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Digital economy, technological innovation, and carbon productivity: Empirical evidence from the Yellow River Basin

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ABSTRACT

The digital economy has emerged as a significant engine for attaining high-quality and low-carbon development. Based on the panel data of 9 provinces (regions) in the Yellow River Basin of China from 2013 to 2021, this article measures the level of digital economic development, technological innovation capacity, and government governance ability in the region by using the entropy power method, and analyzes their influence on carbon emission efficiency. Meanwhile, it empirically examines the impact of the digital economy on carbon productivity through a two-way fixed effect model, a mediation mechanism model, and a threshold mechanism model. The results show that (1) The development of the digital economy can enhance carbon productivity, and this conclusion remains valid after a series of robustness tests. (2) The heterogeneity analysis reveals that the development of the digital economy in the middle and upper reaches of the Yellow River significantly enhanced the carbon productivity of this region, which is significantly different from the lower reaches of the Yellow River. (3) The mediating effect test shows that the digital economy can enhance carbon productivity through technological innovation. (4) The results of the threshold effect analysis demonstrate that the government's governance capacity has obvious threshold characteristics and has a positive moderating effect in the process of the digital economy promoting the improvement of carbon productivity. This paper provides a realistic reference for promoting the ecological protection and high-quality development of the Yellow River Basin.

1. Introduction

Currently, the promotion of green, low-carbon and sustainable development has emerged as an essential path foimajor countries around the world to achieve high-quality development. In September 2020, during the general debate of the 75th session of the United Nations General Assembly, the Chinese government declared that it would endeavor to reach the peak of carbon dioxide emissions before 2030 and attain carbon neutrality before 2060. Recently, China has attained certain achievements in the research and development of green and low-carbon technologies and equipment. As a result, China's carbon emission intensity in 2022 decreased by approximately 51 % compared with that in 2005. At present, China's economic and social development is still predominantly driven by various factors. To ensure the timely realization of the "dual carbon" goal and achieve high-quality economic and social development, it is crucial not to contemplate reducing carbon emissions at the expense of economic and social progress. Based on the above considerations, to guarantee the healthy and stable development of the economy while fulfilling the mission of low-carbon development as a major country, implementing green technological innovation and enhancing the efficiency of technological innovation to influence carbon productivity will be the optimal choice for ensuring the timely realization of the "dual carbon" goal. Simultaneously, a new round of technological and industrial transformation has expedited the development of the digital economy, which has gradually emerged as a new tipping point and growth engine for economic development. In 2023, the added value of the core industries within China's digital economy constituted 10 % of the Gross Domestic Product (GDP). The digital economy is characterized by innovation, penetration, and sharing. It has the ability to permeate all facets of production and consumption. Moreover, it can reshape production relations and facilitate the accumulation of advanced production factors within the new-quality industrial chain. By doing so, it transforms the momentum of economic development and endeavors to attain maximum economic benefits with the lowest

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possible low-carbon emissions or environmental costs, thereby enhancing carbon productivity. As a crucial ecological barrier and economic belt in China, the Yellow River Basin assumes a pivotal role in further deepening all-around reforms and advancing Chinese-style modernization. Nevertheless, for an extended period, the economic development of the provinces (regions) in the Yellow River Basin has been predominantly driven by traditional industries featuring high pollution and high energy consumption. Simultaneously, there exists an uneven distribution of innovative resource elements among the upstream, middle, and lower reaches. Additionally, disparities in the development foundation and industrial structure are also evident. These factors have decelerated the progress of ecological protection and high-quality development in the Yellow River Basin. Thus, it is imperative to break through the constraints of energy, resources, and the environment and achieve green and low-carbon transformation and development.

In the context of global sustainable development, the digital economy and carbon productivity are receiving increasing attention from the academic community. Scholars have explored the digital economy and carbon productivity from different perspectives using various methodologies. Research related to the digital economy mainly focuses on the economic and environmental effects it brings. Bao Zhenshan et al. [1] and Zhao Tao et al. [2] demonstrated that the digital economy significantly promotes economic growth. Hu Shan et al. [3] established that the digital economy enhances enterprise innovation capabilities, accelerating development across industries. Deng Rongrong et al. [4] revealed that the digital industry's emergence improves governmental energy regulation through enhanced timeliness and effectiveness, guiding the formulation of green environmental policies. Research on carbon productivity primarily examines impacts from environmental regulations, foreign direct investment (FDI), and industrial structure optimization. Li Xiaoping et al. [5] argued that environmental regulations stimulate corporate R&D investment, thereby improving productivity and ecological benefits. Tian Zuhai et al. [6] identified a nonlinear relationship between FDI and carbon productivity: while FDI's promoting effect strengthens with scale expansion, it weakens with advances in green technological innovation and stricter environmental regulations. Xu Shan et al. [7] demonstrated that industrial structure upgrading effectively enhances green total factor productivity. Studies regarding the digital economy's impact on carbon productivity mainly focus on its carbon reduction effects through digital economy development and supporting policies. Zhang et al. [8] suggested digital economy development improves carbon emission performance. Taglioni et al. [9] and Ali et al. [10] found digital technologies facilitate resource integration in both Western and Asian economies, reducing national energy consumption. Han et al. [11] revealed the digital economy's impact on total factor carbon productivity exhibits threshold effects dependent on technological accumulation levels - higher accumulation intensifies the promoting effect. Yi et al. [12] and Zhu et al. [13] proposed that the digital economy reduces carbon emissions via technological innovation and energy structure optimization, with significant spatial spillover effects. Minzhe D et al. [14] attributed improved ecological efficiency in low-carbon pilot cities to green technological innovation mechanisms. Chang Haoliang et al. [15] confirmed China's national big data pilot zones effectively reduce power consumption carbon emissions. Minzhe D et al. [16] documented significant carbon efficiency improvements stemming from China's Green Finance Reform Pilot Zone policies.

While numerous studies have investigated the digital economy and carbon productivity, several research gaps persist. First, limited regional-level analyses exist regarding the digital economy's impact on carbon productivity, with no consensus established about their relationship. Second, insufficient empirical evidence supports the regional heterogeneity and threshold effects in this relationship. Addressing these gaps, this study examines the Yellow River Basin through multiple analytical dimensions. Based on this, we first construct indicator systems for digital economy development, technological innovation, and government governance capacity, applying the entropy weight method to quantify these dimensions across provincial-level administrative units in the basin. Subsequently, carbon productivity metrics are calculated for each region. We then empirically analyze the digital economy-carbon productivity relationship, as well as the mediating effect of technological innovation and the threshold effect of government governance capacity.

This study's contributions are threefold: From a research perspective, unlike most studies that only focus solely on the analysis of the influencing factors of carbon productivity, the digital economy, and technological innovation, this paper incorporates the digital economy, technological innovation, and carbon productivity into the same research framework and explores the impact of the digital economy on carbon productivity from both theoretical assumptions and empirical research levels. From the perspective of the research subject, the research subject of this paper is the Yellow River Basin, with a more detailed and focused spatial scale. The research conclusion can provide a scientific basis for promoting the sustainable development of the Yellow River Basin, and also offer references for regions such as the Yangtze River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area in China to accelerate the development of the digital economy and enhance carbon productivity. From the perspective of the research content, this paper takes into account spatial heterogeneity and discusses the mechanism of the impact of the digital economy on carbon productivity from the perspectives of technological innovation and government governance capacity.

2. Mechanism analysis and research hypothesis

2.1. The impact of the digital economy on carbon productivity

The ecological protection and high-quality development strategy of China's Yellow River Basin has put forward new requirements for the development of nine provinces (regions) along the Yellow River Basin, which should consider economic development and ecological protection, and take the path of sustainable development. In this process, carbon productivity can be affected by leveraging the abundant wind, light, and heat resources in the western region, integrating the electricity demand for data center development, zero-carbon energy endowment, vigorous development of the digital economy, and improvement of digital infrastructure. On the one hand, the growth pole effect was brought into play. The development of the digital economy can be used to promote the digital transformation of industries, facilitate the transfer of production factors from low-efficiency sectors to high-efficiency sectors [17], and realize the transformation of old and new kinetic energy. Regional carbon productivity can be influenced by the agglomeration of advanced green production factors. On the other hand, the effect of structural optimization should be considered. Carbon productivity can be increased by developing a digital economy, improving production methods [18], and optimizing the structure of energy consumption. Carbon productivity can also be improved by squeezing out high-energy-consuming, high-polluting, and low-output production capacity and expanding the development space of low-energy-consuming, low-emission, and high-output industries. Based on this, this study proposes the research hypothesis H1.

Hypothesis 1. (*H1*) *The development of the digital economy promotes the improvement of carbon productivity in the Yellow River Basin.*

2.2. The intermediary transmission mechanism of the digital economy to carbon productivity

Since its emergence and development, the digital economy has accelerated the generation, promotion, and application of a new generation of digital low-carbon and energy development and utilization technologies. This promotes the optimization and reengineering of production processes [19]. Promote the transformation of production methods, achieve low-carbon and clean production, and simultaneously reduce energy consumption per unit of output and achieve Pareto improvement in energy utilization. The induced invention theory holds that changes in the relative prices of factors of production can change the production costs of enterprises, thereby stimulating technological innovation. The development of the digital economy precisely promotes the accelerated sharing of data elements, weakens or eliminates the barriers for different innovation entities to obtain resources and information, prompts the optimal allocation of element resources such as talents, platforms, and technologies, thereby reducing the production costs of enterprises, releasing space for enterprises to increase capital investment in technological innovation. Thus, it provides the possibility to enhance production efficiency and reduce carbon emissions through technological innovation. Based on this, this study proposes the research hypothesis H2.

Hypothesis 2. (*H2*) *The digital economy can enhance carbon productivity in the Yellow River Basin by promoting technological innovation.*

2.3. The threshold effect of government governance capacity on the digital economy and carbon productivity

The non-exclusivity and non-competitiveness of data determine that the digital economy is a public economy [20]. As the most important public economic entity, the government has provided a good data infrastructure system and environmental guarantee for the development of the public economy. To ensure that the "dual carbon" goal will be achieved as scheduled, the government and the market undertake to give full play to the "promising" and "effective" functions and drive the improvement of carbon productivity through joint efforts. The "promising" role of the government is mainly reflected in the level of government governance system and governance capacity. In other words, the development of the digital economy is guided by the macro guidance of the government, and the government's governance capacity is an important institutional prerequisite for the impact of the digital economy on carbon productivity. The stronger the government's governance capacity, the more complete the institutional (such as the energy quota trading system, etc. [21]) and regulatory systems to promote green development and the better the market environment for the development of the digital economy. This ensures that the digital economy has an impact on energy allocation, energy consumption optimization, and carbon emission reduction [22]. Based on this, this study proposes the research hypothesis H3.

Hypothesis 3. (*H3*) *There is an obvious threshold effect of government governance capacity on the process of promoting carbon productivity improvement in the Yellow River Basin by the digital economy.*

3. Methodology and data

3.1. Model construction

3.1.1. Benchmark model

Drawing on the research method of Baixue et al. [23], the following benchmark regression model was constructed to study and analyze the impact of the digital economy on carbon productivity: verify hypothesis H1:

$$cp_{it} = \alpha_0 + \alpha_1 dige_{it} + \phi_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{1}$$

In Eq. (1), i represents the province and t represents the year; cp_{it} characterizes the carbon productivity of each province (region); $dige_{it}$ characterizes the level of development of the digital economy; X_{it} characterizes the control variables; α_0 is the coefficient of the constant term, α_1 is the regression coefficient of the digital economy, and φ_k is the regression coefficient of the control variable. μ_i is the province fixed effect, ν_t is the time fixed effect, and ε_{it} is the random perturbation term.

3.1.2. Intermediary model

Drawing on relevant research on the mediating effect test of Jiangting [24], the following model is constructed to test the mediating effect of technological innovation and verify hypothesis H2:

$$tic_{it} = \beta_0 + \beta_1 dige_{it} + \phi_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{2}$$

$$cp_{it} = \sigma_0 + \sigma_1 dige_{it} + \sigma_k tic_{it} + \phi_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{3}$$

In Eqs. (2) and (3), tic_{it} represents technological innovation. The steps for testing the mediating effect are as follows: First, test whether the positive promoting effect of the digital economy on carbon productivity exists, that is, whether α_1 in Eq. (1) is significantly positive. Second, after Eq. (1) is verified, test whether the digital economy has a positive promoting effect on the mediating variable, that is, whether β_1 in Eq. (2) is significantly positive. Third, after Eq. (2) is verified, test whether the mediating effect of the mediating variable exists when the digital economy and the mediating variable are included in the same model. If σ_k and σ_1 are both significant in Eq. (3), it indicates that the mediating variable is a partial mediator; if σ_k is significant but σ_1 is not, it indicates that the mediating variable is a complete mediator; if σ_k is not significant, it indicates that the mediating variable does not have a mediating effect.

3.1.3. Threshold model

Drawing on the research method of Hansen [25], a threshold effect model with government governance capacity as the threshold variable was constructed to test hypothesis H3:

$$\begin{aligned} cp_{it} = {} & \alpha_0 + \alpha_1 dige \cdot I(gc \le \gamma_1) + \alpha_2 dige \cdot I(\gamma_1 < gc \le \gamma_2) + \cdots + \\ & \alpha_n dige \cdot I(\gamma_{n-1} < gc \le \gamma_n) + \phi_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \end{aligned} \tag{4}$$

In Eq. (4), gc denotes the ability of the government to govern, and $\gamma_1 \dots \gamma_n$ is the threshold value, $I(\cdot)$ is the indicative function, when the conditions in parentheses are satisfied, the value is 1, otherwise the value is 0, $\alpha_1 \dots \alpha_n$ is the corresponding regression coefficient.

3.2. Variable selection and measurement

3.2.1. Explained variable - carbon productivity (cp)

Drawing on relevant studies on carbon productivity by Kaya et al. [26], Pan Jiahua et al. [27], and Sun Huaping et al. [28], the carbon productivity of the nine provinces (regions) in the Yellow River Basin was measured using the following formula:

$$cp_{it} = GDP_{it} / CO_{it} \tag{5}$$

In Eq. (5), cp_{it} characterizes the carbon productivity of each province (region), GDP_{it} characterizes the gross domestic product of each province (region), and CO_{it} characterizes the total carbon emissions of each province (region). Carbon emissions were measured using the carbon emission estimation formula published by the United Nations Intergovernmental Panel on Climate Change (IPCC) in the IPCC Guidelines for National Greenhouse Gas Emission Inventories [29], as follows:

$$C_t = \sum E_{it} \times F_i \tag{6}$$

In Eq. (6), C_t represents the carbon emissions of the t-th year, E_{it} represents the consumption of the i th energy in the t-th year, and F_i represents the carbon emission coefficient of the i th energy. The carbon emission coefficient refers to the relevant research of Wen Xueying et al. [30], and selected from the average value of seven units of the United States Energy Information Administration, the Energy Economic Research Institute of Japan, the Energy Research Institute of the National Development and Reform Commission, the Energy Institute of the State Planning Commission, the Climate Change Project of the State Science and Technology Commission, the Greenhouse Gas Control Project of the State Environmental Protection Administration, and the Chinese Academy of Engineering. Of this, the coal carbon emission factor (on average) is 0.72 tC/tce, the oil carbon emission factor (on average) is 0.56 tC/tce, and the natural gas carbon emission factor (on average) is 0.42 tC/tce.

3.2.2. Core explained variable - digital economy (dige)

At this stage, there is no unification in the academic world regarding the measurement method and index of the digital economy. Therefore, this study draws on the relevant studies of Mi Guofang et al. [31] and Liu Jun et al. [32] to construct an index system of the digital economy development level from four dimensions: digital infrastructure, digital industry development, digital technology application, and digital development environment (see Table 1), and uses the entropy power method to measure the development level of the digital economy.

3.2.3. Intermediary variable – technological innovation (tic)

Referring to related studies [34–35], this study constructs an index system of scientific and technological innovation capability from the two dimensions of R&D investment and R&D results and uses the entropy weight method to measure scientific and technological innovation capability (see Table 2) to characterize the technological innovation level of intermediary variables. Among them, the number of authorized green patent inventions is based on the "International Patent Classification Green List" provided by WIPO (World Intellectual Property Organization), and the corresponding IPC (International Patent Classification) classification numbers are obtained through the incopat global patent database search. To avoid omissions and repetitions, the classification numbers are based on the publication (announcement) dates from 2013 to 2021.

3.2.4. Threshold variable – governance capacity (gc)

As with the digital economy, there is currently no unified standard for measuring the government's ability to govern. Therefore, based on a study by Liu et al. [36] and other related studies, this paper constructs an index system of government governance capacity of threshold variables from four dimensions: government performance, regulatory quality, people's livelihood security, and public goods supply (see Table 3), and uses the entropy weight method to measure government governance capacity.

3.2.5. Control variables

In order to improve the interpretation of the regression results of the model, in this study, three indicators were selected as control variables, including regional economic development level (PGDP, measured by the per capita GDP of each province (region) with reference to the relevant studies of Shao Shuai et al. [37] and Cao Huaying [38]), industrial structure (IUP, referring to the relevant research of Xu Deyun [39], measured by the industrial structure index of each province (region), and the formula is as Eq. (7)), and environmental regulation (ER, referring to Zhang Ziyu et al. [40], measured by the ratio of the completed investment in industrial pollution control to the industrial added value of each province (region)).

$$iup = \sum_{n=1}^{3} nI_n = I_1 + 2I_2 + 3I_3 \tag{7}$$

Table 2
Index system of scientific and technological innovation capability.

Primary Indicators	Secondary Indicators	Tertiary indicators	Unit	Attribute
Scientific and Technological Innovation Capabilities	R&D Investment	Full-time Equivalent of R&D Personnel in Industrial Enterprises Above Designated Size	Number-year	+
		R&D Investment Intensity	10,000 yuan	+
	R&D Results	The number of authorized green patent inventions	Piece	+
		Turnover of Contracts in the Technology Market	10,000 yuan	+

Table 3
Governance capacity index system.

Primary Indicators	Secondary Indicators	Tertiary indicators	Unit	Attribute
Governance Capacity	Government Performance	Government expenditure/total population	yuan/-	+
		Number of people employed in public administration, social security and social organizations/total population	—	+
	Regulatory Quality	Harmless treatment rate of domestic waste	%	+
	People's Livelihood Security	Disposable income per capita	yuan	+
	Public Goods Supply	Road transport mileage	km	+

Table 1
Index system for the level of development of the digital economy.

Primary Indicators	Secondary Indicators	Tertiary indicators	Unit	Attribute
Digital Economy	Digital Infrastructure	Mobile Phone Subscribers	10,000	+
		Cell phone penetration rate	%	+
		Number of Internet broadband access ports	10,000	+
		Number of Internet Web Pages	10,000	+
		Number of Internet domain names	10,000	+
	Digital Industry Development	Software Business Revenue	10,000 yuan	+
		Electronic Information Manufacturing Enterprises	unit	+
	Digital Technology Application	Revenue from express delivery business	10,000 yuan	+
		Enterprises with e-commerce transaction activities	unit	+
	Digital Development Environment	Proportion of employed persons in information transmission, software and information technology services	%	+
		Practitioners in the software and information technology services industry	10,000	+
		Digital Financial Inclusion Index[33]	—	+

3.3. Data sources and descriptive statistics

The research object of this paper is the relationship between digital economy and carbon productivity in the nine provinces (regions). Following the principles of data availability, completeness and comparability, the research period is set as 2013 to 2021. The energy data, intermediary variables, and control variable data required for carbon emission accounting are mainly derived from the China Statistical Yearbook and the statistical yearbooks of various provinces (regions). The data on the indicators of the development level of the digital economy are derived from the China Statistical Yearbook, Statistical Yearbook of China's Tertiary Industry, Statistical Yearbook of China's Electronic Information Industry, Yearbook of China's Information Industry, and Peking University Digital Financial Inclusion Index report. To eliminate the influence of multicollinearity and heteroskedasticity on the research results, the data for some control variables were logarithmically processed. Descriptive statistics for the variables are presented in Table 4.

4. Empirical result

4.1. Test of the relationship between digital economy and carbon productivity

4.1.1. Benchmark regression

Before the benchmark model regression, the data were subjected to the F-test and Hausman test, and the results passed the 1 % significance level test. Secondly, to ensure the robustness of the test results, cluster robust OLS regressions were also performed, and the regression results are presented in Table 5. The results show that the positive effect of the digital economy on carbon productivity is relatively stable when adding control variables one by one. After adding all control variables, the impact of the digital economy on carbon productivity passes the 1 % significance level test, and every 1 % change in the digital economy will increase carbon productivity by 1.1967 %. This proves that H1 is true. Mainly due to the improvement of digital infrastructure and the development of digital industries in the process of digital economic development, the barriers of information transmission and the flow of production factors have been broken through, promoting the transfer of production factors from low-efficiency sectors to high-efficiency sectors and fully releasing the carbon emission reduction potential of the industrial structure [41]. Meanwhile, the construction of digital infrastructure helps to blur the boundaries of the three major industries, enhance the integration and coordination among industries [42], and thereby significantly increase the overall productivity of each industry, thereby reducing the consumption of resources per unit of GDP and effectively improving carbon productivity. Observing the control variables, it was found that the level of regional economic development and industrial structure were positively correlated with carbon productivity and passed the 1 % significance level. This indicates that the improvement of the regional economic development level and the optimization and upgrading of the industrial structure will increase carbon productivity. The main reason is that the improvement of the economic development level can provide sufficient resource and element input for green technological innovation, enhance the efficiency of green technological innovation, and reduce carbon emissions. The control variable Environmental regulation was positively correlated with carbon productivity and passed the 5 % significance level test. This shows that increasing the intensity of environmental regulations increases carbon productivity. This may be related to the fact that since the "dual carbon" goal was proposed, various localities have formulated strict ecological and environmental systems and actively promoted the development of new energy industries, effectively reducing carbon emissions.

Table 5
Benchmark regression results.

variables	Carbon Productivity (CP)				
	FE				OLS
	(1)	(2)	(3)	(4)	(5)
dige	2.0761***	1.4950***	1.2510***	1.1967***	1.1967**
	(9.99)	(5.95)	(5.21)	(5.05)	(3.04)
lnpgdp		0.5574***	0.6472***	0.6521***	0.6521*
		(3.56)	(4.45)	(4.57)	(2.11)
iup			1.2212***	1.0152***	1.0152*
			(3.58)	(2.89)	(1.87)
er				0.0545**	0.0545**
				(1.90)	(2.48)
obs	81	81	81	81	81
Province fixed effect	YES	YES	YES	YES	YES
Time fixation effect	YES	YES	YES	YES	YES
R^2	0.5507	0.3983	0.3011	0.2784	0.2784

Note: *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Table 5–9 is the same.

4.1.2. Endogeneity, robustness and mediating effect test

(1) Endogeneity problem test. Omitted variables or two-way causal relationships can lead to endogeneity problems in explanatory variables, resulting in biased and inconsistent estimation coefficients. The instrumental variable (IV) approach is a primary method for addressing endogeneity in regression models. Its core principle involves introducing an IV that is correlated with the explanatory variable but uncorrelated with the error term, thereby correcting the estimation bias of OLS. Following related studies by Nunn and Qian [43] and Huang Qunhui et al. [44], this paper adopts the IV approach to mitigate endogeneity concerns. Specifically, we construct an IV for the core explained variable, "digital economy" using the logarithm of the interaction terms between the number of post offices per million people in each province in 1984 and the number of mobile Internet users in the country in the previous year. The IV regression results are reported in Column (1) of Table 6. After accounting for potential endogeneity, the estimated coefficient of the core explained variable remains statistically significant at the 1 % level and

Table 4
Descriptive statistics of variables.

Variable type	variables	Obs	mean	standard deviation	Min	Max
Explanatory variables	cp	81	0.5967	0.3431	0.1724	1.6698
Core explanatory variables	dige	81	1.3436	0.2623	1.0481	1.9235
Instrumental Variable	IV	81	10.9150	0.33679	10.1921	11.5613
Replace the explanatory variable	icp	81	0.2681	0.1447	0.0729	0.5993
Mediation variables	tic	81	0.3289	0.2537	0.1000	1.0000
Threshold variables	gc	81	1.5131	0.1142	1.2864	1.8099
Control variables	lngdp	81	10.7966	0.2966	10.0962	11.2912
	iup	81	2.3510	0.0768	2.1477	2.5205
	er	81	0.4795	0.4519	0.0369	2.8039

Table 6
Test results.

cp	Endogeneity problem test	Robustness test		mediating effect test	
	Instrumental Variable (1)	Replace the explanatory variable (2)	Adjust the sample time (3)	tic (4)	cp (5)
dige	0.9366***	0.3318***	1.1010***	0.3667**	1.0605***
	(8.71)	(4.45)	(2.90)	(2.10)	(4.46)
tic					0.3714**
					(2.19)
Control variables	YES	YES	YES	YES	YES
obs	72	81	63	81	81
Province fixed effect	YES	YES	YES	YES	YES
Time fixation effect	YES	YES	YES	YES	YES
R^2	0.7768	0.2627	0.2437	0.7645	0.3042

retains a positive sign, consistent with the baseline regression findings.

(2) Robustness test. To ensure the accuracy and reliability of the research conclusions, a robustness test of the benchmark regression results was conducted by substituting the explanatory variables and adjusting the sample time. Carbon productivity is measured by the ratio of industrial added value to carbon emissions, as shown in Column (2) of Table 6. The study period was adjusted to 2015–2021, and the results are shown in Column (3) of Table 6. The robustness test results of the two methods show that the digital economy's impact on carbon productivity is consistent with the benchmark regression results, indicating that the research conclusions are robust.

(3) Mediating effect test. As shown in Columns (4) and (5) of Table 6, the regression coefficient of the digital economy in Column (4) passes the 5 % significance level test and is positive, indicating that the digital economy can promote technological innovation. In column (5), the symbol of the regression coefficient of the digital economy has not changed, and it passes the 1 % significance level test, indicating that the digital economy has a positive effect on improving carbon productivity. At the same time, the regression coefficient of technological innovation is significantly positive at the 5 % significance level, indicating that technological innovation also has a positive promoting effect on improving carbon productivity. This indicates that the digital economy can have an impact on carbon productivity by giving full play to the mediating effect of technological innovation, which proves that hypothesis H2 is valid.

4.2. Regional heterogeneity analysis

There are always differences in economic and social development, and development of the digital economy is no exception. As a result, there are differences between regions, industries, and enterprises in terms of resources, information, mastery, and application of technology. This has led to the emergence of an information gap or "digital divide" phenomenon. Therefore, in the context of insufficient and unbalanced economic and social development and differences in resource endowments in the upper, middle and lower reaches of the Yellow River Basin, will there also be such differences in the impact of the digital economy on carbon productivity? Based on the above considerations, this paper conducts a regional heterogeneity test in the upper, middle and lower reaches of the Yellow River Basin.

Referring to the Yellow River Conservancy Commission's division of the upper, middle and lower reaches of the Yellow River Basin, and combining with the relevant studies of Zhao Mingliang et al. [45] and Xue Xandeng et al. [46], this paper categorises Inner Mongolia, Sichuan, Gansu, Qinghai and Ningxia as the upper reaches of the Yellow River Basin, Shaanxi and Shanxi as the middle reaches of the Yellow River Basin, and Henan and Shandong as the lower reaches of the Yellow River Basin, to explore the regional variability of the impacts of the digital economy on carbon productivity, and the regression results are shown in Table 7. The results show that in the upper and middle reaches of the Yellow River basin, the regression coefficients of the digital economy on carbon productivity are positive, with coefficients of 1.8822 and 1.7940 respectively, and both are significant at the 1 % significance level. This indicates that the digital economy has a significant positive effect on carbon productivity in the upper and middle reaches of the Yellow River Basin. On the one hand, the construction and subsequent use of digital infrastructure requires a large amount of power resources, while the upper and middle reaches of the Yellow River Basin are relatively rich in green energy, such as wind power, photovoltaics, hydrogen energy, and pumped storage, which can not only meet the electricity demand for the development of the digital economy but also will not increase carbon emissions. On the other hand, the state has launched the "Eastern Data and Western Computing" project in the upper and middle reaches of the Yellow River Basin to build data center clusters to undertake the computing power needs of the eastern region. In the lower reaches of the Yellow River Basin, the regression coefficient of the digital economy to carbon productivity is positive, but it does not pass the significance test, indicating that the digital economy has not shown a significant positive effect on carbon productivity in the lower reaches of the Yellow River Basin. This is due to the fact that the economic structures of Henan and Shandong in the lower reaches of the Yellow River Basin are still biased towards coal, and the economic structure is still heavy. From 2013 to 2021, the proportion of coal consumption in energy consumption in Shandong and Henan provinces remained consistently above 60 %, and was always higher than the national average. Although the development of the digital economy in these two provinces started early and the layout of digital infrastructure is more comprehensive, the increase in electricity demand in the development of the digital economy means an increase in coal consumption and an increase in carbon emissions, thereby not significantly improving carbon productivity.

Table 7
Results of regional heterogeneity.

cp	Upper reaches of the Yellow River (1)	Middle reaches of the Yellow River (2)	Lower reaches of the Yellow River (3)
dige	1.8822***	1.7940***	0.1449
	(4.42)	(6.42)	(0.22)
lnpgdp	0.5148**	−0.4771	−2.2419***
	(2.35)	(−1.51)	(−4.81)
iup	0.6281	0.3387	8.7322**
	(1.27)	(0.75)	(3.14)
er	0.0562	−0.1124	−1.3867***
	(1.41)	(−1.72)	(−2.22)
obs	45	18	18
Province fixed effect	YES	YES	YES
Time fixation effect	YES	YES	YES
R^2	0.4285	0.9183	0.0102

4.3. Threshold effect analysis

According to H3, the relationship between the digital economy and carbon productivity is influenced by a government's ability to govern. Therefore, this study applied a threshold model to test it. Before carrying out the threshold model regression, a threshold test is conducted to test whether there is a threshold effect and whether there are multiple threshold values in the government's governance ability. The test results are shown in Table 8. In the single threshold model, the F-value passed the test at the 1 % significance level. In the double threshold model, the F-value failed in the significance test. This shows that there is only a single threshold for the model, with a threshold value of 1.5346.

Table 9 shows the threshold model regression results. This shows that, when the government's governance capacity is <1.5346, the digital economy coefficient is significantly positive at the 1 % significance level. Compared with the regression coefficients in column (4) of Table 5, it is found that when the government governance capacity is <1.5346, it can enhance the positive promotion effect of the digital economy on carbon productivity. When the government's governance capacity is greater than or equal to 1.5346, the digital economy coefficient is significantly positive at the 1 % significance level, indicating that the digital economy will improve carbon productivity. The regression coefficient is also greater than the regression coefficient in column (4) of Table 5. The results show that when the level of government governance capacity is greater than or equal to 1.5346, it will also enhance the positive effect of the digital economy on carbon productivity. The digital economy's effect on carbon productivity is affected by the government's governance ability. With the improvement of government governance capabilities, regulatory policies and regulations that adapt to the development of the digital economy will be more sound and perfect. At the same time, supervision and risk prevention and control in all fields of the digital economy will be strengthened to create a good market environment for fair competition and development of the digital economy. The role of the digital economy in promoting carbon productivity is even more significant. Prove that hypothesis H3 is true.

Table 9
Threshold effect regression results.

Variable	Carbon Productivity (cp)	
	coefficient	t Value
dige(gc<1.5346)	1.2305***	6.53
dige(gc≥1.5346)	1.3142***	7.10
lnpgdp	0.3723***	4.25
iup	0.7124***	4.12
er	0.0580**	2.61
obs	81	
Province fixed effect	YES	
Time fixation effect	YES	
R^2	0.3227	

5. Conclusions and suggestions

5.1. Conclusions

Taking the Yellow River Basin as the research object, this paper selects the panel data of nine provinces (regions) in the Yellow River Basin from 2013 to 2021 to test the impact of digital economy on carbon productivity and the mechanism of the role between them. The results show that: (1) The digital economy has a positive promoting effect on the improvement of carbon productivity. After the endogeneity problem test and the robustness test, this conclusion still holds. (2) There is regional heterogeneity in the impact of digital economy on carbon productivity. In the upper and middle reaches of the Yellow River Basin, the digital economy plays a role as a "digital dividend" and significantly promotes the improvement of carbon productivity. (3) Technological innovation is an important channel for the digital economy to enhance carbon productivity and plays a mediating role in the process of promoting carbon productivity improvement through the digital economy. (4) There are obvious threshold characteristics of government governance capacity, which has a positive moderating effect in the process of promoting carbon productivity improvement in the digital economy.

Although this paper supplements the study of digital economy and carbon productivity, providing theoretical and practical references for the digital economy to promote the improvement of carbon productivity, there are still certain limitations that need to be further improved. (1) As the concept of digital economy has only been around for a relatively short period of time, the measurement methods and indicators for digital economy have not yet been unified. The measurement methods for the development level of digital economy still need to be further optimized, and the indicator system still needs to be further improved. (2) This paper finds that the impact of digital economy on carbon productivity in the Yellow River Basin shows regional heterogeneity. However, due to the spatial limitations of this paper, the spatial influence is not considered. Subsequent studies can further explore the spatial spillover effect of the digital economy on carbon productivity.

5.2. Suggestions

(1) It is necessary to vigorously develop the digital economy. The results show that the digital economy has a positive impact on the improvement of carbon productivity. Therefore, it is necessary to increase investment in scientific and technological research and development, cultivate digital talents, and focus on supporting technology research and development in the fields of general computing, intelligent computing, supercomputing, and quantum computing. It is necessary to build digital infrastructure in advance, accelerate the formation of a regional integrated computing power system, and promote the deep integration of the digital economy and the real economy.

(2) Carry out research and development of green and low-carbon technologies to enhance energy utilization efficiency. The results show that the digital economy boosts carbon productivity by driving technological innovation. Therefore, it is necessary to systematically plan and build a green and low-carbon technology development system, continuously improve the supporting mechanisms for green and low-carbon development, expand the industry coverage of the national carbon emission trading market, and comprehensively apply various policy measures such as fiscal fund guidance, tax regulation and government green procurement to promote the research and development of low-carbon technologies such as green hydrogen energy utilization and carbon capture, and support the growth of carbon productivity. Give full play to the role of enterprises as the main body of innovation, use digital intelligence technology and green technology to transform and upgrade traditional industries, promote

Table 8
Threshold effect test.

Variables	Threshold	Threshold Values	P-Value	F-Value	Critical Value		
					1 %	5 %	10 %
Governance capacity	Single threshold	1.5346	0.0067	23.17***	20.5096	16.8622	13.8676
	Double threshold	1.4153	0.1167	14.25	31.3588	19.2461	15.5448

industrial transformation and upgrading, and improve energy efficiency.

(3) It is necessary to guide the upper, middle and lower reaches of the Yellow River Basin to strengthen exchanges and cooperation. The results show that there is regional heterogeneity in the impact of digital economy on carbon productivity. Therefore, it is necessary to build a new mechanism for cross-administrative cooperation and development among regions, jointly research, formulate and implement policies and measures related to green development, jointly carry out environmental pollution control and ecological restoration, and promote regional integrated development.

(4) The energy efficiency of government governance should be solidly improved. Research findings show that government governance capacity is the key to enhancing the impact of the digital economy on carbon productivity. Thus, when formulating policies and deploying development directions and key tasks, the relevant government departments should focus on the carbon emission reduction effect of the digital economy, and link and infiltrate the digital economy and digital technology into the path of "reducing carbon emissions and sequestering carbon".

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reports a relationship with that includes:. Has patent pending to. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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