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Deciphering the Impact of Digital Inclusive Finance on Carbon Emissions: Evidence from the Yangtze River Delta Cities

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Abstract: The rise in carbon emissions from human activities has intensified global ecosystem alterations, underscoring the need to achieve equilibrium between economic expansion and minimal carbon emissions. The Yangtze River Delta cities have experienced an increase in energy consumption and greenhouse gas emissions, highlighting the urgent necessity for green and sustainable economic development. Digital inclusive finance, including green credit and green finance, can help the region's economy and industry become more sustainable, reducing urban carbon emissions. This study employs a fixed-effects panel model to investigate the relationship between digital inclusive finance and urban carbon emission intensity. The analysis focuses on 27 central cities within the Yangtze River Delta, covering the period from 2011 to 2019. In addition, the underlying mechanisms for how digital inclusive finance affects urban carbon emissions will be explored. The study yielded the following findings:1) The emergence of digital inclusive financial services initially results in an uptick in carbon emissions, which is subsequently followed by a decline. Extended reach and intensified use are the main drivers of carbon emission reduction. 2) Digital finance impacts carbon emissions in different ways by city tier. It is relatively insignificant in lower tier cities, but significant in higher tier cities. 3) The carbon-reducing effect of digital inclusive finance is amplified by green technology, increasing its overall impact.

Keywords: digital inclusive finance, carbon emission reductions, Yangtze River Delta, green innovation.

1. Introduction

Overdependence on fossil fuels, which has led to increased carbon emissions, has resulted in significant global climate change. China has contributed greatly to global carbon emissions along with its rapid economic growth. Its share rose from 10% in 1990 to 30.7% in 2020. This has harmed ecosystems, health, and social progress [1]. In China, the Yangtze River Delta area exhibits the most significant clustering of industrial enterprises., particularly in petrochemicals, textiles, and paper manufacturing. In 2019, it consumed 520.86 million tons of standard coal equivalent, representing 16.2% of China's total industrial energy consumption. Reducing carbon emissions and achieving sustainable development in the region is crucial for China's climate change challenges.

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Digital inclusive finance helps achieve regional carbon neutrality by integrating digital technology with financial inclusivity. With the deepening integration of digitalization and finance, digital inclusive finance's carbon reduction impact can ultimately contribute to sustainable development. Exponential Roadmap shows how industrial digitization could cut global carbon emissions by 15%. Full implementation of ICTs could reduce global carbon emissions by 15% to 20% [2]. While digital inclusive finance can help cut urban carbon emissions, the precise way it does so is unclear. What is the pathway of this influence? It would be of interest to ascertain whether the effect differs at various stages of development. The objective of this study is to analyze the levels of digital inclusive finance and carbon emissions in 27 major cities within the Yangtze River Delta, focusing on the years 2011 to 2019. The aim is to assess the impacts and further explore the underlying mechanisms.

In conclusion, the innovations presented in this paper are primarily reflected in three key areas: the research topic and perspective, data processing, and research content. Firstly, this paper presents a novel approach to examining digital finance's impact on urban carbon emission, including an investigation of the mediating effect of green innovation. Secondly, the measurement of indicators and the selection of samples are more representative. This paper uses the digital inclusive finance index from Guo et al. [3], based on Ant Financial data, ensuring a reliable and representative result. Furthermore, it analyzes carbon emissions in 27 key cities, offering valuable insights for green development in the Delta. Thirdly, the research content represents a significant innovation and distinctive contribution to the field. This paper puts forth a novel proposition: green innovation serves as a mediator between urban carbon emissions and digital inclusive finance. This hypothesis is subsequently subjected to empirical testing.

2. Literature Review

2.1. Finance Inclusive Finance

Inclusive finance was introduced to China after 2005. In late 2015, the State Council published a plan for advancing inclusive finance. It defined inclusive finance as financial services for all, based on equal opportunity and commercial sustainability. Scholars have developed digital inclusive finance indicator systems to measure and enhance inclusive finance globally. The IMF has created an index to evaluate digital finance inclusion in 52 developing countries, considering both access and usage of digital finance.[4] The digital financial development indicator system devised by Banik and Roy [5] includes three dimensions: foundational aspects, governance, and service provision. It supports a thorough and systematic evaluation of digital finance development in 60 prominent economies around the world from 2018 to 2022. Guo et al [3] constructed an index based on Ant Financials' data. This index measures digital finance across three key dimensions: coverage breadth, usage depth, and digitization level. The data set encompasses three levels of geographical analysis: county, city, and province, within the context of China. From a developmental perspective, digital inclusive finance has the potential to effectively promote the growth of the real economy [6].

2.2. Carbon Emission

Presently, two relatively authoritative data sources are available for estimating China's carbon emissions. The first is the International Energy Agency, which conducts periodic assessments of carbon dioxide emissions by countries around the world. The second data source is the CEADs carbon emission database, which provides annual provincial-level carbon emission inventories for China. However, as of 2019, publicly available data on carbon emissions at the municipal level remained unavailable, necessitating self-estimation. At present, the predominant methodology employed by domestic and international scholars for estimating carbon emissions at the provincial and municipal levels is based on three principal approaches. The first method uses carbon emission calculation

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techniques used by international organizations. This approach calculates the emissions of different energy sources based on their carbon emissions factors. For example, Hirano et al. [7] used coal, oil, and natural gas consumption to calculate carbon emissions for different regions. The second method provides more detailed resolution by estimating carbon emissions based on comprehensive traffic data. This method allows estimation of carbon emissions for individual roads. For example, McKinnon and Piecyk [8] used road traffic models to predict carbon emissions in urban areas. The third method estimates urban carbon emissions using nighttime light data [9]. Nighttime light data in cities can, to some extent, reflect economic activity, which in turn indicates energy consumption levels.

2.3. Digital Inclusive Finance and Carbon Emissions

Implementing digital inclusive finance can greatly decrease carbon emission intensity in specific regions. However, given the heterogeneous nature of regional development, this initiative's impact on carbon emissions also reveals notable variability. [2] [10]. In southern China, digital inclusive finance's carbon reduction impact is particularly strong, but it is not as pronounced in the northern regions.[11]. Numerous studies on the Yangtze River Delta suggest that the implementation of digital finance can significantly reduce carbon emissions in its cities. The initial decline in carbon emission efficiency is followed by an increase, with fluctuations remaining relatively small and stable. Regarding the mechanisms of influence, most studies continue to concentrate on analyzing the general factors affecting carbon emissions. Wan et al [12] underscored the pivotal roles of the entrepreneurial effect, innovation effect, and industrial upgrading effect as mechanisms through which finance facilitates carbon reduction. Chu et al. [13] stressed that digital finance inclusion could prove instrumental in the reduction of urban carbon emissions, through the stimulation of innovation in green technologies.

2.4. Comprehensive Review of Literature

Notwithstanding the comprehensive nature of the existing research on carbon emissions, the role of digital finance in reducing urban emissions is understudied, and the specific mechanisms and pathways of these effects have yet to be fully studied. Further investigation is required to elucidate the manner in which digital inclusive finance contributes to the reduction of carbon emissions. This may be achieved, for instance, through the adoption of green finance, green credit, and a variety of financial instruments. A number of studies have recently initiated an investigation into the carbon reduction impact of digital inclusive finance in the Yangtze River Delta. [11] Nevertheless, there is a paucity of empirical research examining the relationship between the two.

In conclusion, while existing research offers a preliminary understanding of the relationship between digital finance and carbon emissions, further investigation is needed to gain more nuanced insights.

3. Research Hypotheses

Digital inclusive finance could reduce carbon emissions by changing how we use energy, structure industry, and innovate green technology. Some hypotheses should be tested.

Hypothesis 1: Digital inclusive finance may reduce carbon emissions, with an initial increase followed by a decrease.

This paper synthesizes prior research on the link between digital finance and carbon emissions from both digital and financial perspectives. Digitization of finance boosts economic activity, which increases carbon emissions [13]. The digital transformation of finance has resulted in increased energy consumption and urban carbon emissions. As digital technologies continue to mature,

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financial attributes become increasingly important. They cut innovation costs, back green tech, promote energy savings and emissions reductions, and help upgrade urban industrial structures. Technological advancement reduces urban carbon emissions [14]. Digital applications can cut material use, help businesses grow and boost efficiency. We believe there is a U-shaped relationship between digital inclusive finance and urban carbon emissions.

Hypothesis 2: Green innovation technology affects digital finance progress, which in turn affects urban carbon emissions.

A review of the aforementioned literature reveals that the entrepreneurial effect, innovation effect, and industrial upgrading effect are the primary mechanisms through which finance facilitates carbon reduction [12]. The present study posits that digital inclusive finance exerts a pronounced impact on urban carbon emissions, primarily through the promotion of green technology and the reinforcement of corporate carbon reduction initiatives. It facilitates emissions reduction through the stimulation of corporate innovation and the advancement of green, low-carbon industries. [13].

4. Research Design

4.1. Model Design

4.1.1. Fixed Effects Model

A fixed effects model has been developed for the purpose of examining the impact of digital inclusive finance on urban carbon emissions, utilizing panel data. To avoid heteroscedasticity, all variables are transformed into logarithms prior to analysis. The baseline regression model is constructed as follows:

$$\ln CEI = \alpha_0 + \alpha_1 \ln DIF_{it} + \alpha_2 \ln DIF_{it}^2 + \alpha_3 \ln \mathrm{CONTROL}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

Where:

- $\ln CEI$ is a log of annual number of carbon emissions
- $\ln DIF_{it}$ and $\ln DIF_{it}^2$ are the log of annual digital inclusive finance index and its squared term, respectively
- $\ln CONTROL_{it}$ includes the control variables in logarithmic form
- μ_i is the individual fixed effect
- γ_t is the time fixed effect
- ε_{it} is the error term.

4.1.2. Mediation Effect Model

Referring to the mediation effect model theory proposed by Wen and Ye [15], this study uses a mediation effect model to investigate how digital inclusive finance affects urban carbon emissions. The models are specified as follows:

$$\ln GREE = \beta_0 + \beta_1 \ln DIF_{it} + \beta_2 \ln DIF_{it}^2 + \beta_3 \ln CONTROL_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

$$\ln CEI = \theta_0 + \theta_1 \ln DIF_{it} + \theta_2 \ln DIF_{it}^2 + \theta_3 \ln GREE_{it} + \theta_4 \ln \mathrm{CONTROL}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (3)$$

Where:

- $\ln GREE_{it}$ is the log of annual number of green patent applications, which serves as the mediating variable.
- β_1, β_2 and θ_3 are the coefficients of interest, representing the influence of digital inclusive finance on green innovation and the impact of green innovation on carbon emissions, respectively.
- θ_1 , θ_2 are the impact of digital inclusive finance on carbon emissions.

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If the coefficients β_1, β_2 and θ_3 are significant, and θ_1 , θ_2 is also significant, this indicates that the mediation effect is significant.

4.2. Data Sources and Descriptive Statistics

This study uses panel data from 27 central cities in the Yangtze River Delta between 2011 and 2019. It was sourced from the China City Statistical Yearbook, the Peking University Digital Inclusive Finance Index, the National Bureau of Statistics, and the National Intellectual Property Administration. The variable design is presented in detail in Table 1.

Table 1: Indicator System of Carbon Emissions and Finance Inclusive System

Variable Type	Variable Name	Symbol	Definition
Dependent Variable	Carbon Emissions	CEI	Carbon emissions in various regions
Independent Variable	Digital Inclusive Finance Index	DIF	Level of digital inclusive finance development
Sub-dimension	Coverage Breadth	CB	Extent of coverage of digital accounts and services
Sub-dimension	Usage Depth	UD	Use of digital financial services
Sub-dimension	Digitization Degree	DI	Ease of accessing digital financial services
Mediating Variable	Green Innovation	GREE	Number of green patent applications
Control Variable	Economic Development Level	GDP	Total GDP of the year
	Industrial Structure Level	IND	Proportion of the secondary industry in GDP
	Financial Deepening Level	FIN	Ratio of the year-end balance of RMB loans to total GDP
	Internet Penetration Rate	INT	Number of broadband internet access users
	Resident Income Level	SAL	Average annual salary of employees in the city
	Population Density	PD	Density of the permanent population in the city

To address potential heteroscedasticity issues arising from significant discrepancies in variable values, this study employs a logarithmic transformation on all variables. Table 2 displays descriptive statistics results. The data ranges from 0.858 to 2.374, with an average value of 1.617. This suggests a significant overall level of carbon emissions and substantial variations among the 27 cities analyzed. The Digital Inclusive Finance Index shows a minimum value of 1.627 and a maximum of 2.489, highlighting the uneven development of digital inclusive finance across the various cities.

Table 2: Descriptive Statistics of Variables

Variables	Observations	Cross sections	Mean	Median	Minimum	Maximum	Std. Dev.
CEI	243	27	1.617	1.578	0.858	2.374	0.340
DIF	243	27	2.244	2.293	1.627	2.489	0.189
CB	243	27	2.233	2.281	1.536	2.480	0.179

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Table 2: (continued).

UD	243	27	2.266	2.280	1.769	2.508	0.178
DI	243	27	2.208	2.363	1.144	2.527	0.329
GREE	243	27	1.852	1.908	0.000	3.222	0.652
GDP	243	27	3.529	3.551	2.571	4.582	0.396
IND	243	27	1.688	1.692	1.431	1.873	0.063
FIN	243	27	0.071	0.045	-0.250	0.721	0.155
INT	243	27	2.089	2.121	0.969	2.949	0.388
SAL	243	27	4.807	4.808	4.520	5.205	0.123
PD	243	27	2.812	2.808	2.226	3.583	0.265

5. Empirical Analysis

5.1. Baseline Regression

Table 3 shows the results from this study's baseline regressions. Column 1 presents the regression results using DIF and its squared term, without control variables. Subsequent columns show the results as control variables are added. Column 7 shows regression results with controls. As control variables are introduced, the coefficient of DIF remains positive, while the squared term remains negative. The results (Column 7) show digital finance development is associated with higher carbon emissions in the Yangtze River Delta. The negative coefficient of the squared term suggests a potential decrease in emissions. The results show a positive impact of digital finance at the 1% confidence level and a negative impact at the 5% confidence level. This supports the hypothesis that digital inclusive finance has a positive impact on carbon reduction up to a certain point.

Table 3: Results of Benchmark Regression Analysis

	1	**2**	**3**	**4**	**5**	**6**	**7**
Variables	CEI						
DIF	**2.0653** (1.9844)**	**2.0655** (1.9847)**	**2.0637** (1.9797)**	**2.1764** (2.0729)**	**2.1298** (2.0228)**	**2.2375** (2.1453)**	**3.1937*** (2.9864)***
DIFSQ	-0.3082 (-1.0219)	-0.3186 (-1.0559)	-0.3207 (-1.0612)	-0.3291 (1.0878)	-0.3262 (-1.0770)	-0.3623 (-1.2072)	**-0.6713** (-2.1573)**
GDP		0.1483 (1.0040)	0.1358 (0.9080)	0.1127 (-0.7431)	0.0971 (0.6338)	0.0918 (0.6053)	0.0327 (0.2180)
IND			0.1010 (0.5764)	0.0824 (0.4665)	0.0901 (0.5091)	0.0272 (0.1536)	-0.0563 (-0.3200)
FIN				-0.0476 (-0.9226)	-0.0448 (-0.8649)	0.0334 (-0.6476)	-0.0145 (-0.2854)
INT					0.0371 (0.7497)	0.0534 (1.0800)	**0.0897* (1.7968)**
SAL						**0.5445** (2.3002)**	**0.5390** (2.3230)**
PD							**0.4189*** (3.0421)**
Constant	**-1.4550* (-1.6792)**	**-1.9261** (-1.9548)**	**-2.0377** (-2.0260)**	**-2.1320** (-2.1081)**	**-2.0779** (-2.0474)**	**-4.6638*** (-3.0938)***	**-6.1213*** (-3.9411)***
R-squared	0.9773	0.9774	0.9774	0.9775	0.9776	0.9782	0.9791
F	264.164	239.5477	232.4929	226.3882	220.2664	219.588	223.3834

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are t-statistics. The same notation applies to the following tables.

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By 2019, digital inclusive finance in the Yangtze River Delta cities exceeded the turning point, reducing urban carbon emissions. Shanghai and Nanjing were the first cities in the Yangtze River Delta to cross the tipping point. By 2017, all central cities in Zhejiang and Jiangsu had reached a level of digital inclusive finance above the tipping point. Cities in Anhui Province crossed the tipping point later.

5.2. Heterogeneity Analysis

5.2.1. Dimensional Heterogeneity Analysis

To investigate the disparate impacts of various dimensions of digital inclusive finance on urban carbon emissions, this study employs three secondary indicators—Coverage Breadth, Usage Depth (UD), and Digitization Degree (DI)—to analyze the heterogeneous effects of these variables on carbon reduction.

Table 4 shows that digital inclusive finance reduces urban carbon emissions through two dimensions. Expanding coverage breadth widens the reach of inclusive financial services, supporting individuals, businesses, and small and medium-sized enterprises (SMEs) in environmentally sustainable production. As usage depth increases, financial applications broaden, enabling individuals and enterprises to adopt sustainable practices and reduce urban carbon. The degree of digitization does not appear to influence urban carbon reduction. China's digital infrastructure is underdeveloped, so digital services have not reached their full potential. Further investment in digital infrastructure is required to harness the potential of digitization in carbon reduction.

Table 4: Result of Dimensional Heterogeneity Analysis

	1	**2**	**3**
Variables	CB	UD	DI
CB	**2.1201*** (2.4600)**		
CBSQ	**-0.4561* (-1.7740)**		
UD		**5.4954*** (3.8944)**	
UDSQ		**-1.1588*** (-3.2772)**	
DI			-0.1148 (-0.3376)
DISQ			-0.0156 (-0.1545)
Control Variables	Yes	Yes	Yes
Constant	**-4.8848*** (-3.3446)**	**-9.3617*** (-5.0127)**	**-2.9599** (-2.2408)**
R-squared	0.9789	0.9794	0.9771
F	221.1114	226.7897	203.2869

5.2.2. Regional Heterogeneity Analysis

Digital inclusive finance may affect carbon reduction differently in different cities due to economic and technological differences. This study investigates the effects of digital inclusive finance on carbon reduction in both higher-tier and general-tier cities, classifying them according to their per

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capita GDP rankings for 2023. The 27 central cities in the Yangtze River Delta and the provincial capitals are classified as higher-tier cities. The remaining cities are classified as general-tier cities.

Table 5: City Tier Classification

Higher-tier	Shanghai, Nanjing, Wuxi, Suzhou, Changzhou, Nantong, Zhenjiang, Yangzhou, Taizhou, Hangzhou, Shaoxing, Ningbo, Zhoushan, Hefei
General-tier	Yancheng, Wenzhou, Jiaxing, Huzhou, Jinhua, Taizhou, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, Xuancheng

Regression results for higher- and general-tier cities are in columns (1) to (3). Column (1) shows findings for higher-tier cities from 2011 to 2019. DIF and its square are explanatory variables, with control variables also considered. Column (2) presents the results for general-tier cities from 2011 to 2019. Column (3) focuses on general-tier cities using only DIF, with control variables also considered.

The relationship between digital inclusive finance and carbon emissions in higher-tier cities is "U-shaped," increasing then decreasing. The presence of digital inclusive finance leads to a significant reduction in carbon emissions within urban settings. The non-linear relationship in general-tier cities is not statistically significant. At the 1% confidence level, digital inclusive finance shows a notable positive effect. Yet, this has resulted in a small increase in carbon emissions among general-tier cities. In comparison, higher-tier cities have advanced to a stage where digital inclusive finance is contributing to lower carbon emissions.

Table 6: Result of Regional Heterogeneity Analysis

	1	**2**	**3**
Variables	Higher tier	General tier	General tier
DIF	**4.7772*** (2.2490)**	3.3485 (1.7160)	**0.8693*** (2.6625)**
DIFSQ	**-1.2230*** (-2.3430)**	-0.7088 (-1.2886)	
Control Variables	Yes	Yes	Yes
Constant	-2.5366 (-0.7180)	**-7.5815*** (-2.8965)**	**-5.3489*** (-2.7163)**
R-squared	0.9897	0.9529	0.9520
F	317.2163	63.5145	65.3206

5.3. Mediating Effect Analysis

This section presents a mediation effect model for investigating the role of green innovation in urban carbon reduction. The impact of digital inclusive finance on green technology innovation and carbon emissions exhibits an inverted U-shaped pattern, as illustrated in Table 9. It stimulates the development of green technology, yet concurrently exhibits a parallel decline in its impact on emissions. Moreover, the number of green technology innovation applications has been observed to exert a notable inhibitory impact on carbon emissions. The addition of the variable for green

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technology innovation applications resulted in a further enhancement of the carbon reduction effect of digital inclusive finance, indicating that the mediation effect of these applications is considerable.

Table 7: Results of the Mediation Mechanism Examination

Variables	Green Innovation (GREE)	Carbon Emissions (CEI)
DIF	**15.4166*** (5.6038)**	**3.8514*** (3.3600)**
DIFSQ	**-3.7097*** (-4.6343)**	**-0.8297*** (-2.5424)**
GreeD		**-0.0427* (-1.5576)**
C	**-13.5214*** (-3.3841)**	**-6.6982*** (-4.2090)**
Control Variables	Yes	Yes
R-Squared	0.9576	0.9794

5.4. Robustness Tests

To validate the effectiveness of the baseline regression results, this study employs two methods for robustness checks: variable substitution and the inclusion of a time trend term (T). After variable substitution, digital inclusive finance's effect on carbon emission intensity shows a linear increase at the 1% confidence level and a marginal diminishing effect at the 5% confidence level. After adding the time trend term, DIF continues to show a significant linear increase and marginal diminishing effect on carbon emissions. These results confirm the reliability of the baseline regression results.

6. Conclusions and Discussions

This study uses panel data from cities in the Yangtze River Delta region from 2011 to 2019 to analyze the impact of digital inclusive finance on urban carbon emissions. The findings indicate that digital inclusive finance initially increases, then decreases urban carbon emissions, confirming an inverted U-shaped relationship. Moreover, digital inclusive finance significantly reduces urban carbon emissions, primarily through coverage breadth and usage depth. In higher-tier cities, the correlation with carbon emissions is nonlinear, whereas this pattern is not observed in general-tier cities, where digital inclusive finance contributes more noticeably to the reduction of carbon emissions. Finally, digital inclusive finance reduces urban carbon emissions by stimulating green technological innovation.

Considering the findings, a series of recommendations are put forth as follows:

1) Strengthen the comprehensive planning for 'low carbon' growth in the Yangtze River Delta region, improve the implementation of digital finance and carbon reduction policies, and reduce the development gap in digital inclusive finance between cities of different levels.
2) Increase policy support for green technology innovation industries, promote the efficient output of green technology, and establish a coordination mechanism among cities in Shanghai, Jiangsu, Zhejiang, and Anhui that links digital finance, carbon reduction, and green technological innovation to enhance the synergistic effects among these three areas.
3) Create a sustainable framework for the thorough integration of digital technology with the 'dual carbon' targets by harnessing technologies like cloud computing, big data, and artificial intelligence. Achieve the 'dual carbon' goals and promote the green transformation of the Yangtze River Delta through digital means.

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