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Original Paper

Research on the Green Development Effect of Digital Economy under the Threshold of Environmental Regulation: An Empirical Test Based on China's Provincial Panel Data

Kaiwen Zhou[1]

[1] School of Economics and Management, Guangxi Normal University, Guangxi Zhuang Autonomous Region, China

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Abstract

Under the current macro trend of deep integration of global green transformation and digital revolution, the relationship between the digital economy and environmental sustainability has become a cutting-edge issue as a key force in reshaping the economic and social form. However, digital technology is a "double-edged sword", which may also be accompanied by new resource consumption and governance challenges while enabling efficiency improvement and model innovation. Although existing studies have focused on the impact of digital economy on green development, most of them focus on the discussion of linear relationships, and lack of systematic testing of their inherent complex mechanisms, especially ignoring the nonlinear moderating effects that may arise from institutional factors such as environmental regulation, as well as the structural constraints caused by the dependence on traditional development paths. Based on this, this study aims to construct an integrated analysis framework including direct effects, nonlinear thresholds and structural constraints, and deeply reveal the complex mechanism of digital economy development affecting green development efficiency. Based on the panel data from 2011 to 2022 in 30 provinces in China, this study uses the two-way fixation effect model, panel threshold model and dynamic lag model to conduct an empirical test. The results show that, firstly, the development of digital economy has a significant and continuous direct promotion effect on green development efficiency, and this conclusion is still stable after endogenous treatment and lag effect analysis, which confirms that digital technology effectively drives the "decoupling" of economic growth and ecological pressure by optimizing resource allocation, improving energy efficiency and promoting green business formats. Secondly, the intensity of environmental regulation plays a key nonlinear moderating role in the relationship between the two,

showing a significant single threshold effect: when the intensity of environmental regulation is in a reasonable range (below the threshold value), it forms an "incentive compatibility" effect with the digital economy, jointly promoting the improvement of green efficiency. However, when the intensity of regulation exceeds the critical point, excessive compliance costs and innovation crowding out effects will weaken the green empowerment potential of the digital economy, resulting in a diminishing marginal contribution. Finally, the study also identifies important structural constraints: the traditional extensive urbanization model and the under-optimized government intervention mode have a significant inhibitory effect on green efficiency, which highlights the necessity of collaborative promotion of governance and development mode transformation in the process of digital transformation. The contribution of this study is not only to empirically verify the green dividend of the digital economy, but more importantly, to reveal the institutional conditions and structural constraints of this dividend release, breaking through the linear assumptions of previous studies. The conclusion provides multi-dimensional enlightenment for policy formulation: at the strategic level, we should adhere to the synergy of digitalization and greening; At the regulatory level, it is necessary to implement precise and differentiated environmental policies and seek a dynamic balance between "incentive innovation" and "strict constraints"; At the path level, it is necessary to promote the transformation of urbanization and government governance to a high-quality model, so as to systematically unlock the green development potential of the digital economy.

Keywords

Digital economy, green development efficiency, environmental regulation, two-way fixed effect model, panel threshold model

1. Introduction

In the contemporary context of the increasing urgency of global climate governance and sustainable development as a general consensus, how to coordinate the relationship between economic growth and environmental protection and resource conservation has become a common challenge faced by all countries in the world. As the world's largest developing country, China is in a critical period of economic transformation and upgrading and ecological civilization construction, and the strategic goal of "carbon peaking and carbon neutrality" marks that green development has become the core orientation of the country's long-term development. In this process, the digital economy, as an important driving force for a new round of scientific and technological revolution and industrial transformation, is penetrating into all fields of economy and society with unprecedented breadth and depth, not only reshaping the mode of production, consumption and governance, but also providing a new possible path for promoting the comprehensive green transformation of economic and social development. Therefore, in-depth exploration of the influence mechanism and effect of digital economy development on green development efficiency not only has important theoretical value, but also has urgent practical guiding significance. Green development efficiency emphasizes the maximum

economic and social output with the least resource consumption and environmental cost, and is the core indicator to measure the degree of coordination between the economic system and the natural system. Existing studies have mostly discussed its improvement path from the traditional perspectives of environmental regulation, industrial structure, and technological progress, but the role of the digital economy as an emerging systemic variable has been relatively insufficient. In fact, the digital economy may reconstruct the logic of green development from multiple dimensions through the embedding of data elements, the connectivity of network platforms and the empowerment of intelligent technology: on the one hand, digitalization can directly promote energy conservation, emission reduction and efficiency improvement by empowering energy management, optimizing resource allocation, and improving production and circulation efficiency; On the other hand, new formats and models (such as sharing economy, smart energy, remote services, etc.) spawned by the integration of digital technology and industry may also indirectly reduce the material dependence and carbon emission intensity of economic and social development. However, this impact is not always linear, and the energy consumption of digital infrastructure itself, the regional differentiation that the digital divide may lead to, and the consumption growth and e-waste associated with digitalization may also pose complex challenges to green development. At present, the academic community has carried out preliminary discussions on the relationship between digital economy and green development, but most of the studies are still stuck in theoretical deduction or local effect analysis, and there is a lack of comprehensive empirical testing based on the perspective of system efficiency and taking into account multi-dimensional transmission mechanisms, especially in terms of mechanism identification, nonlinear relationship and regional heterogeneity. Based on China's regional development practice, this study attempts to construct an integrated analytical framework to systematically investigate the impact of digital economy development on green development efficiency, transmission paths and boundary conditions. This study intends to use a quantitative model covering China's provincial panel data, and empirically test the causal relationship between the two on the basis of accurately measuring the level of digital economy development and green development efficiency, and further reveal its internal mechanism from the aspects of technological innovation effect, structural optimization effect and regulatory strengthening effect, and examine the heterogeneous impact of different regional characteristics and policy environments. This study hopes to provide evidence support for understanding the new paradigm of green development in the digital economy era through rigorous theoretical and empirical analysis, and also provide a scientific basis for government departments to formulate differentiated and collaborative digital empowerment green transformation policies, so as to help promote the deep integration of high-quality development and ecological civilization construction.

2. Research Hypotheses

Chen et al. (2025) believe that the digital economy can positively affect the efficiency of green development through the parallel and chain intermediary paths of urban cooperation and innovation,

industrial structure upgrading, and green technology innovation. Lu and Guo (2025) proved that the digital economy can promote green development efficiency by enhancing scientific and technological innovation capabilities and optimizing industrial structure, and has a spatial spillover effect. Enhancing the vigorous development of the digital economy relies on the wide application of data elements, the deep penetration of information and communication technology, and the network effect of the platform economy, which together constitute an important foundation for promoting the green transformation of the economy and society. From the perspective of direct mechanism, the development of the digital economy promotes the improvement of green development efficiency through various paths: first, at the technical level, digital technologies such as the Internet of Things, big data analysis and artificial intelligence can realize real-time monitoring and intelligent optimization of energy consumption, material flow and emission processes, thereby greatly improving resource utilization efficiency and reducing the environmental cost per unit of output; Second, at the level of model innovation, the digital economy has given birth to new formats such as sharing economy, product service system and circular economy platform, which reduces dependence on natural resources and waste generation by extending product life cycle and improving asset utilization. Third, at the governance level, digital tools help enhance the transparency and accessibility of environmental information, support the government to implement more precise environmental supervision and policy interventions, and stimulate public participation in green actions, forming a multi-party ecological governance pattern. Together, these mechanisms enable the development of the digital economy to directly promote the evolution of the economic system in the direction of resource conservation and environmental friendliness, thereby improving the efficiency of green development, that is, achieving greater economic output with less resource input and pollution emissions. However, this direct promotion effect does not occur in a vacuum, but is embedded in a specific institutional and policy environment, in which the intensity of environmental regulation, as a key external moderating variable, profoundly affects the actual effect of the digital economy in empowering green development. Ma and Liu (2024) have proven that the digital economy promotes green technology innovation in enterprises in national self-creation zones through the transmission of dual environmental regulations, thereby affecting the improvement of green development efficiency. Environmental regulation usually refers to the constraints and guidance imposed by the government on the environmental behavior of enterprises through laws and regulations, standard setting, economic incentives, etc., and the difference in intensity will change the strategy and motivation of enterprises to respond to the application of digital technology. At this time, enterprises tend to regard digital technology as an “innovation compensation” tool, that is, using digital means to efficiently and cost-effectively meet environmental requirements, and even develop new green products and services, thereby amplifying the role of the digital economy in promoting green efficiency. For example, companies may invest in smart energy management systems to reduce energy consumption to meet emission standards or use data analytics to optimize supply chains to reduce their carbon footprint, where environmental regulation creates synergistic enhancements with the digital economy. However,

as the intensity of environmental regulation continues to increase and cross a certain critical point, its role may shift from “enabler” to “restrictor”, resulting in the weakening of the digital economy’s role in promoting green efficiency. This is because excessive regulatory intensity often comes with significant compliance costs, including expensive investment in end-of-line treatment facilities, complex monitoring and reporting obligations, and potential fine risks. At the same time, overly rigid or standardized high-intensity regulations may inhibit enterprises from exploring flexible and diverse green solutions in the context of digitalization, forcing them to adopt standardized compliance strategies rather than innovative paths, which weakens the potential of digital technology to stimulate fundamental process reengineering and paradigm change. In addition, if high-intensity regulation lacks supporting market incentives or differentiated policy tools, it may inhibit the vitality of digital economy entities, especially for small and medium-sized digital enterprises, high compliance costs may threaten their survival and limit the popularization of digital technology and the diffusion of innovation. Based on these mechanisms, the intensity of environmental regulation constitutes a nonlinear regulating factor between the development of the digital economy and the efficiency of green development, and its influence shows a threshold effect: when the intensity of environmental regulation is lower than a certain threshold, it can form a synergy with the digital economy and strengthen the promotion of digital technology on green efficiency. Once the intensity of environmental regulation exceeds this threshold, the cost pressure, innovation crowding and rigid constraints brought by it will gradually dominate, partially offsetting the enabling potential of the digital economy, resulting in the weakening of the marginal role of digital economy development in promoting green development efficiency. This logical inference is rooted in an in-depth analysis of the interaction between technological innovation and the institutional environment, emphasizing the need to balance regulatory intensity with digital innovation space in the process of promoting green transformation to avoid the possible negative effects of “one-size-fits-all” policies. Therefore, based on the above mechanism analysis, this study proposes research hypotheses:

The development of the digital economy has a direct positive promotion effect on the efficiency of green development, but this effect is non-linearly moderated by the intensity of environmental regulation, which is manifested as a single threshold effect - when the intensity of environmental regulation is low, the promotion effect is significant. When the intensity of environmental regulation crosses the threshold value, its promoting effect will tend to weaken.

3. Research Design

Based on the above mechanism analysis, this paper selects data and models to carry out research. In terms of data, this paper covers 30 provinces and autonomous regions in China. The research content is the direct impact of digital economy development on green development efficiency in various regions from 2011 to 2022, taking into account the nonlinear impact. Referring to the practice of Guo et al. (2020), this paper selects three dimensions: digital infrastructure, digital industry development and

digital inclusive finance to construct an evaluation index system for the development of the digital economy, and uses the entropy method to synthesize the comprehensive value of the development of the digital economy in each region, which is used as the core explanatory variable (De). Drawing on the approach of Tian et al. (2022), this paper selects three types of indicators: input, expected output, and non-expected output to construct an evaluation index system for provincial green development efficiency, and refers to the research ideas of Oh (2010), and uses the super-efficiency SBM model to measure provincial green development efficiency, using it as the core explained variable (Gde). Referring to the methods of Liu et al. (2021) and Hu et al. (2023), the proportion of industrial pollution control investment in the added value of the secondary industry is used to measure the intensity of regional environmental regulation (Er), which is used as a threshold variable. Considering the influence of other variables, six variables, namely the degree of technology market development, the level of urbanization, government intervention, the degree of opening up, the employment density and the intensity of regional financial development, were included as control variables in the model for regression.

$$Gde_{it} = \alpha_0 + \alpha_1 De_{it} + \alpha_2 Control\_Var_{it} + \mu_i + \varphi_t + \varepsilon_{it} \quad (1)$$

In the above equation, Gdeit is the explained variable, representing the green development efficiency value of province i in year t, De it is the core explanatory variable, representing the digital economy development level of province i in year t, Control_Varit is the control variable, including the degree of technology market development, urbanization level, government intervention, degree of opening up, employment density and regional financial development intensity, α0, α1 and α2 are the regression coefficients of constant terms, core explanatory variables and control variables, respectively. μi represents the province fixed-effect dummy variable, φt represents the year fixed-effect dummy variable, and εit represents the random perturbation term.

The panel threshold model is selected for the test of the threshold effect, and the model is as follows:

$$Gde_{it} = \mu_i + \beta_1 De_{it} I(Er_{it} \le \gamma) + \beta_2 De_{it} I(Er_{it} > \gamma) + \varepsilon_{it} \quad (2)$$

In the above equation, i is the individual, t is the time variable, Gdeit is the explained variable, Deit is the explanatory variable, Erit is the threshold variable, γ is the threshold threshold, μi is the time-independent individual fixed effect, εit is the random error term of the model, and I(•) is the indicative function.

4. Empirical Analysis

4.1 Descriptive Stats

In the table below, the observation sample is 360 sets of data from 30 provinces and autonomous regions from 2011 to 2022, with the maximum value of the core explanatory variable (De) being 0.7120, the minimum value being 0.0170, the mean value being 0.1454, and the standard deviation

being 0.1169. This shows that, firstly, the overall is still at a low level and underdeveloped, with an average value of only 0.1454, which is significantly lower than the theoretical median, indicating that there is still huge room for improvement in the overall penetration and driving efficiency of the digital economy into the economy. Secondly, there is a huge disparity in the "digital divide" between provinces, with a range difference of 0.695, the highest value is about 42 times the lowest value, and the standard deviation (0.1169) is close to the mean, reflecting a serious regional development imbalance. The maximum value of the core explanatory variable (Gde) was 1.0400, the minimum value was 0.1279, the mean was 0.3744, and the standard deviation was 1586, indicating that the overall green development efficiency of China's provinces was at a moderately low level and the inter-provincial differences were significant. The average value of 0.3744 is far lower than the frontier level (maximum value 1.0400), indicating that most provinces have not yet been able to give full play to their resource and environmental potential to achieve better green economic output, and there is huge room for improvement as a whole. At the same time, the extreme deviation is as high as 0.9121, and the standard deviation (0.1586) reaches 42.4% of the mean, reflecting a serious regional development imbalance - some leading provinces (such as reaching or close to the efficiency frontier of 1.0400) have formed a relatively mature green production model, while the backward provinces (the minimum value is only 0.1279) are still in the extensive development stage, which may hinder the coordinated progress of the national green transformation. It is worth noting that the highest value exceeding 1 may mean that individual provinces have shown technical super-efficiency characteristics in a specific period or condition, becoming a benchmark for national green development. Overall, the data not only reveals that our country's green development as a whole is still facing the general challenge of efficiency improvement, but also highlights the urgency of coordinating regional coordination and promoting the diffusion of green technology and management experience.

Table 1. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Gde	360	0.3744	0.1586	0.1279	1.0400
De	360	0.1454	0.1169	0.0170	0.7120
Er	360	0.2566	0.2709	0.0044	2.4509
Ope	360	0.1371	0.1328	0.0041	0.6768
Urb	360	0.6000	0.1216	0.3503	0.9377
Stop	360	0.0179	0.0303	0.0002	0.1910
Gov	360	0.2590	0.1115	0.1050	0.7583
Jde	360	0.0256	0.0380	0.0044	0.2171
Fdl	360	3.4376	1.0848	1.6879	7.6178

4.2 Benchmark Regression Analysis

Table 2. Baseline Regression Results

	(1)
	Gde
De	0.412***
	(0.063)
Ope	0.099
	(0.071)
Urb	-0.805***
	(0.120)
Stop	-0.071
	(0.249)
Gov	-0.285***
	(0.093)
Jde	-0.114
	(0.570)
Fdl	-0.006
	(0.009)
_cons	(0.024)
	0.782***
N	360
R2	0.966

Based on the empirical analysis of 30 provinces in China, the results of this study show that the level of digital economy development (DE) has a significant and stable positive promotion effect on green development efficiency (GDE), and its regression coefficient is 0.412 and highly significant at the level of 1%, which fully confirms that the digital economy effectively promotes the green transformation of regional development through technology penetration, efficiency optimization and model innovation. At the same time, it is found that the urbanization level (URB) and government intervention (GOV) have a significant inhibitory effect on green development efficiency, with coefficients of -0.805 and -0.285, respectively, suggesting that the scale expansion in the current urbanization process may be accompanied by the increase of resource and environmental pressure, and some government intervention methods may also inhibit the vitality of green innovation to a certain extent. Other control variables such as opening up, technology market development, employment density and financial development level did not show significant effects, indicating that under the framework of green transformation driven by the digital economy, the direct linear effect of these factors is not prominent,

and their effects may be realized through more complex mechanisms or nonlinear paths. Overall, the results not only clarify the core role of the digital economy as a key driving force for green development, but also reveal the structural contradictions that may exist between urbanization and government behavior in the process of improving green efficiency, and provide important empirical basis and policy enlightenment for the overall promotion of the coordinated development of digitalization and greening.

4.3 Threshold Effect Analysis

Firstly, the threshold value is calculated by using the Bootstrap method, and the number of Bootstrap sampling checks is set to 300, and the threshold values of each threshold effect are obtained respectively, and the specific results are as follows:

Table 3.The Threshold Value Calculated by the Bootstrap Sampling Method

Threshold variable	F-value	P-value	Threshold value	95% confidence interval
Er	36.44	0.0333	0.0129	[0.0115,0.0134]

From the above table, it can be seen that in the process of the mechanism of digital economy development affecting the efficiency of green development, the threshold value of environmental regulation intensity is 0.0129, which is significant at the level of 5%.

Table 4: The Threshold Effect Regressed the Results

	(1)
	Gde
ope	-0.257***
	(0.069)
urb	0.300***
	(0.070)
stop	0.959***
	(0.243)
gov	-0.474***
	(0.087)
jde	0.205
	(0.602)
fdl	0.006
	(0.009)
Er≤0.0129	0.678***
	(0.063)

Er＞0.0129	0.435***
	(0.069)
_cons	0.246***
	(0.039)
N	360
R^2	0.766

The empirical results of this study based on the threshold regression model confirm that the intensity of environmental regulation has a significant nonlinear moderating effect on the development of the digital economy in the process of affecting the efficiency of green development, showing a single threshold effect (the threshold value is 0.0129). Specifically, when the intensity of environmental regulation is low (≤0.0129), the development of the digital economy has a strong promoting effect on the efficiency of green development (coefficient 0.678), while when the intensity of environmental regulation crosses this threshold (>0.0129), its promotion effect is still significant, but the effect is significantly weakened (coefficient 0.435). This result supports the hypothesis that "excessive regulation may inhibit the green empowerment potential of the digital economy", indicating that excessive environmental regulation intensity may partially offset the green efficiency improvement effect brought by technology penetration and model innovation of the digital economy by increasing corporate compliance costs, crowding out innovation resources, and strengthening institutional rigidity. At the same time, government intervention (GOV) and opening up to the outside world (OPE) significantly inhibit green efficiency, while urbanization (URB) and technology market development (STOP) significantly promoted, further revealing the complex influence paths under the interweaving of multiple factors. In summary, the study not only provides contextual evidence for understanding the relationship between digital economy and green development, but also suggests that policy formulation should pay attention to the "moderation" of environmental regulation, avoid "one-size-fits-all" high-intensity constraints, and focus on building a collaborative governance system that can not only stimulate the vitality of digital innovation but also steadily improve environmental standards.

4.4 Robustness Analysis

Table 5. Robustness Regression Results

	(1)
	Gde
L.de	0.456***
	(0.071)
ope	0.089
	(0.080)

urb	-0.842***
	(0.123)
stop	-0.226
	(0.263)
gov	-0.232**
	(0.097)
jde	0.171
	(0.729)
fdl	-0.009
	(0.010)
_cons	0.810***
	(0.069)
N	330
R2	0.808

The empirical results show that the estimated coefficient of the digital economy development level (L.De) is 0.456, which is highly significant at the statistical level of 1%, indicating that the early digital economy development has a significant and steady positive promotion effect on the current green development efficiency, and further strengthens the causality and sustainability of the "digital empowerment green" effect. In terms of control variables, the coefficients of urbanization level (URB) and government intervention degree (GOV) were -0.842 and -0.232, respectively, and were significantly negative at the levels of 1% and 5%, respectively, indicating that if the urbanization process continues the traditional extensive path, and improper or excessive government intervention will still significantly inhibit the improvement of green efficiency. However, the influence of other control variables such as opening up to the outside world (OPE), technology market development (STOP), employment density (JDE) and financial development level (FDL) has not passed the significance test, indicating that after considering the lag effect of the digital economy, the independent impact of these factors on green efficiency is not significant, and its role may be more indirect or complex. Overall, the results further confirm the digital economy as a long-term driving force for green transformation, and also reveal the urgency of optimizing urban development models and government governance methods, providing an empirical basis from a dynamic perspective for the coordinated promotion of digitalization and greening.

5. Conclusion

Based on a series of empirical tests in 30 provinces in China, this study systematically reveals the impact of digital economy development on green development efficiency and its action boundaries, and the main conclusions are as follows: First, digital economy development is the key driving force for improving green development efficiency, and this promotion role is stable and sustainable. Both the benchmark regression and lagging models confirm that both the current and previous digital economy developments have a significant positive impact on the green efficiency of the current period (coefficients of 0.412 and 0.456, respectively). This shows that the digital economy can effectively promote the "decoupling" of economic growth and resource and environmental consumption through technology penetration, efficiency optimization and model innovation, and its green dividends have a cross-term continuous effect, providing solid empirical evidence for "digital empowerment green transformation". Secondly, it is found that the intensity of environmental regulation plays a key nonlinear moderating role in this influence process, and there is an obvious single threshold effect. When the intensity of environmental regulation is at a low level (≤ threshold value of 0.0129), the promotion effect of the digital economy on green efficiency is the strongest (coefficient of 0.678). However, once the intensity of environmental regulation crosses this threshold, the promotion effect is still significant, but the intensity is significantly weakened (the coefficient drops to 0.435). This verifies the hypothesis of "too much": moderate environmental regulation can form incentives and compatibility with enterprises' digital green innovation, while excessive regulatory intensity may inhibit the full potential of digital technology due to heavy compliance costs and crowding out innovation resources, thereby weakening its green empowerment effect. In addition, the study reveals the complex influence of other structural factors. The level of urbanization and the degree of government intervention were significantly negative in the multiple regressions, indicating that the traditional extensive scale expansion and possible improper government intervention have become prominent shortcomings restricting the improvement of green efficiency. The development of technology markets has a positive effect in some scenarios, while the direct effects of factors such as opening up and financial development are not entirely significant, suggesting that their impact may be realized through more indirect or non-linear paths.

In summary, this study constructs and confirms a comprehensive analysis framework including "core drive-threshold adjustment-structural constraints". The conclusion shows that the promotion of green development cannot rely on a single policy in isolation, but requires systematic coordination: while firmly developing the digital economy and consolidating its green empowerment foundation, it is necessary to carefully design environmental regulation policies, seek the dynamic optimal balance between "incentive innovation" and "strict constraints", and simultaneously promote the transformation of urbanization model and the optimization of government governance methods. Only in this way can we maximize the green growth potential of the digital age and solidly promote the comprehensive green transformation of economic and social development.

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