

Digital finance, Green Innovation and environmental pollution

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Abstract. Based on the panel data of 282 cities at prefecture level and above in China from 2011 to 2019, this paper uses the fixed effect model to explore the impact of digital finance, green innovation and their associated effects on pollution emissions, and further builds a panel threshold model with digital finance as the threshold to explore the pollution reduction mechanism of green innovation. At the same time, the impulse response function is used to explore the long-term continuation mode and impact effect of the two on pollution emission. Finally, the different dimensions of digital finance, the degree of Internet use and regional heterogeneity are analyzed. The results show that: firstly, digital finance and green innovation significantly reduce pollution emissions during the period; Secondly, green innovation plays a positive and nonlinear role in promoting pollution reduction at different digital financial levels. Third, both digital finance and green innovation will reduce pollution emission level in the long term and the driving effect will gradually slow down over time. This paper provides reference value for the study of the relationship between digital finance, green innovation and pollution reduction, and has innovative and practical significance.

Key words: digital finance; Green innovation; Pollution discharge; Threshold effect; Impulse function.

1. Introduction

In the new era, Chinese General Secretary Xi Jinping has put forward the new concept of green development that "clear waters and green mountains are gold and silver mountains", which indicates that on the way of sustainable economic development, China should not only have "gold and silver mountains", but also have "clear waters and green mountains". Since the 21st century, China's economy has maintained rapid development, with the total size and growth rate of its economy ranking among the top in the world. However, the disadvantages of long-term extensive economic development have gradually emerged, and ecological pollution has become a widespread concern of the world. According to Greenpeace India, in 2018, anthropogenic sulphur dioxide hot spots released nearly 30 million tons of sulphur dioxide into the atmosphere. That's about the same amount as more than 300 volcanic eruptions, posing a huge risk to the environment and human health. released a report from The Ministry of Ecology and Environment about China's ecological and environmental conditions in 2020 said that 40.1 percent of 337 cities at prefecture level and above still failed to meet air quality standards. This shows that pollution prevention and control has become an urgent problem in China's green development process.

In order to achieve green development, it is necessary not only to regulate enterprises, but also to use effective financial measures to deal with environmental pollution in the long term. At present, China has stepped into the stage of digital economy, and cutting-edge digital technologies such as artificial intelligence and big data can be combined with financial services to provide a new direction for industry development. Digital finance can integrate financial resources, increase enterprise productivity, make industrial structure more advanced and improve the efficiency of financial resources allocation. Green innovation can optimize energy structure, eliminate and transform inefficient enterprises, promote low-carbon industry development and improve the conversion rate of green innovation achievements through knowledge spillover effect and input-output effect. However, will digital finance and green innovation have an impact on pollution emissions? Is the effect positive or negative? Does this relationship differ in sensitivity due to the heterogeneity of cities? This is the key problem that the majority of scholars and policy makers urgently need to solve and answer. The

answers to the above questions have important policy implications for China to promote green development.

At present, the academic circle has not systematically discussed the relationship between digital finance and environmental pollution. The research focuses on the impact of financial development on environmental pollution, but there are different views on this. Existing studies can summarize the following three viewpoints: Firstly, financial development can reduce the level of environmental pollution. Financial liberalization and openness (Tamazian et al., 2009) and electronic finance (Elheddad et al., 2021) can both reduce carbon dioxide emissions and pollution rates. In addition, the development of traditional finance can also enable green economy and reduce air pollution by optimizing capital allocation (Nguyen et al., 2021). Secondly, financial development has a negative impact on the environment and aggravates environmental pollution. The phenomenon of "structural curse" exists in financial development. A market-oriented financial system will eventually aggravate the emission of carbon dioxide and other gases (Kim et al., 2020). Third, there is a nonlinear relationship between financial development and environmental pollution. For example, financial development and carbon emissions can present an inverted U-shaped relationship (Charfeddine and Khediri, 2016). Regarding the relationship between green innovation and pollution reduction, existing studies have found that green innovation can improve the production efficiency of traditional industries (Wang Weiguang et al., 2015) and promote the development of low-carbon industries through knowledge spillover effect, human capital effect and input-output effect (Gu Shengzhu, 2018; Huiyan Wang, 2019).

For this reason, this article is based on the country's 282 cities as panel data from 2011 to 2019, with Peking University pratt & whitney financial development index as a digital proxy indicator of financial development, through the fixed effects regression model to explore digital financial influence on urban pollution, green innovation, and uses the threshold model, impulse function to examine the relationship between them.

Compared with the existing literature, the contribution of this paper is mainly in the following three aspects: Firstly, from the perspective of research, this paper has enriched the research on digital finance, green innovation and pollution emission. This paper mainly analyzes the impact of digital finance and green innovation on urban pollution reduction from the city level and brings them into the same framework in the analysis. Although existing studies have investigated the impact of green innovation on urban pollution emissions, they lack analysis of the impact of green innovation from the perspective of digital finance. Secondly, in terms of research methods, this paper uses impulse response function to analyze the dynamic impact effect and continuation mode of digital finance and green innovation on urban pollution reduction in the long term. Thirdly, in the heterogeneity analysis, this paper first carries out a sub-dimensional heterogeneity analysis of digital finance, and finds that the depth of use has a better emission reduction effect; In addition, we also tested heterogeneity in places with different levels of Internet use, and digital finance and green innovation were more likely to reduce pollution emissions in areas with high levels of Internet use.

The remaining arrangement of this paper is as follows: The second part is literature review and theoretical analysis; The third part discusses the empirical strategies and data; The fourth part reports the results of baseline model regression, threshold regression, impulse response function and other empirical tests. The fifth part is the summary and policy suggestions.

2. Theoretical analysis and research hypothesis

(I) Digital finance and pollution reduction

As for the relationship between finance and environment, it is generally believed that the characteristics of financial system to optimize resource allocation and promote technological progress make financial development become an important factor influencing the growth of total factor productivity (TFP) in a country, which is of great significance to the green development of economy (Demirguc-Kunt and Levine, 2008). Artur et al. (2009) first studied the relationship between financial

development and environmental quality and believed that financial development could restrain environmental quality degradation. Subsequently, Jalil and Feridun (2011) used data in China and Zaidi et al. (2019) used panel data of 17 countries from 1990 to 2016 to conclude that financial development can significantly reduce carbon emissions. Similarly, Li et al. (2019) took The Beijing-Tianjin-Hebei region as the research object and concluded that green credit would restrain the increase of carbon emissions. In addition, studies on the impact mechanism of financial development on environmental pollution basically follow the decomposition of the environmental effects of economic activities by Grossman et al. (1992), namely, scale effect, technological effect and structural effect. However, finance is inherently characterized by favoring the poor and favoring the rich and pursuing profits, leading to stratification of resource flows and mismatch between resources and fields (Huang Tingting and Gao Bo, 2020), which reduces service quality and efficiency and affects the operational efficiency of the real economy. Infrastructure construction and labor costs also limit the inclusiveness of traditional finance (Bell et al., 2012), making it difficult to reach micro, small and medium-sized enterprises or private manufacturing industries, resulting in financing difficulties. All these have weakened the contribution of finance to corporate pollution reduction, so innovative financial services are essential to promote pollution reduction. However, traditional financial institutions have many problems. For example, they cannot serve the people in remote areas and lack the support of financial services, which is not conducive to the development of economic activities such as entrepreneurship (Aghion et al., 2007), hindering regional economic development.

Digital finance, as an emerging industry formed by deep integration of finance and digital technology, has become the focus of scholars' research and national development. First of all, digital finance uses emerging Internet technologies such as big data to change the "80/20 rule" of traditional finance, and can use database mining data to reduce location resistance, break the natural segmentation of the market, and better integrate financial resources. Zeng and Reinartz (2003) pointed out that digital finance can evaluate the financing of small and micro enterprises with low cost and solve the financing difficulties of small and micro enterprises. At the same time, the flow of data resources can improve cross-industry operation capacity, and inter-industry production resources will be more rationally allocated, which is conducive to realizing economies of scale to improve enterprise management efficiency and increase enterprise productivity (Li Tang et al., 2020). Digital finance can promote the high flow of information to accelerate the transformation of new technologies, improve the efficiency of financial services and capital allocation, improve the utilization rate of capital, effectively alleviate the financing difficulties of micro, small and medium-sized enterprises and manufacturing industry, and make the industrial structure more advanced, which is conducive to pollution reduction. Secondly, digital finance not only promotes information exchange, but also broadens the financing channels of enterprises, reduces liquidity constraints and improves the allocation efficiency of financial resources (Feng Sixian et al., 2021). At the same time, digital finance has the characteristics of policy, targeting and wide coverage, which is conducive to the integration of logistics, capital flow and information flow (Wang Yanan, 2020), the docking of supply and demand, and the integration of digital economy and real economy. Finally, the factor allocation effect of digital finance can help high-efficiency industries obtain more resources, which is conducive to the optimization and upgrading of industrial structure. Therefore, hypothesis 1 is proposed:

Hypothesis 1: Digital finance helps reduce pollution.

2. Green innovation and pollution reduction

In recent years, more scholars have focused on the impact of green innovation on pollution emissions. Some scholars have found that green innovation can significantly reduce pollution emissions. Carrion-flores et al. (2010) studied the 1989-2004 data of 127 manufacturing industries in the United States and found that green innovation was the main driving factor for the reduction of polluting gas emissions in the United States. On the other hand, stricter pollution control targets would lead to innovation. Constantini et al. (2013) measured internal innovation by environmental patents based on regional and sectoral data in Italy and found that ecological innovation can reduce environmental degradation through direct and indirect effects, and the size of the effect is related to

the type of technology and pollution. In recent years, Ghisetti et al. (2017) used green patent to measure green innovation and environmental productivity to measure environmental performance to conduct research and found that regional sectors with higher level of green technology had better environmental performance. On the contrary, some scholars concluded that green innovation worsens environmental pollution. For example, Constantini et al. (2016) used the data of 27 EU countries from 1995 to 2009 and found that not only did ecological innovation reduce sectoral environmental degradation, but also the spillover effect of inter-sectoral ecological innovation could seriously affect environmental quality. In addition, some scholars also concluded that green innovation has no significant impact on environmental pollution. For example, Ding et al. (2016) used Italian regional panel data to analyze the relationship between green technology progress and carbon dioxide emission and its emission efficiency, and found that green technology significantly improved environmental productivity, but did not play a significant role in environmental protection.

At present, China is in a transition stage from efficiency-driven economic development to innovation-driven economic development. Different from traditional innovation, green innovation is conducive to both environmental protection and high-speed and high-quality economic development. Firstly, green innovation optimizes the energy mix and promotes the development of clean energy, which is conducive to energy conservation and emission reduction across the whole industrial chain. At the same time, the application of green industries and green products has had a profound impact on the market environment and improved the direction and efficiency of resource allocation by eliminating and transforming a large number of inefficient enterprises. In addition, with the development of green technology, green innovation resources of emerging industries will be extended to traditional industries, improving the production efficiency of traditional industries (Wang Weiguang et al., 2015), helping traditional industries to achieve smooth transformation and upgrading, and promoting pollution reduction. Moreover, green innovation can not only promote the technological progress of enterprises through the market mechanism, reduce the external environmental cost and improve the quality of supply. Besides, it can promote the development of low-carbon industry through knowledge spillover effect, human capital effect and input-output effect (Gu Shengzu, 2018; Huiyan Wang, 2019). In addition, green products conform to the current environmental protection concept of consumers, increase consumer demand, improve the conversion rate of green innovation results, promote the transformation process of knowledge to wealth, stimulate enterprises to increase investment in green innovation, accelerate the progress of environmental protection technology, and improve the green manufacturing capacity of the industry. Finally, the national and local governments' preferential policies for environmentally friendly enterprises promote enterprises to actively carry out independent innovation activities, expand the green innovation market, and promote the improvement of the quality and environmental characteristics of export products, improve the quality of opening up to the outside world, and achieve pollution reduction. Based on the above analysis, hypothesis 2 is proposed:

Hypothesis 2: Green innovation can promote pollution reduction.

(3) The moderating effect of digital finance on green innovation in promoting pollution reduction

The green innovation of enterprises is characterized by high financing cost, irreversible process, sunk input, uncertain outcome, lagging output and transformation, etc., which need financial resources to support. However, due to the short-sighted nature of traditional finance in selecting credit customers, it is difficult to help enterprises with high R&D intensity, market potential and environmental protection to obtain financing, which has a negative impact on the green technology innovation of enterprises. By improving the disadvantages of high threshold and high cost of traditional financial services, the rapidly developing digital inclusive finance can improve the loan approval efficiency of financial institutions (Huang et al., 2018), reduce financing constraints and financing costs of enterprises (Zeng and Reinartz, 2003), and avoid resource waste and moral hazard (Demertzis et al., 2018) to promote technological innovation in enterprises. The development of digital inclusive finance also provides a good opportunity for green innovation of enterprises. The role of digital finance in promoting enterprise green innovation is reflected in the following aspects:

From the direct effect, digital inclusive finance really achieves "universal" and "beneficial" (Gomber et al., 2017), which broadens the source of funds for small and medium-sized enterprises with green projects and strong loan needs; Cloud computing, big data and other digital technologies can help enterprises determine the direction and path of innovation by searching and analyzing users' consumption information, and improve the success rate of research and the conversion rate of results. In addition, with the improvement of digital finance, financial inclusiveness will be enhanced, which is conducive to easing the financial constraints of education in backward areas, increasing their human capital, promoting the development of regional green innovation, and strengthening the internal driving force of green innovation to promote pollution reduction. Based on the analysis above, this paper can put forward hypothesis 3:

Hypothesis 3: Digital finance has a positive effect on the promotion of green innovation to pollution reduction.

3. Study design

(I) Model construction

1. Baseline regression setting

This paper constructs model (1) in order to better explore the impact of digital finance and green innovation on pollution reduction. In addition, in order to avoid the possible influence of omitted variables on the results, on the basis of Model (1), the important factors affecting pollution reduction: industrial structure (ind), investment in scientific research and development (rd), foreign investment (fdi), degree of government intervention (gov), human capital (hum) are introduced into the equation to construct model (2) :

$$\ln so_{2it} = \alpha_0 + \alpha_1 \ln df_{it} + \alpha_2 \ln gi_{it} + \varepsilon_{it} \quad (1)$$

$$\ln so_{2it} = \alpha_0 + \alpha_1 \ln df_{it} + \alpha_2 \ln gi_{it} + \beta_i \ln X_{it} + \varepsilon_{it} \quad (2)$$

so_{2it} is the emission of SO_2 of city i in the year t , which is used to measure the local pollution; df_{it} is the level of digital financial development of the city; gi_{it} is the green innovation level of the city; X_{it} is the control variable affecting urban pollution emission, including industrial structure (ind), investment in scientific research and development (rd), foreign investment (fdi), degree of government intervention (gov) and human capital (hum). ε_{it} is the residual term.

2. Panel threshold regression model

Differences in the development level of urban digital finance and in the financing scale and intensity of innovation subjects participating in green innovation may lead to nonlinear impact of green innovation on pollution reduction. A panel model is constructed to verify this impact and explore the digital finance threshold effect of green innovation on pollution reduction:

$$\ln so_{2it} = \alpha_0 + \alpha_1 \ln df_{it} \cdot I(\ln gi_{it} \leq c) + \alpha_2 \ln gi_{it} \cdot I(\ln gi_{it} > c) + \beta_i \ln X_{it} + \varepsilon_{it} \quad (3)$$

c is the digital financial threshold value, $I(\cdot)$ is the indicator function, and other variables are the same as above.

(2) Index selection

1. Explained variables

Environmental pollution (lnso2). The logarithm of industrial sulfur dioxide emissions is selected to measure the level of urban environmental pollution. As these indicators are all negative indicators, so is the environmental pollution index. The more sulfur dioxide emissions, the greater the environmental pollution index, meaning the more serious environmental pollution.

2. Explained variables

Digital Finance (lndf). This paper selects the second phase of "Peking University Digital Inclusive Finance Index" jointly compiled by Peking University Digital Finance Research Center and Ant Financial to represent the level of digital finance of the city.

Green Innovation (*lngi*). The data comes from Wang et al. (2020) and the invention patents published by the state intellectual property office patent database information. Then use "international patent classification green list" published by the world intellectual property organization in 2010 to further identify green patent and match the micro data of listed companies to the prefecture level. Ultimately get level city green invention patent applications as a proxy variable of urban green innovation level.

3. Control variables

In order to ensure the robustness of the basic regression estimation results, this paper selected a series of city-level control variables, including : (1) industrial structure (*ind*), measured by the ratio of the GDP of the secondary industry to the GDP of the tertiary industry; (2) Human capital (*lnhum*), measured by the logarithm of the number of students in universities; (3) Degree of government intervention (*gov*), measured by the proportion of fiscal expenditure in GDP; (4) R&d investment (*rd*), measured by the proportion of r&d expenditure in financial expenditure; (5) Foreign investment (*fdi*), measured by the ratio of actually utilized fdi to GDP.

(3) Sample selection and data sources

In this paper, panel data of 282 cities at prefectural level and above from 2011 to 2019 were selected from China Urban Statistical Yearbook, statistical Bulletin of cities, statistical yearbook of provinces and EPS database. In addition, all data were paired to alleviate the potential heteroscedasticity of the model. Table 1 shows descriptive statistics of raw data.

Table 1. Descriptive statistics

type	name	symbol	value	mean	standard deviation	minimum	maximum
explained variable	pollution emissions	<i>lnso₂</i>	2,256	9.4967	2.7422	0.0000	13.1832
explanatory variables	green innovation	<i>ln_{df}</i>	2,256	4.2234	1.7397	0.0000	10.0880
	digital financial	<i>lngi</i>	2,256	4.9497	0.5245	2.8344	5.7735
control variables	industrial structure	<i>ind</i>	2,256	1.2749	0.5966	0.0000	5.7138
	foreign investment	<i>fdi</i>	2,256	0.0175	0.0183	0.0000	0.2003
	R&D	<i>rd</i>	2,256	0.0163	0.0166	0.0000	0.2068
	human capital	<i>hum</i>	2,256	10.3573	1.9714	0.0000	13.9579
	government intervention	<i>gov</i>	2,256	0.2033	0.1299	0.0000	2.3488

4. Empirical analysis

(1) Baseline regression

Table 2 reports the baseline regression results of the impact of digital finance and green innovation on pollution reduction respectively. Columns (1) and (2) respectively show the influence of digital finance on pollution emission under the condition of fixed effect and random effect considering control variables. Hausman test significantly rejects the null hypothesis, so we use the fixed effect model for analysis. As can be seen from column (1), the estimated coefficients of *ln_{df}* are significantly negative at the statistical level of 1%, and the estimated coefficient in the regression results of column (3) is -1.2393, indicating that every 1% increase in digital financial development will reduce sulfur dioxide emissions by 1.2393%. This means that digital finance can significantly reduce pollution emissions. The reason may be that digital finance can promote the development of financial inclusion and expand financial accessibility (Yi Xingjian and Zhou Li, 2018; Wu Qingtian and Wang Xinyu, 2021), overcome institutional drawbacks, reduce financial discrimination, amplify financial functions and improve the service capacity of finance to the real economy. Big data, cloud computing and other information technologies in digital finance have broadened the financing channels and ways of enterprises, effectively alleviated the financing dilemma of enterprises' innovation, strengthened their enthusiasm for innovation and helped enterprises to establish innovation consciousness and implement emission reduction actions.

Columns (3) and (4) respectively show the influence of green innovation on pollution emission under the condition of fixed effect and random effect considering control variables. Hausman test significantly rejects the null hypothesis, so we select the fixed effect model for analysis. As can be seen from column (3), patent's estimated coefficients are significantly negative at the statistical level of 1%, and the estimated coefficient of regression results in column (3) is 0.8661, indicating that every 1% increase in green innovation reduces sulfur dioxide emissions by 0.8661%, which means that green innovation can significantly reduce pollution emissions. The reason behind this may be that green innovation can not only optimize the energy structure through green technology, but also change the industrial structure, promote the advanced industry and promote pollution reduction. In addition, the development of digital finance can reduce the financing constraints on green innovation enterprises and strengthen the promotion role of green innovation on pollution reduction. The inclusive environment created by digital finance can provide financing support and an orderly environment for green innovation, making up for the disadvantages of high risk and high investment in green innovation. Digital finance further narrows the digital divide between finance and the real economy, makes the spillover effect of innovation more obvious, and green innovation can better serve the work of pollution reduction. In conclusion, digital finance and green innovation reduce pollution emissions.

Table 2. Regression results of digital finance and green innovation on pollution reduction benchmark

variable	(1) FE	(2) RE	(3) FE	(4) RE
<i>Indf</i>	-1.2393*** (0.1322)	-1.4760*** (0.1129)		
<i>lngi</i>			-0.8661*** (0.0822)	-0.3323*** (0.0545)
<i>ind</i>	1.0522*** (0.1811)	0.5862*** (0.1212)	1.1941*** (0.1653)	1.0213*** (0.1208)
<i>rd</i>	-13.2261** (5.9397)	-5.1685 (4.1879)	-7.3607 (5.9898)	-1.3771 (4.7213)
<i>fdi</i>	14.4531*** (5.1726)	8.6021** (3.6591)	13.8091*** (5.1447)	14.7279*** (3.7479)
<i>hum</i>	0.0983** (0.0441)	0.1451*** (0.0329)	0.0915** (0.0438)	0.1980*** (0.0356)
<i>gov</i>	-3.4395*** (0.8819)	-3.5796*** (0.5452)	-4.0513*** (0.8731)	-4.3286*** (0.5810)
cons	13.9332*** (0.9308)	15.2131*** (0.7557)	11.3864*** (0.6949)	8.1915*** (0.4783)
<i>Hausman</i>		24.05*** (0.0005)		219.00*** (0.0000)
<i>R</i> ²	0.0361	0.0851	0.2015	0.1798
<i>Obs</i>	2256	2256	2256	2256

(2) Robustness test

1. Replace explanatory variables

In order to ensure the robustness of the regression results in this paper, the core explanatory variables are replaced. As credit business is an important content in the promotion process of digital finance, this paper chooses "total loan business" as a proxy variable to measure the development degree of digital finance for regression by referring to the practice of Wang Yanan et al. (2020). The regression results are shown in columns (1) and (2) in Table 3. It can be found that regardless of whether a series of control variables are controlled or not, the estimated coefficient of *Incredit* is still significantly negative at the statistical level of 1%, indicating that our results are still robust after replacing the measurement index of digital finance.

As for the variable of green innovation, the number of green utility models applied in the current year is replaced by the number of green inventions applied in the current year for regression, and the

impact of green innovation on pollution emission is investigated. The regression results are shown in columns (3) and (4) in Table 3. It can be found that estimated coefficient of inpatient is significantly negative at the statistical level of 1%, indicating that our results are still robust after the replacement of green innovation measurement indicators.

Table 3. Regression results of replacement explanatory variables

variable	(1)	(2)	(3)	(4)
<i>lncredit</i>	-1.6788*** (0.0979)	-0.9562*** (0.1172)		
<i>inpatient</i>			-1.4876*** (0.0654)	-1.1652*** (0.0857)
<i>ind</i>		1.3788*** (0.1681)		0.7369*** (0.1711)
<i>rd</i>		-18.5617*** (5.9202)		-5.1714 (5.8646)
<i>fdi</i>		14.9808*** (5.2001)		8.7134* (5.0894)
<i>hum</i>		0.0779* (0.0443)		0.0918** (0.0431)
<i>gov</i>		-3.7940*** (0.8841)		-3.6395*** (0.8590)
cons	17.2586*** (0.4555)	12.1653*** (0.8502)	16.2285*** (0.2999)	13.5513*** (0.7287)
R^2	0.0053	0.0651	0.0945	0.1164
<i>Obs</i>	2256	2256	2256	2256

2. Subsample regression

Due to the policy bias, some key cities such as municipalities directly under the central Government and provincial capital cities can easily obtain more preferential policies and economic resources. In order to ensure the universality of the conclusions in this paper, according to Xu Zhao et al. (2021), the robustness test is conducted after excluding municipalities directly under the central government, cities separately listed in the state plan and provincial capital cities. The regression results are shown in Table 4. It can be found from the regression results that the regression results of both digital finance and green innovation on pollution emissions are significantly negative, indicating that the regression results of this paper are still robust after deleting the samples of key cities.

Table 4. Sub-sample regression results

variable	(1)	(2)	(3)	(4)
<i>lndf</i>	-1.9157*** (0.0983)	-1.0925*** (0.1390)		
<i>lngi</i>			-1.3162*** (0.0675)	-0.7964*** (0.0853)
<i>ind</i>		1.1752*** (0.1912)		1.2686*** (0.1764)
<i>rd</i>		-23.5133*** (7.6963)		-14.7114* (7.8199)
<i>fdi</i>		20.5462*** (5.9475)		18.6092*** (5.9233)
<i>hum</i>		0.1009** (0.0433)		0.0927** (0.0430)
<i>gov</i>		-4.2999* (1.6862)		-5.1374*** (1.6421)
cons	18.9905*** (0.4890)	13.2584*** (0.9617)	15.0638*** (0.2891)	11.2382*** (0.7571)
R^2	0.0416	0.0783	0.0419	0.0897
<i>Obs</i>	2256	2256	2256	2256

3. Tail retraction and regression

In order to avoid the influence of outliers existing in the data due to various reasons on the regression results, and considering the robustness of the data Angle, this paper, according to Sheng Dan and Zhang Huiling (2017), conducts tail-tail processing on the extreme outliers of the upper and lower 1% of the explained variables and all continuous variables, and re-conducts the regression estimation. Table 5 reports the regression results after tail reduction. It can be seen that the regression coefficient of digital finance and green innovation is still significantly negative at the statistical level of 1%, and the above results are consistent with the baseline regression results in Table 2 and Table 3. It can be shown that the basic regression results in this paper are still robust after removing the extreme outliers.

Table 5. Regression results after tail reduction

variable	(1)	(2)	(3)	(4)
<i>lndf</i>	-1.8551*** (0.1019)	-1.1821*** (0.1415)		
<i>lngi</i>			-1.2588*** (0.0706)	-0.8179*** (0.0863)
<i>ind</i>		1.0725*** (0.1851)		1.1933*** (0.1716)
<i>rd</i>		-6.7895 (6.3870)		-2.0287 (6.4197)
<i>fdi</i>		10.0515* (5.5684)		9.7363* (5.5375)
<i>hum</i>		0.0639 (0.0466)		0.0578 (0.0463)
<i>gov</i>		-3.0381* (1.6996)		-4.2290** (1.6522)
cons	18.6054*** (0.5047)	13.7771*** (0.9755)	14.4112*** (0.2824)	11.2452*** (0.7566)
R^2	0.0386	0.0634	0.0323	0.0736
<i>Obs</i>	2256	2256	2256	2256

(3) Threshold effect analysis

1. Threshold effect test and threshold value determination

Firstly, bootstrap sampling is used to judge whether there is a threshold effect in digital finance. If there is, the number and value of the threshold are further judged. The threshold test results in Table 6 show that the F-statistic of single threshold of digital finance is 364.13, which significantly rejects the null hypothesis, indicating the existence of first-order threshold effect. The F statistic of double threshold was 55.82, which still significantly rejected the null hypothesis, indicating the existence of double threshold effect. However, in Table 6, the F statistic value of triple threshold is 20.62, and the P value is 0.8133, which is not significant, thus indicating that there is no triple threshold in digital finance in this paper. Therefore, the existence of double threshold can be confirmed. The values are $\mu_1 = 3.9949$, $\mu_2 = 4.0941$ respectively, and the corresponding likelihood ratio test is shown in Figure 1 and Figure 2.

Table 6. Threshold test results of digital finance

threshold variable	threshold Type	threshold value	F Statistic	P-value	10% threshold	5% threshold	1% threshold
Development level of digital finance	Single	4.0941	364.13	0.0000	46.8993	54.2395	72.7505
	Double	3.9949	55.82	0.0033	22.9610	28.7240	36.6230
	Triple	3.9586	20.62	0.8133	58.0212	65.6779	76.7445

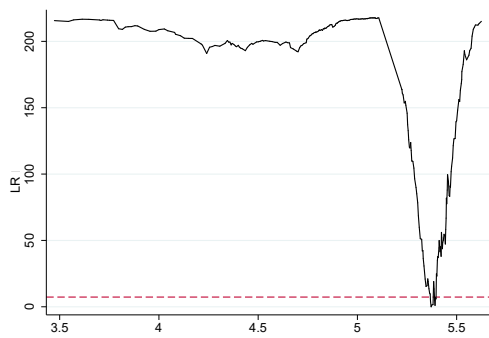


Figure 1. First-round estimation of threshold variable lndf

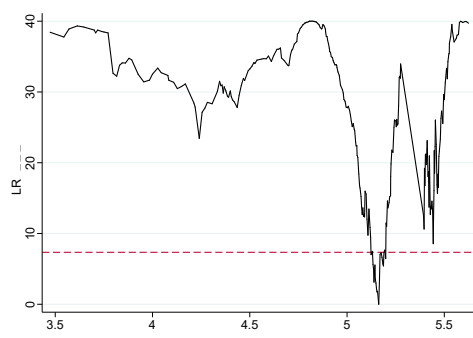


Figure 2. Second-round estimation of threshold variable lndf

2. Parameter estimation and result analysis

With digital finance as the threshold variable, double threshold estimation is carried out, and the results are shown in Table 7: When the development level of digital finance is lower than the first threshold value of 4.63, the estimated coefficient of green innovation on pollution emission is relatively small, which is -0.8421. The possible reason is that at this level, the development of digital finance is limited, and the ability to alleviate financing constraints on green innovation of enterprises is relatively low. Therefore, the promotion effect of green innovation on pollution reduction is limited. When the development level of digital finance is between the first threshold value of 4.63 and the second threshold value of 5.71, the estimated coefficient of green innovation on pollution emission is -1.0446, and the influence is greater than -0.8421, indicating that digital finance has developed rapidly under modern information technology, has a strong ability to absorb social funds, integrates better social resources, greatly alleviates the capital demand of enterprise innovation and makes green innovation play a stronger role in reducing pollution emission level. For the same reason, when the level of digital finance grows to more than 5.71, the estimated coefficient of green innovation on pollution emission is -1.2646, and the impact is greater than -1.0446.

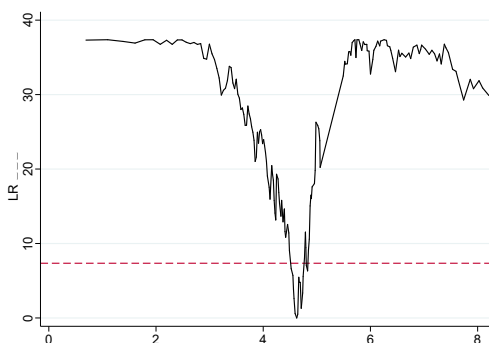


Figure 3. First round estimation of double thresholds

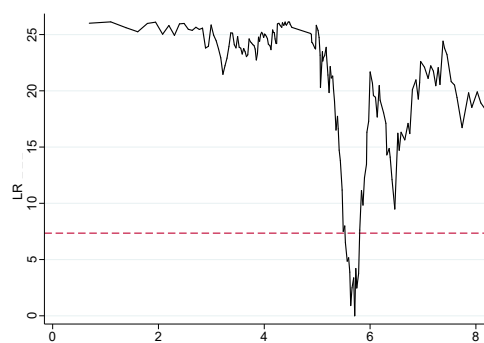


Figure 4. second round estimation of double thresholds

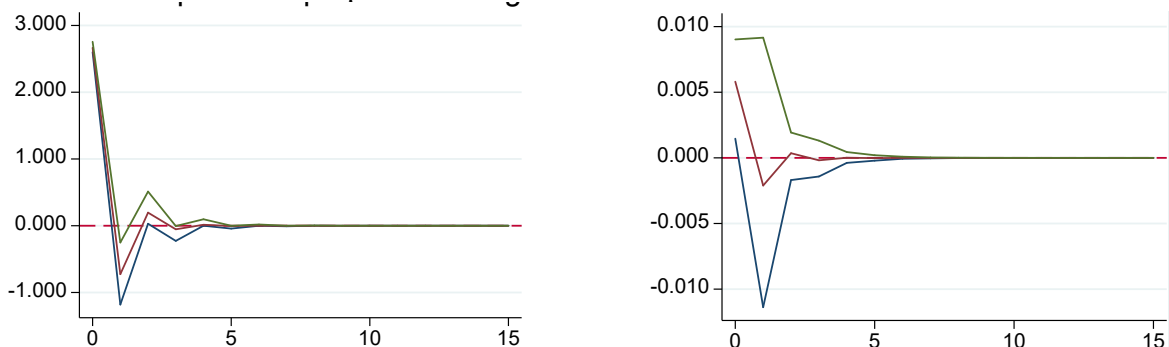
Table 7. threshold regression results

variable	Coef	Std.	t-value	P-value
<i>lngi</i> ($lndf \leq 4.63$)	-0.8421***	0.1389	-6.06	0.000
<i>lngi</i> ($4.63 < lndf \leq 5.71$)	-1.0446**	0.1336	-7.82	0.000
<i>lngi</i> ($lndf > 5.71$)	-1.2646***	0.1310	-9.65	0.000
<i>Ind</i>	0.9377***	0.1789	5.24	0.000
<i>Rd</i>	-7.8814	5.8847	-1.34	0.181
<i>Fdi</i>	14.3448***	5.0894	2.82	0.005
<i>Hum</i>	0.0902**	0.0434	2.08	0.038
<i>Gov</i>	-3.6752***	0.8681	-4.23	0.000
<i>con</i>	12.7774***	0.9266	13.79	0.000
<i>N</i>	2256	2256	2256	2256

(3) Impulse response function

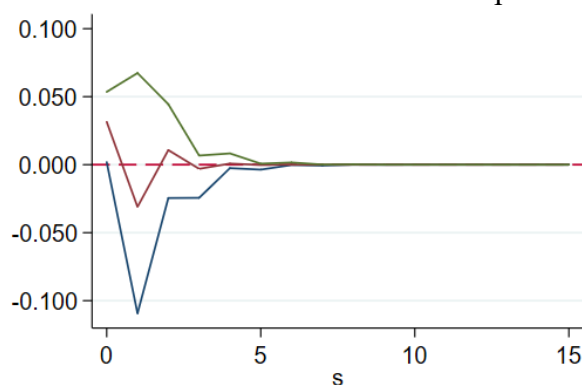
Since the impact of digital finance and green innovation on pollution emissions is in dynamic change, a PVAR model with variable lag term is constructed based on the above research, and the long-term dynamic impact of digital finance and green innovation on pollution emissions is investigated to explore the dynamic transmission effect and impact continuation mode of the two on pollution emissions. LLC method was adopted to test the stationarity of variables, and the test results shows that the null hypothesis of the existence of unit root was rejected for all related variables at the significance level of 1%, that is, all variables were stable. Three methods AIC, BIC and HQIC were used to select the optimal lag order, and digital finance (1), green innovation (1) and pollution emission (1) were selected.

Figure 5 shows the pulse response function of digital finance, green innovation and their own response to pollution emission obtained by using Monte Carlo method to simulate 1000 times. The longitudinal axis, horizontal axis, middle line and two side lines respectively represent impulse response intensity, lag period, impulse response function degree and 95% confidence interval. The influence period is set as 15 periods. It can be seen from Figure 5 that pollution emission has a negative impact on itself and converges to zero scale line in the later period. In the long run, digital finance still plays a role in reducing pollution emissions, and the effect reaches its maximum at about the second phase, and then gradually stabilizes and approaches zero. Under the impact of one standard deviation, the impact of green innovation on pollution emissions is significantly negative and reaches its peak at about the second stage, and then gradually approaches zero axis, which indicates that green innovation can continue to reduce pollution emissions in the long term, and further indicates that innovation can continue to drive pollution reduction from the inside.



(a) Impulse response of pollution emissions to themselves

(b) impulse response of digital finance to pollution emissions



(c) Impulse response of green innovation to pollution emissions

Figure 5. results of impulse response function

(4) Further analysis

1. Sub-dimensional regression results of digital financial inclusion

In order to further study the possible structural effects of digital finance on pollution emissions, this paper uses three subdivision dimensions of digital finance to study the coverage breadth, depth

of use and digitalization degree of digital finance. The results in Table 8 show that the influence coefficients of the three dimensions on pollution emissions are significantly negative at the statistical level of 1%, indicating that the three dimensions can significantly promote pollution reduction. By comparing the coefficient, it is found that the absolute value of the depth coefficient is greater than the extent of coverage and digitalization. The reason may be that the improvement of the depth of use can better meet the needs of enterprise development funds, and the improvement of the coverage and digitalization degree can also expand financing channels, enlarge financial functions, better meet the needs of enterprises and give play to the inclusive function of finance to promote pollution reduction.

Table 8. Sub-dimensional regression results of digital financial inclusion

	(1) coverage breadth	(2)	(3)	(4) using depth	(5)	(6) degree of digitization
<i>lncov</i>	-1.5699*** (0.0933)	-0.8938*** (0.1215)				
<i>lnuse</i>			-2.1135*** (0.1050)	-1.5712*** (0.1490)		
<i>lndig</i>					-1.2117*** (0.0850)	-0.4956*** (0.1063)
<i>ind</i>		1.2701*** (0.1789)		0.8179*** (0.1852)		1.5327*** (0.1782)
<i>rd</i>		-8.1679 (6.4052)		-5.5080 (6.3090)		-10.2621 (6.4639)
<i>fdi</i>		11.5732** (5.5843)		8.0477 (5.5151)		11.1103** (5.6478)
<i>hum</i>		0.0584 (0.0468)		0.0620 (0.0460)		0.0531 (0.0472)
<i>gov</i>		-3.6866** (1.6995)		-2.0797 (1.6811)		-5.1934*** (1.6963)
cons	17.0665*** (0.4551)	12.2018*** (0.8957)	19.8334*** (0.5178)	15.8368*** (1.0059)	15.6654*** (0.4383)	10.4616*** (0.8791)
<i>R</i> ²	0.0156	0.0553	0.0713	0.0843	-0.0244	0.0381
<i>Obs</i>	2256	2256	2256	2256	2256	2256

2. Distinguish the regression results of Internet use

In order to examine whether Internet use degree affected the region's financial impact on pollution reduction or green innovation, this paper classifies the regions according to the median number of Internet use in each region. Areas above the median are areas with high Internet use, while areas below the median are areas with low Internet use. Then conduct sample test. The regression results are shown in Table 9. Columns (1) and (2) of Table 9 report the impact of digital finance on pollution emissions. It can be seen that the regression coefficients of *lndf* are significantly negative, while the absolute value of the coefficient of regions with high Internet use is greater than that of regions with low Internet use. It shows that digital finance has a more obvious effect on emission reduction in areas with high Internet usage. Columns (3) and (4) in Table 9 report the impact of green innovation on pollution emission. It can be found that the regression coefficients of *lngi* are significantly negative, and the emission reduction effect of green innovation is more obvious in areas with high degree of Internet use. The reason behind this may be that digital finance uses emerging Internet technologies such as big data to change the "80/20 rule" of traditional finance, use database mining to reduce location resistance, better integrate financial resources and promote the high flow of information to accelerate the transformation of new technologies. Areas with high levels of Internet use perform this function better.

Table 9. Regression results of distinguishing the degree of Internet use

	(1) high Level of Internet use	(2) low level of Internet use	(3) high Level of Internet use	(4) low level of Internet use
<i>lndf</i>	-1.2560*** (0.4179)	-0.7807*** (0.1401)		
<i>lngi</i>			-0.6971*** (0.2260)	-0.6396*** (0.0917)
<i>ind</i>	3.1119*** (0.7867)	0.9757*** (0.1875)	3.3740*** (0.7233)	1.0034*** (0.1741)
<i>rd</i>	-29.7782** (12.0377)	4.0579 (6.8695)	-25.7447** (12.3653)	6.4377 (6.8475)
<i>fdi</i>	12.2513 (7.9091)	9.9964 (7.2573)	13.2811* (7.8631)	8.3729 (7.2194)
<i>hum</i>	0.1907** (0.0824)	-0.0460 (0.0568)	0.1844** (0.0822)	-0.0435 (0.0564)
<i>gov</i>	-4.2562*** (1.2243)	-3.1660** (1.2676)	-4.4058*** (1.2281)	-3.7582*** (1.2420)
<i>cons</i>	11.6841*** (2.8813)	12.9932*** (1.0096)	8.9335*** (2.0529)	11.5085*** (0.7918)
<i>R</i> ²	0.2239	0.1613	0.2246	0.1493
<i>Obs</i>	699	1,557	699	1,557

3. Regional heterogeneity analysis

In order to investigate whether digital finance and green innovation have differences in urban environmental pollution emissions due to different regions, according to the regional division of China Statistics Bureau, the sample is divided into eastern, central, western and northeastern regions for sample regression. Table 10 reports the regression results. Among them, items (1) - (4) are listed as regression of digital finance to pollution emission in different regions. It can be found that the suppression effect of digital financial development on pollution emission is reflected in east, west and northeast China, but there are certain regional differences. From the eastern region, the estimated coefficient is significantly negative at the statistical level of 5%. For every 1% increase in digital financial development, sulfur dioxide emissions will decrease by 0.6668%. For the central region, the estimated coefficient is significantly negative at the statistical level of 1%. For each 1% increase in digital financial development, sulfur dioxide emissions will decrease by 1.2762%. For the western region, the estimated coefficient is significantly negative at the statistical level of 1%. For each 1% increase in digital financial development, sulfur dioxide emissions will decrease by 0.9544%. For northeast China, the estimated coefficient is significantly negative at the statistical level of 10%. For each 1% increase in digital financial development, sulfur dioxide emissions will decrease by 0.7478%. On the whole, digital finance is stronger in the central and western regions, followed by the eastern regions and weakest in the northeastern regions.

Items (5) - (8) are listed as regression of green innovation in different regions to urban pollution emission. It can be found that the inhibition effect of green innovation on pollution emissions is reflected in east, west and northeast China, but there are certain regional differences. First of all, for the eastern, middle and western regions, the estimated coefficients are significantly negative at the statistical level of 1%. For the northeast region, the estimated coefficient is significantly negative only at the statistical level of 10%. This shows that the inhibition effect of green innovation on pollution emissions is more obvious in the east, middle and west regions than in the northeast and north regions. In addition, in the eastern region, every 1% increase in green innovation leads to a 0.4660% reduction in sulfur dioxide emissions. For the central region, every 1% increase in green innovation resulted in a 0.8075% reduction in sulfur dioxide emissions. In western China, every 1% increase in green innovation leads to a 0.8962% decrease in sulfur dioxide emissions. In northeast China, for every 1% increase in digital financial development, sulfur dioxide emissions will decrease

by 0.5170%. On the whole, green innovation is stronger in the central and western regions, followed by the eastern regions and weakest in the northeastern regions.

Table 10. regional heterogeneity analysis

	(1) east	(2) central	(3) west	(4) northeast	(5) east	(6) central	(7) west	(8) northeast
<i>ln_{df}</i>	-0.6668** (0.2767)	-1.2762*** (0.2804)	-0.9544*** (0.2246)	-0.7478* (0.4072)				
<i>ln_{gi}</i>					-0.4660*** (0.1708)	-0.8075*** (0.1499)	-0.8962*** (0.1579)	-0.5170* (0.2959)
<i>ind</i>	2.2272*** (0.6201)	1.9830*** (0.3577)	0.6326** (0.2734)	-0.9409** (0.4128)	2.1594*** (0.6090)	2.2043*** (0.3215)	0.5430** (0.2567)	-0.8515** (0.4007)
<i>rd</i>	-10.8844 (7.7418)	-21.2062* (11.7157)	3.8086 (12.1172)	126.7688*** (44.9773)	-9.4440 (7.7952)	-12.8404 (11.9240)	6.7677 (11.9385)	145.0385*** (43.7829)
<i>fdi</i>	13.9213 (8.5295)	44.8111*** (11.3839)	40.9718** (20.3691)	-4.1672 (9.4440)	13.7086 (8.4672)	43.4891*** (11.3048)	36.0760* (20.0865)	-6.2758 (9.6076)
<i>hum</i>	0.2054*** (0.0683)	0.0931 (0.0934)	0.0992 (0.0718)	-0.1885 (0.1356)	0.1982*** (0.0680)	0.0772 (0.0926)	0.1023 (0.0706)	-0.1776 (0.1355)
<i>gov</i>	-5.4438 (4.1172)	-5.0411 (4.8905)	-2.5431*** (0.9070)	-13.8337*** (3.0130)	-5.3655 (4.0869)	-6.9528 (4.6576)	-3.1142*** (0.9018)	-14.6634*** (2.8812)
<i>cons</i>	9.2063*** (2.0808)	12.2110*** (1.9428)	12.7462*** (1.5130)	18.0637*** (2.6553)	8.3862*** (1.7334)	9.3308*** (1.6039)	11.5595*** (1.0960)	15.9809*** (1.9299)
<i>R</i> ²	0.2350	0.2716	0.2896	0.2438	0.2004	0.2798	0.1753	0.2428
<i>Obs</i>	688	816	480	272	688	816	480	272

5. Conclusions and suggestions

Based on the panel data of 282 cities at prefecture-level and above in China from 2011 to 2019, this paper uses the fixed effect model to explore the impact of digital finance and green innovation on pollution emission in China, and further builds a panel threshold model with digital finance as the threshold to explore the pollution emission reduction mechanism of green innovation. At the same time, the impulse response function is used to explore the long-term continuation mode and impact effect of the two on pollution emission. Finally, the heterogeneity of different dimensions of digital finance and the degree of Internet use is analyzed. The results show that: firstly, digital finance and green innovation significantly reduce pollution emissions during the study period; Secondly, green innovation plays a positive and nonlinear role in promoting pollution reduction at different digital financial levels. Thirdly, both digital finance and green innovation will reduce pollution emission level in the long run, and the driving effect will gradually slow down as time goes by. Fourthly, through heterogeneity analysis, it is found that digital finance and green innovation have stronger emission reduction effects in areas with higher Internet usage.

Based on the above research, the following suggestions are given: Firstly, continuously strengthen the combination of digital technology and financial services to provide new driving force for pollution reduction. First of all, provide infrastructure support for the development of digital finance, use modern scientific and technological means to build digital financial platforms, fully mobilize financial institutions at all levels to actively make use of their advantages, combine finance with digitalization, and improve the inclusiveness and coverage of finance. Besides, we should strengthen the supervision of digital finance and fully release the driving effect of digital finance on green development by establishing a digital financial center. In addition, the regulatory standards of the government and regulatory agencies should be unified to strengthen the regulation of the behavior of financial market participants and promote the improvement of regulatory capacity. In the end, we should focus on supporting the development of digital finance in backward areas. The level of digital finance in some poor and backward areas lags behind the national average. Local governments should strengthen the construction of relevant financial hardware facilities and improve the recognition and application ability of local enterprises to digital finance. Secondly, we need to guarantee the high-

quality development of green innovation. To start with, it is necessary to strengthen the system construction of green innovation, improve the database system of green innovation, establish the green evaluation mechanism of the government, strengthen financial and fiscal support, subsidize enterprises' green innovation actions and establish enterprises' awareness of green research and development. Then strengthen the cultivation and incentive mechanism of green innovative talents and build an innovation platform. At the same time, the establishment of green technology standards forces enterprises to carry out technological research and development, establish and improve the green technology trading mechanism, increase the technology conversion rate, and stimulate learning, demonstration and spillover effects in the transformation process of innovation achievements. Finally, China should actively participate in global technology exchanges, learn from the excellent experience of foreign countries, deeply participate in global environmental governance, and use green innovation achievements to help reduce urban pollution.

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