Research on the Impact of the Digital Economy on Carbon Emissions in Chinese Urban Agglomerations

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Abstract. Urban agglomeration represents the apex of spatial organization and serves as a critical investigative lens for materializing the "dual carbon" directive. This research confidently assesses data from seven prominent urban agglomerations spanning 2011 to 2019, utilizing metrics for the digital economy and carbon intensity. The aim is to explore the impact of the digital economy on carbon emissions whilst concurrently scrutinizing the resultant heterogeneity across diverse urban agglomerations. The research concludes the following: (1) Across the board, carbon emissions from urban agglomerations can be mitigated by the growth of the digital economy. Empirical data show that every 1 percent rise in the digital economy index reduces local carbon intensity by an estimated 0.2956. (2) Except Chengdu-Chongqing agglomeration, where the growth of the digital economy has led to an increase in carbon intensity, the remaining six urban agglomerations consistently showed an inverse link with carbon emissions intensity. (3) Further investigation revealed the links between the digital economy and carbon emissions in agglomerations of Beijing-Tianjin-Hebei, Yangtze River Delta, Central Plains, and Guanzhong Plain followed an "inverted U-shape" pattern. In contrast, the link of Guangdong-Hong Kong-Macao Greater Bay Area formed a "U-shape" pattern. The nonlinear test for Chengdu-Chongqing and the Yangtze River middle reaches agglomerations is not valid. In light of these heterogeneity outcomes, this paper concludes with recommendations for targeted strategies.

Keywords: urban agglomerations; digital economy; carbon intensity; heterogeneity

1 Introduction

Environmental degradation has become a contemporary and future reality due to human activities such as population expansion, economic growth, and industrial consumption. China's massive population and economic expansion have made it the world's greatest carbon-emitting economy [1]. The Chinese government's "dual-carbon" strategy poses a new challenge to reduce carbon dioxide emissions through economic and energy restructuring, as well as enhancing energy intensity [2]. Efforts have been made by various parties, including the government, industry, and consumers, to work towards achieving the "dual carbon" goal [3].

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Urban agglomeration refers to the integration of cities within a defined region that forms a close relationship based on basic conditions. Throughout the development from the early stage to the maturity of urban agglomerations, the population spatial distribution from an unbalanced to a more balanced dispersion [4]. By the end of 2022, the urbanization rate among China's resident population increased by 0.5%, attaining 65.22% which was a growth from the prior year. However, urban development quality is under duress due to social and environmental issues that have arisen from population migration, industrial agglomeration, and transportation emissions. As industries commence their progression of upgrading, it's anticipated that the economic growth fallout will reveal a tendency towards attenuation, especially visible through its impact on carbon emissions [5]. As urban areas transition towards developing a low-carbon economy, the period from 2003 to 2018 has witnessed a gradual surge in the marginal abatement cost of carbon emissions coinciding with a decrease in carbon intensity [6]. In light of the rapid growth of urban agglomerations in China, regional studies on the digital economy emerge as critically crucial. This not only aids in curtailing carbon emissions but also engenders a consistent enhancement throughout the development quality of urban agglomerations.

The excellence of China's economy indeed unveils new opportunities by virtue of the digital economy. Furthermore, it supports industrial restructuring while addressing environmental concerns. The information infrastructure bolsters the greenhouse gas emission performance in Chinese cities substantially. Nonetheless, a notable enhancement in emission reduction performance is predominantly evidenced in cities of large scale, those harboring an advanced digital economy, and those leading economic status [7]. Urbanization and construction growth drive energy use [8]. As the digital economy grows, coal's effect on carbon emissions steadily decreases in the energy mix [9]. Promoting the use of renewable energy and the Internet as strategic means of reducing carbon dioxide emissions has become critical [10]. Examining the scope and direction of the digital economy's impact on the carbon intensity of urban agglomerations reveals the origins of carbon emission disparity within those agglomerations. This understanding assists in clarifying the link between the digital economy and the carbon intensity of urban agglomerations.

2 Models and Data

Based on the research question and data characteristics, namely the impact of the digital economy on carbon emissions in urban agglomerations, and the limited time series of panel data, a Hausman test was conducted on the sample with Prob=0.0000, indicating the rejection of the original hypothesis and the choice of a fixed effects model. Choose Stata15 software and select the robust regression command. We establish a fixed effects model represented by equation (1). Herein, i signifies varied regions, while t represents various years. $COE_{i,t}$ and $DIG_{i,t}$ designate carbon intensity and the digital economy index, respectively. $CONTROL_{i,t}$ signifies control variables, which encompass *LFA*, *OPE*, *LAB*, *DEN*, *SCI*, and *EDU*. μ_i and δ_i each respectively represent individual-fixed effects and time-fixed effects, and $\varepsilon_{i,t}$ is the randomized perturbation term. β_0 is the constant term, β_1 signifies the regression coefficient, and β_2 denotes the regression coefficients of control variables impacting carbon intensity.

$$COE_{i,t} = \beta_0 + \beta_1 DIG_{i,t} + \sum \beta_2 \, CONTROL_{i,t} + \mu_i + \delta_i + \varepsilon_{i,t} \qquad (1)$$

Equation 2 presents a nonlinear test model that demonstrates the potential impact of digital economy expansion on carbon emission intensity. We use $SDIG_{i,t}$, to calculate the quadratic term of the digital economy. The meanings of other variables are the same as equation 1.

$$COE_{i,t} = \beta_0 + \beta_1 DIG_{i,t} + \beta_2 SDIG_{i,t} + \sum \beta_3\, CONTROL_{i,t} + \mu_i + \delta_i + \varepsilon_{i,t} \qquad (2)$$

The focus of the investigation is on the panel data collected from seven key urban agglomerations from 2011 to 2019. The statistics are from the China Urban Statistical Yearbook, CSMAR, and other databases. Individual missing data is filled up using interpolation. The variable selection and measurement methods are displayed in Table 1.

Table 1. Variable Measurement and Descriptive Statistics

Variable	Notation	Measure	Mean	Sd	Min	Max
Carbon Emission Intensity	COE	Carbon emission/GDP	0.3628	0.2022	0.0547	1.0323
Digital economy	DIG	Improved entropy method	0.1006	0.0624	0.0279	0.3889
Fixed capital investment stock	LFA	Fixed capital investment stock in logarithms	17.9308	0.8243	16.2242	19.9349
Openness to the outside	OPE	Gross export/import expenditures/GDP	0.2168	0.3297	0.0035	1.7268
Labor productivity	LAB	GDP/number of persons working in establishments	44.7899	15.4135	16.1546	95.1285
Urbanization	DEN	Total population/land area	0.0550	0.0334	0.0091	0.2232
Technological level	SCI	Expenditures on science programs in local finances/GDP	0.0035	0.0032	0.0006	0.0200
Educational level	EDU	Expenditures on education in local finances/GDP	0.0313	0.0130	0.0144	0.0890

3 Analysis of results

3.1 Regression to Basics

Table 2 tests the magnitude of the role of the digital economy in affecting carbon emissions in urban agglomerations and the intensity of the impact, dividing the research sample into two groups: urban and non-urban agglomeration cities. Column (1) shows the regression coefficient of DIG on COE is -0.8147, which has the statistical significance at 1% level, suggesting that the digital economy plays a noteworthy function in lowering carbon emissions within urban agglomerations. From an economic perspective, it is worth considering the average intensity of carbon emissions, which stands at 0.3628, every 1% escalation in the digital economy index of urban agglomerations will decrease local carbon intensity by approximately 0.2956 (0.8147*0.3628) on the mean. The impact of the digital economy on carbon emissions among non-urban agglomerations is illustrated with a regression coefficient of 0.0640, as shown in column (2). The discrepancy between these two coefficient sets is subjected to testing, resulting in a Chi-squared value of 34.08, reaching a significance at 1%

level, indicating that the digital economy has varying impacts of different urban agglomerations on carbon emissions.

Table 2. Overall regression test of seven major urban agglomerations in China

	(1) COE	(2) COE	(3) COE	(4) COE
DIG	-0.8147***	0.0640	1.6492***	1.7385
	(-5.9660)	(0.0699)	(4.7726)	(0.8989)
SDIG			-2.3416***	-4.1320
			(-4.8446)	(-1.2861)
CONTROL	YES	YES	YES	YES
_CONS	5.9638***	4.0312**	0.0229	4.1294**
	(7.4880)			
Chi2		34.08***		47.57***
N	1170	1368	1170	1368
adj. R^2	0.306	0.213	0.143	0.214

[a] t-values are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% statistical levels respectively. Same as mentioned below.

3.2 Heterogeneity Analysis

Considering China's regionally disparate progression, marked by varying digital economy indicators and carbon intensity across regions, the results conducted on a national scale may exhibit substantial discrepancies. According to "Opinions of the Central Committee of the Communist Party of China and the State Council on Establishing a New Mechanism for More Effective Coordinated Regional Development (2018)", we subdivided the research sample into seven urban agglomerations: Beijing-Tianjin-Hebei agglomeration, Yangtze River Delta agglomeration, Guangdong-Hong Kong-Macao Greater Bay Area, Chengdu-Chongqing agglomeration, Yangtze River middle reaches agglomeration, Central Plains agglomeration, and Guanzhong Plain agglomeration to conduct a heterogeneity test. The results are shown in Tables 3 through 9.

Table 3. Heterogeneity test based on Beijing–Tianjin-Hebei agglomeration

	(1) COE	(2) COE	(3) COE	(4) COE
DIG	-1.4038*	-0.7968***	4.2708***	2.1415***
	(-1.7253)	(-3.0437)	(2.6731)	(3.3191)
SDIG			-13.8155***	-7.9089***
			(-3.6422)	(-5.0443)
CONTROL	YES	YES	YES	YES
_CONS	-12.9821***	6.4131***	-12.8120***	4.3684***
	(-2.7813)	(7.2781)	(-4.4976)	(7.3924)
Chi2		7.61***		13.33***
N	117	2421	117	2421
adj. R^2	0.776	0.109	0.827	0.229

Table 4. Heterogeneity test based on Yangtze River Delta agglomeration

	(1) COE	(2) COE	(3) COE	(4) COE
DIG	-0.7331***	-0.6576**	2.7056***	2.2756***
	(-3.4885)	(-2.1909)	(3.0461)	(3.2780)
SDIG			-7.9418***	-8.3036***
			(-3.9452)	(-4.7902)
CONTROL	YES	YES	YES	YES
_CONS	2.5540	6.3630***	2.8638*	4.0486***
	(1.5621)	(6.9228)	(1.8095)	(6.6349)
Chi2		30.01***		62.59***
N	243	2295	243	2295
adj. R^2	0.310	0.122	0.339	0.247

Table 5. Heterogeneity test based on Guangdong-Hong Kong-Macao Greater Bay Area

	(1) COE	(2) COE	(3) COE	(4) COE
DIG	-0.2562**	-0.8275***	-0.8057***	2.2288***
	(-2.2966)	(-2.5799)	(-3.5886)	(3.3304)
SDIG			0.6349**	-8.3280***
			(2.4115)	(-4.9313)
CONTROL	YES	YES	YES	YES
_CONS	-2.4338***	6.1223***	-3.0207	4.2156***
	(-2.9376)	(7.0021)	(-1.7255)	(7.2189)
Chi2		55.40***		42.40***
N	81	2457	81	2457
adj. R^2	0.341	0.132	0.427	0.255

Table 6. Heterogeneity test based on Chengdu-Chongqing agglomeration

	(1) COE	(2) COE	(3) COE	(4) COE
DIG	0.6879	-0.8570***	2.7175*	4.3752***
	(1.3771)	(-3.2397)	(2.0795)	(4.0979)
SDIG			-8.8623	-5.8027***
			(-1.6162)	(-3.1519)
CONTROL	YES	YES	YES	YES
_CONS	9.4730	5.9650***	9.9459*	0.9786
	(1.7412)	(6.6256)	(1.7732)	(1.0573)
Chi2		0.13		11.78***
N	144	2394	144	2394
adj. R^2	0.483	0.121	0.487	0.097

Table 7. Heterogeneity test based on Yangtze River middle reaches agglomerations

	(1) COE	(2) COE	(3) COE	(4) COE

	(1)	(2)	(3)	(4)
	COE	COE	COE	COE
DIG	-2.3093***	-0.7842**	0.2440	2.5925***
	(-3.0959)	(-2.4968)	(0.1730)	(3.0190)
SDIG			-7.8359*	-8.8962***
			(-1.9347)	(-5.3158)
CONTROL	YES	YES	YES	YES
_CONS	1.9123	6.0886***	2.8063*	3.9146***
	(0.6294)	(3.7617)	(1.7760)	(3.3268)
Chi2		11.96***		0.13
N	252	2286	252	2286
adj. R^2	0.420	0.219	0.353	0.332

Table 8. Heterogeneity test based on Central Plains agglomeration

	(1)	(2)	(3)	(4)
	COE	COE	COE	COE
DIG	-1.0600***	-0.7686**	6.6699***	4.3813***
	(-3.1606)	(-2.3715)	(3.7139)	(8.0033)
SDIG			-13.0300***	-5.6556***
			(-3.7977)	(-6.5959)
CONTROL	YES	YES	YES	YES
_CONS	16.9075***	5.9179***	3.8022**	1.1103*
	(2.8201)	(3.8135)	(2.2268)	(1.7547)
Chi2		6.33**		4.57**
N	261	2277	261	2277
adj. R^2	0.561	0.207	0.201	0.097

Table 9. Heterogeneity test based on Guanzhong Plain agglomeration

	(1)	(2)	(3)	(4)
	COE	COE	COE	COE
DIG	-0.8441	-0.8176***	13.2432**	4.2342***
	(-0.8112)	(-2.6012)	(2.2633)	(7.9806)
SDIG			-37.5595*	-5.5956***
			(-1.8906)	(-6.7448)
CONTROL	YES	YES	YES	YES
_CONS	18.0820**	5.9612***	7.8748***	0.9639
	(2.4557)	(3.9116)	(2.6773)	(1.5763)
Chi2		7.19***		18.84***
N	99	2439	99	2439
adj. R^2	0.487	0.213	0.141	0.098

The heterogeneity test conclusions can be found in Table 10.

Table 10. Summary of findings from tests based on heterogeneity of urban agglomerations

	Beijing-Tianjin-Hebei		Yangtze River Delta		Guangdong-Hong Kong-Macao		Chengdu-Chongqing		Yangtze River middle reaches		Central Plains		Guanzhong plain	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Regression to the base	-	-	-	-	-	-	+(x)	-	-	-	-	-	-(x)	-
Inverted U-shape	Y	Y	Y	Y		Y		Y		Y	Y	Y	Y	Y
U-shape					Y									
No nonlinear							Y		Y					

[a] "-" is negatively significant; "+" is positively significant; "-(x)" is negatively insignificant; "+(x)" is positively insignificant; "Y" is yes.

4 Conclusion and Discussion

Collectively, the seven primary urban agglomerations could see a substantial decrease in carbon intensity due to the transformative potential of the digital economy. The conclusion is consistent with reference [7]. For every 1% increase in the digital economy, there is a corresponding decrease of 0.8147% in carbon emission intensity within urban agglomerations. It has been observed that the correlation between the digital economy and carbon intensity follows an "inverted U-shaped" pattern. The curve's turning point occurs at a digital economy index of 0.3522. In all urban agglomerations, other than Chengdu-Chongqing where it has a positive impact, the digital economy has a dampening impact on carbon intensity with differential effects. When the digital economy index rises by 1%, the average drop in carbon intensity in the urban agglomerations of Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao, Yangtze River middle reaches, Central Plains, and Guanzhong Plain are 1.4038%, 0.7331%, 0.2562%, 2.3093%, 1.0600%, and 0.8441%, respectively. The conclusion is partly consistent with reference [5]. The test for nonlinearity fails to hold relevance in the agglomerations of Chengdu-Chongqing and those in Yangtze River middle reaches. In Guangdong-Hong Kong-Macao Greater Bay Area, it appears that the impact of the digital economy on carbon intensity follows a "U-shaped" pattern, whereas in four urban agglomerations - Beijing-Tianjin-Hebei, Yangtze River Delta, Central Plains, and Guanzhong Plain - it demonstrates an "inverted U-shape".

The effectiveness of each urban agglomeration varies. The possible reason is that, firstly, the Chengdu-Chongqing agglomeration is mostly located in mountainous areas, and the low level of urbanization also poses a considerable threshold for the layout of digital infrastructure. Moreover, the service industry mainly composed of broadcasting and television, cultural tourism, etc. is in the development stage, and the digital transformation in industries such as industry and intelligent manufacturing is at an early stage. The energy consumption has not been alleviated yet, and the carbon emission intensity is relatively high. Secondly, the Beijing-Tianjin-Hebei agglomeration has strong advantages in the development of digital industries in fields such as education, media, government affairs, and healthcare, and these industries have low energy dependence. Therefore, there is a significant negative correlation between the digital economy and carbon emission intensity. Thirdly, the Yangtze River Delta agglomeration is actively developing in areas such as digital culture, digital finance, and e-commerce. The "home economy", "online life", and "cloud economy" have become the main choices for young people. The breakthrough innovation and business format innovation have also reduced dependence on energy. Fourthly, the Guangdong-Hong Kong-Macao Greater Bay Area has market and policy advantages in building a "green digital bay area". In recent years, Guangdong's digital economy scale, industrial scale, Internet enterprises are in the forefront of China, and have made steady progress. The prosperous digital economy makes the promotion of green production, low-carbon consumption, clean living, green finance, energy management and other activities more efficient, which helps to promote the modernization of national governance, achieve deep integration of digital economy and green development, and reduce carbon emission intensity. Fifthly, as the largest agglomeration in terms of area, the Yangtze River middle reaches agglomeration is in a period of intense competition for the development of the digital economy in various regions. As an emerging core area for the development of the digital economy, it can drive the digital economy to radiate from coastal areas to inland areas. Sixth, the digital economy development of the Central Plains agglomeration is in its early stages and has achieved results in various fields. The population advantage of the Central Plains agglomeration has enormous market potential. Through the construction of digital industrial parks, a leading industry with intelligent manufacturing, industrial Internet, digital finance, as the core will be formed. Relying on digital technology diffusion, regional industrial agglomeration and spillover will be promoted to upgrade of manufacturing industries in various regions. Utilize the digital economy through multiple channels to reduce carbon emission intensity. Seventh, the cities in the Guanzhong Plain agglomeration are mainly located in the west. Most of the resource-based cities in the Guanzhong Plain have path dependence in the development model of resource consumption driven economy. The lifeline of urban economy mainly comes from resource consuming industries, and economic development is accompanied by increasingly severe resource consumption and environmental pollution. Therefore, carbon emissions remain high, and the effect of the digital economy on reducing carbon emission intensity is not significant.

Based on the research findings, the following countermeasures and suggestions are proposed. Firstly, computing power, positioned as the crucial productivity for valuable national development resources, will drive the extensive proliferation of industrial internet convergence applications into instrumental industries of the nation’s economy. The marriage of “digital data from the east and computation from the west” with the industrial internet assures a steadfast fundamental safeguard for data elements to facilitate industrial digitization, subsequently attaining a reduction in carbon emissions. Secondly, it’s vital to fully capitalize on the influence of Internet infrastructure on data elements, enhance the level of cohesion and compatibility amongst digital elements across regions, and ensure the spillover and fluidity of capital, technology, labor, and other production factors cross-regionally. This will serve as a fundamental guarantee for the stimulation of green innovation vitality within enterprises. Thirdly, it is imperative to vigorously foster the overflow and diffusion of market information and technological knowledge from Yangtze River Delta urban agglomeration in the east to Central Plains urban conglomeration, Guanzhong Plains urban amalgamation, and other regions in central and western areas. This will advocate for the aligned development of these regions and shared prosperity, thereby actualizing a reduction in carbon emissions across the urban agglomerations.

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