022), which has an important driving role in green eco-efficiency.

3.3. Industrial Transformation and Upgrading

The digital economy can promote industrial transformation and upgrading (Tian, Xiujuan and Li, Rui, 2022, Liao, Xinlin and Yang, Zhengyuan, 2021), not only through the substitution effect of eliminating the traditional backward industries with high pollution and energy consumption, but also through the enabling effect of applying new technologies to generate new industries, new business forms and new modes of green environmental protection, so as to improve the efficiency of green ecology.

3.4. Environmental Regulatory

Over the past 40 years of reform and opening up, China's economy has relied excessively on resource consumption and crude scale expansion. In the face of complex environmental problems, if the government relies solely on traditional management means and financial and material resources, then the difficulty of supervision will be greatly increased. The emergence and development of digital technology has facilitated the establishment of information management systems of ecology environment data by many local governments and relevant management departments, forming a comprehensive and complete environmental supervision system, which allows the government to accurately quantify the amount of sewage discharged

by producers and their ability to treat sewage through the digital supervision platform, so as to carry out targeted tracking and management of heavily polluting industries and enterprises, and to efficiently implement environmental regulations (Xu Xianchun, 2019). The digital economy makes ecological environment supervision more accurate, and makes ecological environment decision-making more scientific, resulting in further improving urban green ecological efficiency.

3.5. Spatial Spillover Effects

Cities are not independent individuals, especially the Yangtze River Delta city cluster has a vast economic hinterland, modern river and sea ports and airports. The density of public and railroad transportation lines is leading in the country, the degree of connectivity is high, and the trans-regional economic cooperation is more frequent, so it is necessary to consider the spatial interaction between the Yangtze River Delta city cluster. On the one hand, the digital economy is characterized by externalities. Especially, effected by Moore's Law, data and information can be disseminated across time and space at a lower cost, and this significant networked feature can break down regional and spatial barriers and create convenient conditions for the cross-regional flow of all kinds of factors, and thus may have a spatial spillover effect on the green ecological efficiency of the surrounding areas; on the other hand, the digital economy may also cause a "siphon effect". The development of the digital economy in developed regions drives the high-quality development of the region's economy, which is extremely attractive to neighboring regions, and may lead to the agglomeration of some factors of production in less developed regions to the developed regions, thus inhibiting the improvement of the green ecological efficiency of the neighboring regions.

Based on this, this paper proposes the following research hypothesis: the digital economy is positively related to urban green eco-efficiency, but the spatial spillover effect is uncertain.

4. Research Design

4.1. Spatial Weight Matrix Setting and Modeling

4.1.1. Spatial Economic Geography Nested Matrices

The economic geographic distance between cities was calculated based on the latitude, longitude and GDP of each city. The formula for the calculation is:

$$W_4 = \varphi W_1 + (1 - \varphi)W_2$$

Of these, the W_1 and W_2 are the geographic distance matrix and economic distance matrix, and the φ denotes the proportion of the geographic distance weight matrix, which is taken as 0.5 in this paper.

4.1.2. Model

This paper adopts the Spatial Durbin Model (SDM) to construct the following theoretical model for the relationship between digital economy and urban green ecological efficiency:

$$\begin{aligned}
gee_{it} = & \alpha + \rho \sum_{j \neq i, j=1}^N w_{ij} gee_{it} + \beta_1 dig_{it} + \beta_2 eco_{it} + \beta_3 fdi_{it} + \beta_4 ind_{it} + \beta_5 fin_{it} + \beta_6 gov_{it} \\
& + \lambda_1 \sum_{j \neq i, j=1}^N w_{ij} dig_{it} + \lambda_2 \sum_{j \neq i, j=1}^N w_{ij} eco_{it} + \lambda_3 \sum_{j \neq i, j=1}^N w_{ij} fdi_{it} \\
& + \lambda_4 \sum_{j \neq i, j=1}^N w_{ij} ind_{it} + \lambda_5 \sum_{j \neq i, j=1}^N w_{ij} fin_{it} + \lambda_6 \sum_{j \neq i, j=1}^N w_{ij} gov_{it} + \mu_i + v_t + \varepsilon_{it}
\end{aligned}$$

Of these, the explained variable gee_{it} denotes the green eco-efficiency of city i in year t , the core explanatory variable dig_{it} denotes the level of digital economic development of city i in year t ; ε_{it} is the residual; μ_i and v_t are the spatial and temporal effects, ρ is the spatial lag coefficient, w_{ij} is the spatial weight matrix, λ is the coefficient of the spatial lag term of each explanatory variable.

4.2. Selection of Variables

4.2.1. Explained Variable: Green Eco-efficiency (Gee)

By studying the existing literature on measuring green eco-efficiency, it is found that there are mainly the following methods for measurement: first, by constructing an indicator system and utilizing the Super-SBM model or the Super-EBM model for measurement (Feng Ximing and Zhang Renjie, 2021; Pan Mingming and Xie Rongmian, 2019); Second, the factor decomposition method was used to measure green energy efficiency and green environmental efficiency from two perspectives (He Weida et al., 2022). Third, the super-efficient EBM model was used to quantitatively evaluate green efficiency by adding non-expected output factors and considering non-directed, scale reward invariant factors at the same time (Zhao Lin et al., 2021). Fourth, the DEA model was utilized to address the input-output inconsistency problem, while considering environmental pollution as a non-consensual factor (Grosskopf et al., 1989). Among the above methods, the super-efficient SBM model is the most widely used and provides a more comprehensive assessment of green eco-efficiency.

This paper synthesizes and references existing studies, gives priority to the calculation of Hu Xiaozhen and Yang Long (2011), and finally calculates the green eco-efficiency based on the global reference DEA analysis framework, taking into account the Super-SBM model of non-expected outputs and the influencing factors of Malmquist productivity index. The utilized data are mainly compiled from China Statistical Yearbook, China Industrial Economic Statistical Yearbook, China Environmental Statistical Yearbook and China Regional Economic Statistical Yearbook. The desired output indicator was selected as the regional GDP at constant price, the input indicators were electricity consumption, employment and capital stock, and the non-desired output indicators were waste water emission, industrial soot emission, sulfur dioxide emission and PM2.5.

4.2.2. Explanatory Variable: Digital Economy (Dig)

Most of the measurements of digital economy indicators in existing studies are focused on the provincial level, such as measuring the digital economy by dividing it into three dimensions: informatization development, Internet development and digital transaction development (Liu Jun, 2020). However, the digital economy measurement of prefecture-level cities needs to be reduced by some indicators due to the limitation of data availability. This paper draws on Zhao Tao (2020) to improve the measurement of digital economy at the city level, and evaluates the level of digital economy development from two perspectives: digital finance and Internet development. Among them, the digital finance dimension is measured using the digital inclusive

finance index compiled by the Digital Finance Research Center of Peking University (Guo Feng et al.,2020). The Internet development is measured by four indicators: Internet penetration rate, related employees, related output and cell phone penetration rate, and the data are mainly obtained from the China Urban Statistical Yearbook. Finally, the data were standardized and downscaled using principal component analysis to derive the digital economy index.

4.2.3. Control Variables

By referring to the research on factors affecting green eco-efficiency (Chen Yang and Tang,2018; Yanli Ji et al.,2022; Liu Winshi et al.,2018), this paper uses the level of economic development (eco), foreign investment (fdi), industrial structure (ind), financial development (fin) and government intervention (gov). The level of economic development is measured using the gross domestic product per capita of the region. Foreign investment is measured by the ratio of actual utilized foreign capital to GDP. Industrial structure is the ratio of tertiary sector output to total output. Financial development is measured using the ratio of total deposits and loans to GDP for the region. Government intervention is the ratio of public fiscal expenditure to regional GDP.

5. Empirical Findings

5.1. Spatial Correlation Tests

The existence of spatial spillovers between the digital economy and green eco-efficiency determines the accuracy of the spatial econometric model used. In this paper, the statistical analysis software matlab (2019) was used to determine the correlation between the variables using the Moran index. The value of Moran's index was tested to be -0.10207 and significant at the 5% level of significance. It proves the existence of spatial correlation between the existence of digital economy and green eco-efficiency.

5.2. Spatial Measurement Tests

Table 1. Steps and results of spatial econometric model testing

	statistical value	statistical value	contingent probability
global relevance	Moran'I	-0.10207	0.02997
LM test	LM-lag	4.7608	0.029
	R-LM-lag	1.0463	0.306
	LM-error	16.6483	0.000
	R-LM-error	12.9338	0.000
SDM Spatio-temporal double fixed effects	LR test	318.2848	0.000
Hausman test for SDM model	Hausman test	-110.5622	0.000
Wald test	Wald-lag (SAR)	136.6373	0.000
	Wald-lag (SEM)	133.6075	0.000

According to the testing ideas of Elhorst (2014) and Han Feng (2017), this paper adopts the methods of "from specific to general" and "general to specific" to test the spatial econometric model. First, the results of OLS regression and LM test show that LM-lag, LM-error, and R-LM-error all pass the test at the 5% significance level, and R-LM-lag does not pass the significance level test, which indicates that the SEM model can be used. Furthermore, the more general SDM model can be used. Second, the SDM estimation of the temporal, spatial, and spatio-temporal dual effects are respectively used, and LR test for decomposition and fixed effects is tested. The result shows that the LR test rejects the original hypothesis which indicates there are spatio-temporal double fixed effects. Third, Hausman test is conducted to reject the original hypothesis of random effects, and the fixed effects SDM model should be used. Fourth, the Wald test is conducted to determine whether the SDM model can be simplified to a SAR or a SEM model,

and the results show that it can not be simplified, so the SDM model was the most appropriate estimation method. The results of the spatial measurement model test are shown in Table 1.

5.3. Analysis of Empirical Results

After the modeling tests described above, we used the spatial Durbin model for estimation. Table 2 reports the estimation results of the spatial Durbin model. The core explanatory variable digital economy (dig) is 0.000003 and significant is at the 5% level. The coefficient is positive, indicating that the development of digital economy can drive the green eco-efficiency of the city.

Table 2. Estimates of green eco-efficiency of cities driven by the digital economy

variant	SDM
dig	0.000003** (2.087986)
eco	0.001053 (0.108765)
Ind	0.182964 (0.478732)
Fin	-0.034727 (-0.732499)
Fdi	-1.001249 (-1.109063)
gov	0.727537 (1.185273)
W×dig	0.000000 (0.012662)
W×eco	-0.304934*** (-9.754491)
W×ind	9.388383*** (7.182443)
W×fin	0.597473*** (3.382706)
W×fdi	-41.744696*** (-7.958743)
W×gov	3.081738 (0.875067)
W x dep. var.	0.108015 (0.725156)
Log-lik	235.0334
R2	0.8828

Note: t-values in parentheses in the table, *, **, and *** indicate significant at the 10%, 5%, and 1% levels respectively.

Following this, we decompose the spatio-temporal double fixed effects SDM model, the results of which are reported in Table 3. From the estimation results of the direct effects, the coefficients of the core explanatory variables are significantly positive at the 10% level, suggesting that the development of the digital economy can drive the improvement of green eco-efficiency. The indirect effect, as the result of most interest in this paper, can be seen as having a positive but not significant coefficient value, indicating that the development of the

digital economy level in neighboring regions does not drive the green eco-efficiency improvement in this region.

Table 3. Direct and indirect effects of the digital economy driving green eco-efficiency in cities

variant	direct effect	indirect effect
dig	0.000002* (2.039746)	0.000000 (0.131125)
eco	-0.000426 (-0.043406)	-0.352077*** (-4.468201)
ind	0.246315 (0.632552)	10.869060*** (4.339309)
fin	-0.030194 (-0.667531)	0.683539** (2.650483)
fdi	-1.200741 (-1.289943)	-48.173652*** (-4.857756)
gov	0.701149 (1.163378)	3.423680 (0.891166)

Note: t-values in parentheses in the table, *, **, and *** indicate significant at the 10%, 5%, and 1% levels respectively.

6. Main Conclusion and Policy Recommendations

6.1. Main Conclusion

This paper combs the role mechanism of digital economy driving urban green eco-efficiency improvement from five aspects: marginal cost, technological innovation, industrial transformation and upgrading, environmental regulation, and spatial spillover effect, and tries to establish the green eco-efficiency based on the DEA analytical framework of global parametrics, taking into account the Super-SBM model of non-desired outputs and the influencing factors of Malmquist productivity index. Then, it takes the Yangtze River Delta city cluster as a sample from 2011-2019 to test the direct, indirect and spatial effects of digital economy on urban green ecological efficiency, the results show that: digital economy can drive the green ecological efficiency improvement in the region, but the radiation-driven effect on the green ecological efficiency of the neighboring regions is not significant, and the efficacy of the digital economy in the growth of green ecological efficiency has not yet been fully released.

6.2. Policy Recommendations

6.2.1. Promoting the Infrastructure on Which the Digital Economy is Depended on

The new infrastructure mainly includes telecommunication equipment and services, computer software and computer hardware, providing basic equipment support and technical guarantee for the smooth development of the digital economy. Strengthening the construction of digital infrastructure is conducive to laying a solid foundation for China's digital development, improving the level of digitization in the region, fully releasing the dividends of the digital economy, and providing basic guarantees for the transformation and upgrading of industries and the green development of cities.

6.2.2. Increase Investment in Government Talent Policies

At present, China's talent policy support is relatively small, the state's financial investment in talent is far less than the direct investment in patent subsidies. But like the development of digital technology, the most important thing is still "people", so we should highlight the importance of people in digital technology innovation and development. In addition, direct

patent subsidies and tax incentives are likely to lead to rent-seeking behavior of market players in order to obtain subsidies, but the rent-seeking behavior of talent policy is less (Liu Chunlin, 2022), and it has a stronger effect on the promotion of technological progress and innovation. Therefore, in order to realize the rapid development of digital technology, the government should put talent policy in a more important position.

6.2.3. Establishing a Global Mindset to Unleash the Spatial Effects of the Digital Economy

Although the digital economy is characterized by permeability, its spatial spillover effect on green ecological efficiency has not yet been fully released. Therefore, it is important for all regions to establish a global strategic mindset, actively promote interregional exchanges and cooperation in digital technology and other aspects, push forward the acceleration of the construction of a unified national market, and give play to the radiation leading role of the more economically developed regions, so as to further unleash the spatial effects of the digital economy.

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