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Original Research

Does Digital Economy Development Successfully Drive the Quality of Green Innovation in China?

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Abstract

Based on the systematic analysis of the development trend of the digital economy and regional structure, we focused on the heterogeneous influence mechanism of digital economy development on regional green innovation quality. The research finds that, on the whole, the development of the digital economy has a significant promoting effect on the improvement of regional green innovation quality. Interestingly, with the improvement of the development level of the digital economy, there are differences in its driving mechanisms for the quality of regional green innovation. A lesser level of digital economy development is not conducive to improving the quality of regional green innovation. But when digital economy development rises, it can positively drive the quality of regional green innovation. Once the level of digital economy development breaks through the critical scale. In other words, the higher the level of inter-regional digital economy development, the more beneficial it is to promote the quality of green innovation.

Keywords: digital economy development, green innovation quality, threshold effect, China

Introduction

At present, the conflict between global resource and energy consumption and environmental pollution still exists, and how to achieve sustainable economic development under such a conflict is a major problem encountered in the process of economic development of all countries. As one of the most industrially diverse economies in the world, China is under tremendous pressure to protect the environment. At the same time, air quality deterioration is particularly serious in China under the traditional development model. Therefore, under the global green competitive environment and the huge pressure of domestic resource carrying capacity, the improvement of China's green innovation quality has become a focal issue of worldwide concern. The Chinese government has set "high-quality development" as one of the important guiding ideologies for economic and social development in the 14th Five-Year Plan period. The crude development model characterized by high speed and low quality has been challenged, and green development has become an important path to promote China's economic development transformation. The quality

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of green innovation is the improvement of quality and competitiveness in terms of innovation fields, innovation methods, and innovation results to cope with environmental problems and achieve sustainable development for environmental purposes [1-2]. The quality of green innovation leads to the development of innovation in the direction of environmental protection, which must be able to reduce the input in terms of resources, reduce the pressure of environmental pollution, save resource costs and achieve the development of the regional economy in the direction of high quality [3]. Green and innovation as the two cores to promote the implementation of the global economic quality development strategy, which is the organic combination of green development strategy and innovation-driven strategy, but also China to build an innovative country, to solve the key power of environmental pollution.

As the global economy enters a new normal, the digital economy with Internet technology at its core, as the most active field in international economic development, is playing an increasingly important role in fostering new dynamics of economic development, stimulating consumption, and enhancing innovation capacity. The definition of "digital economy" was first proposed by Tapscott [4], who considered the digital economy as an economic system that makes extensive use of information and communication technologies (ICT). As scholars have explored the concept of the digital economy in depth, the digital economy has been divided into a narrow and a broad sense. The digital economy in a narrow sense is understood as an industrial economy, i.e., digital industrialization, which is the production, consumption, and distribution of digital services or goods spun off from traditional national economic sectors. The digital economy in a broad sense is considered an economic activity, which is typically characterized as the sum of economic activities in which digital information and knowledge are used as new factors of production to promote efficiency improvement and macroeconomic structural optimization by using information technology networks as carriers [5]. The digital economy has become an important engine driving China's economic growth and an effective tool to enhance the quality of green innovation. Therefore, Can digital economy development effectively improve the quality of green innovation? What are the non-linear effects of digital economy development on the quality of green innovation? A discussion of these issues is worthwhile. In summary, the contribution of this study are as follows: We analyze and explore the impact mechanism on green innovation quality from the perspective of digital economy development. By constructing a panel threshold model, we innovatively verify the heterogeneous threshold characteristics of green innovation quality generated under different levels of digital economy development, and further answer the contribution that digital economy development would bring to green innovation quality improvement.

The rest of the article are as follows: Section 2 reviews and summarizes the related literature, Section 3 constructs a digital economy development index system to discuss the current level of digital economy development in China, and Section 4 constructs a threshold model. Section 5 derives empirical results and discuss how different levels of digital economy development would affect the quality of regional green innovation, and Section 6 proposes policy recommendations based on the empirical results.

Literature Review

The expanding application of digital technology in modern economic activities has not only improved economic efficiency but also transformed economic structures. Digital technology, as an economic engine in the post-epidemic era, has been incorporated into the strategic agenda of many countries for their economic development. For example, the National Cyber Strategy promulgated by the United States includes the digital economy as an important part of its development strategy; the White Paper on China's Digital Economy Development and Employment released by the China Academy of Information and Communication Research shows that the size of China's digital economy will grow by 16.2% year-on-year to reach 45.5 trillion yuan in 2021, and the digital economy has become an important part of China's industrial development. In terms of the development of the digital economy, the 1960s saw the beginnings of digitalization in the form of commercial mainframe computers. By the mid-1980s, the advent of the personal computer made digital tools and computerized manufacturing technologies increasingly sophisticated. The Internet-centered digital economy encompasses and transforms all areas of global economic and social life [6]. In recent years, the literature has begun to establish indicator systems to quantify the level of development of the digital economy. For example, Liu et al. [7] conducted a comprehensive evaluation of China's provincial digital economy in terms of information development, Internet development, and digital transaction development. From the city level, Zhao et al. [8] measured the level of digital economy development in terms of two dimensions: internet development and digital financial inclusion. Yang et al. [9] measured the digital economy in terms of three indicators: digital financial inclusion index, Internet broadband access rate, and the proportion of cell phone users.

At the same time, China's current energy consumption is accelerating and ecological and environmental pressures are increasing dramatically, so how to drive green innovation quality through the transformational development of the digital economy has become a hot topic of academic research. At present, many studies show that digital economy development significantly improves the quality of green innovation. For example, Ma and Zhu [10] demonstrated that the digital economy can directly drive high-quality green development. From the regional perspective, Luo et al. [11] found that the digital economy significantly promotes the efficiency of green development in China based on data from 108 cities in China's Yangtze River Economic Zone from 2011-2019. Wang et al. [12] indicated that the digital economy promotes high-quality energy development in China. Yang et al. [13] showed that the digital economy positively impacts high-quality economic development, innovative development, and green development.

As scholars delve deeper, the relationship between digital economic development and the quality of green innovation remains uncertain for now, and in some cases may show negative or even non-linear effects. Van Ark [14] argued that although the digital economy is currently growing rapidly due to the emergence of digital technologies such as big data and cloud computing, it is still not reaching its maximum potential and there is still much room for progress in promoting economic development. Acemoglu and Restrepo [15] found that the overuse of AI technologies can have some substitution effect on the middle and lower end of the labor force, leading to a misallocation of capital and labor, thus undermining productive efficiency. In addition, Zhu et al. [16] concluded that the digital economy empowers urban innovation capabilities, especially in intellect-intensive and capital-intensive high-tech industries, where talent scarcity and financing difficulties are the main obstacles limiting digital innovation in enterprises. While Männasoo et al. [17] argued that talent concentration positively regulates the relationship between the digital economy and the innovation capacity of cities both by affecting the integration of the digital economy with other innovation resources. Luo et al. [18] used a stochastic nonparametric data envelope (stoNED) model to measure green development efficiency and used a mediating effects model to test the impact of the digital economy on green development efficiency and assessed the mechanisms from a Chinese perspective, finding that the digital economy can contribute to green development efficiency in the Yangtze River Economic Zone through technological innovation, human capital accumulation, and industrial structure upgrading. Lyu et al. [19] constructed a spatial econometric model and a mediating effect model to test the spatial spillover effects and transmission mechanisms between the digital economy and green total factor productivity on the basis of a comprehensive explanation of the impact mechanisms. The results show that the digital economy has a significant U-shaped characteristic with positive direct effects and spatial spillover effects on green total factor productivity, and these effects mainly come from the promotion of the digital economy on green technological progress.

Based on this, this paper refines the existing research in three ways: First, existing studies do not include digital economy development and regional green innovation quality in a unified research framework. Most studies focus only on the factors influencing regional green innovation quality. However, the relationship between digital economy development and green innovation quality during China's digital transformation cannot be viewed in isolation. To make up for the shortage of existing studies, we incorporate digital economy development and regional green innovation quality into a unified research framework, innovatively demonstrate the nonlinear threshold effect on regional green innovation quality under different digital economy development levels, and have theoretical significance for China to promote the improvement of regional green innovation quality in China through guiding digital economy development levels according to the differences of digital economy development in different regions.

Second, there is no unified standard for measuring the development of the digital economy. Therefore, based on compiling and summarizing the literature on concepts and indicator systems related to digital economy development, we construct a digital economy evaluation indicator system including three subsystems, which are digital infrastructure construction, digital industrialization development, and industrial digitalization development. The three subsystems consist of nine guideline layers and fourteen measurement indicators. Our indicator system provides a specific measurement of the development level of the digital economy in each region of China, overcoming the measurement bias caused by using a single digital economy indicator measurement and providing a direction and reference for existing research.

Third, ignoring the nonlinear threshold of digital economy development can bias the research results. Therefore, we consider the nonlinear threshold effect of digital economy development in our analysis, introduce the digital economy development threshold factor into the influence mechanism of green innovation quality, and reveal the role of how different degrees of digital economy development affect regional green innovation quality and its differences to test whether digital economy development effectively improves green innovation quality in each region of China.

Measuring Digital Economy Development

Indicator Construction

According to the United Nations' definition of the concept of the digital economy, the digital economy can be divided into three levels: At the bottom is the core digital sector, i.e. IT and ICT industries, extending on this concept, together with business activities such as platform economy, sharing economy and digital services that rely on digital technology, constitutes a narrow-caliber digital economy. Expanding on this foundation and adding all digitalized economic activities, i.e., the digitization of industries, constitutes a broad-caliber digital economy. The constructed indicators on the development of the digital economy mainly include primary indicators such as broadband access, human capital, digital technology application, digitalization of public services, and secondary indicators such as broadband penetration rate, mobile data communication, Internet users, and ICT patent design. Although research around the digital economy has emerged and achieved certain results, there are still shortcomings: first, there is a lack of empirical research on the measurement of the overall development level of the digital economy; second, the coverage of digital economy indicators in existing studies is insufficient, mostly analyzed from a single perspective; third, there is a lack of analysis of the regional heterogeneity of the digital economy; fourth, the development trend of the digital economy in time and space still needs further exploration. How to construct and measure the digital economy is an important proposition for the high-quality development of China's economy, which is particularly important for the sustainable and healthy development of China's economy, among which we believe that the construction and measurement of the digital economy indicator system should be defined mainly according to its connotation. By definition, the digital economy is based on infrastructure construction as the "ballast stone", supported by the development of digital industries, and focused on the deep integration of industrial digitalization, and constantly expanding the depth and breadth of the development of the digital economy. Thus, based on the existing research, we construct the digital economy development evaluation index system from the concept of digital economy development, taking into account the data accessibility of indicators, and using the entropy value method to measure it. It includes three subsystems, nine guideline layers and fourteen measurement indicators for digital infrastructure construction, digital industrialization development and industrial digital development. The specific measures are shown in Table 1.

(1) Digital infrastructure development. Digital infrastructure includes both hardware facilities and software facilities. Specifically, the level of hardware facility construction is measured by three indicators: fiber optic cable density, cell phone exchange density, and mobile base station density [6], and the level of software facility construction is measured by Internet broadband access density [9].

Table 1. Digital economy development measurement system.

Objectives	Subsystems	Guideline layer	Specific Metrics	Indicator measurement method
Digital Economy Development	Digital Infrastructure Development	Hardware	Fiber optic cable density	Fiber optic cable length/province area [6]
			Cell phone exchange density	Cell phone exchange capacity / total population [6]
			Mobile base station density	Number of cell phone base stations/ province area[6]
		Software Facilities	Internet broadband access density	Number of Internet broadband access users/total population[9]
	Digital Industrialization Development	Employment of personnel	Related Practitioners	Number of employees in the computer services and software industry [6, 10]
		Telecommunications	Telecommunications services per capita	Total telecom business/total population [6, 10]
		Software Industry	Software business revenue per capita	Software business revenue/total population [6, 10]
		E-commerce	E-commerce transaction volume	(E-commerce sales + E-commerce purchases)/2 [6, 10]
		Communications	Communication industry fixed asset investment	Information transmission computer services and software industry all-social fixed asset investment / all-social fixed asset investment [6, 10]
	Industrial digitalization development	Financial Digitization	Digital Inclusive Finance	Digital Inclusive Finance Index [9, 20]
		Enterprise Digitalization	Enterprise e-commerce transaction activities	Number of enterprises with e-commerce trading activities [21]
			Number of corporate domain names	Number of Domains[21]
			Number of corporate websites	Number of IPV4 addresses [21]
			Number of corporate pages	Number of pages [21]

(2) Digital industrialization development. Digital industrialization means developing the software and hardware information industry by effectively integrating four technologies of artificial intelligence, blockchain, cloud computing and data science, so that digital products and digital services can gradually squeeze out traditional products and traditional services, thus expanding the scale of the digital economy. The development level of digital industrialization covers five dimensions: employment, telecommunication industry, software industry, e-commerce, and communication industry, and the corresponding dimensions are reflected by the relevant personnel employment, per capita telecommunication business volume, per capita software business income, e-commerce transaction volume, and fixed asset investment in the communication industry [6, 10]. (3) Industrial digitalization development. Industrial digitalization accounts for about 80.9% of the digital economy, and the level of industrial digitalization development is examined from two aspects: financial

Table 2. Digital economy development level in 30 regions of China (2013-2020).

Area	2013	2014	2015	2016	2017	2018	2019	2020	Average
Anhui	5.8400	6.2637	6.5135	6.6000	6.6058	6.7287	6.8747	6.9257	6.5440
Beijing	6.9252	7.6778	7.4199	7.4827	8.0202	8.0255	8.1915	8.2573	7.7500
Fujian	6.1705	6.1888	6.3838	6.5701	6.6577	6.6836	6.8413	6.8931	6.5486
Gansu	4.2548	4.6267	4.8560	4.9343	4.9660	5.0298	5.0856	5.1633	4.8646
Guangdong	7.4959	7.6793	7.7712	7.9288	8.0558	8.2018	8.3557	8.3888	7.9847
Guangxi	5.0680	5.3790	5.4980	5.6426	5.6696	5.7476	5.9568	6.0759	5.6297
Guizhou	4.9797	5.1927	5.4415	5.7845	5.6920	5.7155	5.6818	5.7951	5.5354
Hainan	4.1389	4.6015	4.7412	4.7577	4.7954	4.6613	4.9420	5.0396	4.7097
Hebei	5.6928	5.9684	5.8567	6.1230	6.3877	6.2969	6.3376	6.5054	6.1461
Henan	5.7839	6.2313	6.3602	6.5333	6.6289	6.7145	6.7104	6.7599	6.4653
Heilongjiang	4.9409	4.9665	4.7590	4.8034	5.1207	5.0542	5.0903	5.1879	4.9904
Hubei	5.8324	6.1538	6.2995	6.4757	6.5364	6.5530	6.7202	6.7893	6.4200
Hunan	5.7644	6.0357	6.1649	6.3463	6.3848	6.5896	6.6291	6.7608	6.3345
Jilin	4.6261	4.9296	4.8487	4.9756	5.1566	5.2325	5.1591	5.1786	5.0134
Jiangsu	7.0804	7.3098	7.3490	7.3009	7.3290	7.4486	7.5496	7.7310	7.3873
Jiangxi	5.4700	5.4578	5.8795	5.8864	6.0863	6.1628	6.2966	6.4231	5.9578
Liaoning	5.7212	5.9302	5.9328	5.8369	6.0808	6.3029	6.4111	6.4495	6.0832
Neimenggu	4.2498	4.6170	5.2191	5.4042	5.4493	5.5142	5.7042	5.8175	5.2469
Ningxia	4.1466	4.3366	4.4763	4.5561	4.6134	4.6440	4.5502	4.6081	4.4914
Qinghai	3.2378	3.5015	4.2557	4.4311	3.9551	3.9816	4.1031	4.1252	3.9489
Shandong	6.7011	6.9404	6.9349	7.3548	7.5552	7.7561	7.5567	7.6272	7.3033
Shanxi	5.1222	5.2380	5.2744	5.4488	5.5443	5.8532	5.8830	5.9064	5.5338
Shaanxi	4.9771	5.4025	5.5304	5.8212	5.9287	6.0315	6.1385	6.2229	5.7566
Shanghai	6.6445	7.3684	7.3849	7.5434	7.5563	7.6017	7.7508	7.9066	7.4696
Sichuan	5.6525	6.0603	6.2615	6.5211	6.6368	6.7063	6.9185	7.0430	6.4750
Tianjin	5.6763	5.9743	6.1843	6.0987	6.1002	6.1652	6.2768	6.3972	6.1091
Xinjiang	3.9569	4.5345	4.8874	4.6322	4.7311	4.9315	5.0430	5.1113	4.7285
Yunnan	5.2038	5.6014	5.7884	5.7373	5.7409	5.7592	5.8797	6.0482	5.7198
Zhejiang	7.0900	7.2008	7.2665	7.4089	7.3965	7.4463	7.5898	7.6600	7.3824
Chongqing	5.2183	5.7447	5.9465	6.2110	6.2411	6.3293	6.4161	6.5795	6.0858
National	5.4554	5.7704	5.9162	6.0384	6.1208	6.1956	6.2881	6.3792	6.0205

digitalization and enterprise digitalization, respectively. Specifically, the level of financial digitization is revealed by digital financial inclusion [9, 20], and the level of enterprise digitization is characterized by enterprise e-commerce transaction activities, number of enterprise domain names, number of websites, and number of web pages [21].

Measurement Results and Analysis

Although political factors such as multinational protectionism and the new epidemic, as well as the climate and energy crises, have put the global economy to an important test, the digital economy has bucked the trend and entered the "fast lane" of development, becoming an important driving force for rational optimization of global resources and global economic development. In this context, we take the development of China's digital economy as an example and try to provide Chinese experience and solutions for the development of the global digital economy, and continuously improve the influence of China's digital economy in domestic as well as international aspects. From Table 2 and Fig. 1, we can see that the average value of China's digital economy development level from 2013 to 2020 is 6.0205, and overall China's digital economy development level has always maintained an increasing trend over a longer time, which has some coordination with the developing characteristics of China's macroeconomy. This is mainly due to China's emphasis on digital infrastructure development since the 13th Five-Year Plan, from the construction of broadband in China to the telecom industry's "speed and fee reduction", which has effectively bridged the digital infrastructure gap between regions by promoting the development of China's digital infrastructure in an orderly manner with a region-wide perspective. Meanwhile, the digital economy has become an important driver of high-quality economic development since China implemented supply-side structural reforms in 2015.

In addition, in terms of the trend of change, the developed digital economy regions, mainly Guangdong, Beijing, Shanghai and Jiangsu, are in a relatively high level of digital economy development due to their geographical location, economic base and resource advantages. The low level of digital economy development in Qinghai, Ningxia, Hainan, Xinjiang and other provinces in the sample period is mainly due to the late start of digital economy development in these provinces, coupled with the imperfect infrastructure conditions and the lack of technical personnel. This will, to a certain extent, have an impact on the economic and social development in the current period, while the "digital economy gap" between the various regions due to the constraints of various factors has not only not improved, but also has a tendency to widen. Therefore, as China enters the 14th Five-Year Plan period, how to comprehensively and systematically improve the level of digital economy development in less developed regions is an important issue to be faced in the future.

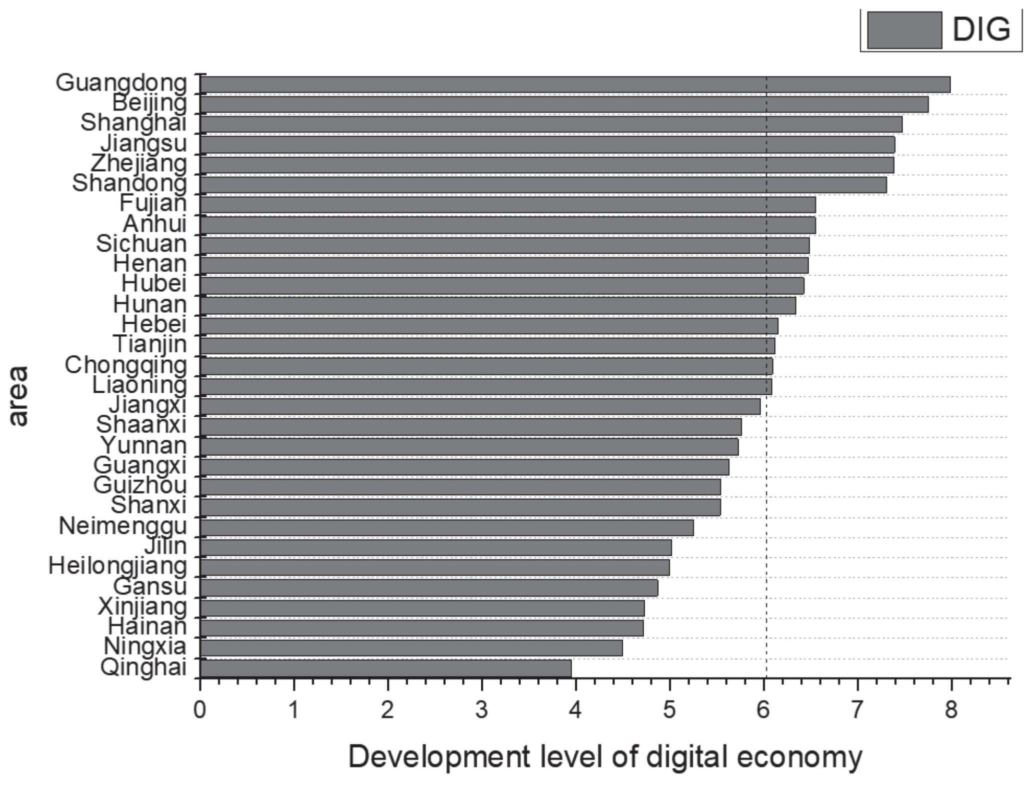

Fig. 1. Average digital economy development levels in 30 regions in China (2013-2020).

Threshold Model Construction

Model Design

To verify the nonlinear threshold effect of digital economy development on regional green innovation quality, we adopt the Hansen panel threshold effect model. The traditional empirical practice of dealing with nonlinearity is usually to include quadratic or cubic terms of the explanatory variables to reflect the curvilinear relationship between the variables; or to use group regressions with different group regression results differing to indirectly test whether there is a nonlinear relationship. These research methods have significant limitations: the inclusion of a partial explanatory variable squared term in the explanatory variables often leads to very serious covariance problems; secondly, the structural change cut-off point is difficult to determine, and an incorrect subjective cut-off point can lead to serious bias. Thus, based on these limitations, this paper adopts and extends the Hansen threshold model through the automatic identification of sample data can well capture the nonlinear threshold characteristics generated by sudden structural changes in the economic system, while also having good characteristics of the general panel data model to deal more objectively and accurately with nonlinear problems of structural changes. And add factors affecting regional green innovation quality such as environmental regulation, education level, science and technology expenditure level, and intellectual property protection, and combine the regional characteristics of China's digital economy development level, thus we analyze the threshold panel model on regional green innovation quality under different digital economy development levels [22]. Set panel threshold model (single threshold):

$$\mathrm{GIQ_{it}} = \theta + \alpha_1 \mathrm{REG_{it}} + \alpha_2 \mathrm{EDL_{it}} + \alpha_3 \mathrm{TEL_{it}} + \alpha_4 \mathrm{IPR_{it}} + \beta_1 \mathrm{DIG_{it}} I(\mathrm{DIG_{it}} \le \gamma) + \beta_2 \mathrm{DIG_{it}} I(\mathrm{DIG_{it}} > \gamma) + \mu_i + \vartheta_t + \varepsilon_{it}$$

Where DIG is digital economy development, GIQ is regional green innovation quality, REG is environmental regulation, EDL is education level, TEL is science and technology expenditure level, IPR is intellectual property protection, I(·) is the indicator function, γ is the threshold, μ_i is the individual-specific effect, ϑ_t is the time-specific effect, and ε_{it} is the random disturbance term. Panel multi-threshold model (double threshold as an example):

$$\mathrm{GIQ_{it}} = \theta + \alpha_1 \mathrm{REG_{it}} + \alpha_2 \mathrm{EDL_{it}} + \alpha_3 \mathrm{TEL_{it}} + \alpha_4 \mathrm{IPR_{it}} + \beta_1 \mathrm{DIG_{it}} I(\mathrm{DIG_{it}} \le \gamma_1) + \beta_2 \mathrm{DIG_{it}} I(\gamma_1 < \mathrm{DIG_{it}} \le \gamma_2) + \beta_3 \mathrm{DIG_{it}} I(\mathrm{DIG_{it}} > \gamma_2) + \mu_i + \vartheta_t + \varepsilon_{it}$$

Where each symbol is the same as the above equation.

Variable Description and Data Processing

Explained variable: green innovation quality (GIQ). Wang et al. [23] argued that green innovation can be a model to achieve sustainable development by saving resources and energy, preventing environmental pollution, etc. It needs to balance both knowledge spillover and ecological environmental protection and is characterized by complexity, systematicity and uncertainty. In contrast, Lanjouw and Schankerman [24] argued that the quality of innovation includes two aspects, one being the technological breakthrough of the innovation and the other being the ability to have practical prospective value in economic and social terms. Green innovation quality is innovation outcome-oriented and refers to the results generated by innovation activities, the value created or sustained through innovation. Technological complexity, economic efficiency, and technological impact are the main ways to measure the quality of green innovation. Combining the views of scholars, we believe that the quality of green innovation is the technological innovation achieved by optimizing production, processes, management and services to protect the ecological environment, and can also generate a certain commercial value. To a certain extent, patents can reflect the status of regional technological innovation and invention progress, while green patents can directly reflect the green innovation activities driving the quality development of innovation factors and can be used to measure the quality of regional green innovation. Thus, we select the number of green utility model patents in each region to reflect the quality of regional green innovation [25].

Explanatory variable: digital economy development (DIG). As a new model of economic and social development in the post-epidemic era, the digital economy can, to a certain extent, bring into play the advantages of digital technology to improve the quality of regional green innovation. At the same time, due to the emergence of this new economic development model, it also promotes the flow of information technology and talents among regions and provides important support for the improvement of the quality level of green innovation in other regions by bringing into play the spillover effect and demonstration effect among regions. Therefore, we choose the Digital Economy Development Level Index to reflect the development of China's digital economy [20-21].

Control variables:

(1) Environmental Regulation (REG). The "Porter hypothesis" has been challenged by neoclassical economists, who argued that environmental regulations will increase regional production costs and have a "crowding-out effect" on regional investment in green innovation quality, which to a certain extent will be counterproductive to the improvement of regional green

Table 3. Descriptive statistics of the variables.

Variable	Mean	p50	sd	min	max
DIG	6.021	6.003	1.055	3.238	8.389
GIQ	0.430	0.222	0.606	0.003	4.579
REG	24.531	17.463	22.933	0.048	141.600
EDL	4.293	4.351	0.793	1.623	5.518
TEL	0.022	0.015	0.015	0.005	0.068
IPR	0.017	0.008	0.028	0.000	0.176

innovation quality. Therefore, we express the intensity of environmental regulation in terms of the amount of completed investment in industrial pollution control in each region [12].

(2) Educational attainment (EDL). In general, the level of education and the quality of regional green innovation are positively correlated. Highly educated regions have greater access to green innovation activities. High-quality talents are more important for the improvement of regional innovation quality than the quantity of personnel, mainly because they help optimize the structure of the labor force, improve the efficiency of labor and resource utilization, and can directly influence the quality of green innovation in the region. Therefore, the number of students per 10,000 population in general higher education schools is used to measure educational attainment [3].

(3) Science and technology expenditure level (TEL). Innovation needs to be supported by the level of science and technology, which in turn depends on adequate investment. The government spends part of the science and technology expenditure on the improvement of the quality of regional green innovation and uses the funds to engage in green economic activities to help improve the quality of innovation. We choose the ratio of S&T expenditure in general public budget expenditure to indicate the level of S&T expenditure [3].

(4) Intellectual Property Protection (IPR). The level of IPR indicates the extent to which green innovations are protected by law. Therefore, we chose the ratio of technology market turnover to local GDP to measure IPR [26].

Data Sources and Processing

The data we use is Chinese regional panel data from 2013 to 2020 (Tibet Autonomous Region and Hong Kong, Macao and Taiwan are not included in the study sample due to the serious data missing). The original data is obatained from the Digital Inclusive Finance Index jointly compiled by the Digital Finance Research Center of Peking University and Ant Group, China's National Bureau of Statistics and Energy Bureau, the IPCC Guidelines for National Greenhouse Gas Inventories, Guotaian and CNRDS databases. The descriptive statistics for all variables are shown in Table 3.

Empirical Results and Discussion

Estimation Results of Dynamic Threshold Effects

Taking the regional heterogeneity threshold of digital economy development as the entry point, a panel threshold model is used to explore the impact on regional green innovation quality under different levels of digital economy development. First, the F-value and the "self-sampling method" P-value are obtained by the threshold effect test. The results in Table 4 show that both the single and double threshold effects are significant at the 1% level, while the triple threshold effect is not significant. Therefore, we use the double threshold model to analyze the green driving effect of digital economy development.

According to the threshold theory, the role of digital economy development on regional green innovation quality has a significant double threshold effect with threshold values of 7.414 and 8.356, which lie within the 95% confidence interval [7.368, 7.420] and [8.356, 8.356], respectively, as shown in Table 5. Therefore, based on these two thresholds, three types can be

Table 4. Threshold effect test.

				Threshold value		
	F-value	P-value	Number of BS	1%	5%	10%
Single Threshold	55.109***	0.003	300	37.681	14.812	10.43
Double Threshold	86.099***	0.020	300	100.160	33.795	0.223
Three-fold threshold	0.591	0.510	300	24.922	11.187	5.442

Table 5. Threshold estimation results.

Threshold	Threshold estimates	95% confidence interval
Single Threshold	7.385	[7.368, 7.602]
Double Threshold	8.356	[8.356, 8.356]
	7.414	[7.368, 7.420]
Three-fold threshold	7.731	[7.602, 7.731]

classified as low digital economic development level (DIG≤7.414), medium digital economic development level (7.414<DIG≤8.356), and high digital economic development level (DIG>8.356). The trend of the corresponding threshold variable „likelihood ratio" series as a function of the threshold value is shown in Figs 2 and 3. Figs 2 and 3 reflect the structure of the estimated thresholds and the construction of confidence intervals, and it is clear that there is a significant double-threshold effect of digital economy development on the improvement of regional green innovation quality.

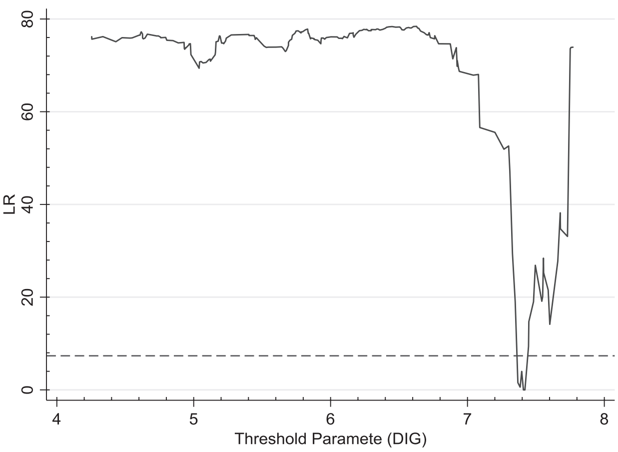

Fig. 2. Likelihood ratio function plot for the single threshold model.

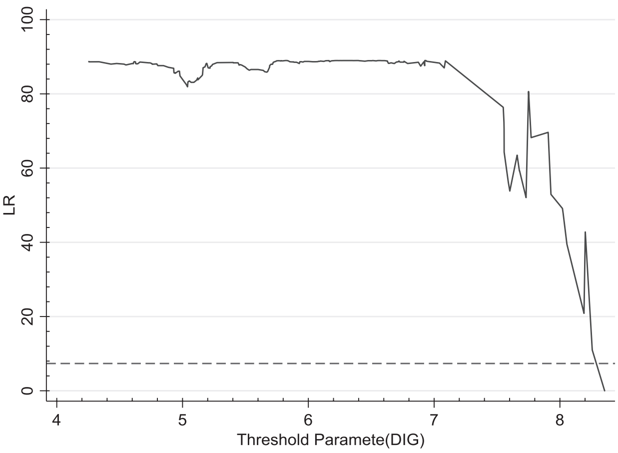

Fig. 3. Likelihood ratio function plot of the double threshold model.

We also compare the threshold effects under different intervals of regional digital economy development according to different intervals of threshold values, and the estimated results are shown in Table 6.

The results in Table 6 show that, in general, the development of the digital economy has a significant contribution effect on the improvement of regional green innovation quality. With the development of the digital economy, there are differences in its driving mechanism for the quality of regional green innovation. Digital economy development has a suppressive effect on regional green innovation quality when the level of digital economy development is below the threshold value of 7.414. The coefficient becomes positive but insignificant for the threshold level of digital economy development between 7.414 and 8.356. When the level of digital economy development is higher than 8.356, the development of the digital economy starts to have a significant improvement effect on the quality of regional green innovation. It shows that as the threshold level of digital economy development keeps increasing, the coefficient of the degree of influence on the quality of regional green innovation increases sequentially, and the direction of influence also changes, from an insignificant negative influence to a significant positive influence eventually, showing the obvious threshold effect characteristics. A lower level of digital economy development is not conducive to improving the quality of regional green innovation, while a higher level of digital economy development can positively drive the improvement of regional green innovation quality. Theoretically, it reflects the existence of a „critical scale" for the impact of digital economy development on regional green innovation quality. Once the level of digital economy development breaks through the critical scale, higher levels of digital economy development will improve the quality of green innovation.

As for the control variables, the level of education, the level of science and technology expenditure, and the protection of intellectual property rights show a significant positive correlation to green innovation quality. Therefore, it is necessary to pay attention to the cultivation of high-quality talent, and the Chinese government should increase the level of spending on green innovation to take advantage of talents and funds to improve the comprehensive utilization efficiency of energy resources, and thus improve the quality of regional green innovation. The effect of environmental regulations on the quality of green innovation is significantly negative, indicating that China still needs to bear a large degree of environmental constraint cost in its economic development, and the „Porter effect" cannot be realized in a short period of time, and there is an inverse ratio between environmental regulation and regional green innovation quality. Finally, the regional distribution of the different intervals per year can be seen in Table 7.

In general, the digital economy development in most

Table 6. Parameter estimation results.

	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
REG	-0.003**	0.002	-2.07	0.040	-0.006	0.000
EDL	0.524**	0.206	2.55	0.011	0.119	0.930
TEL	22.109 ***	3.761	5.88	0.000	14.694	29.525
IPR	10.533 ***	2.851	3.69	0.000	4.912	16.153
DIG (DIG≤7.414)	-0.008	0.077	-0.10	0.917	-0.160	0.144
DIG (7.414<DIG≤8.356)	0.084	0.076	1.11	0.267	-0.065	0.234
DIG (DIG>8.356)	0.345***	0.083	4.13	0.000	0.180	0.509
_cons	-2.446***	0.709	-3.45	0.001	-3.844	-1.048

Table 7. Regional heterogeneity distribution of digital economy development thresholds.

	Year							
	2013	2014	2015	2016	2017	2018	2019	2020
DIG≤7.414	29	28	28	27	26	24	24	24
7.414<DIG≤8.356	1	2	2	3	4	6	6	5
DIG>8.356	0	0	0	0	0	0	0	1

of China's regions is at a low threshold level, mainly concentrated in the low digital economy development interval (DIG≤7.414). Although several regions developed to the medium digital economy development level in 2013-2020, almost no regions reached the high digital economy development level, except for the Guangdong Province in 2020. This indicates that China still needs to pay attention to the support in the development of the digital economy, which is a gradual process and may have phased development characteristics. Therefore, at this stage, there is still a need to pay attention to improving the level of China's digital economy development and better play a role in guiding and promoting the quality improvement of regional green innovation.

Discussion

In general, the quality of green innovation needs to be supported by a certain digital economy. The impact of digital economy development on the quality of green innovation is reflected in two main aspects: First, the ICT industry itself in the digital economy has rich innovation resources, with active internal innovation activities and easy to produce digital innovation results. Second, the use of digital technologies such as big data, cloud computing, and blockchain enables pre-research of green product information and green consumer preference information, to make better judgments for the future direction, potential and path of green innovation in the region, and achieve more effective green technology R&D decisions. However, unlike previous studies, we do not single out the impact of digital economy development on regional green innovation quality but find that the impact on green innovation quality within Chinese regions is different at different threshold levels of digital economy development.

There is a non-linear relationship between the development of the digital economy and the quality of regional green innovation. When the development level of the digital economy is at a low level, it is difficult to solve information asymmetry in the market, the transparency mechanism of the market is not perfect, and the innovation factors are difficult to achieve accuracy in the process of input and use, and the relatively loose management structure makes the economic subjects within the economic system have relatively limited ability to collect, organize and process information. The relatively loose management structure makes the ability of economic agents within the economic system to collect, organize and process information relatively limited, and each product and consumption agent cannot grasp the best product information and consumption status in a timely and comprehensive manner, which also leads to the inability of innovation agents to capture effective demand and information promptly in the innovation field, making innovation easily fall into a mismatch between supply and demand [27]. Meanwhile, the ways to enhance the quality of regional green innovation can be roughly divided into two kinds: one is the accumulation of knowledge within the region; the other is to obtain external knowledge through knowledge spillover. However, when the level of development of the digital economy is relatively low, it is difficult to achieve deep integration with traditional industries and provide a broader innovation space for the development of traditional industries to drive the renewal of own knowledge in the region [28].

The digital economy is an application of disruptive innovation, whose essential feature is the rational allocation of resources through the Internet platform. It is the emergence of the Internet platform has changed the global traditional industrial economic development model, providing new ideas and directions for the traditional economy to carry out transformation and upgrading, and the ever-improving market, as well as the continuous accumulation of innovation resources, have provided important support for the digital economy to drive the improvement of the quality of green innovation in various countries. Under the influence of IoT technology, the innovation factors are prompted to break through the geographical production limits and greatly reduce the allocation cost of innovation resources. From the innovation production side, the emergence of various digital economy platforms promotes the transformation of innovation organization to networking, the cross-spatial allocation of innovation resources between regions can reduce the production and transaction costs that exist in the innovative production process, and various innovative platforms build platforms for the participation of diversified innovation agents and enrich the content of innovation [29]. From the innovation consumer side, the demand generated by the digital economy can guide the innovation subjects to widely participate in the practice of innovation activities utilizing big data, and use digital technology to invest in R&D innovation, while the consumers' requirements for the quality and personalization of innovation, with the support of data platforms, the innovation production side can precisely locate the consumer demand, so that various digital innovation platforms can provide a bridge for the producers in this way, various digital innovation platforms build a bridge between producers and consumers for innovation exchange and production, reducing the waste of resources and cost loss caused by information asymmetry, and the transparent trading market inadvertently intensifies the competition between manufacturers and promotes the high-quality development of green innovative products. In addition, the higher the level of development of the digital economy, the technology diffusion effect, and resource allocation function generated between regions will promote the development of innovation in neighboring regions or across regions, realize collaborative innovation between regions, attract more high-quality human and material resources, enrich innovation input resources, and further promote the quality of green innovation within China's regions.

For other factors affecting the quality of green innovation, the higher the level of education and the higher the quality of the personnel engaged in innovation activities, the more conducive to improving the quality of green innovation. The government increases its investment in scientific research and attracts innovative talents to carry out innovative activities, providing important material guarantees and financial support for the improvement of the quality of regional green innovation. With the improvement of the level of intellectual property protection, the phenomena of patent infringement and product imitation are effectively curbed, providing legal protection for the innovation environment, thus stimulating the active participation of innovation subjects in R&D activities and promoting the quality of regional green innovation. However, the development of green innovation quality in the Chinese region still requires a large degree of environmental constraint costs, and the "Porter effect" cannot be realized in a short time.

Conclusion

We measure the level of digital economy development based on Chinese regional data from 2013 to 2020, systematically explore the heterogeneous threshold effects on regional green innovation quality under different levels of digital economy development through a panel threshold measure, and find that:

(1) The average value of China's digital economy development level from 2013 to 2020 is 6.0205. Overall, China's digital economy development level has always maintained an increasing trend over a longer time, which has some coordination with the developing characteristics of China's macroeconomy.

(2) In general, the development of the digital economy has a significant contribution effect on the improvement of regional green innovation quality. As the level of development of the digital economy increases, there are differences in its driving mechanism for the quality of regional green innovation. A lower level of digital economy development is not conducive to improving the quality of regional green innovation, and a higher level of digital economy development can only have a positive driving effect on the improvement of regional green innovation quality. Once the level of digital economy development breaks through the critical scale, the higher the level of inter-regional digital economy development, the more beneficial it is to promote the quality of green innovation. However, in terms of interregional development trends, China's digital economy development has not yet reached the threshold level that can enhance the quality of regional green innovation, and still needs to pay attention to the driving role of digital economy development.

(3) For the other driving factors affecting the quality of green innovation, education level, science and technology expenditure level, and intellectual property protection have significant positive effects on the quality of regional green innovation, while environmental regulations show significant negative effects on the quality of regional green innovation.

Policy Recommendations

We focus on the relationship between the impact of digital economy development on regional green innovation quality and establish diverse path options for enhancing green innovation quality in conjunction with heterogeneous threshold mechanisms. Based on this, the following practical insights and recommendations are proposed:

(1) The development of digital economy carriers should be continued. As the cornerstone of the digital industry development and industrial digital integration, the role of digital economy carriers is essential. A sufficient digital economy carrier can provide powerful support for the development of the digital industry, continuously extend the scope of the digital industry, and play the advantages of the digital economy carriers to boost the rapid development of the digital industry. It is necessary to focus on accelerating the construction of new digital infrastructures, extending the scope of application of digital technology in the real economy, promoting the integration and penetration of digital information technology in industrial development, forcing traditional industries to undergo digital transformation and upgrading, and taking the development of the digital economy as one of the important ways to enhance the quality of regional green innovation.

(2) The innovation incentive policy mechanism should be improved to strengthen the interaction and integration of the digital economy and regional green research. For green innovation activities carried out in the region to give corresponding financial technical support and tax relief, give full play to the incentive effect of financial subsidies, and strengthen the investment of each region in green innovation and quality improvement. Encourage regional development and universities and research institutions to carry out in-depth cooperation between industry, academia and research, strengthen the integration of traditional industries and Internet industries in the region, to gradually apply Internet information technology to green innovation R&D by attracting high-quality R&D personnel through incentives to improve the digital awareness and Internet skills of R&D personnel in the region, use the Internet to strengthen inter-regional resource sharing and information flow, enhance inter-regional exchanges and cooperation, continuously absorb and learn from external advanced green technologies, and increase investment in Internet and digital infrastructure fitness to ensure a sound digital infrastructure supply and hardware support in the region.

(3) The government should further optimize the digital economy development environment in response to the level of digital economy development in different regions. Expanding the dimension of digital economy applications will prompt the digital economy to release greater effectiveness. Specifically, for the more developed level of development of the digital economy in the region, it should continuously improve the quality of the electronic information technology industry. For example, by increasing the number of the top 100 Internet companies and the number of ICT listed companies, we can take advantage of the core position of developed digital economy regions and play the technology spillover effect on the surrounding regions with relatively low levels of digital economy development. For the less developed regions of digital economy development should continue to increase the number of digital industries, the Chinese government to strengthen the guidance and support in the development of the digital economy, and gradually get rid of the digital industry "low-level trap". The integration of the digital economy and the industrial house should be gradual, and the degree of application of the digital economy in the primary and secondary industries can be improved first, and then gradually integrated with the tertiary industry. It is also essential to further strengthen the construction of Internet infrastructure, carry out pilot digital technology development adapted to local industries based on natural resource endowments, form new models of industrial development with regional characteristics, build regional synergistic development networks, realize cross-regional division of labor and cooperation, and fully release the driving role of digital economy development in coordinated regional development.

(4) The quality of regional green innovation can be enhanced based on other driving mechanisms. The Chinese government should strengthen the assessment of the quality of green innovation and take the quality of green patents as an important criterion for policy support. while the government's measurement of the quality of green innovation cannot be objective and accurate due to the limitation of information asymmetry. At this point, local governments can use the role of the market to help identify high-value green technologies, provide financial support for these patented technologies, and achieve simultaneous growth in the quantity and quality of green innovation. A diversified and multi-channel financial science and technology expenditure system can be established to realize the synergy between regional internal and external R&D investment funds, guarantee that the funds are tilted towards regional green innovation activities, and promote the improvement of regional green innovation quality. According to the innovation characteristics of each region, differentiated intellectual property protection policies should be formulated to effectively protect R&D in the field of high-level innovation. It is also necessary to increase support for high-quality innovation activities, clarify the areas of support for special funds, focus on the setting of intellectual investment in talents, and provide effective legal protection for the improvement of regional green innovation quality.

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Conflicts of Interest

The authors declare no conflict of interest.

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