

Analysis of Carbon Emission Reduction Effect and Mechanism of Digital Economy: A Perspective to Protect Environment

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Abstract:

In recent years, digital technology has comprehensively empowered the economic and social system, which has undergone earth-shaking and far-reaching changes, and the digital economy has also shown good effects of energy conservation and emission reduction. In order to achieve environmental sustainability as soon as possible, this paper analyzes the theoretical mechanism and transmission process of the digital economy's impact on carbon emission from the perspectives of direct effects, indirect effects and spatial spillover effect. It takes 17 cities in Henan province as research objects to conduct an empirical analysis of their panel data from 2011 to 2019. The main findings are: (1) In the process of promoting the development of digital economy, Henan province indeed reduced carbon emissions on the whole; (2) The development of digital economy in Henan province ultimately reduced carbon emissions by promoting industrial structure upgrading and green technology innovation. (3) The carbon emission reduction effect of the digital economy in Henan province has obvious spatial spillover effect, which can reduce the carbon emissions in the surrounding areas; (4) The development of digital economy indeed increases carbon emissions in the early stage, which is an inevitable phenomenon. This paper not only provides a provincial perspective for systematically understanding the impact of digital economy on carbon emissions, but also provides theoretical foundation for promoting the comprehensive green transformation of economic and social development, actively and steadily promoting carbon neutrality.

Keywords: carbon emission reduction; digital economy; Henan province, effect analysis

INTRODUCTION

Global warming is a huge challenge for all human beings. The massive increase in carbon dioxide and other greenhouse gases emissions has caused global warming, climatic anomaly and sea level rising, which has brought a series of negative impacts on human production and life, economic and social development. As a responsible country and the world's largest CO₂ emitter, China has made active efforts to address global climate governance and made a solemn commitment at the UN General Assembly, setting forth the strategic goal of achieving carbon peak by 2030 and carbon neutrality by 2060 ("double carbon" goal). The 14th Five-Year Plan and the Outline of the Vision Goals for 2035 of China both pointed out that promoting green and low-carbon economic and social development is a key point to achieve sustainable and high-quality development. To be specific, the whole society need to coordinate industrial restructuring, pollution control, ecological protection, tackle climate change, and work together to reduce carbon and pollution, promote green growth, and give priority to ecology to protect environment. The pressure of carbon emission reduction has been elevated to an unprecedented level in our country. How to effectively reduce carbon emissions has become an urgent problem to be solved, thus to realize the goals of carbon peaking, carbon neutrality and environment-friendly society. Some scholars have found that China's carbon emissions show a rising trend in terms of time, and a stairway of high in the east and low in the west in terms of space [1,2]. Through empirical studies, many scholars found the implementation of environmental regulations [3], the improvement of innovation level [4,5], and the transformation and upgrading of industrial structure [6] are the powerful ways to reduce carbon emissions and protect environment.

In the context of sluggish economic growth in the world, the digital economy has played an important role in creating jobs, promoting innovation, stimulating consumption and driving investment through deepening integration with all sectors of society, and has become an emerging force to leverage a new round of high-speed economic development. So how to improve the quality and competitiveness of economic development with the help of the tide of digital economy has become an crucial topic of academic attention. In recent years, the digital economy has developed at an unprecedented speed, scope and deep influence, and it is becoming a key force in restructuring global factor resources, reshaping global economic structure and changing global competition. According to the White Paper on China's Digital Economy Development, China's digital economy achieved a new breakthrough in 2021, with the scale of digital economy reached 45.5 trillion yuan, and with a year-on-year nominal growth of 16.2%. At the same time, the digital economy is accounting for 39.8% of GDP, and plays a more stable and supportive role as a "stabilizer" and "accelerator" in the national economy. The 14th Five-Year Plan for the Development of Digital Economy set out the guiding ideology, basic principles, development goals, key tasks and safeguard measures for promoting the healthy development of digital economy during the period of the 14th Five-Year Plan.

More advantageous support for the "double carbon" goal lies in the fact that the digital economy has the special nature of environmental friendliness. The innovation of information technology caused by the digital economy provides a more efficient way of information exchange around the world, speeds up the transformation of economic structure. Digital economy can continuously improve the digitalization, networking and intellectualization level of economy and society. And by alleviating information asymmetry, promoting technological innovation, eliminating negative externalities [7], strengthening foreign investment introduction and control [8] and other factors, the digital economy not only reduces urban carbon dioxide emissions, but also significantly reduces industrial dust and wastewater emissions [9,10], which contributes to the reduction of urban carbon emissions [11], the improvement of total factor carbon productivity [12] and sustainable development, fully demonstrates the low-carbon governance capability of digital economy [12]. These characteristics coincide with the vision of "double carbon" goal, and also provides a new idea and feasible path for realizing green and low carbon development for China [13].

Then what is the current development level of digital economy in Henan Province, China? While promoting economic development, does the digital economy also provide new driving force for urban carbon emission reduction and environment-friendly society? If so, what is the impact mechanism of digital economy on carbon emissions reduction? Is there spatial heterogeneity effect in different cities? The results of these questions help to answer the theoretical mechanism and policy arrangement of realizing the "double carbon" goal in Henan Province.

THEORETICAL ANALYTICAL FRAMEWORK

Digital economy, as a new form of economic development, will not only provide new driving forces for economic and social development, but also exert certain influence on environmental protection and sustainable development [14-16]. This paper analyses the direct, indirect and spatial spillover effect of digital economy on ecological civilization from the perspective of reducing the carbon emission.

Direct Effect of Digital Economy On Carbon Emission Reduction

The direct effects of digital economy on carbon emission reduction mainly reflect in efficiency improvement, monitor and control, transformation of the lifestyle and consumption patterns, and so on [17,18]. Firstly, various organizations can improve transaction efficiency and alleviate information asymmetry by digital transformation. To be specific, the companies adopt advanced digital technology achievements to realize the cost reduction in all aspects, and the governments improve service efficiency through digital governance. These measurements can save a lot of human, material and other resources, and reduce carbon emissions to some extent, and also increase satisfaction. Secondly, the advanced digital technologies can monitor and control the carbon emissions of companies and some regions. The monitors of the carbon emissions collect and analyze the monitored and collected data to acquire the change and law of carbon emission data. Therefore, there are well-founded data to control the production process, implement of carbon reduction targets more accurate and better. Thirdly, the digital economy transforms the lifestyle and consumption patterns, and it also contributes to the carbon reduction targets. For example, the behaviors such as online payment, shopping, tourism and ticket purchasing save a lot of paper, decrease the use frequency of disposable products, and energy consumption due to transportation. Sharing economy based on digital technology, such as shared bikes, shared electric cars, second-hand shopping platforms, plays an important role in improving the use efficiency of commonly used products, saving resources and energy consumption, and reducing carbon emissions. Moreover, an increasing number of online classes and conferences in the current context, can save participants' round-trip transportation, catering, accommodation, etc., and also play a positive role in reducing carbon emissions. As an emerging and highly efficient retail method, live-streaming e-commerce has unique advantages such as intuitiveness, strong interaction, and no limits in time and region. Based on the internet and digital technology, on the one hand, it improves transaction efficiency, reduces retail costs, and greatly promotes the growth of sales volume and sales amount. On the other hand, it changes the consumption pattern of consumers and reduces carbon emissions, so as to stimulate green consumption. To sum up, digital economy affects the entire economic and social system in all aspects, as well as specific production and life styles, and ultimately reduces carbon emissions.

Indirect Effect of Digital Economy On Carbon Emission Reduction

The indirect effects of digital economy on carbon emission reduction mainly reflect in industrial structure optimization and green technology innovation [11,19-21]. For enterprises and individuals existing in the economic system, they will be affected by the subversion and influence of the overall industrial structure upgrading and green technology innovation brought by the form of digital economy [22]. It will not only improve the efficiency of the whole society, but also make up for the problems of environmental protection and ecological destruction as far as possible, especially the worldwide concern of carbon emission.

On the one hand, digital economy comprehensively transforms traditional industries, especially manufacturing industries with high resource consumption and high carbon emissions. The digital economy transforms traditional industries in the aspects of research and development, product design, process and technology, marketing and sales, supply chain management, personnel and financial management. While optimizing region industrial structure, digital economy can achieve the effects of reducing costs and improving transaction efficiency, thus reducing carbon dioxide emissions on the whole. On the other hand, digital economy, with its strong innovation and iteration, generates new industries, new business models and operation models, new processes and technologies, and promotes the rationalization and upgrading of regional industrial structure in an environmentally friendly and sustainable way. These new forms of business eliminate backward production capacity, optimizes traditional industries, and increases advanced production capacity, thus reduces carbon dioxide emissions on the whole [23].

In addition, the transformation of industrial structure and business model will fundamentally accelerate the transformation of residents' consumption concept and consumption mode, and further force a series of more convenient, digital, environmentally friendly production and life style. These approaches are also important in promoting green technology innovation in production and living, thus driving the reduction of carbon dioxide emissions [24]. The development and prosperity of digital economy needs a sequence of supporting software technology foundation and hardware infrastructure. These supporting facilities are the embodiment of innovation achievements, but also the progress of the overall level of science and technology. What the digital economy wants to achieve is a green and sustainable economic development, so the technological innovation of supporting facilities required by digital economy must be green, in line with the trend of the times, and conducive to reducing carbon dioxide emissions.

Spatial Spillover Effect of Digital Economy On Carbon Emission Reduction

Digital economy has advantages and characteristics such as rapid spread, high permeability and external economy. It can easily cross the restrictions of time and region, with a wide range of radiation, and each user gets relatively high utility. An innovative digital technology, aided by the Internet, spreads so fast that it benefits the surrounding region and even the world [25,26]. Therefore, while playing the direct and indirect effects of carbon emission reduction, the digital economy will also play a strong spatial spillover effect [27], which is mainly manifested in the following aspects.

First of all, the construction and updating of digital technology infrastructure, transmission and coverage of digital signals and other aspects, have spillover effects themselves, which can achieve a virtuous cycle of sharing technology, sharing cost, opportunity and risk with the surrounding areas. Secondly, the new industries, business models and operation models formed on the basis of digital technology can further form industrial parks and industrial clusters. And they will affect the surrounding areas to varying degrees in terms of increasing employment, upgrading industrial structure, and improving the gross regional product and resident income. For the large number of enterprises, they have complicated supply chains and value chains, and there is cooperation or competition with the surrounding region or even the whole world. Therefore, the carbon emission reduction effect obtained by their adoption of digital information technology is reflected in multiple processes and links, with obvious regional spillover effect. In addition, the digital governance carried out by the government with the latest information technology, can largely realize the use value of public data, implement the efficient governance of the city and promote the construction of smart city as soon as possible. As a consequence, the digital governance can improve the operation efficiency of public data, and reduce carbon emissions in the process of public affairs. At present, digital governance and smart city construction are entering the fast track of development, which will promote a larger scale of carbon emission reduction in the near future.

Negative Effect of Digital Economy On Carbon Emission

Through the evolution mode of digital industrialization and industrial digitization, digital economy continuously improves the level of digitalization, networking and intelligence of economic society. While effectively promoting high-quality urban development, it also shows certain environmental improvement effect. However, there are some studies indicate that the digital economy may also exacerbate regional imbalances in carbon emissions, increase carbon emissions from certain industries, and result in increasing the total emissions [28]. Weixiang [29] found the differences in the impact of digital economy on carbon emissions in different regions from the perspective of spatial effects. Digital economy can significantly reduce carbon emissions in eastern Chinese cities, but increase carbon emissions in central Chinese cities, while have no significant effect on western cities. Lujun et al. [30], Fei and Changle [8], Wei et al. [31] and other scholars have found that there is a nonlinear relationship between digital economy and carbon emissions. In addition, as a core component of the digital economy, the development and prosperity of information technology and related industries will lead to the growth of energy consumption and electricity consumption, thus increasing local carbon emissions [32]. At the same time, the improvement of residents' living standards brought by digital economy will increase residents' demand for energy consumption, thus increasing carbon emissions [33].

These phenomena such as mobile payment, delivering food and packages, live streaming and various forms of media, new energy-related products, and a growing urban population, are consuming resources and energy and releasing waste into nature all the time, and even more.

EMPIRICAL MODEL SPECIFICATION

Model Building

On the basis of the above theoretical discussion of digital economy and carbon emission, this paper constructs panel data model, mediation effect model and spatial econometric model respectively to empirically test the relationship between digital economy and carbon emission in Henan Province, and precisely analyze the direct effect, indirect effect and spatial spillover effect of digital economy development on carbon emission reduction.

The panel data model is shown below:

$$CE_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_2 Dig2_{it} + X_{it}\beta + \delta_t + \eta_i + \varepsilon_{it} \quad (1)$$

Where, i represents the individual unit, namely 17 cities in Henan Province, t represents time. X_{it} is the control variable, and δ_t represents the non-observed effect of time, which mainly reflects the influence over time. The η_i represents the non-observed effect in different regions, which mainly reflects the persistent differences of model difference, preference difference, regulation difference, etc. The ε_{it} is a random error term.

The mediation effect model is shown below:

$$CE_{it} = \pi_0 + \pi_1 Dig_{it} + \pi_2 Dig2_{it} + X_{it}\beta + \sigma1_{it} \quad (2)$$

$$Ind_{it} = \theta_0 + \theta_1 Dig_{it} + \theta_2 Dig2_{it} + X_{it}\beta + \sigma2_{it} \quad (3)$$

$$GTI_{it} = \rho_0 + \rho_1 Dig_{it} + \rho_2 Dig2_{it} + X_{it}\beta + \sigma3_{it} \quad (4)$$

$$CE_{it} = \pi_0 + \pi_1 Dig_{it} + \pi_2 Dig2_{it} + \varphi_1 Ind_{it} + X_{it}\beta + \sigma4_{it} \quad (5)$$

$$CE_{it} = \pi_0 + \pi_1 Dig_{it} + \pi_2 Dig2_{it} + \varphi_2 GTI_{it} + X_{it}\beta + \sigma5_{it} \quad (6)$$

Economic entities in geographical proximity have more opportunities for exchange and cooperation, and the utilization of data elements can be improved by sharing open data, thus enhancing the spatial spillover effect of regional low-carbon development. In this paper, a Spatial Dubin Model is established based on spatial proximity matrix. When there is a common boundary between two regions, 1 is used to indicate spatial correlation between them; otherwise, 0 is used. The Spatial Durbin Model combines the characteristics of spatial error model and spatial autocorrelation model, and introduces the explained variables and the spatial lag term of the explanatory variable into the model.

$$Y = \rho WY + X\beta + \varphi WX + \varepsilon, \varepsilon \sim N(0, \delta^2 I_n) \quad (7)$$

Where, ρ is spatial autoregressive coefficients, W is spatial weight matrix, WY is the spatial lag term of the explained variables, WX is the spatial lag term of the explanatory variables and the control variables. β is the regression coefficient of explained variable, ε is a random error term obeying the normal distribution.

Variable Definition

The explained variables of this paper are the carbon emissions (CE) and per capita carbon emissions (PCE) of 17 cities in Henan Province, and the explanatory variable is the comprehensive index of development level of digital economy (Dig). Considering the availability of data, this paper establishes an evaluation system with five indicators, and uses entropy weight method to

calculate the comprehensive index. The five indicators respectively are the number of Internet users among 100 people, the proportion of information transmission, software and information technology service workers in urban employment, the total number of telecom services per capita, the number of mobile phone users among 100 people, and digital financial inclusion index. In addition, in order to test the nonlinear or more complex relationship (inverted U-shaped relation) between digital economy and carbon emission, the explanatory variable in this paper also includes the square of the comprehensive index of development level of digital economy (Dig2).

The intermediate variable of this paper is the upgrading of industrial structure (Ind), which is expressed by the ratio of output value of tertiary industry to secondary industry. As we all know, the output value and proportion of the tertiary industry reflects the degree of cleanliness and digitalization of the industrial structure, as well as the sustainability in the future. Another intermediate variable is the green technology innovation level (GTI), which is represented by the number of green invention patent applications, including green product innovation and green process innovation.

Table 1. Variable and variable definition in the paper

Variable	Symbol	Unit	Definition
Carbon emissions	CE	million tons	The total amount of carbon emissions from energy consumption in a given region.
Per capita carbon emissions	PCE	tons	The per capita carbon emissions in a given region.
Digital economy	Dig	/	Comprehensive index of development level of digital economy calculated by entropy weight method.
Digital economy squared	Dig2	/	The squared comprehensive index.
Upgrading of industrial structure	Ind	/	Ratio of output value of tertiary industry to secondary industry.
Green technology innovation	GTI	unit	Number of green invention patent applications.
Level of economic development	PGDP	yuan	The per capita GDP in a given region.
Urbanization rate	Urban	/	The proportion of the resident population of a town in the total resident population of a given region.
Foreign direct investment	FDI	/	Ratio of foreign direct investment to GDP.
Financial development level	Fin	/	Ratio of deposits and loans balance in financial institutions to GDP.
Energy consumption	Ene	kwh	Per capita electricity consumption in a given region.
Government support	Gov	/	Ratio of general public budget expenditure to GDP.

There are 6 control variables in this paper (Table 1). GDP has extensive and far-reaching influence on all aspects of economic and social system, and will also become a interfering factor of carbon emission reduction in many links. Therefore, per capita GDP (PGDP) is used in this paper to control the possible nonlinear influence of economic development level on carbon emission. The second is the urbanization rate (Urban), which is the proportion of the resident population of a town in the total resident population of a given region. Areas with a relatively high urbanization rate have a higher quality of life, and energy consumption and waste emissions tend to be higher than average. The ratio of foreign direct investment to GDP is used to measure the level of regional foreign direct investment (FDI). Foreign investment may introduce enterprises with high energy consumption and more pollution to the environment. It may also generate technology spillover benefits, improve energy efficiency and reduce transaction costs, so as to reduce pollution and discharge. Financial development level (Fin), is calculated by the ratio of deposits and loans balance in financial institutions to GDP. A good financial environment can provide a impressive financial services to the government, enterprises and individuals, so as to promote the research and development and utilization of green innovative technologies, and bring positive impacts to the environment. Energy consumption (Ene) directly leads to the increase of carbon emissions. Controlling the variable of energy consumption can analyze the relationship between digital economy and carbon emissions more accurately and clearly. The last control variable is government support (Gov), which is measured by ratio of general public budget expenditure to GDP. Environmental regulation supported by the government plays a significant role in reducing carbon emissions, so it is taken as a control variable.

Data Sources

The data in this paper covers 17 cities in Henan Province, including Zhengzhou, Luoyang, Kaifeng, Shangqiu, Jiaozuo, Jiyuan, Xinxiang, Anyang, Hebi, Puyang, Zhoukou, Luohe, Xuchang, Zhumadian, Pingdingshan, Nanyang, Xinyang and Sanmenxia. After 2011, China officially began to implement the comprehensive construction of Internet, and applied the Internet to the construction of related industries and urban infrastructure. In 2012, the Broadband China Project was implemented, and the technological innovation and industrial development of cloud computing was accelerated. At the same time, the number of

netizens using mobile phones to access the Internet exceeded that of desktop computers. Since then, the digital economy has grown even more. After 2020, although the epidemic has accelerated the development and prosperity of the digital economy, it is an abnormal state. Various economic data and carbon emissions cannot reflect the real situation of economic and social system. Therefore, the time range in this study is 2011-2019. Carbon emissions are from CEADs database [34,35], and the digital financial inclusion index is from the Institute of Digital Finance Peking University and the Ant Technology Group Research Institute [36]. Other data in this paper are from regional statistical yearbooks, annual statistical reports, industry reports, other relevant literature, and the missing data are also processed correspondingly.

RESULTS AND DISCUSSION

The descriptive statistics of all variables in this paper are presented in Table 2, the regression results of the basic panel model and the intermediary model are presented in Table 3, and the regression results of the Spatial Durbin Model are presented in Table 4.

Baseline Regression Analysis

Table 2. The descriptive statistics of all variables

Variable	Capacity	Average	SD	Minimum	Maximum
CE	153	3.376	0.66	1.768	4.67
Dig	153	0.266	0.158	0.055	0.859
Dig2	153	0.096	0.143	0.003	0.737
Ind	153	0.786	0.309	0.061	1.56
GTI	153	3.803	0.895	1.099	5.011
PGDP	153	10.565	0.376	9.664	11.636
Urban	153	47.489	9.147	31.13	77.3
FDI	153	0.039	0.059	0.008	0.358
Fin	153	2.134	1.674	1.018	9.588
Ene	153	7.957	0.518	6.506	8.82
Gov	153	0.16	0.049	0.037	0.343

In this paper, the development level of digital economy is included in the regression model, other variables that may affect carbon emissions, and as well as time and individual effects are controlled. It is found that digital economy has a negative impact on carbon emissions, but it fails the significance test. The square of the digital economy is added to the model to investigate whether the digital economy affects carbon emissions in a non-linear relationship. The results show that the coefficient of the primary term of the digital economy is positive and passes the significance test of 10%, while the coefficient of the secondary term of the digital economy is negative and passes the significance test of 5%. This phenomenon fully indicates that there may be a significant inverted U-shaped relationship between the digital economy and carbon emissions, which is consistent with the previous theoretical analysis and the results of other scholars. In the early stage of the digital economy, on the one hand, more infrastructure and energy input are needed in the process of digital industrialization, industrial digitization and digital governance. On the other hand, the improvement of living standards and scientific and technological research form the superimposed impact of energy and resources input, which generally improves the carbon emission level of production and life. With the continuous development and maturity of the digital economy, various inputs in the early stage gradually have positive effects. The industrial structure has achieved green transformation and upgrading, energy efficiency and green technology research and development efficiency have been improved, and the application of green technology innovation has continued to energize energy conservation and emission reduction, thus significantly reducing the level of carbon emissions.

As for the control variables in columns 1 and 2 of Table 3, their effects on carbon emissions are basically similar. The coefficient of per capita GDP is positive and passes the significance test of 10%. This indicates that the higher the living standard of residents, the more energy will be consumed, and the consumption demand will increase, the carbon emissions will eventually be more. The coefficient of foreign direct investment in Henan province is negative, which has a positive effect on carbon emission reduction. It indicates that Henan province is cautious in its attitude towards foreign investment, not only focusing on its profitability, but also giving full consideration to its production business, research and innovation and performance in environmental protection. At present, urbanization rate and financial development level have a weak impact on carbon emissions, while energy consumption and government support both have a significant impact on carbon emissions. The former directly increases carbon emissions, while the latter reduces carbon emissions, which is consistent with reality. The government has

introduced a series of policies and measures for energy conservation and emission reduction, especially the strategic plan for the double-carbon target proposed in 2020. Whether it is publicity, advocacy, or mandatory enforcement measures, it shows a clear tendency to reduce carbon emissions, and will effectively promote carbon emission reduction.

Table 3. The regression results of the models

Variable	(1) CE	(2) CE	(3) Ind	(4) CE	(5) GTI	(6) CE
Dig	-0.0981 (0.361)	0.803* (1.502)	-0.239** (-0.513)	0.773* (1.446)	-2.161** (-0.992)	0.754* (1.590)
Dig2		-1.537** (-1.527)	0.127** (0.145)	-1.520** (-1.514)	1.254** (0.306)	-1.466** (-1.556)
Ind				-0.128** (-1.223)		
GTI						-0.0233** (-1.040)
PGDP	0.259* (1.473)	0.264* (1.508)	-0.332** (-2.182)	0.222** (1.243)	0.275* (0.385)	0.271** (1.544)
Urban	-0.0207 (-0.629)	-0.0119 (-0.358)	0.0496* (1.718)	-0.00553 (-0.165)	0.290** (2.146)	-0.0187 (-0.551)
FDI	-0.539* (-0.690)	-0.491* (-0.632)	1.003 (1.482)	-0.363** (-0.463)	-0.503 (-0.159)	-0.503** (-0.647)
Fin	0.00338 (0.117)	0.00131 (0.0452)	0.0529** (2.106)	0.00809 (0.275)	0.0655** (0.556)	0.00283 (0.0980)
Ene	0.0998*** (0.547)	0.131*** (0.718)	-0.177** (-1.114)	0.108** (0.592)	-0.283** (-0.381)	0.124** (0.681)
Gov	-0.00511** (-0.00785)	-0.0282** (-0.0435)	0.764* (1.356)	-0.126* (-0.193)	1.342*** (0.509)	-0.00313* (-0.00483)
Constant	0.813** (0.378)	0.0617*** (0.0281)	3.369* (1.762)	0.493 (0.222)	1.15* (1.804)	0.438** (0.197)
time	Yes	Yes	Yes	Yes	Yes	Yes
ind	Yes	Yes	Yes	Yes	Yes	Yes
Observations	153	153	153	153	153	153
R-squared	0.964	0.965	0.878	0.965	0.681	0.965

Mediation Mechanism Analysis

Next, the intermediate effect model is used to test whether there are mediating effects between industrial structure upgrading, green technology innovation and digital economy influencing carbon emissions, and the mediation mechanism is analyzed. The digital economy has a significant impact on the industrial structure upgrading at the significant level of 5%, in which the coefficient of the primary term of digital economy is negative and the coefficient of the secondary term is positive. It indicates that the digital economy first inhibits and then promotes the industrial structure upgrading, showing a U-shaped relationship (column 3 of Table 3). As a new form of economic development, digital industrialization, industrial digitization and digital governance themselves will optimize the industrial structure, and expand the proportion of the tertiary industry. However, in the early stage of digital economy, many industries are still in a wait-and-see state, focuses on the investment of traditional production factors, and also gradually strengthens the construction of digital infrastructure. The penetration and application of digital economy in all walks are not strong, and the effect to optimize the industrial structure is not strong, or even inhibiting. The digital economy and the upgrading of industrial structure are integrated into the model to investigate the impact on carbon emissions (column 4 of Table 3). The impact of digital economy on carbon emissions still presents a significant inverted U-shaped relationship, and the regression coefficient of the upgrading of industrial structure on carbon emissions is significantly negative at the significance level of 5%. This indicates that the upgrading of industrial structure has a significant inhibitory effect on carbon emissions. With the transformation and upgrading of industrial structure, carbon emissions will gradually decrease. In addition, after adding the variable of upgrading of industrial structure, the regression coefficient of digital economy on carbon emissions has decreased, whether it is the primary term or the square term, and the upgrading of industrial structure has played a part of the intermediary role.

At the same time, the digital economy has a significant impact on green technology innovation level at the significant level of 5%, where the coefficient of the primary term of digital economy is negative, and the coefficient of the secondary term is positive. It indicates that the digital economy also has a U-shaped relationship on green technology innovation level (column 5 of Table 3). Technological innovation requires investment from many aspects such as funds, equipment, experimental sites, talents and time, and the resulting scientific research results also have a time lag. The more basic and strategic technological innovation, the longer the scientific research cycle is required and the more elements are invested. At the early stage of the digital economy, a lot of resources need to be invested, which occupies a part of the resources of scientific and technological innovation. Therefore, the initial stage of the digital economy also has a certain inhibitory effect on the green technology innovation level. The development process of digital economy is itself the promotion process of green technology innovation, so with the gradual development of digital economy, the level of green technology innovation will continue to improve. Then, digital economy and green technology innovation level are integrated into the model to investigate the impact on carbon emissions (Column 6 of Table 3). The impact of digital economy on carbon emissions is still a significant inverted U-shaped relationship, and the regression coefficient of green technology innovation level on carbon emissions is significantly negative at the significance level of 5%. It indicates that green technology innovation has a significant inhibition effect on carbon emissions. With the increasingly strong atmosphere of innovation in society, the improvement of green technology innovation level will promote the gradual reduction of carbon emissions. In addition, after the variable of green technology innovation level is added, the regression coefficient of digital economy on carbon emissions decreases. Whether it is primary term or square term, green technology innovation level also plays a part of the intermediary role, and the intermediary effect is stronger than that of industrial structure upgrading. To sum up, the digital economy will indirectly exert significant inhibition on the carbon emissions of Henan province by influencing the industrial structure and green technology innovation. However, the overall level of digital economy development in Henan province is relatively low, and it is still in the stage of construction and promotion. Coupling with the realistic contradiction of unbalanced development between regions and the existence of hysteresis effect, the digital economy plays a limited role in indirectly reducing carbon emissions by improving the advanced industrial structure and the level of green technology innovation.

Spatial Effect Analysis

This paper uses the spatial Dubin model to empirically test and analyze the spatial spillover effects of digital economy on carbon emissions in Henan province (Table 4). The results in column 1 show that the coefficient of the primary term of digital economy is positive, and the coefficient of the secondary term is negative, and both are significant at the significance level of 5%. The impact of the digital economy on carbon emissions is still a significant inverted U-shaped relationship. The second column shows that the regression coefficient of the spatial lag term of the digital economy also shows a significant inverted U-shaped feature. At present, the development of the digital economy among cities in Henan province has a relatively obvious impact on the carbon emission reduction of neighboring cities. Columns 3-5 reflect the direct, indirect and total effects of each explanatory variable on carbon emissions, respectively. Only the square term of the direct effect of the digital economy on carbon emissions passes the significance test of 10%, indicating that the non-linear impact of the digital economy on carbon emissions in this region is small. The indirect and total effects of the primary and square terms of the digital economy are significant at the 5% significance level, indicating that the digital economy has an obvious nonlinear relationship on carbon emissions in the surrounding areas and in general. The spatial spillover effect is significant.

Among the other variables, the level of economic development has a significant positive spatial spillover effect on carbon emissions. The higher the level of economic development in a region, the more energy consumption will bring more carbon emissions to the region and neighboring regions. Government support has a significant negative indirect and total effect on carbon emissions, and it indicates that environmental regulations of local governments also have a positive impact on neighboring regional carbon emission reduction. Energy consumption has a significant spatial spillover effect on carbon emissions. Compared with indirect effect and total effect, energy consumption has a more significant increase on local carbon emissions. In the indirect effect, FDI has a positive impact on carbon emissions, which may increase carbon emissions in neighboring regions. The possible reason is that regions with high economic development level have a higher proportion of FDI, which has a more obvious driving effect on the development of surrounding regions, resulting in an increase in carbon emissions.

Table 4. The regression results of SDM

Variable	(1)	(2)	(3)	(4)	(5)
	CE	spatial lag term	direct effect	indirect effect	total effect
Dig	0.410** (0.547)	2.472** (1.175)	0.187* (0.572)	1.895** (0.946)	2.082** (1.015)
Dig2	-0.413** (0.921)	-3.969** (1.780)	-0.0356 (0.969)	-3.114** (1.482)	-3.149** (1.563)
PGDP	0.143* (0.161)	0.0564 (0.304)	0.163* (0.164)	0.013** (0.257)	0.15** (0.241)
Urban	0.0138 (0.0166)	-0.0352* (0.0211)	0.0172 (0.0177)	-0.0329 (0.0204)	-0.0157 (0.0109)
FDI	-0.771 (0.719)	2.459* (1.444)	-1.002 (0.758)	2.272** (1.22)	1.269 (1.136)
Fin	0.0228 (0.0258)	0.00416 (0.0455)	0.0228 (0.0275)	-0.00508 (0.0389)	0.0177* (0.0355)
Ene	0.349** (0.182)	-0.138 (0.259)	0.366** (0.203)	0.224* (0.254)	0.141** (0.177)
Gov	-0.652** (0.582)	-2.106* (1.107)	-0.492 (0.551)	-1.445* (0.846)	-1.937** (0.886)
rho	-0.364*** (0.116)				
sigma2_e	0.0164*** (0.00204)				
Observations	153	153	153	153	153
R-squared	0.461	0.461	0.461	0.461	0.461
Number of id	17	17	17	17	17

CONCLUSIONS

This paper analyzes the theoretical mechanism and transmission process of the impact of digital economy on carbon emissions from the perspectives of direct effect, indirect effect and spatial spillover effect. It takes 17 cities in Henan province as research objects to conduct empirical analysis of their panel data from 2011 to 2019. The results of the study are as follows: (1) In the process of promoting the development of the internet and digital economy, the 17 cities in Henan province have indeed reduced carbon emissions on the whole. (2) The development of digital economy in Henan province ultimately reduced carbon emissions by promoting industrial structure upgrading and green technology innovation. (3) The carbon emission reduction effect of Henan's digital economy has obvious spatial spillover effect, which can reduce carbon emissions in surrounding areas, bring digital development dividends, and promote common prosperity. (4) The development of the digital economy indeed increases the carbon emissions in the early stage, and also leads to unbalanced development and increases the carbon emissions of some industries, which is an inevitable phenomenon. Digital transformation is a long-term process that requires the joint efforts of government sectors, enterprises and citizens to constantly innovate and adapt to changing technologies and needs. For example, change cognition, create a good business environment, accelerate the construction of digital governance system, build a platform for scientific and technological innovations, and advocate a green and low-carbon lifestyle, are the keys to be an environment-friendly society.

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