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The Impact of China's Digital Economy Development on Ecological Efficiency: A Perspective Based on Environmental Regulation

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Abstract: *This paper measures China's digital economy from 2011 to 2020 based on the two dimensions of digital industrialization and industrial digitization, and empirically analyzes the impact of digital economy development on China's ecological efficiency by using two-way fixed effects, adjustment effects, and threshold effects. The research finds: (1) The development of the digital economy significantly promotes the improvement of ecological efficiency, and this conclusion still holds after robustness tests such as staged samples, instrumental variables, and variable substitution. (2) While the impact of environmental regulation on eco-efficiency is positive, it also has a significant positive regulatory effect on the digital economy boosting the development of eco-efficiency. The results show that the positive impact of the digital economy has a nonlinear increasing characteristic of "marginal effect", and there is also a threshold effect on the interaction term with environmental regulation. Therefore, the research in this paper provides data support and a perspective for evaluating China's digital economy's impact on ecological efficiency and provides a policy reference for exploring ways to improve ecological efficiency.*

Keywords: *the digital economy development; ecological efficiency; two-way fixed effect model; environmental regulation*

1. Introduction

At present, China's economy is entering a new era of high-quality development. With the innovation of digital technologies such as big data, cloud computing, blockchain, and artificial intelligence, China's digital economy is based on the era of big data. Integrate into the whole process of social development in various neighborhoods, give full play to information-sharing capabilities, and improve economic benefits with efficient and low-cost transactions. According to the "White Paper on the Development of China's Digital Economy (2021)", China's total digital economy has jumped to second place in the world in 2020, reaching 39.2 trillion yuan, accounting for 36.2% of GDP. The digital economy of 13 provinces including Guangdong, Shanghai, Jiangsu, and Zhejiang has exceeded 1 trillion yuan. The digital economy of Beijing and Shanghai accounts for more than 50% of the GDP. The growth of the digital economy in Guizhou, Chongqing, and Fujian still leads the country. It can be seen that the digital economy is a new economic growth point and has vast development advantages. However, with the rapid economic development, there are also ecological and environmental problems such as a large number of pollutant accumulation and resource waste. The economic development speed exceeds the carrying capacity of resources and the environment, and the impact of environmental pollution exceeds environmental governance. The problems of "imbalance and inadequacy" such as effects are still serious[1]. Therefore, it is urgent to deal with the coordinated development of economy and resources and environment, to achieve a win-win situation between economy and ecology, and ecological efficiency is an effective green indicator to measure the coordinated relationship between economy and resources and environment[2].

Empowering ecological and environmental governance with digitalization is in line with the trend of digital economic development, is conducive to promoting the construction of a new pattern of green development, and is also a key step to help solve ecological and environmental problems, improve ecological efficiency and achieve high-quality development, just as General Secretary emphasized: digital. The economy is the future development direction of the world. It is necessary to vigorously develop the digital economy. It can be seen that the development of the digital economy has a bright future and has become a new driving force for economic growth. So, in the context of China's rapidly

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changing digital economy, has it effectively promoted the improvement of China's ecological efficiency? What kind of regulatory and supporting role does environmental regulation as a policy tool play in the process of the digital economy affecting ecological efficiency? Answers to the above questions will help promote the improvement of ecological efficiency and the development of the digital economy in China's provinces under the new situation, as well as promote the construction of ecological civilization and achieve high-quality development. Therefore, it is of great significance to fully explore the impact mechanism of the digital economy on ecological efficiency.

2. Mechanism analysis and theoretical assumptions

Eco-efficiency is the ratio of output to input that integrates economic benefits and eco-efficiency, while a digital economy is a new form of high-quality economic development that guides the reallocation and regeneration of resources throughout the society through the digital evolution of all economic elements. With the development of the Internet, the digital economy can not only significantly reduce transaction costs and improve economic benefits, but also effectively eliminate the excessive consumption of energy and assets, environmental pollution, ecological deterioration, and other hazards, and achieve sustainable social and economic development, thereby increasing resources and environmental input-output efficiency, and ultimately promote the improvement of urban ecological efficiency. In addition, from the perspective of environmental regulation, the digital economy, as the main component of my country's new economy, will adopt more environmental policies and governance plans as the government and enterprises attach more importance to the new economy to accelerate the reconstruction of economic development and governance models.

2.1 Analysis of the mechanism of digital economy affecting urban ecological efficiency

Although environmental damage under the digital economy such as e-waste and electromagnetic radiation has triggered a new ecological crisis, opportunities and challenges coexist, and overall play a significant positive impact. First, from the perspective of the element empowerment of the digital economy, digital technology empowerment is innovation-driven, reducing transaction thresholds and costs [3], promoting the efficient operation of the socio-economic system and reducing resource waste, while digital value empowerment is a green driver of ecological sustainability, constituting green finance, inclusive finance, in addition, the possibility of data production factors causing environmental pollution during use is almost zero, and traditional natural resources can be empowered by data. In the process of acquisition and flow, the traditional economic growth mode of high pollution and energy consumption is broken, which is very in line with the eco-efficiency nature of low input and high output, combined with ecological and environmental issues such as data resource utilization and pollutant emissions, the improvement and enhancement of eco-efficiency cannot be separated from the development of digital economy. Second, from the perspective of digital technology, the output of technological innovation is to reduce the cost of environmental pollution with the help of new concept technology, reduce the burden of raw materials and energy use, lead scientific and technological innovation in key areas based on the concept of green development, use advanced digital technology and energy-saving and environmental protection technology to achieve high-end high-tech between enterprises and industries, and digital enterprises rely on their own data advantages for efficient data exchange [4], which greatly reduces the negative impact on ecology. The digital economy has now become a new driving force to stimulate independent innovation of Chinese enterprises, which shows that the digital economy develops with the development of digital technology and plays a certain role in improving the ecological environment. Third, from the perspective of the supervision and governance of the digital economy, the rapid development of the digital economy has caused new challenges, and improving the governance capacity of the digital economy is the only way[5], and the key guarantee is the rule of law, which involves the dynamic supervision of platform behavior, the integration of relevant laws, regulations and policies, multi-dimensional governance of cyberspace, and accelerates the formation of the systematization of legal norms for ecological environmental protection and the institutionalization of the working mechanism of environmental governance. It is necessary to rethink the issue of rule-making in the future digital economy, and use advanced regulatory technology to improve the level and efficiency of digital economy supervision, strengthen collaborative governance, green governance, and future-oriented sustainable digital governance, in order to achieve optimal ecological efficiency. Based on this, this paper proposes the following assumptions:

Hypothesis 1: The development of digital economy has a significant positive effect on urban ecological efficiency.

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2.2 Analysis of the moderating effect of the digital economy on ecological efficiency under the background of environmental regulation

The regulating effect of environmental regulation is mainly reflected in the following three aspects: the characteristics of the connotation model of the development of the digital economy, the transformation of the traditional development model, and the production of the industrial industry. First of all, China's 14th Five-Year Plan for digital development in the new requirements for digital development is a major task, digital industrialization, and industrial digitalization are in urgent need of green transformation, and it is necessary to simultaneously improve the regulatory system of the digital economy and the environment to accelerate the development of ecological and environmental friendliness[6]. On the other hand, the development of the digital economy has laid a solid foundation for the upgrading of traditional industries, provided reliable power, built an innovation platform, and strictly controlled the standards of the production environment. Finally, with the advancement of digital technology, the effect of environmental regulation such as emission right trading and taxation mechanism in China has been significantly strengthened, the pace of green transformation and upgrading of industrial enterprises has accelerated, and the scientific improvement of environmental protection and pollution control technology has been promoted, starting from high standards and strict environmental standards, forcing traditional industrial industries to transform and upgrade, based on reality, and coordinating the promotion of environmental protection, ecological safety, and public safety. Based on this, this paper proposes the following assumptions:

Hypothesis 2: The intensity of environmental regulation enhances the impact of the digital economy on eco-efficiency.

3. Materials and Methods

3.1 Model Setting

Reviewing the research results of existing scholars, it is found that ecological efficiency will be affected by factors such as the level of economic development and scientific and technological effects. Considering the heteroscedasticity problem of various data and the elastic meaning of economic variables in this paper, the logarithm of the main variables is now constructed. The benchmark regression model of the impact of the digital economy on ecological efficiency in each province is presented, as shown in formula (1). Based on the theoretical assumptions in Chapter 2 of this paper, to verify the adjustment effect of environmental regulation, based on formula (1), the interaction terms between environmental regulation and digital economy and environmental regulation are added, as shown in formula (2):

$$\ln EE_{i,t} = \beta_0 + \beta_1 \ln DE_{i,t} + \varepsilon Control_{i,t} + \mu_t + b_i + \delta_{it} \quad (1)$$

$$\ln EE_{i,t} = \beta_0 + \beta_1 \ln DE_{i,t} + \beta_2 \ln DE * \ln ER\varepsilon + Control_{i,t} + \mu_t + b_i + \delta_{it} \quad (2)$$

Among them, $EE_{i,t}$ represents the ecological efficiency of the i-th province in the t-year; β_0 is the intercept term; $DE_{i,t}$ is the core explanatory variable of this paper, representing the digital economy development level of the i-th province in the$t$-year; $\beta_1$is the focus coefficient value, representing the impact of digital economy development on ecological efficiency; ε is the coefficient value of a series of control variables; μ_t represents the fixed effect of control time, and b_i represents the individual fixed effect of the province that does not change with time. δ_{it} is the random error term. $ER_{i,t}$ is a moderating variable, which represents the environmental regulation of the i-th province in the t-year. By testing the significance of the interaction coefficient, we can judge whether there is a moderating effect of environmental regulation.

3.2 Variable Selection

3.2.1 Core explanatory variable: Digital Economy Development Index (DE).

At present, there is no unified method for measuring the development level of the digital economy. By combing the literature and combining the latest statistical classification results of the digital economy industry scope published by the National Bureau of Statistics of China, this paper selects two first-level indicators of digital industrialization and industrial digitalization and comprehensively analyzes China's Scholars have researched indicators of digital economy and the Internet. This paper starts with the

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construction of digital industrialization indicators from the aspects of digital infrastructure and its integrated application. Inclusive finance, technological investment, and innovation characterize the digitalization level of China's industries. According to the availability of data, a three-level indicator system for digital economy development is constructed, as shown in Table 1.

Table 1: Construction of digital economy development index system

First indicators	Secondary indicators	Indicator description
digital industrialization	size of infrastructure	Number of Internet broadband access ports (thousands)
		Mobile phone penetration rate (hundred people)
		Cable length (km)
	Fusion application	Total telecom business (100 million yuan)
		Technology market turnover (100 million yuan)
		Added value of transportation and postal services (yuan)
industrial digitization	digital finance	Peking University Digital Financial Inclusion Index
	investment output	Internal expenditure of R&D funds/GDP (%)
		Number of patents granted for invention, utility model (items)
		Number of express services (10,000 pieces)

To investigate the development level of the digital economy in various provinces in China, this paper uses the entropy weight method to weight the indicators, and now the index is constructed:

Step 1: Standardize the indicators. Since the measurement units of different indicators are different, they cannot be directly compared. Given the positive correlation between the digital economic indicators selected in this paper and their development, the positive indicator calculation method - range standardization is adopted to remove the influence of dimensions. The formula is as follows:

$$X'_{it,j} = \frac{X_{it,j} - \min_j\left\{X_{it,j}\right\}}{\max_j\left\{X_{it,j}\right\} - \min_j\left\{X_{it,j}\right\}} \tag{3}$$

In formula (3), $X'_{it,j}$ is the new normalized data, and the value range is [0, 1]; $X_{\mathrm{it,j}}$ is the original index value; $\max_{\mathrm{j}}\{X_{it,j}\}$ and $\min_{\mathrm{j}}\{X_{it,j}\}$ are the maximum and minimum values of the index values in all years.

Step 2: Determine the indicator weights.

First, calculate the proportion of the j-th indicator value of the i-th province in the t-th year under the j-th indicator:

$$p_{it,j} = \frac{X'_{it,j}}{\sum_{t=1}^{T}\sum_{i=1}^{N} X'_{it,j}} \tag{4}$$

where $N = 30$ is the number of cross-sections, and $T = 10$ is the number of years.

Second, calculate the information entropy and redundancy of the j-th index:

$$e_j = -\left(\frac{1}{\ln(NT)}\right)\sum_{t=1}^{T}\sum_{i=1}^{N}\left[p_{it,j} \times \ln\left(p_{it,j}\right)\right] \tag{5}$$

$$d_j = 1 - e_j \tag{6}$$

where $e_j \in [0,1]$.

Finally, calculate the weight of the j-th indicator:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{7}$$

where $\mathrm{m} = 8$ is the number of indicators.

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Step 3: Calculate the level of digital economic development in each province in the t-th year.

$$DE_{it} = \sum_{j=1}^{m} w_j X'_{it,j} \tag{8}$$

3.2.2 Explained variable: Ecological Efficiency Index (EE)

Combining the considerations of scientific rationality and availability of index data selection, and drawing on the practices of relevant scholars at home and abroad, the ecological efficiency input index in this paper includes resource and environmental input, and the output index includes expected output and undesired output. The specific indicators are shown in Table 2.

Table 2: Eco-efficiency index system

index	constitute	Representation and units
input	Labor input	Number of employed persons in urban units (10,00)
	Capital investment	Fixed asset investment stock (million yuan)
	Water consumption	Total water consumption (tons)
	Land resource consumption	Built-up area (km²)
	Energy consumption	Annual electricity consumption (kW)
Expected output	Real GDP	Annual Gross Regional Product (100 million yuan)
Undesired output	Wastewater discharge	Total wastewater discharge (tons)
	Exhaust emissions	Sulphur dioxide emissions from exhaust gases (tons)
	Solid waste discharge	General industrial solid waste generation (tons)

At present, the popular ecological efficiency measurement method in academia is data envelopment analysis (DEA) proposed by Charnes et al.[7], but the traditional DEA (CCR, BCC) model does not consider the relaxation of input and output, which affects the accuracy of measurement efficiency values to a certain extent. In response to this problem, Tone [8]proposes a non-angular and non-radial SBM model, but the SBM model with non-desired output may have multiple DMU efficiency values of 1 at the same time, which is not conducive to DMU evaluation and ranking. In the process of economic development, by-products such as "three wastes" and other environmental pollution, that is, undesired output, and the development of ecological efficiency in several different regions will be at the forefront of DEA efficiency at the same time, so this paper uses the Tone[9] improved non-desired output Super-SBM model to evaluate the ecological efficiency of provinces and municipalities. The formula is as follows:

Among them, $\lambda, s^-, s^+ \geq 0$; (x_i, y_r, b_t) represent the values of each decision unit respectively; (s_i^-, s_r^+, s_t^{b-}) represents the relaxation variable, which refers to the part where the input is more than the ideal input, the part where the expected output is less than the ideal expected output, and the part where the undesired output is more than the ideal undesired output; ϕ^* represents the eco-efficiency value for each decision unit.

$$\phi^* = \min \frac{1 + \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{ij}}{1 - \frac{1}{q_1 + q_2}\left(\sum_{r=1}^{q_1} s_r^+ / y_{ik} + \sum_{t=1}^{q_2} s_t^{b-} / b_{rk}\right)}$$

$$s.t. \begin{cases} \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1, j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \geq y_{rk} \\ \sum_{j=1, j\neq k}^{n} b_{tj}\lambda_j - s_t^{b-} \leq b_{tk} \\ 1 - \frac{1}{q_1 + q_2}\left(\sum_{r=1}^{q_1} s_r^+ / y_{ik} + \sum_{t=1}^{q_2} s_t^{b-} / b_{rk}\right) > 0 \end{cases} \tag{9}$$

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3.2.3 Control variables

To more comprehensively analyze the spillover effect of the digital economy in the process of ecological efficiency improvement, and to sort out relevant literature, this paper sets the control variables that may have an impact on this process, as follows: the level of human capital(HUC) is expressed by the ratio of the total number of faculty and staff in ordinary institutions of higher learning to the number of employed persons in urban units; the level of financial input(LF) is expressed by the ratio of expenditure within the fiscal budget to the region; the level of industrial structure upgrading(IS) is expressed by the ratio of the output value of the tertiary industry to the regional GDP; the level of opening to the outside world(OPEN) is expressed by the proportion of total imports and exports in the region.

3.2.4 Adjustment variable: Environmental regulation (ER)

By reviewing the existing literature, it is found that at present, scholars measure environmental regulation from the perspective of government investment and the pollution discharge effect. In this paper, considering the availability of data, the ratio of local fiscal environmental protection expenditure to regional GDP is selected to represent the intensity of environmental regulation. Fiscal environmental protection expenditure and industrial three-waste emissions are used to test the robustness of the adjustment mechanism.

3.3 Data sources and descriptive statistics

3.3.1 Data sources

This paper selects the provincial panel data from 2011 to 2020, taking into account the availability of data, excluding Hong Kong, Macao, Taiwan, and Tibet. The city data comes from China Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, China Information Industry Yearbook, and Peking University Digital Financial Inclusion Index. In addition, the missing data of some cities are supplemented through the statistical yearbooks and statistical reports of various provinces.

3.3.2 Descriptive Statistics

The descriptive statistics of the main variables are shown in Table 3. The results show that the mean value of the ecological efficiency index(EE)is 0.505, the maximum value is 1, the minimum value is 0.240, and the standard deviation is 0.197, indicating that there are large differences in ecological efficiency between different regions. The digital economy development index(DE) and the intensity of environmental regulation (ER) are also small in mean and large in standard deviation. From the perspective of control variables, there are also obvious differences in different human capital levels(HUC), financial input levels(LF), industrial structures(IS)and levels of opening to the outside world(OPEN).

Table 3: Descriptive Statistics for Primary Variables

category	variable	unit	mean	standard	minimum	maximum
Explained variable	EE	-	0.505	0.197	0.240	1.000
core explanatory variables	DE	-	0.191	0.161	0.015	0.796
Adjustment variables	ER	yuan/ton	0.820	0.559	0.212	4.344
Control variables	HUC	%	0.150	0.004	0.007	0.025
	LF	%	0.264	0.115	0.119	0.758
	IS	%	0.492	0.897	0.327	0.837
	OPEN	%	0.119	0.172	0.0001	0.974

4. Empirical test

4.1 Basic regression results

Before performing regression, we must first determine whether to use a fixed-effects model or a random-effects model and perform the Hausman test on the collected panel data. The test P-value is 0, so the fixed-effects panel model is used. Then, to test the regional fixed effect, time fixed effect, and double fixed effect, which of the three effects is most suitable for this study, the results show that the

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model has both time and regional effects, so the two-way fixed effect model is selected.

Table 4: Basic Regression Results Test

variable	(1)	(2)	(3)	(4)	(5)
lnDE	0.2219*** (0.0472)	0.7964*** (0.1126)	0.0641 (0.0606)	0.146** (0.067)	0.2241*** (0.0805)
lnHUC			0.5771*** (0.0832)	0.664*** (0.089)	0.7239*** (0.0983)
lnLF			-0.7500*** (0.1156)	-0.689*** (0.116)	-0.6514*** (0.1343)
lnIS			1.7105*** (0.1220)	1.639*** (0.123)	1.5521*** (0.1304)
lnOPEN			-0.1478*** (0.0180)	-0.170*** (0.020)	-0.1928*** (0.0235)
Constant term	-0.3337*** (0.0973)	0.7396*** (0.2108)	1.5068*** (0.4111)	1.989 (0.433)	2.3018*** (0.4653)
city fixed	NO	YES	NO	NO	YES
year fixed	NO	YES	NO	NO	YES
N	300	300	300	300	300
R^2		0.0629			0.6603

Note: Robust standard errors are reported in brackets in the table, ***, **, and * indicate that the regression results passed the significance test at 1%, 5%, and 10% confidence levels, respectively, the same below.

This paper conducts basic regression on the basic model for 30 provinces across the country, in which all the main variables are data from 2011 to 2020. The specific regression results are shown in Table 4. Table 4 reports the linear estimation results of the impact of the digital economy on eco-efficiency. Combined with the meaning of each variable, in the random-effect model (1) and the time-region fixed-effect model (2) without adding control variables, the estimated coefficients of the digital economy development index are all significantly positive, indicating that the development of the digital economy has promoted the development of various eco-efficiency. In models (3), (4), and (5) with control variables added, the results of random effects, maximum likelihood estimation (MLE), and two-way fixed effects regression are shown respectively. The coefficient directions of all main variables in the three regressions are the same. The same, but the core explanatory variable coefficients in the two-way fixed effect are more significant, indicating that the two-way fixed effect model used in this paper is the most suitable. The coefficient value of the level of financial input in the model (5) is negative and significant, indicating that government financial input has significantly inhibited the improvement of ecological efficiency in the region. It may be because, with the expansion of the scale of financial expenditure, the government's intervention in the market economy is greater, it is easy to cause environmental damage caused by low energy utilization efficiency, which is not conducive to the improvement of my country's ecological efficiency; there is also a significant negative correlation between the level of opening up and ecological efficiency, indicating that in the context of globalization, the production of a large number of primary products Exports hurt country's ecological and environmental protection. The imperfect market mechanism, laws and regulations, and weak environmental awareness and environmental law enforcement legislation have produced many behaviors that are not conducive to ecological environmental protection and are not conducive to the improvement of ecological efficiency. For the level of human capital and the advanced level of industrial structure, there is a significant positive correlation with ecological efficiency, which shows the importance of human capital and industrial structure in improving regional ecological efficiency: educational human capital can promote the innovation of various technological activities, increase the strong intellectual endowment for the development of green technology, reduce production costs, and improve the ecological efficiency; under the new normal, the tertiary industry is dominant in the advanced industrial structure, and with the advancement of technology, the overall quality and efficiency of the industry continue to develop to a higher level, providing assistance for the optimal allocation of resources, thereby improving ecological efficiency. In summary, Hypothesis 1 is verified.

4.2 Moderating effect test

Based on the above confirms that the digital economy has a significant positive impact on high-quality development, verifying whether environmental regulation has a moderating effect is mainly judged by observing the significance of adding the intersection of environmental regulation intensity and

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the digital economy development index. As shown in Table 5, model (1) the intensity of environmental regulation has a significant moderating effect on the effect of the digital economy on the eco-efficiency path. And the coefficient of the intersection of the environmental regulation intensity and the digital economy development index in the model (1) is 0.1704, indicating that the adjustment variable environmental regulation intensity enhances the impact of the digital economy on ecological efficiency, and Hypothesis 2 holds.

To verify the reliability of the conclusion that environmental regulation has a moderating effect on the impact path of the digital economy on ecological efficiency, and to avoid the endogeneity problem and the accidental phenomenon of empirical results due to the selection of specific variables, we now choose to select local fiscal environmental protection expenditures and industrial three-waste emissions. The ratio is used to test the robustness, and it becomes the moderating variable environmental regulation substitute variable, and the robustness test is carried out. The specific results are shown in model (3). The cross term with the digital economy also positively affects the ecological efficiency at the 1% significance level, which is consistent with the regression results of model (1), and the replacement variable can fit the environmental regulation for the impact of the digital economy on the ecological efficiency mechanism.

Table 5: Moderating effect test

Model	(1)	(2)	(3)
lnDE	0.2359*** (0.0784)	0.222*** (0.07975)	0.8319*** (0.2363)
lnER	0.4207*** (0.1019)	0.1265** (0.0504)	0.4352*** (0.0538)
lnDE × lnER	0.1704*** (0.0516)		0.0.1001*** (0.0306)
Constant term	2.2255*** (0.4646)	2.0613 (0.4705)	4.3823*** (0.7513)
control variable	YES	YES	YES
city and year fixed	YES	YES	YES
N	300	300	300
R^2	0.6790	0.6669	0.7513

4.3 Robustness test

To ensure the reliability of the empirical conclusions, this paper adopts the following three methods to test the robustness.

4.3.1 Staged regression

Since the adoption of the G20 Digital Economy Development Cooperation Initiative in September 2016, China's digital economy development has undergone extensive and far-reaching integration with all aspects of society, and the development of the digital economy has become a national strategy. Therefore, to test the robustness of the basic regression and understand the different effects between the two periods, this paper divides the sample data into two periods: 2011-2016 and 2017-2020. The regression results are shown in models (1) and (2) in Table 6. The impact of the digital economy on eco-efficiency is still significantly positive, and it is more significant after 2016, and the impact coefficient is greater than that of the previous results, which is in line with the country's initiative to vigorously develop the digital economy after 2016.

4.3.2 Instrumental variables

Another solution to the endogeneity problem is to select appropriate instrumental variables for the core explanatory variables. This paper draws on the method of relevant scholars using historical data such as the postal telephone as an instrumental variable for the development of the digital economy, considering that the Internet is a continuation of the development of traditional communication technology, and traditional telecommunication tools such as post offices gradually decline with the decrease in the frequency of economic development and are gradually independent of Social and economic development in the 21st century. Combined with the availability of data, the number of post offices per million people and the number of telephone users per million people in each province in 1998 were selected as instrumental variables, and a time-varying data processing method was introduced by Nunn and Qian. The variable is the number of Internet broadband access ports in each province in the

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previous year, and the interaction terms are constructed with the number of post offices per million people in each province and the number of telephone users per million people in each province in 1998, as the instrument variable of the provincial digital economy index for that year. The results in columns (3) and (4) of Table 6 show that after using instrumental variables to reduce endogeneity, the impact of the digital economy on the development of eco-efficiency is significantly positive at the 1% level. In addition, the p-values of Kleibergen-Paaprk's LM statistic are all less than 0.01, which significantly rejects the hypothesis of "insufficient identification of instrumental variables"; Kleibergen-Paaprk's Wald F statistic is greater than 15.6. In general, the above test shows the rationality of selecting the number of post offices per million people in each province in history, the number of telephone users per million people, and the scale of Internet users as the instrumental variables for the development level of the digital economy.

4.3.3 Replace the core explanatory variables

Table 6: Robustness Test Results

variable	2011-2016	2017-2020	Instrumental variables		Variable substitution
	(1)	(2)	(3)	(4)	(5)
lnDE	0.091* 0.051	0.562** (0.254)	3.410*** (0.534)	1.672*** (0.394)	0.1144*** (0.0244)
lnHUC	0.190*** 0.059	1.365*** (0.248)		0.391** (0.179)	0.9002*** (0.0978)
lnLF	-0.084 0.088	-0.6418* (0.352)		-0.435** (0.192)	-0.6461*** (0.1307)
lnIS	0.474*** 0.090	1.941** (0.739)		0.483 (0.346)	1.0755*** (0.1779)
lnOPEN	-0.109*** 0.015	-0.093** (0.054)		-0.310*** (0.060)	-0.1412*** (0.0232)
Kleibergen-Paap rk LM Statistics			33.097 [0.0000]	15.531 [0.0001]	
Kleibergen-Paap rk Wald F Statistics			42.267 {16.38}	17.911 {16.38}	
City fixed	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES
N	300	300	300	300	300

Note: The value in ( ) is the robust standard error, the value in [ ] is the P-value, and the value in { } is the critical value at the 10% level of the Stock-Yogo weak identification test.

This paper also performs variable substitution processing, changing the core explanatory variable to the Peking University Digital Financial Inclusion Index measured by Guo Feng et al. Regression analysis was performed on the index and eco-efficiency, and the results are shown in Table 6. (5) is obtained by estimating the fixed-effect model, which shows that the digital financial inclusion index of the economic belt has a positive role in promoting ecological efficiency. Consistently, it proves again that the regression results in this paper are robust.

5. Further discussion

5.1 Threshold effect test

While the development level of the digital economy has a significant positive impact on ecological efficiency, there may also be a threshold characteristic of obvious nonlinear spillover effects, that is, with the gradual improvement of the development level of the digital economy in various regions, the impact on ecological efficiency is likely to occur. Jump-type changes are different from linear and smooth development in the traditional sense. To further explore the detailed mechanism by which the development level of the digital economy affects the ecological efficiency, considering the mechanism and path of the development level of the digital economy in each region acting on the ecological efficiency may have a significant jumping impact. This paper uses the threshold panel regression method to introduce the development level of the digital economy as a threshold variable into the threshold regression model based on the previous basic model and establishes a piecewise function with ecological efficiency. The model is as follows:

$$\ln EE_{i,t} = \beta_0 + \beta_1 \ln DE_{i,t} * I_{i,t}\left(\ln DE_{i,t} \leq \gamma_1\right) + \beta_2 \ln DE_{i,t} * I_{i,t}\left(DE_{i,t} > \gamma_1\right) + \varepsilon Control_{i,t} + \mu_t + b_i + \delta_{it} \quad (10)$$

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$$\ln EE_{i,t} = \beta_0 + \beta_1 \ln DE_{i,t} * ER_{i,t} * I_{i,t}\left(\ln DE_{i,t} \le \gamma_2\right) + \beta_2 \ln DE_{i,t} * \ln ER_{i,t} * I_{i,t}\left(\ln DE_{i,t} > \gamma_2\right) + \varepsilon Control_{i,t} + \mu_t + b_i + \delta_{it} \quad (11)$$

Among them, DE_{it} is threshold variable; $I(\cdot)$ is the indicator function of the model; γ_1、γ_2 are the threshold values to be estimated; equations (10) and (11) are the single threshold model, and the multi-threshold model can be extended accordingly. To test whether there is a threshold effect, firstly obtain the estimated threshold values—γ_1、γ_2 and the coefficients of the variable—$lnDE_{i,t} * lnER_{i,t}$, to be investigated, estimate and test the significance of the number and value of the threshold, and test the significance and confidence interval of the threshold effect on this basis. Before estimating the threshold model, a panel threshold existence test was firstly performed based on the fixed effects method of Hansen (1999), and the bootstrap method was used to verify the statistical significance of the threshold value by repeated sampling 400 times, as shown in the following table. As shown in *Table* 7, the results show that the p-values of the digital economy in the two models are less than 0.1 and 0.05, respectively, and both only pass the single threshold test.

Table 7: Threshold effect test

threshold variable	threshold number	F-Value	P-Value	Bootstrap number	Critical values		
					10%	5%	1%
$lnDE$ (1)	1	28.54	0.07	400	26.066	31.917	40.993
	2	15.65	0.18	400	29.665	44.178	94.485
	3	9.96	0.50	400	31.887	41.896	67.087
$lnDE$ (2)	1	32.59	0.0125	400	19.969	24.691	34.497
	2	12.81	0.3350	400	20.283	24.351	34.420
	3	10.55	0.3725	400	19.648	28.124	48.973

5.2 Threshold regression results

Further, this paper uses Stata15.0 software to carry out the threshold regression model, estimates and determines the variable coefficients, and obtains the regression results in Table 8. It is found from the model (1) that when the digital economy index is less than -0.7438, the threshold coefficient is 0.2451, and there is a significant positive correlation at the 1% level; when the digital economy development index is greater than -0.7438, the threshold coefficient becomes 0.9643, There is also a significant positive correlation at the 1% level. It can be seen that with the increase of the value of the digital economy development index, the impact of the digital economy on ecological efficiency continues to increase, that is, the ecological efficiency spillover effect of the digital economy shows a significant positive and nonlinear characteristics of increasing "marginal effects". In model (2), the threshold coefficient of the digital economy is also significantly positive at the 1% level, and it can be seen that the impact of the digital economy on the environmental regulation on the ecological efficiency adjustment mechanism is continuously increasing, indicating that the digital economy has an impact on ecology. The dynamic impact of efficiency is not only affected by its level but also has a moderating effect on the interaction item of environmental regulation, which is reflected in the positive interaction between the digital economy and environmental regulation.

Table 8: Regression Results of Threshold Model

variable	(1)	(2)
Threshold γ	-0.7438	-2.689
$\mathrm{lnDE} \cdot \mathrm{I}(\mathrm{lnDE} \le \gamma)$	0.2451*** (0.0772)	0.1376*** (0.0503)
$\mathrm{lnDE} \times \mathrm{lnER} \cdot \mathrm{I}(\mathrm{lnDE} > \gamma)$	0.9643*** (0.1669)	0.3849*** (0.0665)
Control variables and constant terms	control	control

6. Conclusions and Policy Recommendations

In recent years, China's digital economy has developed rapidly, gradually integrating and infiltrating into the fields of government governance, enterprise production, and residents' life, and has emerged early in the high-quality development and new pattern. In this context, based on the panel data of 30 provinces in China from 2011 to 2020, this paper uses the time-region double fixed-effect model, the threshold model, and adds environmental regulation adjustment variables to empirically test the impact of China's digital economy on ecological efficiency and its internal mechanism. The digital economy has significantly improved ecological efficiency. After the robustness test was carried out using methods such as staged regression, instrumental variable method, and substitution of explanatory variables, the conclusion still holds. Further research found that the impact of the digital economy has passed the single threshold test, indicating that the digital economy has a threshold characteristic of obvious nonlinear spillover effects on ecological efficiency. In addition, the regulatory effect of environmental regulation has also been confirmed, indicating that the intensity of environmental regulation can help strengthen the improvement of ecological efficiency by the digital economy. According to the analysis of the results of the control variables, the level of human capital and the level of the advanced industrial structure have a significant positive impact on ecological efficiency. The advanced level of capital and industrial structure and the improvement of the environment have shown a coordinated development trend. The expansion of government financial investment has an inhibitory effect on ecological efficiency. Although government adjustment plays an important role in improving ecological efficiency and environmental protection work, it may be because the government's adjustment by increasing financial investment often lags behind market changes. It is necessary to rationalize the control measures in promoting the improvement of ecological efficiency, and the level of opening to the outside world is also negatively affected, indicating that a large number of primary products and large exports during the opening-up period hurt China's ecological and environmental protection.

Based on the above conclusions, the following recommendations are put forward:

First, vigorously develop the digital economy. On the one hand, to build a complete digital infrastructure system, given the gap between China's current "new infrastructure" construction level and developed countries, it is necessary to learn from each other's strengths to make up for the shortcomings, to solidify the foundation of the digital economy, and to give full play to the efficient use of resources by the digital economy. At the same time, data elements are used to support urban industrial innovation and green research and development, and improve the utilization efficiency of resources such as the proportion of renewable energy.

Second, based on the actual performance of the digital economy, it will help improve ecological efficiency. With the continuous improvement of information technology interconnection configuration requirements, the demand for digital talents increases, and education human capital must increase investment, and at the same time rationally allocate talents, to stimulate innovation vitality and promote the development and use of new products, new processes and new technologies in cities, the development of digital industrialization and industrial digitization should continuously improve the market-oriented allocation of factors, ensure the efficient allocation of factors, and at the same time promote the research and development and innovation of digital technology.

Third, maintain high-quality economic development. As the supply-side structural reform puts forward higher requirements for high-quality development, the new formats, new patterns, and new models derived from the digital economy require that only by continuously strengthening, expanding, and optimizing the digital economy can they integrate into and serve the new development pattern, Only by maintaining high-quality economic development can we completely change the old development method of exchanging ecological environment for development speed.

Finally, the development of the national digital government is accelerating. With the support of digital technology, government data governance, government services, government processes, etc. tend to be modernized, and the government can better play its role, thereby promoting its economic regulation, public services, market supervision, and environmental protection.

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