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Will researching digital technology really empower green development?

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ABSTRACT

The information industry has become a "new engine" driving the growth of the world economy. However, there are many controversies about whether digital technology can reduce the intensity of carbon emissions. Based on OECD data, KPWW method and multiple panel regression, this paper explores the impact and mechanism of digital technology innovation and technology spillover to the domestic carbon emission intensity. Through impulse response analysis and variance decomposition, the comprehensive impact of digital technology on carbon intensity is clarified. This paper concludes that technology innovation in the information industry will increase the intensity of carbon emissions, while cross-industry technology spillovers are persistent for reducing the intensity of domestic carbon emissions. Since the emission reduction effect of technology spillover is greater than the emission increase effect of technology innovation, the digital technology would empower domestic green development. Increasing the proportion of non-fossil energy use and optimizing the industrial structure are effective mechanisms for digital technology innovation to reduce carbon emission intensity.

1. Introduction

The information industry[1] has become a "new engine" driving the growth of the world economy in the information revolution era, occupying an important position in the global economic development agenda [1]. In recent years, the development and expansion of emerging digital technology such as blockchain technology, 3D printing technology, Internet of Things, 5G, cloud computing, automation and robotics, artificial intelligence and data analysis, has enabled more and more value chains to be digitally connected. According to data from the China Academy of Information and Communications Technology [2], the total digital economy of the G20 countries reached $26.17 trillion in 2017, an increase of 8.64% from 2016, significantly ahead of the Gross Domestic Product (GDP) growth rate over the same period. The emergence and popularization of information industry is commonly deemed societally and economically [3]. However, a general consensus has yet to be reached on the environmental impact of the development of the information industry. Some research argues that information industry would improve the environment through cross-industry technology spillover changing the industrial structure from manufacturing to services and technology empowerment thereby changing the energy consumption structure [4–6]. For instance, during the period of rapid development of China's information industry, China's energy consumption structure has been significantly optimized [7].[2] On the other hand, the total carbon emissions of the world information industry itself stabilized at 180 million tons after reaching its peak, which has not been reduced with the technology innovation of the information industry [8]. Therefore, some scholars believe that the development of information industry would not reduce carbon emissions after concerns about the environmental consequences caused by the manufacturing, and operation and logistics of the information industry [9–11]. To clarify the impact of information industry development on the environment, it is necessary to explain the reasons for the increasing carbon emissions and the path to reduce carbon emissions of the information industry.

Cross-industry emission reduction through technology spillover happens to be an important path for energy conservation and emission

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[1] The OECD first put forward the concept of information industry, which includes hardware facilities, digital goods and digital services that can ensure the smooth progress of digital transactions. This paper draws on the OECD classification method and defines the (1) computer, electronic and optical products, (2) publishing, audiovisual and broadcasting activities, (3) telecommunications and (4) IT and other information services as the information industry.

[2] In 2019, the proportion of China's fossil energy consumption decreased by 10.8% compared with 2012. The proportion of clean energy consumption continues to rise, which accounted for 23.4% in 2019, an increase of 5.6% from 2012.

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reduction in information industry. Prajogo & Olhager [12] argue that the information industry has significantly reduced the carbon emission intensity of the logistics industry through technologies such as route optimization, capacity allocation and the Internet of Things. Yadegaridehkordi et al. [13]; Hilty et al. [14] and Spinuzzi [15] studied the impact of smart home systems, eco-friendly hotel and remote office systems on reducing carbon emissions in the water supply and heating industries. Xu & Li [16] analyzes the carbon emission reduction effects of industrial Internet technology applied to traditional industries. After installing sensors and chips in traditional manufacturing machines, with the help of 5G technology, the firms can control and deploy the work of each machine at any time with the best and fastest choice. At the same time, with the help of big data and machine learning, data collection and analysis would lead to more efficient production methods and continuously reduce carbon emission intensity. In summary, the cross-industry emission reduction path of technology spillover in the information industry can be summarized in the following five aspects: (1) production process simulation; (2) intelligent design and operation of products and services; (3) smart logistics and distribution; (4) big data matches buyers and sellers; (5) telecommuting.

The above research conclusions provide important guidance for analyzing the impact of digital technology innovation on the environment, but the relevant research is mainly based on case studies and statistical analysis. (1) The positive and negative effects of technology innovation and technology spillover in the information industry on the carbon emission intensity still need to be verified by empirical analysis. (2) What's more, whether the cross-industry emission reduction effect of digital technology spillover can make up for the negative impact of the information industry scale expansion on the environment is also a key issue in judging whether information industry is an environmentally friendly industry. (3) Lastly, it remains to be clarified whether the situations of emerging economies as a "pollution haven" of developed economies can be eased after the global value chains accelerate the international technology spillover of the information industry. In order to explore the above-mentioned problems, (1) this paper puts the direct environmental effects of digital technology innovation and the indirect environmental effects of digital technology empowering traditional industries and foreign industries in a unified analysis framework when analyzing the impact of digital technology innovation on the environment. (2) Using the impulse response model to quantify and compare the direct and indirect effects of technology innovation in the information industry. Then, the direct effects and indirect effects are combined to confirm the comprehensive environmental impact of technology innovation in the information industry. (3) This paper identifies and constructs the influence mechanism of the digital technology to empower the domestic green development, and further clarifies the persistent path of indirect effects to achieve energy saving and emission reduction for OECD countries and non-OECD economies.

The remainder of this paper is organized as follows: in section 2, we review the relevant literature on the relationships of digital technology innovation, technology spillover and carbon emission intensity for formulating testable hypotheses. Section 3 describes the concept and measurement of green development, digital technology innovation, technology spillover and econometric model. Section 4 presents the basic model and influence mechanism of the direct and indirect impact of digital technology innovation on the environment. Section 5 presents the combined effects of direct and indirect effects through impulse response. Further analysis through robustness test to discuss whether information industry cross-border and cross-industry technology spillover are time persistent for helping developing countries reduce emissions.

2. Literature review and hypothetical formulation

2.1. The direct effects of digital technology innovation on the carbon emissions

The relationship between digital technology innovation and carbon emissions has attracted significant attention ever since Roberts [17]. Since digital technology represents the future development direction of science and industry, its role in reducing carbon emissions is highly expected. With the emergence of corresponding statistical indicators and quantitative analysis, the role of digital technology in green development has begun to be questioned [18]. It is possible for a country to be smart but not sustainable and vice versa [19].

Some studies believe that the absorptive capacity of firms directly determines innovation performance [20]. Therefore, insufficient absorption capacity for digital technology innovation and insufficient use of green technologies are considered to be the reasons why digital technology innovation in developing countries has failed to reduce carbon emissions [21–23]. Altinoz ta al. [24] suggest that the internet usage and fixed telephone subscriptions have a positive impact on environmental pollution in the top 10 emerging markets, for instance, Mexico, India, Brazil and Russia. When the research object becomes nine members from the Association of Southeast Asia Nations (ASEAN), digital technology still shows significant to highly significant positive effects on carbon emissions [25]. After investigating the effect of blockchain technology in Malaysian companies, Fernando et al. [26] concluded that blockchain technology cannot significantly reduce carbon emissions.

With the emergence of research focusing on the relationship between digital technology innovation and carbon emissions in developed countries, it suggests that digital technology innovation is not environmentally friendly in both developing and developed countries (Arshad et., al, 2020). Using pooled mean group (PMG), Raheem et al. [27] found that the digital technology has a positive effect on carbon emissions for the G7 countries. Park et al. [28] uses European Union (EU) panel data for the period 2001–2014 to indicate a positive significant relationship between Internet usage and carbon emissions. Some studies believe the failure to consider the digital technology related emissions abatement potential to reduce emissions in other sectors, such as power, energy, agricultural, transport and service sectors, is the main reason why the above studies have concluded that digital technology innovation cannot reduce carbon emissions [3,29,30].

In summary, if the cross-industry and international effects of digital technology innovation are not considered, information industry innovation will have a positive impact on the domestic carbon emissions. Whether this country belongs to mature economies such as the G7 group, the Organisation for Economic Co-operation and Development (OECD), or emerging economies under the Belt and Road Initiative (OBOR), ASEAN, the following hypothesis is formed:

H1. The national carbon emission intensity is positively influenced by the technology innovation of the information industry itself.

2.2. The indirect effects of digital technology innovation on carbon emissions

The current studies introduces the environmental Kuznets curve (EKC) when exploring the long-term relationship among GDP, carbon emissions and digital technology [31–35]. The gradual realization cross-industry and cross-border spillover of digital technology innovation is considered to explain the decline of the inverted U curve from the apex [36,37]. A survey of this literature reveals two research strands: cross-industry digital technology spillover and cross-border technology spillover.

In terms of cross-industry digital technology spillover, Mulder et al. [38] shows that the introduction of digital technology plays a potentially important role on green development across 23 services sectors in 18 OECD countries from the years 1980–2005. When digital technology spills over to the agricultural sector, manufacturing sector and housing construction sector, it can also be propitious to eliminate the level of carbon emissions [39–41]. The analysis of specific application cases of digital technology in various industries shows that digital technology decreases the level of carbon emissions by introducing smart electrical grids, digital transportation system, smart cities and efficient use of energy [42–45].

The effects of "learning by exporting" from exporting to firms' absorptive capacity via R&D collaboration is explored in the research [20,46]. Another strand of literature advocates relaxing trade barriers to promote the flow of information industry products across borders after discovering the carbon emission reduction effects of international digital technology spillover [36,37,47]. However, emerging economies should be alert to the Pollution Haven Hypothesis (PHH) while introducing digital technology, which emphasizes the easy connectivity and ample business opportunities. These can enable developed countries to transfer their dirty technologies to developing countries with relaxed environmental regulation [48–50]. Integrating the performance of digital technology in cross-industry spillover and cross-border spillover, this paper proposed the following hypothesis:

H2. The cross-border and cross-industry technology spillovers negatively affects the domestic carbon emission intensity.

2.3. The comprehensive impact of digital technology innovation on the domestic carbon emission intensity

Since the direct and indirect carbon emission effects of digital technology innovation are not the same, the relevant studies yielded different results to the comprehensive impact of digital technology on carbon emission intensity. Both Nguyen et al. [51] and Faisal et al. [52] use the Fully Modified OLS (FMOLS) method to investigate the long run impact of digital technology innovation on carbon emission intensity. Nguyen et al. [51] concludes that the digital technology innovation is a positive driving factor of carbon emissions in selected G-20 countries, while Faisal et al. [52] implies that pollution declines after attaining a threshold point as the digital technology innovation increases.

The second strand studies employ the life cycle analyses (LCAs) to explore the direct and higher order impacts of digital technology innovation on carbon emissions. Malmodin & Lundén [53]; Pohl et al. [54] and Court & Sorrell [55] indicate that (1) carbon footprints of information industry are significantly smaller than previously forecasted; (2) the digital technology has delivered significant carbon reduction effect and is likely to do so in the future.

The third strand of literature uses the Autoregressive Distributive Lag (ARDL) method to suggest that the long-term relationship between digital technology innovation and carbon emission intensity is not significant. Salahuddin et al. [56] indicate no significant long-term relationship between Internet use and carbon emissions by using ARDL and macro data for Australia. Amri [32] also shows an insignificant impact of digital technology on carbon emissions as a measure of pollution with ARDL and Tunisia data. Salahuddin et al. [57] incorporated PMG method into an ARDL model when measuring the effects of Internet usage on carbon emissions in OECD countries. The coefficient is very small and no causality exists between Internet usage and carbon emissions.

In view of the huge differences in the above results, it is a challenging task to accurately measure the net effect of digital technology innovation and technology spillover on carbon emission intensity. This work has profound meaning for the direction of environmental policy and the development of information industry [58–62]. In line with the previous empirical findings, we test the following hypothesis:

H3. The comprehensive impact of digital technology innovation negatively affects the domestic carbon emission intensity.

2.4. Analyzing the mechanism of digital technology innovation affecting carbon emission intensity

Current literature pays attention not only to digital technology innovation but also to mechanism that digital technology innovation promotes the green development [63]. The mechanisms of digital technology innovation to reduce carbon emission intensity have been discussed from three aspects: boosting non-fossil energy consumption level, improving energy efficiencies and optimizing the industrial structure.

In terms of boosting non-fossil energy consumption level, Ahmed et al. [64] confirms that the cross-industry and cross-border spillover of digital technology could not only increase the harvest of non-fossil energy, but also effectively store this energy, which stimulates the increase in the proportion of non-fossil energy consumption. Additionally, digital technology innovation also effectively promotes the reduction of non-fossil energy consumption costs [65,66].

Diagnosing and dealing with unreasonable and inefficient links in energy production, transportation and consumption systems to improve energy efficiency is another mechanism for digital technology innovation to reduce carbon emission intensity [67–70]. Therefore, some scholars had estimated that the integration of digital technology and the energy sector would reduce the global carbon emission intensity by 3.5%–6.3% by 2020 (Casal et al., 2005). However, some scholars believe that the improvement in energy conservation and emission reduction efficiency of digital technology innovation is slower than the expansion speed of the industry [71–73]. In fact, as the complexity of information industry products increases, the ratio of energy consumption to production continues to decline. According to Koomey's law, the energy consumption of the processor will be halved every 1.5 years [74]. This means that the information industry continues to make technology innovations in terms of energy saving and emission reduction efficiency, and it still cannot catch up with the scale of the industry's development speed. Another reason is that technology innovation has not been compensated by the corresponding economic growth [75]. For example, although the selling price of the 12th generation and the 10th generation Apple mobile phone are almost the same when the phones were first released, its computing speed is doubled according to Moore's law [76].

Comparing the green development experience of emerging economies and mature economies, more and more documents have begun to discuss the impact of industrial structure transformation on carbon emissions [77–79]. Chen [80] uses data from the World Input-Output Database (WIOD) to demonstrate that the transformation of China's industrial structure from manufacturing to service industry has a positive effect on the reduction of global carbon emissions. At the same time, the role of digital technology innovation in promoting the transformation of industrial structure has also attracted the attention of scholars, such as the digital economy driven by digital technology [81,82]. Hence, this paper proposes the following mechanism hypothesis:

H4a. Increasing the proportion of non-fossil energy use is one of the mechanisms for digital technology innovation to reduce the domestic carbon emission intensity.

H4b. Optimizing the industrial structure is another mechanism for digital technology innovation to reduce the domestic carbon emission intensity.

3. Methodology

3.1. Measuring the green development with KPWW

This paper focuses on the application of the Koopman, Powers, Wang and Wei (KPWW, 2010) method to the issue of carbon footprint. The explained variables are expressed in terms of unit value-added carbon emission (CG_r^*) and unit final demand carbon emission (CG_r), which represents domestic green development level. In order to measure the level of green development of an economy, we need to measure the carbon emission per unit of GDP and final consumption. The "carbon dioxide emissions from fuel combustion" data provided by the International Energy Association and the output value data provided by OECD international Input-Output Tables can only estimate carbon dioxide emissions per unit of output value. If we want to realize the conversion of carbon dioxide emissions per unit of output value to unit value-added carbon emission, it is necessary to trace the source of carbon dioxide from where it is emitted to where it is consumed. The KPWW method is widely used in the traceability and decomposition of value-added in trade [83,84]. When the direct value-added shares are replaced by the unit output input labor force coefficient and the unit output carbon emission coefficient, the value-added decomposition method is expanded to the fields of global job distribution [85] and carbon footprint issues [86]. This paper is also based on this method when calculating carbon emissions per unit of GDP.

$$VBY = \begin{bmatrix} V_rB_{rr}Y_r & V_rB_{rs}Y_s & V_rB_{rt}Y_t \\ V_sB_{sr}Y_r & V_sB_{ss}Y_s & V_sB_{st}Y_t \\ V_tB_{tr}Y_r & V_tB_{ts}Y_s & V_tB_{tt}Y_t \end{bmatrix} \rightarrow CBY = \begin{bmatrix} C_rB_{rr}Y_r & C_rB_{rs}Y_s & C_rB_{rt}Y_t \\ C_sB_{sr}Y_r & C_sB_{ss}Y_s & C_sB_{st}Y_t \\ C_tB_{tr}Y_r & C_tB_{ts}Y_s & C_tB_{tt}Y_t \end{bmatrix} \tag{1}$$

As shown in equation (1), B is the well-known Leontief inverse matrix. Y is the final product vector, and BY represents the total output. When the direct value-added shares V is replaced with carbon emission factors C, the value-added decomposition of the final product is also transformed into the carbon emission decomposition of the final product consumption.

$$DV_r = V_rB_{rr}Y_r \rightarrow DC_r = C_rB_{rr}Y_r \tag{2}$$

$$FV_r = V_sB_{sr}Y_r + V_tB_{tr}Y_r \rightarrow FC_r = C_sB_{sr}Y_r + C_tB_{tr}Y_r \tag{3}$$

$$IV_r = V_rB_{rs}Y_s + V_rB_{rt}Y_t \rightarrow IC_r = C_rB_{rs}Y_s + C_rB_{rt}Y_t \tag{4}$$

In equations (2) and (3), the final product output value Y_r is divided into domestic value-added DV_r and foreign value-added FV_r of country r according to the attribution of value-added. Similarly, the carbon emissions produced by country r's consumption of the final product Y_r are also divided into domestic carbon emissions DC_r and foreign carbon emissions FC_r of country r according to their production sources. The sum of off-diagonal elements along a row of matrix (1) provides information on country r's value-added and carbon emissions embodied as intermediate inputs in foreign countries' final product consumption as shown in equation (4).

$$Y_r = DV_r + FV_r \rightarrow CC_r = DC_r + FC_r \tag{5}$$

$$GDP_r = DV_r + IV_r \rightarrow CS_r = DC_r + IC_r \tag{6}$$

Equation (5) presents the total value-added from the consumption of country r's final products. And CC_r represents the country and industry origins of emissions embodied in the consumption and investment of final goods and services by country r's industries and households. Equation (6) presents the value-added obtained by country r (GDP_r) from domestic and foreign final product consumption, and CS_r stands for the country and industry origins of emissions from country r. Therefore, total carbon emissions embodied in final demand by country r FDC_r; and production-based emissions PEC_r is then estimated as follows:

$$FDC_r = CC_r + FNLC_r \tag{7}$$

$$PEC_r = CS_r + FNLC_r \tag{8}$$

where $FNLC_r$ is the vector of direct emission due to the combustion of utility and transport fuels by households. To ensure that all emissions are taken into account, these emissions need to be added to that of matrix CC_r or CS_r. Hence, CG_r is the demand-based carbon emissions per unit of final demand output value. And CG_r^* represents the production-based carbon emissions per unit of GDP.

$$CG_r = FDC_r / Y_r \tag{9}$$

$$CG_r^* = PEC_r / GDP_r \tag{10}$$

3.2. Measuring the core explanatory variable: technology innovation of the information industry

The core explanatory variables of this article include two parts, which are the technology innovation of the domestic information industry itself and technology spilling over to other industries and countries from the information industry. This part employs the approach of Haussman [87] and Liu [88] to measure the technology innovation of the domestic information industry by using the technological sophistication index (TSI). The TSI TSI_r^i is measuring as follow:

$$TSI_r^i = \frac{x_r^i / X_r}{\sum_r x_r^i \Big/ \sum_r X_r} Y_r = RCA_r^i Y_r \tag{11}$$

where X_r and Y_r are the total output value and per capita GDP of country r, respectively. x_r^i is the export value of industry i in country r. Hence, the essence of TSI_r^i is the multiplication of the revealed comparative advantage (RCA) index [89] and labor productivity, which reflects the level of industrial technology through the interactive relationship between labor productivity and international competitiveness.

We made two improvements on Haussman's indicator. First of all, it is necessary to measure the TSI from the perspective of value-added and global value chains (GVCs). To clarify the source of carbon emissions, this paper separately measured the production-based and demand-based carbon emissions from the perspective of GVCs. Since this paper analyzes the impact of digital technology innovation and technology spillover on carbon emissions, we should keep the perspective of two indicators consistent during the measurement. The export value X_r in equation (11) is converted into value-added export (VAX) as shown in equation (12). Johnson [90] defines VAX as the value-added produced by one economy and eventually consumed in other economies. For instance, VAX_r include the direct and indirect value-added absorbed by country r from the consumption of final products in countries s and t. This paper introduces the method of Koopman et al. [83] and Los et al. [91] to revise the RCA index, which was transformed to the revealed value-added comparative advantage index (RVCA). Hence, the TSI ($TSI_r^{i'}$) from the perspective of GVCs is shown in equation (13).

$$VAX_r = \begin{pmatrix} V_r & 0 & 0 \end{pmatrix} \begin{bmatrix} B_{rr} & B_{rs} & B_{rt} \\ B_{sr} & B_{ss} & B_{st} \\ B_{tr} & B_{ts} & B_{tt} \end{bmatrix} \begin{bmatrix} 0 + Y_{rr} + Y_{rt} \\ 0 + Y_{ss} + Y_{st} \\ 0 + Y^{ts} + Y^{tt} \end{bmatrix} = V_rB_{rr}(Y_{rr} + Y_{rt}) + V_rB_{rs}(Y_{ss} + Y_{st}) + V_rB_{rt}(Y_{ts} + Y_{tt}) \tag{12}$$

$$TSI_r^{i'} = \frac{VAX_r^i / VAX_r}{\sum_r VAX_r^i \Big/ \sum_r VAX_r} Y_r = RVCA_r^i Y_r \tag{13}$$

Furthermore, we have added factors representing foreign technology introduction because the interaction between labor productivity and international competitiveness reflects the level of technology innovation independently developed by the country. With the continuous deepening of globalization and vertical specialization, countries have introduced and absorbed a large number of foreign patented technologies, which have effectively increased the TSI of domestic products. The TSI after considering the introduction of foreign technology is measured as follow:

$$TSI_r^{i'} = RVCA_r^i * Y_r * IP_r \tag{14}$$

where IP_r represents the cost of introducing intellectual property rights in country r.

3.3. Measuring the technology spillover from information industry

The cross-industry and cross-border technology spillover from the information industry are also the core explanatory of this paper. The previous literature mainly used case studies to evaluate the indirect effects of technology innovation [92]. This paper attempts to measure digital technology spillover through empirical analysis. According to the upstream and downstream linkages of value chains, the technology spillover from the information industry can be divided into forward technology empowerment and backward technology empowerment. Forward technology empowerment refers to the technology spillover from information industry, which increases the TSI of downstream industries. Backward technology empowerment refers to the increase in technological demand for upstream industries after the innovation of digital technology, i.e., an increase in TSI of upstream industries to meet the needs of the development of the information industry. What's more, considering the difference between global value chain and domestic value chain, digital technology empowerment can also be divided into domestic technology empowerment and international technology empowerment. Based on the classification standards of the upstream, downstream, domestic and foreign countries of the value chain, a total of four digital technology empowerment methods can be introduced.

$$DOMFor_r^i = TSI_r^{i'} * \sum_{j=1, i \neq j}^{n} g_{rr}^{ij} \tag{15}$$

$$INTFor_r^i = TSI_r^{i'} * \sum_{s=1, r \neq s}^{n} \sum_{j=1}^{n} g_{rs}^{ij} \tag{16}$$

$$DOMBack_r^i = \sum_{j=1, i \neq j}^{n} b_{rr}^{ji} * TSI_r^{i'} \tag{17}$$

$$INTBack_r^i = \sum_{s=1, r \neq s}^{n} \sum_{j=1}^{n} b_{sr}^{ji} * TSI_r^{i'} \tag{18}$$

$DOMFor_r^i$ is the domestic technology empowerment of the information industry. It represents the increase in the TSI of the j industry after the technology of the domestic information industry i is applied to the downstream industry j. In equation (15), g_{rr}^{ij} is the element in the block matrix of country r in the Ghosh inverse matrix. This block matrix is summed by rows to obtain the proportion of unit i product embedded in downstream j industry $\sum g_{rr}^{ij}$. Combining the supply coefficient $\sum g_{rr}^{ij}$ with the product TSI $TSI_r^{i'}$, the domestic technology empowerment of the information industry $DOMFor_r^i$ is obtained. Equation (16) sums the elements g_{rs}^{ij} in the Ghosh inverse matrix by rows to obtain the total input coefficients $\sum\sum g_{rs}^{ij}$, which are intermediate products proportion from the information industry of country r embedded in foreign countries. Based on this, the international forward technology empowerment $INTFor_r^i$ of the information industry is obtained. When constructing the information industry's domestic backward technology empowerment $DOMBack_r^i$, we replace the element g_{rr}^{ij} in the Ghosh inverse matrix with the block matrix element b_{rr}^{ji} of the Leontief inverse matrix in equation (17). Equation (18) sums the elements b_{sr}^{ji} of country r's overseas consumption coefficient matrix by column, and finally obtains the international backward technology empowerment $INTBack_r^i$.

3.4. Model design and variables selection

This paper attempts to analyze whether the increasing TSI of the information industry would promote domestic green development. When designing the model, not only the influence of the technology innovation of the information industry on the domestic carbon emission intensity was considered, but also the carbon emission reduction effect of the cross-industry and cross-border technology spillover from the information industry was discussed. The benchmark model is as follow:

$$\begin{aligned} \ln CG_{rt} &= \beta_0 + \beta_1 \ln TSI_{rt}^{i'} + \beta_2 \ln DOMBack_{rt}^i + \beta_3 \ln DOMFor_{rt}^i \\ &\quad + \beta_4 \ln INTBack_{rt}^i + \beta_5 \ln INTFor_{rt}^i + \beta_6 \sum \ln Control_{rt}^i + \mu_r + \mu_t + \varepsilon_{rt}^i \end{aligned} \tag{19}$$

where r represents an economy, i refers to an industry, and t stands for the year. The explained variable carbon emission intensity CG_r and the core explanatory variables technology innovation of the information industry $TSI_r^{i'}$, the domestic technology empowerment of the information industry $DOMFor_r^i$, the international forward technology empowerment $INTFor_r^i$, the information industry's domestic backward technology empowerment $DOMBack_r^i$ and the international backward technology empowerment $INTBack_r^i$. $\sum \ln Control_{rt}^i$ is the set of control variables. Since Grossman & Krueger [93] and Hubler & Keller [94] believe that the relationship between economic activity and the environment includes three aspects: scale effect, structural effect and technological effect, we emphatically considered the scale effect as the supplement to the technical effect and structure effect involved in the core explanatory variables when selecting control variables. The control variables that reflect the scale effect in this paper are: (1) Information industry scale (*VA*). Whether digital technology can be widely promoted and applied depends on the scale of the information industry. This paper employs the value-added of the information industry to represent the scale of the information industry. (2) Economic losses caused by carbon emissions (*Damage*). The study of Xu [95] points out that economic growth in the industrialization process of the emerging countries is accompanied by a large number of pollutant emissions. Then, the increase in pollutant emissions has led to an increase in the intensity of environmental regulations. Hence, there is a development model of "pollution first, governance later." Given the fact that losses caused by environmental pollution go hand in hand with stricter environmental regulations, this paper predicts that the expansion of economic losses caused by carbon emissions will reduce the intensity of carbon emissions. This Paper uses the economic loss caused by environmental pollution as a percentage of national income to express this variable. (3) Outward Foreign Direct Investment (*OFDI*). The research of Song [96] reflects that outflow of FDI is accompanied by technology spillover from the host country, which can reduce the carbon emission intensity of the investing country. This paper uses the ratio of net outward FDI to GDP to represent this variable.

3.5. Data

The carbon emission intensity data is calculated based on the OECD input-output database and "fuel burning CO_2" data of the International

Energy Council. TSI is obtained from OECD Trade in Value-Added (TiVA) database (Domestic value added content of gross exports & Gross exports) and patent fee data in the World Bank database (Charges for the use of intellectual property). There are a total of 64 economies in the OECD database. The data on the scale of information industry and the proportion of the service industry in GDP are also obtained from the TiVA Database (Value added). The energy structure and OFDI data come from the World Bank database (Fossil fuel energy consumption & Foreign direct investment, net outflow). After excluding the economies with missing data, the data of 50 economies[3] from 2005 to 2015 are selected for empirical analysis. Table 1 provides some descriptive statistics of the mentioned variables. The unit of carbon emission intensity (*CG*) is ton per thousand dollars. The unit of scale of the information industry is billion dollars (*VA*). Table 2 demonstrates the correlation analysis, which indicates that most of the variables have a correlation with carbon emission intensity. Correlation coefficient indicates a strong positive correlation between digital technology innovation and carbon emission intensity. The digital technology spillover is negatively correlated with carbon emission intensity.

4. Empirical analysis

4.1. The impact of digital technology innovation on national carbon emission intensity

4.1.1. Analysis of benchmark model results

This section reports the impact of digital technology innovation on national carbon emission intensity from a structural characteristics perspective. We not only estimate the “direct effect” of the digital technology innovation on national carbon emission intensity, but also measure the “indirect effects” of the digital technology spillover to other domestic industries and foreign countries on the national carbon emission intensity, because the technology spillover from the information industry has led to domestic, international, upstream and downstream technology innovation. The “indirect effects” of the information industry’s empowerment are divided into domestic forward, domestic backward, international forward and international backward. Then, by comparing the size and significance of the regression coefficients, it demonstrates the effective path of the digital technology innovation and technology spillover to reduce carbon emission intensity. Finally, statistics of the combined effects of “direct effect” and “indirect effects” illustrate the overall impact of digital technology innovation and technology spillover on carbon emission intensity.

Table 1
Descriptive statistics.

Variable	Maximum	Minimum	Mean	Standard deviation	Observations
CG	1.995	0.129	0.434	0.258	539
CG^*	1.080	0.003	0.205	0.150	539
TSI	844.44	0.04	57.38	119.61	517
DOMFor	474.41	0.007	25.38	57.52	517
INTFor	672.00	0.005	29.48	74.04	517
DOMBack	363.55	0.01	30.75	67.14	517
INTBack	664.58	0.01	28.60	71.08	517
VA	1372.33	0.52	69.38	174.08	539
Damage	4.89%	0.13%	1.01%	0.83%	528
OFDI	301.25%	−87.23%	7.82%	30.84%	539
Energy	99.94%	13.06%	75.05%	16.90%	523
Service	85.89%	38.95%	67.07%	8.69%	539

Source: The author calculated the data based on the OECD input-output database, TiVA database and World Bank database.

Table 3 reports the impact of the digital technology innovation on national carbon emission intensity which includes the “direct effect” and “indirect effects”. The results in column (1) only consider the “direct effect” and “indirect effects” from digital technology spillover to domestic forward and backward linkages. Column (2) also takes into account the “indirect effects” from the digital technology spillover to international industries. The empirical results found that the regression coefficient of the “direct effect” is positive, that is, the technology innovation of the information industry itself (ln *TSI*) will increase the national carbon emission intensity. Empirical results confirm our first hypothesis (H1). That is the main reason why Zhou [3] believes that the information industry itself is not an “environmentally friendly industry.” Digital technology changes frequently with equipment is eliminated and updated extremely quickly and this consumes a lot of chemical, metal and non-metal materials, resulting in more carbon emissions [61,97]. While digital products that have been upgraded with new generations have higher technical content, their prices have remained stable, leading to an increase in carbon emissions per unit of added value [76]. Hence, the technology innovation of the information industry itself has pushed up carbon emission intensity.

Then, we analyze the “indirect effects” of digital technology innovation. Empowering other industries through the information industry is conducive to reducing carbon emission intensity. Among the indirect effects, the national carbon emission reduction from empowering domestic backward linkages has the most prominent effect. Column (2) reports that if digital technology spillover to domestic backward linkage industries with an additional 1% or more, the national carbon emission intensity would decrease by 0.21%, and then followed by international forward linkages and domestic forward linkages with 0.11% and 0.09% decrease in national carbon emission intensity, respectively. However, the information industry empowering international backward linkage industries would not significantly decrease the national carbon emission intensity. Hence, it is the best way to reduce the intensity of carbon emission from the information industry empowering domestic upstream raw materials and manufacturing (backward linkages) which can better adapt the needs of digital economy development. This result echoes the research results of Peng et al. [98] who believes as the world’s factory, China’s upstream production side emissions are greater than downstream consumption side emissions. Therefore, reducing the carbon emission intensity of the domestic upstream production sectors is the “most important factor” for effectively curbing China’s carbon emission. Summarizing the significant regression coefficient in the column (2), the digital technology spillover effectively reduces the carbon emission intensity, thus confirming our second hypothesis (H2).

Column (3) further pays attention to the control variables at the national level that may affect the carbon emission intensity, including industrial scale (ln *VA*), carbon emission damage (ln *Damage*) and outward foreign direct investment (ln *OFDI*). These control variables are negatively related to national carbon emission intensity. The expansion of the information industry scale (ln *VA*) will help empower more traditional industries to upgrade and develop which link the intelligent revolution based on information industry and the green development based on new energy. The increase in the economic loss from carbon emission (ln *Damage*) will lead to tighter environmental regulations, which will “force” the national green development [95], and OFDI promotes low-carbon total factor productivity through reverse green

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[3] The 50 economies selected in this paper include all 36 OECD member countries and 14 non-member economies. These 50 economies specially involve Australia, Austria, Belgium, Canada, Chile, Czech-Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, South Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherland, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States, Argentina, Brazil, Bulgaria, China, Colombia, Cuba, Croatia, Cyprus, India, Indonesia, Malta, Romania, Russia, South Africa.

Table 2
Correlation analysis.

	CG	*TSI*	*DOMFor*	*INTFor*	*DOMBack*	*INTBack*	*VA*	*Damage*	*OFDI*	*Energy*	*Service*
CG	1										
TSI	0.67	1									
DOMFor	−0.45	−0.02	1								
INTFor	−0.38	−0.00	0.71	1							
DOMBack	−0.57	−0.01	0.86	0.92	1						
INTBack	−0.48	−0.00	0.68	0.99	0.90	1					
VA	−0.30	0.32	−0.04	−0.03	−0.04	−0.03	1				
Damage	0.92	−0.14	−0.04	−0.07	−0.06	−0.07	0.00	1			
OFDI	−0.48	−0.04	0.08	0.10	0.10	0.10	−0.03	0.09	1		
Energy	0.58	0.33	0.40	−0.32	−0.30	−0.42	0.13	0.15	0.04	1	
Service	−0.55	0.41	0.31	0.43	0.21	0.33	0.12	−0.50	−0.02	0.04	1

Source: author's calculation based on the OECD input-output database, TiVA database and World Bank database.

Table 3
The impact of digital technological innovation on national carbon emission intensity.

	(1)	(2)	(3)
ln *TSI*	0.13**	0.16***	0.25***
	(0.01)	(0.00)	(0.00)
ln *DOMFor*	−0.10***	−0.09***	−0.06***
	(0.00)	(0.00)	(0.01)
ln *DOMBack*	−0.23***	−0.21***	−0.09**
	(0.00)	(0.00)	(0.01)
ln *INTFor*		−0.11***	−0.19***
		(0.00)	(0.00)
ln *INTBack*		0.06	0.07***
		(0.13)	(0.01)
ln *VA*			−0.48***
			(0.00)
ln *Damage*			−0.03***
			(0.00)
ln *OFDI*			−0.15***
			(0.00)
Observations	468	468	468

R^2 0.47 0.48 0.73.
Note: The p-value of the coefficient are in parentheses. "*", "**" and "***" represent the significance level of 10%, 5%, and 1% respectively.

Table 4
Robustness test result.

	(1)	(2)	(3)	(4)
	ln CG^*	ln CG^*	*Lag*	*Lag*
ln *TSI*	0.12**	0.24***	0.13**	0.23***
	(0.03)	(0.00)	(0.03)	(0.00)
ln *DOMFor*	−0.09***	−0.06***	−0.09***	−0.09***
	(0.00)	(0.00)	(0.00)	(0.00)
ln *DOMBack*	−0.22***	−0.09***	−0.17***	−0.07*
	(0.00)	(0.01)	(0.00)	(0.07)
ln *INTFor*	−0.06	−0.15***	−0.05	−0.16***
	(0.13)	(0.00)	(0.23)	(0.00)
ln *INTBack*	0.03	0.04	0.03	0.06**
	(0.45)	(0.12)	(0.38)	(0.04)
ln *VA*		−0.59***		−0.49***
		(0.00)		(0.00)
ln *Damage*		−0.01*		−0.03***
		(0.06)		(0.00)
ln *OFDI*		−0.14***		−0.11***
		(0.00)		(0.00)
Observations	468	468	419	419
R^2	0.51	0.78	0.37	0.66

Note: The p-value of the coefficient are in parentheses. "*", "**" and "***" represent the significance level of 10%, 5%, and 1% respectively.

technology spillover effects [96].

4.1.2. Robustness test result analysis

The mainstream robustness test methods are divided into two categories. One is the robustness test by replacing indicators and the other is the robustness test by changing the measurement method. Since the numerous indicators describe carbon emission intensity and digital technology innovation, the first method is adopted in this paper to avoid the regression bias of specific indicator on the regression results by using alternative indicators of the explained variable and explanatory variables. Carbon emission per unit of output are used to replace carbon emission per unit of value-added. The results are shown in columns (1) and (2) of Table 4. Then, five explanatory variables are regressed with lagged terms in columns (3) and (4) to test the robustness of the benchmark model results. The regression coefficient of the "direct effect" is still positive after changing the explained variable and explanatory variables. Additionally, "indirect effects" of the digital technology innovation would still significantly reduce carbon emission intensity. As a whole, technology innovation in the information industry effectively reduce national carbon emission intensity in robustness test. Since the results of the robustness test are consistent with the results of the benchmark model, it proves that the estimation results in this paper are reliable. The robustness test further confirms Hypothesis H1 and Hypothesis H2.

4.2. Mechanism test

Optimizing the industrial structure and the energy consumption structure are important channels for improving energy efficiency and reducing carbon emission intensity. Whether the improvement of the technological level of the information industry can optimize the industrial structure and energy consumption structure, and then affect the carbon emission intensity, is the key research content of this part. Mediating effect analysis is an important step to test whether industrial structure or the energy consumption structure becomes a mediating variable and to what extent it plays a mediating role. The variables for the analysis of the mediation effect are as follows. (1) Energy consumption structure (*Energy*). Chen [99] pointed out that the reduction in the proportion of fossil energy use or the increase in clean energy productivity is one of the decisive factors for the decline in carbon emission intensity. Therefore, this paper uses the fossil energy consumption ratio from the World Bank database to reflect the energy consumption structure. (2) Industrial structure (*Service*). Since the changes in the industrial structure of the production sector have caused significant changes in carbon emission intensity, this paper uses the ratio of value added of the service sector to GDP from the OECD input-output tables as an indicator to measure the industrial structure. The mechanism test model is shown in equations (17) and (18).

$$\ln Structure^{i}_{rt} = \delta_0 + \delta_1 \ln TSI^{i}_{rt} + \delta_2 \ln DOMBack^{i}_{rt} + \delta_3 \ln DOMFor^{i}_{rt} + \delta_4 \ln INTBack^{i}_{rt} + \delta_5 \ln INTFor^{i}_{rt} + \ln X^{i}_{rt} + \mu_r + \mu_t + \varepsilon^{i}_{rt} \tag{17}$$

$$\ln CG^{i}_{rt} = \delta_0 + \delta_1 \ln TSI^{i}_{rt} + \delta_2 \ln DOMBack^{i}_{rt} + \delta_3 \ln DOMFor^{i}_{rt} + \delta_4 \ln INTBack^{i}_{rt} + \delta_5 \ln INTFor^{i}_{rt} + \delta_5 \ln Structure^{i}_{rt} + \ln X^{i}_{rt} + \mu_r + \mu_t + \varepsilon^{i}_{rt} \tag{18}$$

$$Structure \in \{Energy,\quad Service\}$$

Table 5 reports the regression results of the mediation effect test. It identifies whether reducing the proportion of fossil fuel consumption is a mechanism for digital technology innovation and digital technology spillover to reduce carbon emission intensity from column (1) to column (4). The results in column (1) show that technology innovation in the information industry has significantly increased the proportion of fossil fuels consumption. For every 1% increase in the TSI of information industry, the proportion of fossil energy consumption will increase by 0.08%, which indicates that the information industry itself is not an “environmentally friendly industry.” However, the international and cross-industry technology spillovers from the information industry have significantly reduced the proportion of fossil energy consumption. For every 1% increase in the TSI of the information industry spillovers to the domestic and international downstream industries, the proportion of the fossil energy consumption in the domestic energy consumption structure will drop by 0.03% and 0.04% respectively. However, it would not significantly change the energy consumption structure after information industry spilling over to its upstream industries.

Column (2) presents the impact of energy consumption structure on carbon emission intensity. For every 1% increase in the proportion of fossil energy consumption, the carbon emission intensity will increase by 0.94%. The results verify that countries whose energy consumption structure is dominated by fossil fuels such as petroleum and coal would show higher carbon emission intensity. In order to reduce the intensity of carbon emissions, EU countries continue to optimize their energy consumption structure which strives to complete the abandonment of coal and nuclear power around 2030 to explore sustainable development paths, namely the 2030 climate target plan [100]. This has some enlightenment for emerging countries like China, whose energy consumption structure is dominated by coal, to reduce the intensity of carbon emissions. Column (3) and column (4) are the regression results of adding control variables. There is no significant change in model coefficients and significance. This proves that optimizing the energy consumption structure is an effective mechanism for digital technology spillover to reduce carbon emission intensity, thus confirming our fourth hypothesis (H4a.)

It identifies whether increasing the proportion of service industry in the national economy is a mechanism for digital technology innovation and digital technology spillover to reduce carbon emission intensity from column (5) to column (8). The regression results in column (5) show that the technology innovation of the information industry itself cannot significantly change the proportion of the service in the industrial structure. When it comes to the digital technology spillover, the technology spillover from the information industry to domestic upstream and downstream industries will significantly increase the proportion of the service industry. For every 1% increase in the technological sophistication index of the information industry flowing to the domestic upstream or downstream industry, the proportion of the service industry will increase by 0.03% and 0.02% respectively. However, international technology spillovers in the information industry have significantly reduced the proportion of domestic service industries. This is because the non-tariff barriers of the service industry far exceed those of the manufacturing industry, making it difficult for overseas service industry to enter target countries. For instance, China’s banking, insurance and telecommunications sectors have obvious restrictions to the entry of corresponding industries in developed countries [101]. Hence, these non-tariff barriers interrupted the path for the feedback effects of the international technology spillovers in the information industry. Column (6) reports the impact of the service industry’s share of GDP on the domestic carbon emission intensity. For every 1% increase in the service industry’s share of GDP, the domestic carbon emission intensity will be reduced by 2.05%. The regression results, after adding the control variables, show that the industrial structure is still the mechanism by which digital technology spills over to reduce the domestic carbon emission intensity. Hence, empirical results confirm our final hypothesis (H4b).

Table 5
Regression results of the mediation effect test.

	Energy consumption structure				Industrial structure			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln *Energy*	ln *CG*	ln *Energy*	ln *CG*	ln *Service*	ln *CG*	ln *Service*	ln *CG*
ln *TSI*	0.08***	0.08	0.08***	0.19***	−0.01	0.14***	−0.01	0.24***
	(0.00)	(0.12)	(0.00)	(0.00)	(0.31)	(0.01)	(0.51)	(0.00)
ln *DOMBack*	−0.01	−0.19***	−0.01	−0.08**	0.03***	−0.14***	0.03***	−0.06*
	(0.37)	(0.00)	(0.48)	(0.01)	(0.00)	(0.00)	(0.00)	(0.08)
ln *DOMFor*	−0.03***	−0.06**	−0.03***	−0.04*	0.02***	−0.05*	0.01***	−0.04**
	(0.00)	(0.02)	(0.00)	(0.07)	(0.00)	(0.07)	(0.00)	(0.04)
ln *INTBack*	−0.01	0.06*	−0.01	0.07***	−0.02***	0.01	−0.03***	0.04
	(0.37)	(0.07)	(0.60)	(0.00)	(0.00)	(0.88)	(0.00)	(0.15)
ln *INTFor*	−0.04***	−0.08**	−0.04***	−0.16***	−0.00	−0.12***	0.00	−0.19***
	(0.00)	(0.04)	(0.00)	(0.00)	(0.68)	(0.00)	(0.51)	(0.00)
ln *Energy*		0.94***		0.83***				
		(0.00)		(0.00)				
ln *Service*						−2.05***		−1.11***
						(0.00)		(0.00)
ln *VA*			0.02	−0.50***			−0.01	−0.50***
			(0.41)	(0.00)			(0.20)	(0.00)
ln *Damage*			−0.01*	−0.02***			0.00**	−0.02***
			(0.05)	(0.00)			(0.02)	(0.00)
ln *FDI*			−0.01	−0.13***			0.03***	−0.11***
			(0.15)	(0.00)			(0.00)	(0.00)
Observations	468	468	468	468	468	468	468	468
R^2	0.08	0.53	0.10	0.77	0.27	0.54	0.36	0.75

Note: “*”, “**” and “***” represent the significance level of 10%, 5%, and 1% respectively.

5. Further analysis

5.1. The comprehensive impact of digital technology on carbon intensity

Technology innovation in the information industry will increase the intensity of carbon emissions, while cross-border and cross-industry technology spillover will reduce the intensity of domestic carbon emissions. Whether digital technology would reduce the intensity of carbon emissions remains to be clarified. This section will employ the impulse response function of the generalized Vector Auto Regression (VAR) model in order to analyze both the long term and short term impacts of the indicators from digital technology innovation and technology spillover on carbon emission intensity. Then decomposes the variance of the VAR model to describe the importance of each shock effect.

It can be seen from Fig. 1 that the carbon emission intensity continued to rise after being impulse by a positive impact from the technology innovation of the information industry, reaching a peak of 25% in the fourth period. Therefore, in the long run, technology innovation in the information industry will increase the intensity of carbon emissions which will have the effect of continuing to undermine the goals of green development and carbon neutrality in the long run.

From Fig. 2a and b, it can be seen that cross-industry spillover of digital technology to domestic upstream and downstream industries will significantly reduce domestic carbon emission intensity in both the long run and short term. This conclusion is consistent with the previous regression analysis in that the digital technology empowering domestic upstream and downstream industries is a stable and energy-saving along with an emission reduction path.

In terms of the international spillover effects of digital technology to foreign countries, the long term and short term effects of carbon emission intensity are not uniform. After a positive impact on carbon emission intensity by international technology spillovers, the carbon emission intensity increased significantly in the first phase. When it comes to the second phase, the carbon emission intensity continued to decrease. This result is related to the industrial transfer sequence in which developed countries first transferred digital technology in manufacturing industries to developing countries for Original Equipment Manufacturer (OEM) production, and then transferred digital technology in service industries [76,101]. The former part also explained that the transformation of the industrial structure from manufacturing to the service industry is an important mechanism for digital technology to empower green development.

In order to clarify the comprehensive impact of digital technology innovation and technology spillover on carbon emission intensity, this paper employs variance decomposition to describe the relative importance of impact in the dynamic changes of *TSI*, *DOMFor*, *DOMBack*, *INTFor*, *INTBack* and carbon intensity emission. The result of variance decomposition is shown in Fig. 3. The direct effect of digital technology innovation is not the main external cause that affects the trend of carbon emission intensity. The impact of direct effect (*TSI*) is less than the domestic cross-industry spillovers (*DOMFor* and *DOMBack*) of digital technology, and greater than the international technology spillovers (*INTFor* and *INTBack*) of information industry. The contribution rates of *DOMFor*, *DOMBack*, *TSI*, *INTFor* and *INTBack* to carbon emission intensity are 7.67%, 5.93%, 4.79%, 2.88% and 2.72%, respectively. Since domestic cross-industry technology spillovers (*DOMFor* and *DOMBack*), which have the largest contribution rate among the five external factors that affect carbon emission intensity, reduce carbon emission intensity, the comprehensive impact of digital technology innovation and technology spillover reduces carbon emission intensity. Hence, green development will be empowered by digital technology, which confirms our third hypothesis (H3).

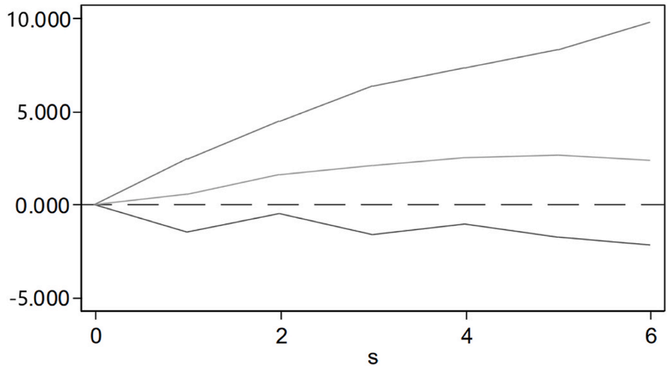

Fig. 1. The Impulse Response of Carbon Emission Intensity to the Technological Innovation of Information Industry. Source: author's calculation based on the OECD input-output database and TiVA database.

5.2. National and time differences in the performance of digital technology empowering green development

The TSI of the information industry in developed countries and emerging economies is quite different. Developed countries use artificial intelligence, machine learning and smart manufacturing more frequently, while emerging economies seldom use digital technology. Whether this difference will only lead to continuous improvement in the carbon emission intensity of developed countries is the focus of this section. Therefore, this section will perform a group regression test on all country samples, which are divided into an OECD group and non-OECD group. In the time dimension, whether the direct and indirect effects between digital technology innovation and carbon emission intensity are time persistent, it has profound meaning in summarizing a stable path to reduce the carbon emission intensity. This paper draws on ideas of Gkypali et al. [20] on path dependence of technology gap catching-up or divergence for conducting the following analysis.

The regression results presented in Table 6 include three time periods and two groups. In both two groups, a time persistent and statistically significant direct effect of digital technology innovation and carbon emission intensity is identified. However, the paths of the two groups indirectly affecting carbon emission intensity through digital technology innovation are not consistent. The regression results of column (1), column (2) and column (3) in Table 6 show that the spillover to the upstream industry abroad will increase domestic carbon emission intensity. The technology spillover from the information industry to domestic upstream and downstream industries as well as foreign downstream industries would reduce the domestic carbon emission intensity in OECD countries. Among them, technology spillover to foreign downstream industries have the most time persistent and largest regression coefficient of reducing carbon emission intensity, for every 1% spillover with 0.25% decrease in the period from 2013 to 2015. Compared with OECD countries, non-OECD economies have fewer paths to reduce carbon emission intensity by means of digital technological spillover as shown in column (4), column (5) and column (6). Additionally, the technology spillover from information industry to the domestic upstream industries is the main path for non-OECD economies to reduce carbon emission intensity during the three periods. According to our calculation based on OECD input-output table, the information industry in non-OECD economies is dominated by electronics manufacturing, it increases strong demand for upstream industry components and raw materials. The reduction of carbon emission intensity produced by these components is crucial for carbon emission reduction in non-OECD economies. For every 1% increase of non-OECD countries' digital technology spillover to domestic upstream industries, the national carbon emission intensity would drop by 0.19% in the period from 2013 to 2015. Considering the degree of reduction of carbon emission intensity and time persistent, the OECD countries presents more paths than non-OECD countries. It illustrates that there are still certain bottlenecks in the digital technology spillover to promote green development in emerging economies.

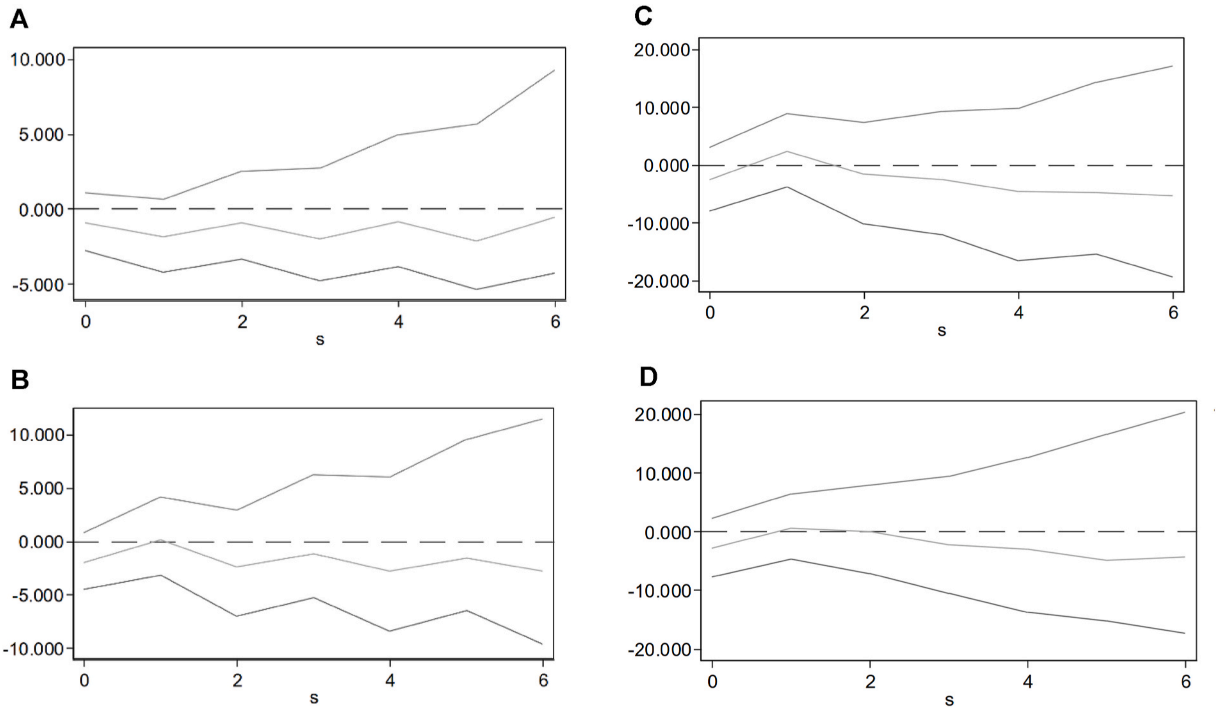

Fig. 2. a. The Impulse Response of Carbon Emission Intensity to the Technological Spillover of *DOMFor*. Source: author's calculation based on the OECD input-output database and TiVA database. 2b. The Impulse Response of Carbon Emission Intensity to the Technological Spillover of *DOMBack*. Source: author's calculation based on the OECD input-output database and TiVA database. 2c. The Impulse Response of Carbon Emission Intensity to the Technological Spillover of *INTFor*. Source: author's calculation based on the OECD input-output database and TiVA database. d. The Impulse Response of Carbon Emission Intensity to the Technological Spillover of *INTBack*. Source: author's calculation based on the OECD input-output database and TiVA database.

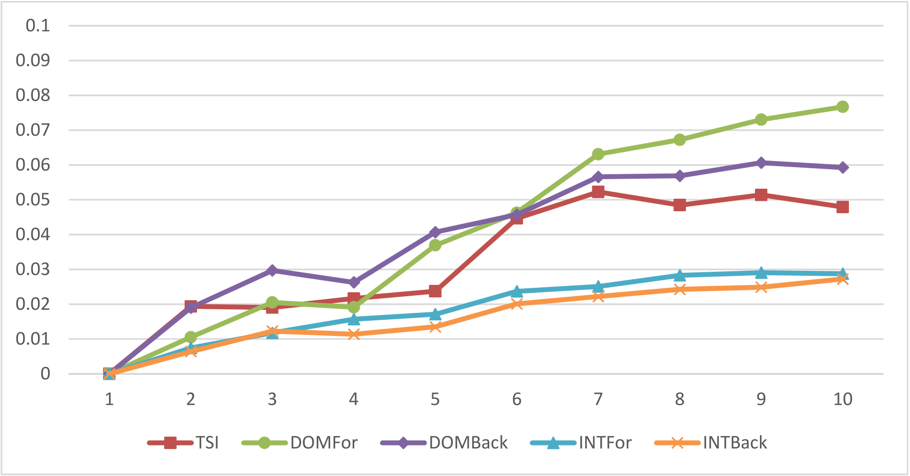

Fig. 3. Variance Decomposition of Carbon Emission Intensity. Source: author's calculation based on the OECD input-output database and TiVA database.

6. Conclusion

This paper uses the data of 50 countries in the TiVA database from 2005 to 2015 to empirically study the relationship of the digital technology innovation, technology spillover and the national carbon emission intensity from three aspects: direct and indirect effects, mechanism identification and persistent paths. Then, the following conclusions are obtained.

It is heterogeneous for the direct and indirect effects of digital technology innovation on the national carbon emission intensity. Although the information industry itself is not an "environmentally friendly industry," the information industry has reduced carbon emission intensity through cross-industry and cross-border technology empowerment. As a whole, the combined impact of digital technology innovation and technology spillover reduces carbon emission intensity at the country level. The domestic backward and forward of the indirect effects have the most prominent emission reduction result which have the largest contribution rate among the five external factors that affect carbon emission intensity and provides a concrete path for reducing the carbon emission intensity. The above conclusion shows that the benefits of digital technology innovation are less than hoped for, especially the carbon emission reduction effects of international technology spillover are not robust. Based on this, when one country attempts to take advantage of the concrete path for reducing the carbon emission intensity, this country needs to increase R&D investment and the introduction of intellectual property to promote the technological

Table 6
Group and time varying test regression results.

	OECD Countries			Non-OECD Economies		
	2005–2008	2009–2012	2013–2015	2005–2008	2009–2012	2013–2015
	(1)	(2)	(3)	(4)	(5)	(6)
ln *TSI*	0.27***	0.25***	0.24***	0.30***	0.29***	0.26***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
ln *DOMBack*	−0.07**	−0.09***	−0.08***	−0.12*	−0.14**	−0.19**
	(0.01)	(0.00)	(0.00)	(0.07)	(0.02)	(0.01)
ln *DOMFor*	−0.07***	−0.10***	−0.12***	−0.01*	−0.02	−0.03
	(0.00)	(0.00)	(0.00)	(0.06)	(0.19)	(0.27)
ln *INTBack*	0.05**	0.09***	0.10**	0.04	0.07	0.06
	(0.02)	(0.00)	(0.01)	(0.57)	(0.49)	(0.12)
ln *INTFor*	−0.20***	−0.23***	−0.25***	−0.05*	−0.07**	−0.12**
	(0.00)	(0.00)	(0.00)	(0.08)	(0.01)	(0.03)
Control Variable	Control	Control	Control	Control	Control	Control
Observations	131	131	105	56	56	42
R^2	0.68	0.77	0.79	0.52	0.67	0.71

Note: "*", "**" and "***" represent the significance level of 10%, 5%, and 1% respectively.

sophistication index of domestic information industry. What's more, it is necessary to strengthen domestic industrial linkages and unblock the upstream and downstream value chains to promote the spillover from digital technology to the other industries in the country.

The adjustment of industrial structure and energy consumption structure are key mechanisms for the technology innovation of the information industry to reduce carbon emission intensity. Countries and regions where the energy structure is dominated by fossil fuels such as petroleum and coal have higher carbon emissions per unit of added value. While the development of the information industry needs to consume a large amount of energy, the empowerment of the information industry is conducive to reducing the proportion of fossil fuels in the energy consumption structure. In order to reduce the intensity of carbon emissions, the EU countries continue to optimize their energy consumption structure, which strive to complete the abandonment of coal and nuclear power by the year 2030. This has a certain blueprint and enlightenment for emerging countries, such as China whose energy consumption structure is dominated by coal. Reducing the proportion of heavy industry and increasing the proportion of the service industry is another mechanism for technology innovation in the information industry to reduce the intensity of carbon emissions. An increase in the proportion of the service industry will significantly reduce the carbon emission intensity of one country. Developed countries transfer assembly, processing and manufacturing linkages to developing countries and maintain R&D, marketing and other service linkages by governing the global value chain [85], which greatly reduces their own environmental pressure. Digital technology innovation promotes a carbon emission reduction mechanism that promotes the service-oriented industrial structure, so that we see the hope of breaking through the zero-sum game strategy of the Pollution Haven Hypothesis.

Compared to OECD countries with developed service industries and reasonable energy consumption structure, emerging economies, including China, enjoy less significant emission reduction effects from digital technology spillover. There are obvious differences in the level of digital technology between developed countries and emerging economies. Only when a country's economic development reaches a certain level can the emission reduction potential empowered by digital technology be fully released. This is bound to cause the "Matthew Effect" on the level of green development. Therefore, all countries should follow the principle of common but differentiated responsibilities, which are according to national conditions and capabilities, in order to maximize actions. Developed countries should earnestly increase the provision of digital technology support to emerging economies.

Our research comprehensively analyzes the direct and indirect effects, and provides new ideas for revealing the feasible paths and related mechanism of carbon emission reduction of digital technology innovation. In addition, we provide empirical evidence on the differences in carbon emission reduction paths between OECD countries and non-OECD economies, which has exposed the bottleneck encountered by non-OECD economies in employing digital technology to empower green development. However, our research work suffers from some limitations. First, the variables related to digital technology innovation and technology spillover are obtained based on the technological sophistication index. Thus, there is a risk of multicollinearity in our regression model. Second, we discuss the four technology spillover effects from the perspective of cross-border and cross-industry. The economic significance and the connection relationship with specific upstream and downstream industries need to be further interpreted, which will make the path of carbon emission reduction more instructive. In our follow-up studies, we will focus on key industries that absorb digital technology spillover and the effects of this part on carbon emissions. Finally, whether the technology spillover from developed countries to developing countries is green technology or dirty technology will also be our future research direction.

Authors' contributions

Lei Wang has made substantial contribution to the conception and design of the work; the acquisition, analysis and interpretation of data for the work. And Lei Wang has drafted the work and revised it critically for important intellectual content.

Yangyang Chen has made important contributions to impulse response analysis, multicollinearity, correlation analysis and comprehensive effect evaluation.

Thomas Stephen Ramsey has contributed to grammatical correctness and paper writing.

Geoffrey J. D. Hewings has contributed a lot in study design and responding to the comments of reviewers.

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Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of me that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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研发数字技术真的能够赋能绿色发展吗？

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摘要：信息产业已经成为拉动世界经济增长的“新引擎”。然而，关于数字技术是否能降低碳排放强度存在诸多争议。基于 OECD 数据、KPWW 方法和多元面板回归，本文探讨了数字技术创新和技术溢出对本国碳排放强度的影响和机制。通过脉冲响应分析和方差分解，我们阐明了数字技术对碳排放强度的综合影响。本文结论显示：信息产业本产业技术创新会提高碳排放强度，而跨行业的技术溢出效应持续且显著降低本国碳排放强度。由于技术溢出的减排效应大于技术创新的排放效应，研发数字技术将赋能本国绿色发展。提高非化石能源利用比重、优化产业结构是数字技术创新降低碳排放强度的有效机制。

关键词：数字技术；技术溢出；碳排放强度

1 引言

信息产业[1]已成为数字经济时代驱动世界经济增长的“新引擎”，在全球经济发展议程中占据重要位置（UNCTAD，2019）。近年来，区块链技术、3D 打印技术、物联网、5G、云计算、自动化和机器人、人工智能和数据分析等前沿数字技术的研发和推广，使越来越多的价值链环节实现数字化连接。根据中国信息通信研究院（CAICT，2018）的数据，2017 年 G20 国家数字经济总量达到 26.17 万亿美元，比 2016 年增长 8.64%，显著领先于各国国内生产总值（GDP）同期增长率。信息产业的出现和普及通常被认为有利于社会和经济发展（Zhou et al. 2019）。然而，关于信息产业发展对环境的影响尚未达成普遍共识。一些研究认为，信息产业将通过跨行业技术溢出来改善环境，包括从制造业向服务业的产业结构升级以及改变能源消费结构（Feuerriegel et al. 2016; Cecere et al. 2014; Daim et al. 2009）。在中国信息产业高速发展时期，中国能源消费结构就得到显著优化（中国国务院新闻办公室，2020）[2]。另一方面，世界信息产业本身的碳排放总量在达到峰值后稳定在 1.8 亿吨，并未随着信息产业的技术创新而减少（OECD，2019）。因此，一些学者在担心信息产业的制造、运营和物流带来负面环境效应，进而导致信息产业技术创新无法减少碳排放（Ercan et al. 2016, Belkhir & Elmeligi, 2018; Joyce

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[1] OECD 首先提出了信息产业的概念，包括硬件设施、数字商品和可以保证数字交易顺利进行的服务。本文借鉴经合组织的分类方法，将（1）计算机、电子和光学产品，（2）出版、视听和广播活动，（3）电信（4）IT 和其他信息服务定义为信息产业。

[2] 2019 年中国化石能源消费比重较 2012 年下降 10.8%。清洁能源消费比重持续上升，2019 年占比 23.4%，较 2012 年上升 5.6 个百分点。

et al. 2019）。要明确研发数字技术对环境的影响，需要探索信息产业技术创新导致碳排放增加的原因和降低碳排放的路径。

研究表明，通过技术溢出实现跨行业减排是信息产业节能减排的重要途径。Prajogo & Olhager（2012）认为，信息产业通过路线优化、容量分配和物联网等技术显著降低了物流行业的碳排放强度。Yadegaridehkordi et al.（2021），Hilty et al.（2014）和 Spinuzzi（2012）研究了智能家居系统、环保酒店和远程办公系统对减少供水和供暖行业碳排放的影响。Xu & Li（2019）分析了工业互联网技术应用于传统行业的碳减排效果。在传统制造业机器上安装传感器和芯片后，借助 5G 技术，企业可以随时控制和部署每台机器的工作，以最佳、最快、最及时的完成决策。同时，借助大数据和机器学习，数据收集和分析将带来更高效的生产方式，不断降低碳排放强度。综上所述，信息产业技术溢出的跨行业减排路径可归纳为以下五个方面：（1）生产过程模拟；（2）产品和服务的智能化设计和运营；（3）智慧物流配送；（4）大数据匹配买卖双方；（5）远程办公。

上述研究结论为分析数字技术创新对环境的影响提供了重要指导，但相关研究主要基于案例研究和统计分析，下列问题仍有待补充完善。（1）信息产业技术创新和技术溢出对碳排放强度的正负效应仍需实证分析验证。（2）此外，数字技术溢出的跨行业减排效应能否弥补信息产业规模扩张对环境的负面影响，也是判断信息产业是否为环境友好型产业的关键问题。（3）最后，新兴经济体长期以来被视为发达经济体“污染避难所”。这一零和博弈困境能否在全球价值链加速信息产业的跨国技术溢出后得到缓解，仍有待厘清。为探讨上述问题，（1）本文在分析数字技术的影响时，将数字技术创新的直接效应与数字技术赋能传统产业和国外产业的间接效应置于统一的分析框架中。（2）利用脉冲响应模型对信息产业技术创新的直接和间接影响进行量化比较。然后，结合直接效应和间接效应，确认信息产业技术创新对碳排放强度的综合效应。（3）本文识别并构建了数字技术赋能本国绿色发展的影响机制，并且进一步明确了经合组织国家和非经合组织经济体实现节能减排的可持续路径。

本文其余部分安排如下：第 2 部分，我们回顾了有关数字技术创新、技术溢出和碳排放强度关系的文献，以设计可验证的假设。第 3 部分介绍了绿色发展、数字技术创新、技术溢出的概念、测度指标以及本文计量模型。第 4 部分汇报了数字技术创新对环境的直接和间接影响模型和影响机制实证分析结果。第 5 部分通过脉冲响应分析衡量了直接效应和间接效应，采用方差分解方法明确了研发数字技术对本国碳排放强度的综合影响。接着，通过稳健性检验分析，进一步探讨信息产业跨行业和跨国界技术溢出对在时间维度是否具持续性，在地区层面是否具有普遍性。最后一部分为本文结论和启示。

2 文献综述和假说提出

2.1 数字技术创新对碳排放的直接效应

自 Roberts（2009）以来，数字技术创新与碳排放之间的关系一直备受关注。由于数字技术代表了科技和产业的未来发展方向，其在减少碳排放方面的作用备受期待。随着相应统计指标和定量分析的出现，数字技术在绿色发展中的作用开始受到质疑（Ospina & Heeks，2010）。数字技术对一个国家来说可能很前沿但不利于绿色发展，反之亦然（Akande et al.2019）。

部分研究认为，企业的技术吸收能力直接决定了创新绩效（Gkypali，2018）。因此，数字技术创新吸收能力不足和绿色技术利用不足被认为是发展中国家数字技术创新未能减少碳排放的原因（Danish et al. 2018a；Nizam et al. 2020；Su et al. 2021）. Altinoz et al.（2020） 认为，在墨西哥、印度、巴西和俄罗斯等前 10 大新兴市场，互联网使用和固定电话用户对环境污染产生了正向推动效应。当研究对象成为东盟（ASEAN）的 9 个成员时，数字技术仍然显示出对碳排放非常显著的正向影响（Lee & Brahmasrene，2016）。在调查了区块链技术对马来西亚公司的影响后，Fernando et al.（2021）得出结论，区块链技术不能显著减少碳排放。

随着针对发达国家数字技术创新与碳排放之间关系的研究出现，数字技术创新被认为在发展中国家和发达国家都不利于绿色发展（Arshad et al. 2020）。Raheem et al.（2019）使用 PMG 方法发现，数字技术对 G7 国家的碳排放产生了正向影响。Park et al.（2018）使用 2001-2014 年期间的欧盟地区数据表明互联网使用与碳排放之间存在显著的正相关关系。一些研究认为，没有考虑数字技术在电力、能源、农业、交通和服务业等信息产业以外部门的减排潜力，是上述研究得出数字技术创新不能减少排放结论的主要原因（Moyer & Hughes，2012；Pan et al.，2017；Zhou et al.，2019）。

综上所述，如果不考虑数字技术创新的跨行业和跨国界减排效应，信息产业创新将对本国碳排放产生正向影响。无论这个国家属于 G7 集团、经济合作与发展组织（OECD）等成熟经济体，还是属于“一带一路”倡议（OBOR）、东盟等新兴经济体，都满足以下假设：

H1：本国碳排放强度受信息产业本产业技术创新的正向影响。

2.2 数字技术创新对碳排放的间接效应

已有研究在探索 GDP、碳排放和数字技术之间的长期关系时引入了环境库兹涅茨曲线 （EKC）（Amri，2018；Arshad et al.，2020 ；Barış-Tüzemen et al.，2020；Khan et al.，2020；Anser et al.，2021）。数字技术创新逐步实现的跨行业和跨国界技术溢出被认为是倒 U 型曲线从顶点下降的原因（Shabani & Shahnazi，2019；Murshed，2020）。对这一议题的研究按照技术溢出范围分为两个研究方向：

跨行业数字技术溢出和跨国界技术溢出。

在跨行业数字技术溢出方面，Mulder et al.（2014）认为，从 1980 年到 2005 年，数字技术的介入对 18 个经合组织国家 23 个服务部门的绿色发展具有重要作用。当数字技术溢出到农业、传统制造业和建筑业时，也有利于降低碳排放强度（Koomey et al. 2013; Shehzad et al. 2020; Walzberg et al. 2020）。对数字技术在各行业的具体应用案例分析表明，数字技术通过引入智能电网、数字交通系统、智慧城市和能源的有效利用来降低碳排放水平（Funk，2015；Higón et al. 2017；Latif et al. 2017；Danish et al. 2018b）。

“干中学”这一出口企业跨国界接受技术溢出的现象同样受到关注（Gkypali，2018；Klingler-Vidra et al. 2021）。另一类文献发现跨国界数字技术溢出的碳减排效应后，主张放宽贸易壁垒，促进信息产业产品跨境流动（Shabani & Shahnazi，2019；Murshed，2020；Ahmed & Le，2021）。然而，新兴经济体在引入数字技术时应警惕“污染避难所”假说（PHH）。发达国家数字技术溢出到发展中国家带来便捷的连接性和充足的商机时，也能够将其高污染技术转移到环境监管宽松的发展中国家（Destek & Okumus, 2019；Ulucak et al. 2020； Ahmed et al. 2021）。综合数字技术在跨行业溢出和跨国界溢出中的表现，本文提出如下假设：

H2：跨国界和跨行业技术溢出对本国碳排放强度产生负向影响。

2.3 数字技术创新对本国碳排放强度的综合效应

由于数字技术创新的直接和间接碳排放效应不尽相同，因此相关研究关于数字技术对碳排放强度的综合影响得出了不同的结论。Nguyen et al.（2020）和 Faisal et al.（2020）都使用 FMOLS 方法研究数字技术创新对碳排放强度的长期影响。Nguyen et al.（2020）得出的结论是，数字技术创新是 G20 国家碳排放的正向驱动因素，而 Faisal et al.（2020）认为随着数字技术创新的增加，污染在达到阈值后会下降。

第二类研究采用生命周期分析（LCA）来探索数字技术创新对碳排放的直接和间接影响。Malmodin & Lundén（2018），Pohl et al.（2019）和 Court & Sorrell（2020）认为（1）信息产业的碳足迹明显小于之前的预测值；（2）数字技术已经产生了显著的减碳效果，并且在未来很可能也会如此。

第三类文献使用自回归分布滞后（ARDL）方法。研究结果表明数字技术创新与碳排放强度之间的长期关系并不显著。Salahuddin et al.（2016a）使用澳大利亚的宏观数据，发现互联网使用与碳排放之间没有显著的长期关系。Amri （2018）采用 ARDL 方法和突尼斯数据，发现数字技术对碳排放量的影响微不足道。Salahuddin et al.（2016b）在衡量经合组织国家互联网使用对碳排放的影响时，将 PMG 方法纳入 ARDL 模型。研究发现互联网使用与碳排放之间不存在因果关系。

鉴于上述结果的巨大差异，准确衡量数字技术创新和技术溢出对碳排放强度的综合效应是一项具有挑战性的任务。这项工作对于环境政策的制定方向和信息产业的长远发展具有深远意义（Røpke & Christensen，2012；Jiang & Liu，2015；Asongu，2018；Zhou et al. 2018；Chen et al. 2019a）。根据上述文献的实证结果，我们提出并检验以下假设：

H3：数字技术创新的综合影响对本国碳排放强度产生负向影响。

2.4 数字技术创新影响碳排放强度的机制分析

已有文献不仅研究数字技术创新对绿色发展的影响，还关注数字技术创新赋能绿色发展的机制（Shobande & Ogbeifun，2021）。相关文献从提升非化石能源消费水平、提高能源效率和优化产业结构三个方面探讨了数字技术创新降低碳排放强度的机制。

在提高非化石能源消费水平方面，Ahmed et al.（2017）证实，数字技术的跨行业、跨国界溢出不仅可以增加非化石能源的产量，还可以有效地储存这些能源，从而刺激非化石能源消费比重的提高。此外，数字技术创新还有效促进了非化石能源使用成本的降低（Lai et al. 2017；Murshed & Tanha, 2020）。

诊断和处理能源生产、运输和消费系统中不合理和低效的环节以提高能源利用效率是数字技术创新降低碳排放强度的另一种机制（Schulte et al. 2016；World Energy Council, 2018；Pasichnyi et al. 2019）。因此，有学者预计，到 2020 年，数字技术与能源部门的融合将使全球碳排放强度降低 3.5%至 6.3%（Casal et al. 2005）。但是，也有学者认为，数字技术创新对节能减排效率的提升慢于行业扩张速度（Sadorsky, 2012；Salahuddin & Alam., 2016；Haseeb et al. 2019）。事实上，随着信息产业产品复杂度的增加，产品能消与产值的比值不断下降。根据 Koomey 定律，中央处理器的能耗将每 1.5 年减半（Koomey et al. 2011）。这意味着虽然信息产业在节能减排效率方面不断进行技术创新，但是节能技术的创新速度始终赶不上信息产业规模扩张速度。另一个“看衰”数字技术赋能绿色发展的理由是技术创新没有得到相应的经济增长补偿（Reinsdorf et al. 2018）。例如，虽然第 12 代和第 10 代苹果手机在首次发布时的售价几乎相同，但根据摩尔定律，其计算速度翻了一番（Lange et al. 2020）。

比较新兴经济体和成熟经济体的绿色发展经验，越来越多的文献开始讨论产业结构转型对碳排放的影响（Wang et al. 2019；Zhang et al. 2018；Yu et al. 2015）。Chen（2019b）利用世界投入产出数据库（WIOD）的数据证明，中国产业结构从制造业向服务业的转变对全球碳排放的减少具有积极作用。同时，数字技术创新在推动产业结构转型中的作用也引起了学者们的关注，特别是数字技术驱动的数字经济（Cardona et al. 2013; Bastida et al. 2019）。因此，本文提出以下机制假设：

H4a：提高非化石能源使用比例是数字技术创新降低本国碳排放强度的机制之一。

H4b：优化产业结构是数字技术创新降低本国碳排放强度的又一机制。

3 研究方法

3.1 用 KPWW 方法衡量绿色发展

本文重点分析 Koopman、Powers、Wang 和 Wei（KPWW, 2010）方法在碳足迹问题上的应用。解释变量用单位增加值碳排放量（CG_r^*）和单位最终产品碳排放量（CG_r）表示，代表本国绿色发展水平。为了衡量一个经济体的绿色发展水平，我们需要衡量单位 GDP 和单位最终产品的碳排放量。国际能源协会提供的“燃料燃烧产生的二氧化碳排放”数据和经合组织国际投入产出表提供的产值数据只能估算单位产值的二氧化碳排放量。如果想实现单位产值二氧化碳排放量转化为单位增加值碳排放量，就需要追溯二氧化碳的来源。KPWW 方法广泛用于贸易中增加值的追溯和分解（Koopman et al. 2010, 2014）。当增加值系数被单位产出投入劳动力系数和单位产出碳排放系数取代时，增值分解方法扩展到全球工作分配领域（Timmer et al. 2013）和碳足迹问题（Wiebe & Yamano，2015）。本文在计算单位 GDP 碳排放量时也是基于这种方法。

$$VBY=\begin{bmatrix} V_rB_{rr}Y_r & V_rB_{rs}Y_s & V_rB_{rt}Y_t \\ V_sB_{sr}Y_r & V_sB_{ss}Y_s & V_sB_{st}Y_t \\ V_tB_{tr}Y_r & V_tB_{ts}Y_s & V_tB_{tt}Y_t \end{bmatrix} \rightarrow CBY=\begin{bmatrix} C_rB_{rr}Y_r & C_rB_{rs}Y_s & C_rB_{rt}Y_t \\ C_sB_{sr}Y_r & C_sB_{ss}Y_s & C_sB_{st}Y_t \\ C_tB_{tr}Y_r & C_tB_{ts}Y_s & C_tB_{tt}Y_t \end{bmatrix} \tag{1}$$

如式（1）所示，B 是著名的 Leontief 逆矩阵。Y 是最终产品向量，BY 表示总产出。当增加值系数 V 被碳排放因子 C 替代时，最终产品的增值分解也转化为最终产品消费的碳排放分解。

$$DV_r=V_rB_{rr}Y_r \rightarrow DC_r=C_rB_{rr}Y_r \tag{2}$$

$$FV_r=V_sB_{sr}Y_r+V_tB_{tr}Y_r \rightarrow FC_r=C_sB_{sr}Y_r+C_tB_{tr}Y_r \tag{3}$$

$$IV_r=V_rB_{rs}Y_s+V_rB_{rt}Y_t \rightarrow IC_r=C_rB_{rs}Y_s+C_rB_{rt}Y_t \tag{4}$$

在式（2）和式（3）中，最终产品的产值按照增加值的归属划分为 r 国的国内增加值和国外增加值。同样的，r 国最终产品所产生的碳排放量，也按照生产来源分为 r 国国内碳排放量和国外碳排放量。如式（4）所示，矩阵（1）非对角线元素按行求和提供了国家 r 中间产品蕴含在其他国家最终产品中的增加值和碳排放量信息。

$$Y_r=DV_r+FV_r \rightarrow CC_r=DC_r+FC_r \tag{5}$$

$$GDP_r=DV_r+IV_r \rightarrow CS_r=DC_r+IC_r \tag{6}$$

式（5）首先呈现了 r 国最终产品的总附加值构成。接着，CC_r 反映了 r 国的最终产品产生碳排放由国内排放和国外排放共同构成。式（6）表示 r 国（GDP_r）从国内外最终产品中获得的增加值，CS_r 代表 r 国碳排放的国家和行业来源。因

此，r 国最终产品需求端蕴含的碳排放 FDC_r 和 r 国产品供给端的碳排放 PEC_r 如式（7）和式（8）所示：

$$FDC_r = CC_r + FNLC_r \tag{7}$$

$$PEC_r = CS_r + FNLC_r \tag{8}$$

其中 $FNLC_r$ 是家庭燃烧公用事业和运输燃料引起的直接排放向量。为确保将所有排放考虑在内，需要将这些排放添加到矩阵 CC_r 或 CS_r 的排放中。 因此，CG_r 是每单位最终需求产值基于需求的碳排放量。 CG_r^* 表示每单位 GDP 的基于生产的碳排放量。

$$CG_r = FDC_r / Y_r \tag{9}$$

$$CG_r^* = PEC_r / GDP_r \tag{10}$$

3.2 衡量核心解释变量：信息产业技术创新水平

本文的核心解释变量包括本国信息产业自身的技术创新和信息产业对跨行业、跨国界技术溢出两部分。这部分采用 Haussman（2008）和 Liu（2015）的方法，利用技术复杂度指数（TSI）来衡量本国信息产业的技术创新。TSI 测量如下：

$$TSI_r^i = \frac{x_r^i / X_r}{\sum_r x_r^i / \sum_r X_r} Y_r = RCA_r^i Y_r \tag{11}$$

其中 X_r 和 Y_r 分别是国家 r 的总产值和人均 GDP。 x_r^i 是 r 国 i 产业的出口值。因此，TSI_r^i 本质是显性比较优势指数（RCA）（Balassa，1965）与劳动生产率的乘积，通过劳动生产率与国际竞争力的交互关系反映产业技术水平。

我们对 Haussman 提出的产品复杂度指标进行了两项改进。首先，有必要从增加值和全球价值链（Global Value Chains，GVCs）的角度来衡量 TSI 以保持统计口径的一致性。为了明确碳排放的来源，本文从全球价值链的角度分别测算了供给型和需求型碳排放量。因此，在衡量技术创新时也应该基于增加值视角。式（11）中的出口值 X_r 被转换为增加值出口（VAX），如式（12）所示。 Johnson（2012）将 VAX 定义为由一个经济体产生并最终在其他经济体中消费的增加值。例如，VAX_r 包括 r 国从 s 国和 t 国的最终产品消费中直接和间接吸收的增加值。本文借鉴 Koopman et al.（2010）以及 Los et al.（2016）的方法改进 RCA 指数，将其转化为显示性增值比较优势指数（RVCA）。因此，从 GVCs 的角度来看的 TSI 如公式 (13) 所示。

$$VAX_r = (V_r \quad 0 \quad 0)\begin{bmatrix} B_{rr} & B_{rs} & B_{rt} \\ B_{sr} & B_{ss} & B_{st} \\ B_{tr} & B_{ts} & B_{tt} \end{bmatrix}\begin{bmatrix} 0+Y_{rs}+Y_{rt} \\ 0+Y_{ss}+Y_{st} \\ 0+Y_{ts}+Y_{tt} \end{bmatrix} = V_r B_{rr}(Y_{rs}+Y_{rt}) + V_r B_{rs}(Y_{ss}+Y_{st}) + V_r B_{rt}(Y_{ts}+Y_{tt}) \tag{12}$$

$$TSI_r^{i'} = \frac{VAX_r^i / VAX_r}{\sum_r VAX_r^i \Big/ \sum_r VAX_r} Y_r = RVCA_r^i Y_r \tag{13}$$

此外，我们还考虑了海外技术引进因素。因为劳动生产率与国际竞争力的相互作用反映了国家自主研发的技术创新水平。随着全球化和垂直专业化的不断深入，各国纷纷引进和吸收大量国外专利技术，有效提高了本国产品的 TSI。考虑引进国外技术后的 TSI 测算如下。其中，IP_r 表示 r 国引进专利时的支出。

$$TSI_r^{i'} = RVCA_r^i * Y_r * IP_r \tag{14}$$

3.3 衡量信息产业的技术溢出

信息产业的跨行业、跨国界技术溢出也是本文的核心解释变量。以往的文献主要使用案例研究来评估技术创新的间接效应（Almeida et al. 2021）。本文试图通过实证分析来衡量数字技术溢出。根据价值链上下游的前向关联和后向关联，信息产业的技术溢出可分为前向技术赋能和后向技术赋能。前向技术赋能是指信息产业的技术外溢，增加下游产业的 TSI。后向技术赋能是指数字技术创新后对上游产业的技术需求增加。即上游产业的 TSI 增加，以满足信息产业发展的需要。此外，考虑到全球价值链和国内价值链的区别，数字技术赋能还可以分为国内技术赋能和国际技术赋能。根据价值链上游、下游、国内和国外的分类标准，本文共引入四种数字技术赋能绿色发展方式。

$$DOMFor_r^i = TSI_r^{i'} * \sum_{j=1, i\neq j}^{n} g_{rr}^{ij} \tag{15}$$

$$INTFor_r^i = TSI_r^{i'} * \sum_{s=1, r\neq s}^{n} \sum_{j=1}^{n} g_{rs}^{ij} \tag{16}$$

$$DOMBack_r^i = \sum_{j=1, i\neq j}^{n} b_{rr}^{ji} * TSI_r^{i'} \tag{17}$$

$$INTBack_r^i = \sum_{s=1, r\neq s}^{n} \sum_{j=1}^{n} b_{sr}^{ji} * TSI_r^{i'} \tag{18}$$

$DOMFor_r^i$ 代表信息产业的国内技术赋能，代表国内信息产业 i 的技术应用到下游产业 j 后，j 产业的 TSI 增加。在等式（15）中，g_{rr}^{ij} 是 Ghosh 逆矩阵中国家 r 的块矩阵中的元素。将该分块矩阵按行求和，得到单位 i 产品嵌入下游 j 行业的比例 $\sum g_{rr}^{ij}$。将供给系数 $\sum g_{rr}^{ij}$ 与产品 TSI 相结合，得到信息产业的国内技术赋能。式（16）将 Ghosh 逆矩阵中的元素逐行求和，得到总投入系数 $\sum\sum g_{rs}^{ij}$，即嵌入国外最终产品的 r 国信息产业中间产品比例。以此为基础，获得信息产业的国际前向技术赋能 $INTFor_r^i$。在构建信息产业国内后向技术赋能系数 $DOMBack_r^i$ 时，我们在式（17）中将 Ghosh 逆矩阵中的元素 g_{rr}^{ij} 替换为 Leontief 逆矩阵的块矩阵元素 b_{rr}^{ji}。式（18）对 r 国海外完全消耗系数矩阵的元素 b_{sr}^{ji} 逐列求和，最终得到国际后向技术赋能。

3.4 模型设计和变量选择

本文试图分析信息产业日益增长的 TSI 是否会促进本国绿色发展。模型设计时，不仅考虑了信息产业技术创新对国内碳排放强度的影响，还讨论了信息产业

跨行业、跨国界技术溢出的碳减排效果。基准回归模型如下：

$$\ln CG_{rt} = \beta_0 + \beta_1 \ln TSI_{rt}^{i'} + \beta_2 \ln DOMBack_{rt}^{i} + \beta_3 \ln DOMFor_{rt}^{i} + \beta_4 \ln INTBack_{rt}^{i} + \beta_5 \ln INTFor_{rt}^{i} + \beta_6 \sum \ln Control_{rt}^{i} + \mu_r + \mu_t + \varepsilon_{rt}^{i}$$

（19）

其中 r 代表经济体，i 代表行业，t 代表年份。被解释变量碳排放强度 CG_r 和核心解释变量信息产业技术创新 $TSI_r^{i'}$ 、信息产业国内前向技术赋能 $DOMFor_r^i$ 、国际前向技术赋能 $INTFor_r^i$ 、信息产业国内后向技术赋能 $DOMBack_r^i$ 和国际后向技术赋能 $INTBack_r^i$ 。$\sum \ln Control_{rt}^i$ 是控制变量的集合。由于 Grossman & Krueger（1995）和 Hubler & Keller（2010）认为经济活动与环境的关系包括规模效应、结构效应和技术效应三个方面，在选择控制变量时，我们将规模效应作为对核心解释变量所涉及的技术效应和结构效应的补充。本文反映规模效应的控制变量有：（1）信息产业规模（ VA ）。数字技术能否得到广泛推广和应用，取决于信息产业的规模。本文采用信息产业的行业增加值来表示信息产业的规模。（2）碳排放造成的经济损失（ $Damage$ ）。Xu（2016）的研究指出，新兴国家工业化进程中的经济增长伴随着大量的污染物排放。另外，污染物排放量的增加导致环境监管力度加大。因此，部分地区形成了“先污染后治理”的发展模式。鉴于环境污染造成的损失与更严格的环境法规并存，本文预测碳排放造成的经济损失扩大将降低碳排放的强度。本文用环境污染造成的经济损失占国民收入的百分比来表示这一变量。（3）对外直接投资（ $OFDI$ ）。Song（2011）的研究表明，FDI 的流出伴随着东道国的技术溢出，可以降低投资国的碳排放强度。本文使用对外直接投资净值与 GDP 的比率来表示这一变量。

3.5 数据

碳排放强度数据基于经合组织投入产出数据库和国际能源理事会“燃料燃烧二氧化碳”数据计算得出。TSI 来自经合组织贸易增加值（TiVA）数据库（国内出口总额和出口总额的增加值）以及世界银行数据库中的专利费数据（知识产权使用费）。经合组织数据库中共有 64 个经济体。信息产业规模和服务业占 GDP 比重的数据也来源于 TiVA 数据库（增加值）。能源结构和对外直接投资数据来自世界银行数据库（化石燃料能源消耗和对外直接投资净值）。剔除数据缺失的经济体后，选取 2005-2015 年 50 个经济体[3]的数据进行实证分析。表 1 提供了上述变量的一些描述性统计数据。碳排放强度（ CG ）的单位是吨/千美元。信息产业规模单位为十亿美元（ VA ）。表 2 展示了相关性分析结果，数据表明大部分变量

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[3] 本文选取的 50 个经济体包括所有 36 个经合组织成员国和 14 个非成员经济体。这 50 个经济体特别涉及澳大利亚、奥地利、比利时、加拿大、智利、捷克共和国、丹麦、爱沙尼亚、芬兰、法国、德国、希腊、匈牙利、冰岛、爱尔兰、以色列、意大利、日本、韩国、拉脱维亚、立陶宛、 卢森堡、墨西哥、荷兰、新西兰、挪威、波兰、葡萄牙、斯洛伐克、斯洛文尼亚、西班牙、瑞典、瑞士、土耳其、英国、美国、阿根廷、巴西、保加利亚、中国、哥伦比亚、古巴、克罗地亚、塞浦路斯、印度 、印度尼西亚、马耳他、罗马尼亚、俄罗斯、南非。

与碳排放强度存在相关性。相关系数表明数字技术创新与碳排放强度之间存在很强的正相关关系。数字技术溢出与碳排放强度呈负相关。

<<此处插入 表1>>

<<此处插入 表2>>

4 实证分析

4.1 数字技术创新对本国碳排放强度的影响

4.1.1 基准模型结果分析

本节首先从结构特征角度报告了数字技术创新对国家碳排放强度的影响。我们不仅估计了数字技术创新对国家碳排放强度的“直接效应”，还测算了数字技术跨行业、跨国界技术溢出对国家碳排放强度的“间接效应”。由于信息产业的技术溢出带动了国内国际、上下游产业的技术创新，“间接效应”被分为国内前向、国内后向、国际前向和国际后向。然后，通过比较回归系数的大小和显著性，我们探索了数字技术创新和技术溢出降低碳排放强度的有效路径。最后，这一部分以“直接效应”和“间接效应”的回归系数统计与比较说明了数字技术创新和技术溢出对碳排放强度的综合影响。

<<此处插入 表3>>

表 3 报告了数字技术创新对国家碳排放强度的影响，包括“直接效应”和“间接效应”。第（1）列的结果只考虑了“直接效应”和数字技术溢出对国内前向和后向赋能的“间接效应”。第（2）列还考虑了数字技术溢出对国际产业赋能的“间接效应”。实证结果发现，“直接效应”的回归系数为正，即信息产业自身的技术创新（$\ln TSI$）会增加国家碳排放强度。实证结果证实了我们的第一个假设（H1）。这也是 Zhou（2019）认为信息产业本身不是“环境友好型产业”的主要原因。数字技术变化频繁，设备淘汰更新速度极快，消耗了大量的化学、金属和非金属材料，导致更多的碳排放（Cho et al. 2007; Zhou et al. 2018）。新一代升级的数字产品虽然技术含量更高，但价格保持稳定，导致单位附加值碳排放量增加（Lange et al. 2020）。因此，信息产业本身的技术创新推高了碳排放强度。

然后，我们分析了数字技术创新的“间接效应”。结果显示通过信息产业赋能其他产业，有利于降低碳排放强度。在“间接效应”中，国内后向赋能对国家碳减排的影响最为突出。回归结果第（2）列显示，如果数字技术对国内后向行业的技术溢出每增加 1%，国内碳排放强度将下降 0.21%。其次是国际前向赋能和国内前向赋能，国家碳排放强度分别下降 0.11%和 0.09%。但信息产业赋能国际后向产业并不会显著降低国内碳排放强度。因此，信息产业为国内上游原材料和制造业（后向产业）赋能，更好地适应数字经济发展的需要，是降低信息产业碳排放强度的最佳途径。这一结果与 Peng et al.（2015）等人的研究结果相呼应。

他们的研究支出，作为世界工厂，中国上游生产侧排放大于下游消费侧排放。因此，中国降低国内上游生产环节的碳排放强度是有效遏制中国碳排放的“重中之重”。总结第（2）列的回归系数显著性和符号可知：数字技术溢出有效地降低了本国碳排放强度，从而证实了我们的第二个假设（H2）。

第（3）列进一步关注了国家层面可能影响碳排放强度的控制变量，包括产业规模（$\ln VA$）、碳排放造成经济损失（$\ln Damage$）和对外直接投资净值（$\ln OFDI$）。这些控制变量与国家碳排放强度负相关。信息产业规模的扩大（$\ln VA$），将有利于其赋能更多传统产业升级发展，将信息产业为基础的智能革命与以新能源为基础的绿色发展相结合。碳排放造成的经济损失增加（$\ln Damage$）将导致更严格的环境法规，这将“倒逼”本国绿色发展（Xu，2016）。OFDI 则通过反向绿色技术溢出效应提高绿色全要素生产率（Song, 2011）。

4.1.2 稳健性检验结果分析

主流的稳健性检验方法分为两类。一类是更换核心解释变量、核心被解释变量等指标的稳健性检验，另一类是改变估计方法的稳健性检验。由于描述碳排放强度和数字技术创新的指标众多，本文采用第一类方法，通过使用被解释变量和解释变量的替代指标来避免特定指标对回归结果产生的偏误。单位产出碳排放量用于替代单位增加值碳排放量。实证结果呈现在表 4 的第（1）和（2）列中。然后，在第（3）和（4）列中使用五个解释变量的滞后项进行回归，以测试基准模型结果的稳健性。改变被解释变量和解释变量后，“直接效应”的回归系数仍为正。此外，数字技术创新的“间接影响”仍将显著降低碳排放强度。整体而言，信息产业的技术创新在稳健性检验中有效降低了国家碳排放强度。由于稳健性检验的结果与基准模型的结果一致，证明了本文的估计结果是可靠的。稳健性检验也进一步证实了假设 H1 和假设 H2。

<<此处插入 表4>>

4.2 机制检验

优化产业结构和能源消费结构是提高能源使用效率、降低碳排放强度的重要途径。信息产业技术水平的提高能否优化产业结构和能源消费结构，进而降低碳排放强度，是这部分的重点研究内容。中介效应分析是检验产业结构或能源消费结构是否成为中介变量以及在多大程度上发挥中介作用的重要步骤。中介效应分析的变量如下文所述。（1）能源消费结构（$Energy$）。Chen（2011）指出：化石能源使用比例的降低或清洁能源生产力的提高是碳排放强度下降的决定性因素之一。因此，本文采用世界银行数据库中的化石能源消费比例来反映能源消费结构。（2）产业结构（$Service$）。由于生产部门的产业结构变化导致碳排放强度发生显著变化，本文以经合组织投入产出表中的服务业增加值与 GDP 之比作为衡量产

业结构的指标。机制检验模型如式（17）和（18）所示。

$$\ln Structure_{rt}^{i}=\delta_0+\delta_1\ln TSI_{rt}^{i}+\delta_2\ln DOMBack_{rt}^{i}+\delta_3\ln DOMFor_{rt}^{i}+\delta_4\ln INTBack_{rt}^{i}+\delta_5\ln INTFor_{rt}^{i}+\ln X_{rt}^{i}+\mu_r+\mu_t+\varepsilon_{rt}^{i} \qquad （17）$$

$$\ln CG_{rt}^{i}=\delta_0+\delta_1\ln TSI_{rt}^{i}+\delta_2\ln DOMBack_{rt}^{i}+\delta_3\ln DOMFor_{rt}^{i}+\delta_4\ln INTBack_{rt}^{i}+\delta_5\ln INTFor_{rt}^{i}+\delta_5\ln Structure_{rt}^{i}+\ln X_{rt}^{i}+\mu_r+\mu_t+\varepsilon_{rt}^{i} \qquad （18）$$

$$Structure\in\{Energy,\ Service\}$$

表 5 报告了中介效应检验的回归结果。表 5 第（1）列至第（4）列是关于降低化石燃料消费比例是否是数字技术创新和数字技术溢出的机制检验。第（1）列的结果表明，信息产业技术创新显著提高了化石燃料消费的比重。信息产业 TSI 每增加 1%，化石能源消费比重将增加 0.08%，这表明信息产业本身并不是“环境友好型产业”。但是，信息产业的跨国界和跨行业技术溢出显著降低了化石能源消费比重。信息产业对国内外下游产业外溢的 TSI 每增加 1%，化石能源消费在国内外能源消费结构中的比重将分别下降 0.03%和 0.04%。信息产业向上游产业外溢后，能源消费结构不会发生明显变化。

表 5 第（2）列显示了能源消费结构对碳排放强度的影响。化石能源消费比重每增加 1%，碳排放强度将增加 0.94%。结果证实，能源消费结构以石油、煤炭等化石燃料为主的国家碳排放强度较高。为降低碳排放强度，欧盟国家不断优化能源消费结构，力争在 2030 年前后完成弃煤、弃核，探索可持续发展路径，即 2030 年气候目标计划（欧盟委员会，2020）。这对中国等能源消费结构以煤炭为主的新兴国家降低碳排放强度具有一定启示。第（3）列和第（4）列是添加控制变量的回归结果。模型系数和显著性没有明显变化。这证明优化能源消费结构是数字技术外溢降低碳排放强度的有效机制，从而印证了我们的第四个假设（H4a）。

<<此处插入 表5>>

从第（5）列到第（8）列，检验了提高服务业在国民经济中的比重是否是数字技术创新和数字技术溢出降低碳排放强度的机制。第（5）列的回归结果表明，信息产业自身的技术创新并不能显著改变服务业在产业结构中的比重。在数字技术溢出方面，从信息产业向国内上下游产业的技术溢出将显著提升服务业的比重。流入国内上游或下游产业的信息产业 TSI 指数每提高 1%，服务业的比重将分别提高 0.03%和 0.02%。但信息产业的国际技术溢出显著降低了国内服务业的比重。这是因为服务业的非关税壁垒远超制造业，海外服务业很难进入目标国家。因此，这些非关税壁垒削弱了国际技术溢出对信息产业的反馈效应。第（6）列报告了服务业占 GDP 的比重对国内碳排放强度的影响。服务业占 GDP 比重每增加 1%，国内碳排放强度将降低 2.05%。加入控制变量后的回归结果表明，产业结构仍是数字技术外溢降低国内碳排放强度的机制。因此，实证结果证实了我们的最终假设（H4b）。

5 进一步分析

5.1 研发数字技术对本国碳排放强度的综合影响

信息产业的技术创新会增加碳排放强度，而跨国界、跨行业的技术溢出会降低国内碳排放强度。数字技术对碳排放强度的综合影响仍有待探索。本节将采用广义向量自回归（VAR）模型的脉冲响应函数，分析数字技术创新和技术溢出指标对碳排放强度的长期和短期影响。 然后借助 VAR 模型进行方差分解，描述每个冲击效应的重要性。

<<此处插入 图1>>

从图 1 可以看出，碳排放强度在受到信息产业技术创新的正向影响后继续上升，在第四期达到 25%的峰值。因此，从长远来看，信息产业的技术创新将增加碳排放的强度，将持续破坏绿色发展和“双碳”目标。

<<此处插入 图2a 和图2b>>

从图 2a 和图 2b 可以看出，数字技术对国内上下游产业的跨行业溢出将在长期和短期内显著降低国内碳排放强度。这一结论与之前的回归分析一致，数字技术溢出赋能国内上下游产业是一条稳定、节能、减排的路径。

<<此处插入 图2c 和图2d>>

从数字技术跨国界溢出效应来看，碳排放强度的长期和短期效应并不一致。在国际技术溢出对碳排放强度产生正向影响后，第一阶段碳排放强度显著增加。进入第二阶段，碳排放强度保持下降。这一结果与发达国家首先将制造业的数字技术转移到发展中国家进行原始设备制造商（OEM）生产，然后转移到服务业的产业转移顺序有关（Liu，2020；Lange et al. 2020）。机制检验部分也证实，产业结构从制造业向服务业转变是数字技术赋能绿色发展的重要机制。

<<此处插入 图3>>

为了阐明数字技术创新和技术溢出对碳排放强度的综合影响，本文采用方差分解来描绘TSI、$DOMFor$、$DOMBack$、$INTFor$和$INTFor$的动态变化对碳强度排放综合影响的相对重要性。方差分解结果如图 3 所示。数字技术创新的直接影响并不是影响碳排放强度趋势的主要外因。直接效应（TSI）的影响小于国内数字技术的跨行业溢出（$DOMFor$和$DOMBack$），大于信息产业的国际技术溢出（$INTFor$和$INTBack$）。$DOMFor$、$DOMBack$、TSI、$INTFor$和$INTBack$对碳排放强度的贡献率分别为 7.67%、5.93%、4.79%、2.88%和 2.72%。由于在影响碳排放强度的五个外部因素中贡献率最大的国内跨行业技术溢出（$DOMFor$和$DOMBack$）降低了碳排放强度，数字技术创新和技术溢出的综合影响降低了碳排放强度。因此，研发数字技术将赋能绿色发展，这证实了我们的第三个假设（H3）。

5.2 数字技术赋能绿色发展的国家和时间异质性分析

发达国家和新兴经济体的信息产业 TSI 差异很大。发达国家更频繁地使用人工智能、机器学习和智能制造，而新兴经济体很少使用数字技术。这种差异是否会导致发达国家碳排放强度单方面的不断降低是本节的重点。因此，本节将对所有国家样本进行分组回归检验，即分为 OECD 组和非 OECD 组。在时间维度上，数字技术创新与碳排放强度之间的直接效应和间接效应是否具有持续性，对于总结出一条降低碳排放强度的稳定路径具有深远的意义。本文借鉴了 Gkypali et al.（2019）关于技术差距追赶或分歧的路径依赖性方法进行以下分析。

<<此处插入 表 6>>

表 6 呈现的回归结果包括三个时段和两个国家分组。分组回归结果确认了数字技术创新对碳排放强度的直接影响持续且显著。然而，OECD 组和非 OECD 组通过数字技术创新间接影响碳排放强度的路径并不一致。表 6 第（1）、（2）和（3）列的回归结果表明，技术溢出到国外上游产业会增加本国碳排放强度。信息产业向国内上下游产业以及国外下游产业技术溢出会降低 OECD 国家的碳排放强度。其中，国外下游产业的技术溢出对降低碳排放强度的持续时间最长，效果最佳。2013-2015 年数字技术每溢出 1%至国外下游，碳排放强度下降 0.25%。与 OECD 国家相比，非 OECD 经济体如第（4）列、第（5）列和第（6）列所示，通过数字技术溢出降低碳排放强度的路径较少。此外，信息产业向国内上游产业的技术溢出是非 OECD 经济体在三个时期降低碳排放强度的主要路径。根据 OECD 投入产出表计算，非 OECD 经济体的信息产业以电子制造业为主，增加了对上游产业零部件和原材料的强劲需求。这些中间产品的碳排放强度降低对于非 OECD 经济体的碳减排至关重要。非 OECD 经济体对国内上游产业的数字技术溢出每增加 1%，2013-2015 年本国碳排放强度将下降 0.19%。考虑到碳排放强度降低的程度和持续时间，OECD 国家比非 OECD 经济体具备更丰富的碳减排路径。这说明数字技术溢出赋能新兴经济体绿色发展仍存在一定瓶颈。

6 结论

本文利用 TiVA 数据库中 50 个国家 2005-2015 年的数据，从直接效应和间接效应、机制识别和持续路径三个方面实证研究了数字技术创新、技术溢出与国家碳排放强度的关系，得到以下结论。

数字技术创新对本国碳排放强度的直接影响和间接影响具有异质性。虽然信息产业本身并不是“环境友好型产业”，但信息产业通过跨行业、跨国界的技术赋能，降低了碳排放强度。总体而言，数字技术创新和技术溢出的综合影响降低了国家层面的碳排放强度。在影响碳排放强度的五个外部因素中，间接效应的国内后向和前向赋能减排效果最为突出，贡献率最大，为降低碳排放强度提供了稳

定路径。上述结论表明，数字技术创新带来的收益不及预期，尤其是国际技术溢出的碳减排效果并不稳健。基于此，当一国试图开辟降低碳排放强度的可持续路径时，该国需要加大研发投入和知识产权引进，以提升国内信息产业的技术复杂度；此外，还要加强国内产业关联，打通国内大循环，促进数字技术向国内其他产业的溢出。

产业结构和能源消费结构调整是信息产业技术创新降低碳排放强度的关键机制。能源结构以石油、煤炭等化石燃料为主的国家和地区，单位增加值碳排放量较高。在信息产业发展需要消耗大量能源的同时，信息产业赋能有利于降低化石燃料在能源消费结构中的比重。为降低碳排放强度，欧盟国家不断优化能源消费结构，力争到 2030 年完成弃煤、弃核。这对新兴国家有一定的启示。降低重工业比重，提高服务业比重，是信息产业技术创新降低碳排放强度的又一机制。服务业比重的提高将显著降低一国的碳排放强度。发达国家将组装、加工和制造环节转移到发展中国家，通过治理全球价值链来维持研发、营销和其他服务环节（Timmer et al. 2013），大大降低了自身的环境压力。数字技术创新推动了碳减排机制，促进了服务型产业结构，让我们看到了突破“污染避难所”假说这一零和博弈结果的希望。

与服务业发达、能源消费结构合理的经合组织国家相比，包括中国在内的新兴经济体借助数字技术溢出的减排效果并不显著。发达国家与新兴经济体的数字技术水平存在明显差异。只有当一国的经济发展达到一定水平时，数字技术赋能的减排潜力才能得到充分释放。这势必造成绿色发展水平上的“马太效应”。因此，各国应遵循共同但有区别的责任原则，根据国情和能力，最大限度地采取环境保护行动。发达国家应切实加大对新兴经济体的数字技术支持力度。

我们的研究综合分析了数字技术赋能绿色发展的直接效应和间接效应，为揭示数字技术创新促进碳减排的可行路径和机制提供了新思路。此外，我们提供了经合组织国家和非经合组织经济体在碳减排路径上存在差异的经验证据，这暴露了非经合组织经济体在利用数字技术赋能绿色发展方面遇到的瓶颈。同时，我们的研究工作仍有所不足。首先，基于技术复杂度指数构建数字技术创新和技术溢出变量使我们的回归模型存在多重共线性风险。其次，我们从跨国界和跨行业的角度讨论了四种技术溢出效应。间接效应的经济意义以及与上下游产业的具体联系有待深入分析，这将使碳减排路径更具指导意义。在后续研究中，我们将重点关注吸引数字技术溢出的关键行业以及数字技术赋能这些行业对碳排放的具体影响。最后，发达国家对发展中国家的技术溢出是绿色技术还是污染技术，也将是我们未来的研究方向。

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表 1 描述性统计

变量	最大值	最小值	均值	标准差	观测值
CG	1.995	0.129	0.434	0.258	539
CG^*	1.080	0.003	0.205	0.150	539
TSI	844.44	0.04	57.38	119.61	517
DOMFor	474.41	0.007	25.38	57.52	517
INTFor	672.00	0.005	29.48	74.04	517
DOMBack	363.55	0.01	30.75	67.14	517
INTBack	664.58	0.01	28.60	71.08	517
VA	1372.33	0.52	69.38	174.08	539
Damage	4.89%	0.13%	1.01%	0.83%	528
OFDI	301.25%	-87.23%	7.82%	30.84%	539
Energy	99.94%	13.06%	75.05%	16.90%	523
Service	85.89%	38.95%	67.07%	8.69%	539

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

表 3 数字技术创新对本国碳排放强度的影响

	（1）	（2）	（3）
ln*TSI*	0.13^{**}	0.16^{***}	0.25^{***}
	（0.01）	（0.00）	（0.00）
ln*DOMFor*	-0.10^{***}	-0.09^{***}	-0.06^{***}
	（0.00）	（0.00）	（0.01）
ln*DOMBack*	-0.23^{***}	-0.21^{***}	-0.09^{**}
	（0.00）	（0.00）	（0.01）
ln*INTFor*		-0.11^{***}	-0.19^{***}
		（0.00）	（0.00）
ln*INTBack*		0.06	0.07^{***}
		（0.13）	（0.01）
ln*VA*			-0.48^{***}
			（0.00）
ln*Damage*			-0.03^{***}
			（0.00）
ln*OFDI*			-0.15^{***}
			（0.00）
样本量	468	468	468
R^2	0.47	0.48	0.73

注: 括号内的系数为 p 值。"*", "**" 和 "***" 分别代表 10%，5%和 1%的显著性水平显著。

表 2 相关性分析

	CG	*TSI*	*DOMFor*	*INTFor*	*DOMBack*	*INTBack*	*VA*	*Damage*	*OFDI*	*Energy*	*Service*
CG	1										
TSI	0.67	1									
DOMFor	-0.45	-0.02	1								
INTFor	-0.38	-0.00	0.71	1							
DOMBack	-0.57	-0.01	0.86	0.92	1						
INTBack	-0.48	-0.00	0.68	0.99	0.90	1					
VA	-0.30	0.32	-0.04	-0.03	-0.04	-0.03	1				
Damage	0.92	-0.14	-0.04	-0.07	-0.06	-0.07	0.00	1			
OFDI	-0.48	-0.04	0.08	0.10	0.10	0.10	-0.03	0.09	1		
Energy	0.58	0.33	0.40	-0.32	-0.30	-0.42	0.13	0.15	0.04	1	
Service	-0.55	0.41	0.31	0.43	0.21	0.33	0.12	-0.50	-0.02	0.04	1

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

表 4 稳健性分析

	(1) $\ln CG^*$	(2) $\ln CG^*$	(3) *Lag*	(4) *Lag*
$\ln TSI$	0.12^{**}	0.24^{***}	0.13^{**}	0.23^{***}
	（0.03）	（0.00）	（0.03）	（0.00）
$\ln DOMFor$	-0.09^{***}	-0.06^{***}	-0.09^{***}	-0.09^{***}
	（0.00）	（0.00）	（0.00）	（0.00）
$\ln DOMBack$	-0.22^{***}	-0.09^{***}	-0.17^{***}	-0.07^{*}
	（0.00）	（0.01）	（0.00）	（0.07）
$\ln INTFor$	-0.06	-0.15^{***}	-0.05	-0.16^{***}
	（0.13）	（0.00）	（0.23）	（0.00）
$\ln INTBack$	0.03	0.04	0.03	0.06^{**}
	（0.45）	（0.12）	（0.38）	（0.04）
$\ln VA$		-0.59^{***}		-0.49^{***}
		（0.00）		（0.00）
$\ln Damage$		-0.01^{*}		-0.03^{***}
		（0.06）		（0.00）
$\ln OFDI$		-0.14^{***}		-0.11^{***}
		（0.00）		（0.00）
样本量	468	468	419	419
R^2	0.51	0.78	0.37	0.66

注: 括号内的系数为 p 值。"*", "**" 和 "***" 分别代表 10%，5%和 1%的显著性水平显著。

表 6 分组和时间变化回归结果

	OECD 组			非 OECD 组		
	2005-2008	2009-2012	2013-2015	2005-2008	2009-2012	2013-2015
	(1)	(2)	(3)	(4)	(5)	(6)
$\ln TSI$	0.27^{***}	0.25^{***}	0.24^{***}	0.30^{***}	0.29^{***}	0.26^{***}
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\ln DOMBack$	-0.07^{**}	-0.09^{***}	-0.08^{***}	-0.12^{*}	-0.14^{**}	-0.19^{**}
	(0.01)	(0.00)	(0.00)	(0.07)	(0.02)	(0.01)
$\ln DOMFor$	-0.07^{***}	-0.10^{***}	-0.12^{***}	-0.01^{*}	-0.02	-0.03
	(0.00)	(0.00)	(0.00)	(0.06)	(0.19)	(0.27)
$\ln INTBack$	0.05^{**}	0.09^{***}	0.10^{**}	0.04	0.07	0.06
	(0.02)	(0.00)	(0.01)	(0.57)	(0.49)	(0.12)
$\ln INTFor$	-0.20^{***}	-0.23^{***}	-0.25^{***}	-0.05^{*}	-0.07^{**}	-0.12^{**}
	(0.00)	(0.00)	(0.00)	(0.08)	(0.01)	(0.03)
控制变量	控制	控制	控制	控制	控制	控制
样本量	131	131	105	56	56	42
R^2	0.68	0.77	0.79	0.52	0.67	0.71

注: "*", "**" 和 "***" 分别代表 10%，5%和 1%的显著性水平显著。

表 5 中介效应回归检验

	能源消费结构				产业结构			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln Energy$	$\ln CG$	$\ln Energy$	$\ln CG$	$\ln Service$	$\ln CG$	$\ln Service$	$\ln CG$
$\ln TSI$	0.08^{***}	0.08	0.08^{***}	0.19^{***}	-0.01	0.14^{***}	-0.01	0.24^{***}
	(0.00)	(0.12)	(0.00)	(0.00)	(0.31)	(0.01)	(0.51)	(0.00)
$\ln DOMBack$	-0.01	-0.19^{***}	-0.01	-0.08^{**}	0.03^{***}	-0.14^{***}	0.03^{***}	-0.06^{*}
	(0.37)	(0.00)	(0.48)	(0.01)	(0.00)	(0.00)	(0.00)	(0.08)
$\ln DOMFor$	-0.03^{***}	-0.06^{**}	-0.03^{***}	-0.04^{*}	0.02^{***}	-0.05^{*}	0.01^{***}	-0.04^{**}
	(0.00)	(0.02)	(0.00)	(0.07)	(0.00)	(0.07)	(0.00)	(0.04)
$\ln INTBack$	-0.01	0.06^{*}	-0.01	0.07^{***}	-0.02^{***}	0.01	-0.03^{***}	0.04
	(0.37)	(0.07)	(0.60)	(0.00)	(0.00)	(0.88)	(0.00)	(0.15)
$\ln INTFor$	-0.04^{***}	-0.08^{**}	-0.04^{***}	-0.16^{***}	-0.00	-0.12^{***}	0.00	-0.19^{***}
	(0.00)	(0.04)	(0.00)	(0.00)	(0.68)	(0.00)	(0.51)	(0.00)
$\ln Energy$		0.94^{***}		0.83^{***}				
		(0.00)		(0.00)				
$\ln Service$						-2.05^{***}		-1.11^{***}
						(0.00)		(0.00)
$\ln VA$			0.02	-0.50^{***}			-0.01	-0.50^{***}
			(0.41)	(0.00)			(0.20)	(0.00)
$\ln Damage$			-0.01^{*}	-0.02^{***}			0.00^{**}	-0.02^{***}
			(0.05)	(0.00)			(0.02)	(0.00)
$\ln OFDI$			-0.01	-0.13^{***}			0.03^{***}	-0.11^{***}
			(0.15)	(0.00)			(0.00)	(0.00)
样本量	468	468	468	468	468	468	468	468
R^2	0.08	0.53	0.10	0.77	0.27	0.54	0.36	0.75

注: "*", "**" 和 "***" 分别代表 10%，5%和 1%的显著性水平显著。

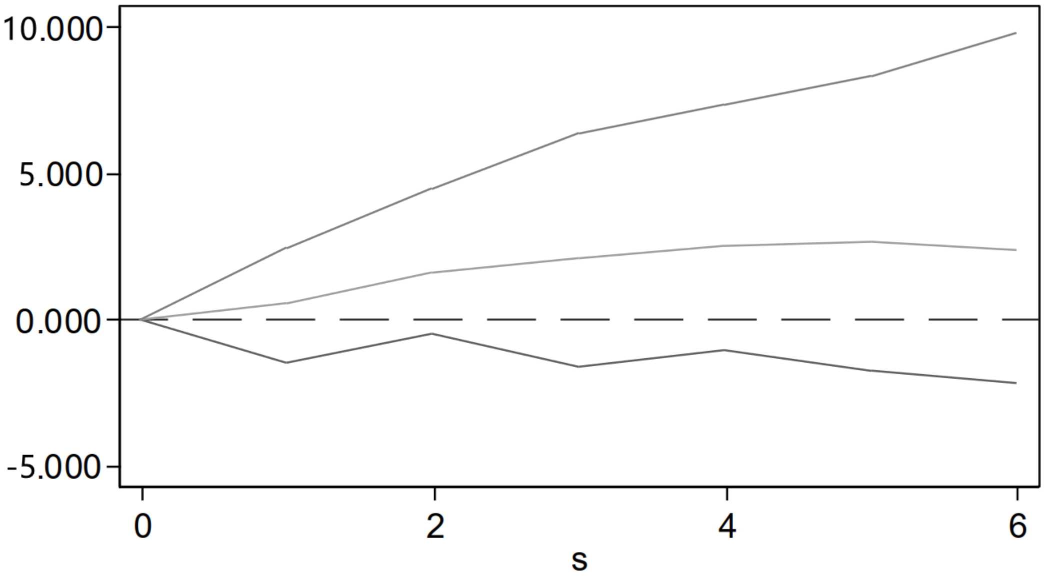

图 1. 碳排放强度对信息产业技术创新的脉冲响应分析

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

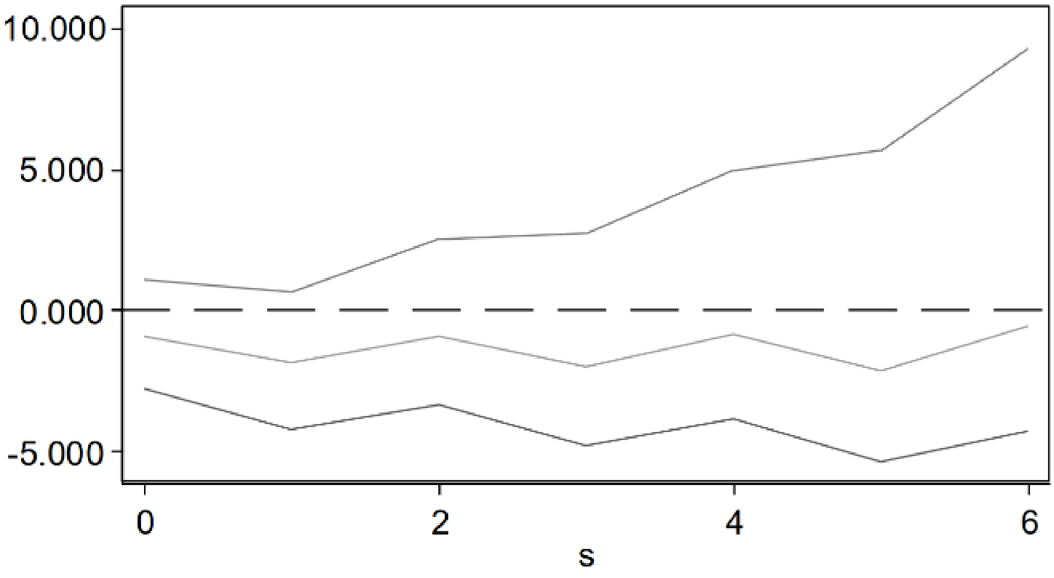

图 2a. 碳排放强度对技术溢出 *DOMFor* 的脉冲响应分析

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

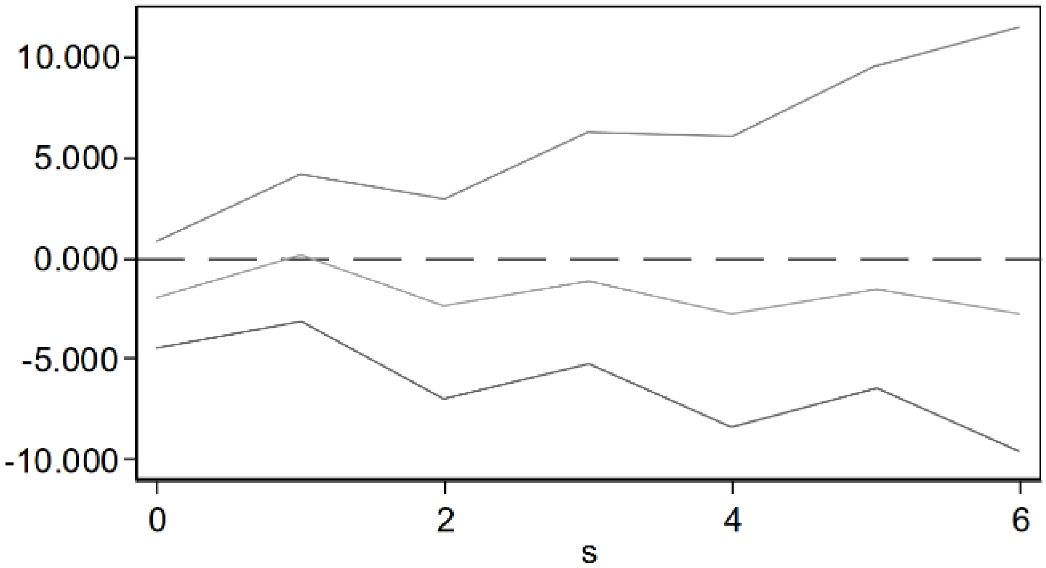

图 2b. 碳排放强度对技术溢出 *DOMBack* 的脉冲响应分析

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

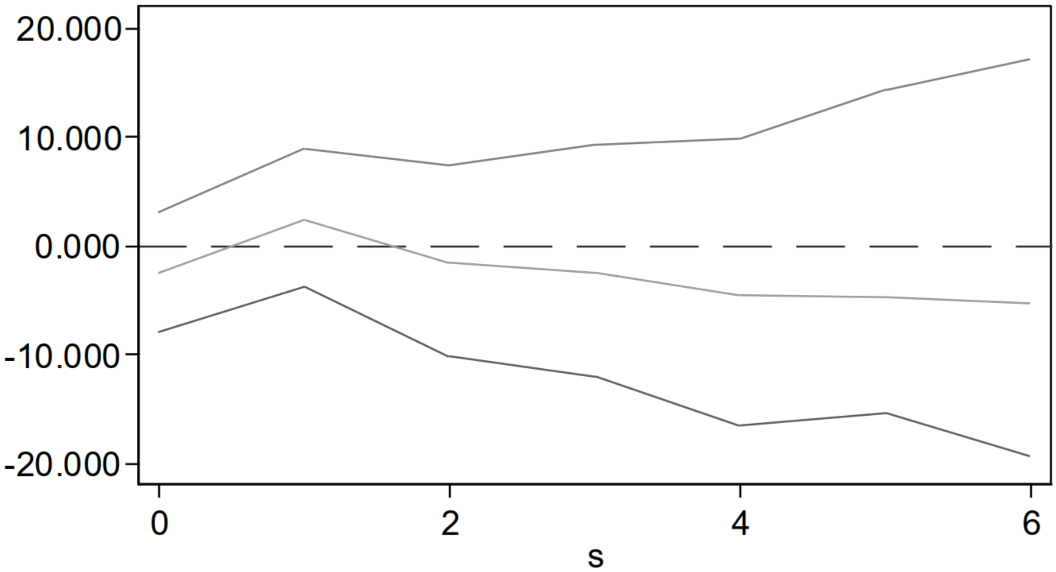

图 2c. 碳排放强度对技术溢出 *INTFor* 的脉冲响应分析

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

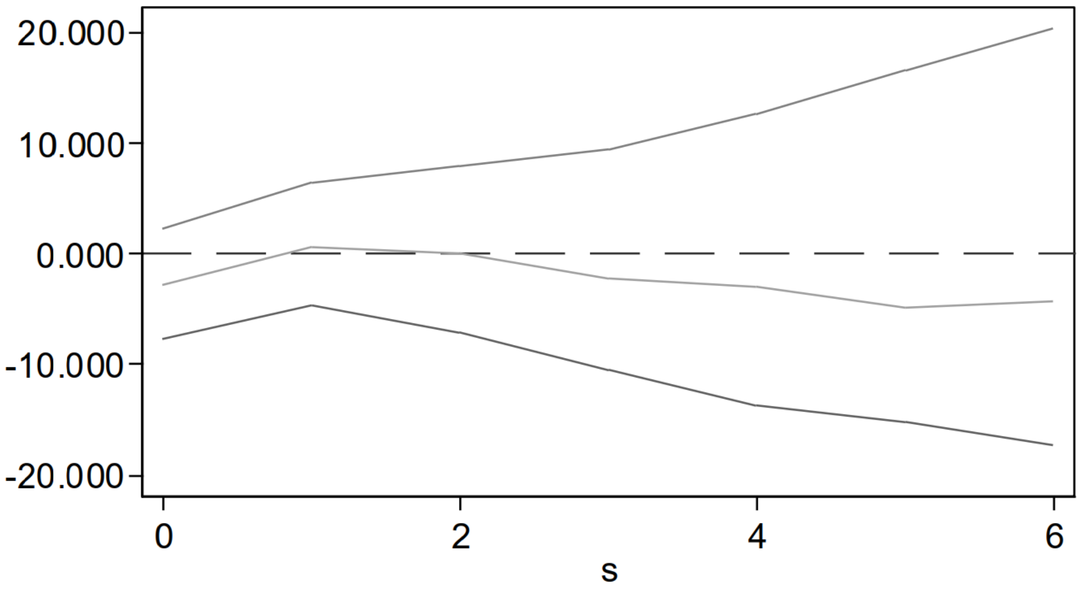

图 2d. 碳排放强度对技术溢出 *INTBack* 的脉冲响应分析

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到

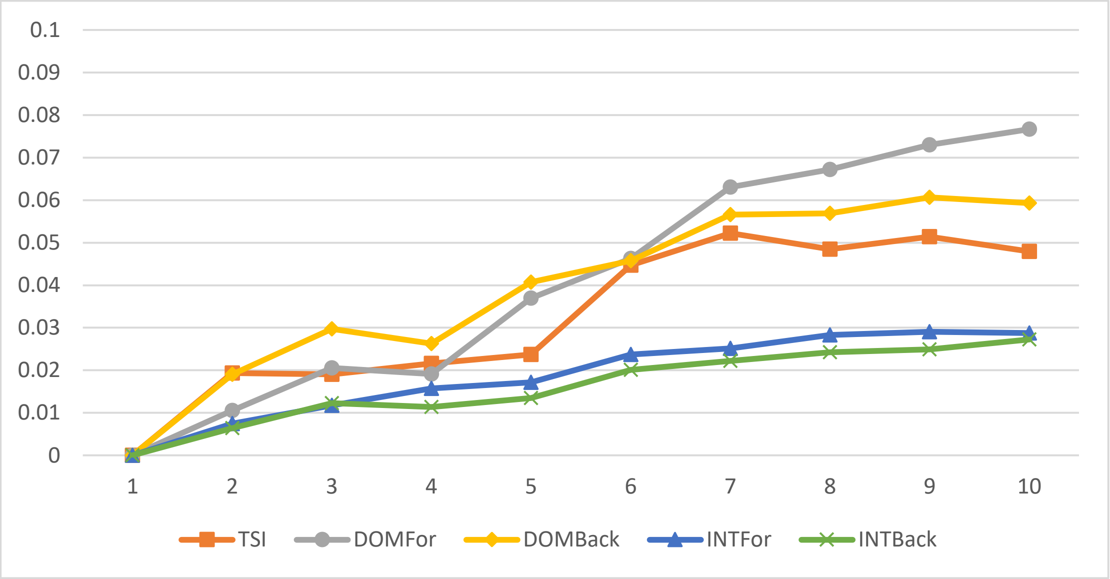

图 3. 碳排放强度的方差分解

数据来源：作者根据 OECD 投入产出数据库，TIVA 数据库和世界银行数据库计算得到