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Towards a low-carbon society: spatial distribution, characteristics and implications of digital economy and carbon emissions decoupling

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Reducing carbon emissions and attaining sustainable economic, social, and environmental development are vital components of the 2030 Agenda for Sustainable Development. Previous research has overlooked the influence of the digital economy on urban carbon decoupling. To bridge this gap, this study employs GIS software and econometric models for analyzing the spatial distribution and characteristics of the digital economy and carbon decoupling and also investigates the direct, heterogeneous, and spatial effects of the digital economy on carbon decoupling. This study reveals: (1) A lesser digital economy presence in the northeast and northwest, while more developed in the Southeast Coast and municipalities directly under the Central Government. Cities with weak carbon decoupling are concentrated in Northeast and North China. (2) The digital economy and the decoupling of urban carbon emissions have spatial correlation and agglomeration characteristics. (3) The digital economy can contribute to decoupling carbon emissions in cities. (4) Improved urban carbon decoupling by the digital economy in central, eastern, and non-resource-based cities. (5) Spatial spillover effect in urban carbon emissions decoupling, yet the digital economy worsens nearby cities' carbon decoupling due to a siphon effect. That research indicates that the digital economy holds significant promise not only in advancing human progress, bridging the digital divide, and fostering social development but also in driving the decoupling of urban carbon emissions.

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Introduction

One of the fundamental requirements to achieve sustainable development encompassing economic, social, and environmental aspects is the reduction of carbon emissions and active engagement in combatting climate change (United Nations, 2015). However, global circumstances significantly impact the progress of worldwide sustainable development. For instance, the Russian-Ukrainian conflict has notably influenced the trajectory of sustainable development across nations. An illustrative example can be found in the World Energy Outlook 2022 (International Energy Agency, 2022) issued by the International Energy Agency (IEA) on October 13, 2022. That report concludes that for numerous countries, the mitigation of carbon emissions is no longer an immediate policy priority, signaling a shift in their short-term policy focus away from carbon emissions reduction. For instance, Germany has raised its coal-fired power generation and dropped its goal of attaining carbon neutrality by 2035. In addition, the conflict has escalated the unstable political environment, resulting in carbon emissions from machinery like airplanes, ships, tanks, and more. These incidents have heightened public apprehension about climate change. It remains crucial to explore and execute measures to curtail emissions in tackling the climate crisis. The present socio-economic system, driven by carbon-intensive economic growth and unsustainable resource use, has led to the emergence of a "greenhouse earth" (Speth and Zinn, 2008; Steffen et al. 2018). The digital economy offers a fresh approach to economic progress, warranting investigation for its potential to support sustainable, zero-carbon, and inclusive growth. Scholars and governments have begun to recognize the link between the digital economy and carbon emissions. Developing the digital economy establishes a closed-loop system for gathering and providing feedback on green development information, enhancing energy efficiency, and refining carbon emission monitoring and management (Wu and Zhu, 2022). Digitalization appears to be a central tool in decoupling economic growth from carbon emissions (Xu et al. 2022). Yet, there's evidence that the digital economy can result in substantial carbon emissions. According to calculations by the Open Data Center Committee, China's data centers consumed 93.9 billion kilowatt hours of energy and emitted 64.64 million tons of carbon in 2020 (ODCC, 2022). Projections suggest that by 2030, China's data center's total energy consumption could skyrocket to about 380 billion kilowatt hours, with carbon emissions surging by over 300% (ODCC, 2022).

Academics have extensively and somewhat successfully investigated how the digital economy influences carbon emissions. However, there are still the following shortcomings: the academic community holds varying conclusions regarding the relationship between the digital economy and carbon emissions (Romm, 2002; Alam and Murad, 2020; Ma et al. 2022; Hao et al. 2022; Wang et al. 2022b; Wu et al. 2023; Zhang et al. 2022; Cheng et al. 2023; Li and Wang, 2022; Xiang et al. 2022). Second, scholars mainly measure the impact of the digital economy on carbon emissions from three aspects: total carbon emissions (Hao et al. 2022; Wang et al. 2022b; Wu et al. 2023; Zhang et al. 2022), intensity (Wang et al. 2022a; Wang and Zhong, 2023; Yan et al. 2022; Zhong et al. 2022), and efficiency (Lyu et al. 2023), but few kinds of literature have studied the digital economy and carbon emissions decoupling based on decoupling theory. Third, existing research on carbon decoupling and the digital economy uses provincial data in China (Lu and Chen, 2022; Zhong et al. 2022), while ignoring urban data. Existing research has ignored the division of decoupling indices in good and bad order (Lu and Chen, 2022; Yu et al. 2022). Fourth, they ignored the spatial effects of the digital economy on carbon decoupling (Lu and Chen, 2022; Yu et al. 2022; Zhong et al. 2022). Hence, this study utilizes data from 281 cities in China spanning from 2012 to 2019 to establish a comprehensive indicator evaluation system for assessing the level of digital economy development. Building upon this, we used ArcGIS software and analyzed the spatial distribution and agglomeration of the digital economy and carbon emissions decoupling. In addition, we examined the direct effects, heterogeneity, and spatial impacts of the digital economy on carbon emissions decoupling. Excessive carbon emissions resulting from human activities exemplify negative external economies. The digital economy, with its technological and knowledge spillovers, serves as a prime instance of spillover effects. Hence, this article investigates the spatial characteristics and connection of the digital economy and decoupling carbon emissions, adopting a fresh spatial perspective that unveils their intrinsic relationship more effectively. Investigating this matter can offer a fresh perspective and valuable insights for tackling carbon emissions.

This paper contributes in several ways. Firstly, we utilize Tapio's decoupling theory to categorize carbon emissions decoupling into different levels. This method enhances accuracy in assessing the digital economy's impact on carbon emissions and economic growth, improving our understanding of their sustainable relationship. Secondly, we analyze data from 281 Chinese cities between 2012 and 2019 to investigate the link between the digital economy and carbon emissions decoupling, a topic not previously studied. Our city-level data provides more reliable insights into urban structures compared to provincial data. Given that cities contribute to 75% of anthropogenic greenhouse gas emissions, their role in achieving carbon peaking and neutrality is crucial. Thus, examining factors influencing urban emission reduction becomes practically significant. Thirdly, by applying Tobler's first law of geography, we examine the spatial distribution and clustering of the digital economy and carbon emissions decoupling. We also explore how the digital economy affects nearby regions in terms of carbon decoupling, identifying whether it has a siphon or spillover effect. This approach yields unique insights into the spatial patterns of digital economy-driven carbon emissions decoupling, which aids discussions on sustainable urbanization.

We have found disparities in the distribution of the digital economy and urban carbon decoupling across China. Both exhibit positive spatial correlation and clustering. Moreover, we have noted that the influence of the digital economy on urban carbon decoupling hinges on the city's types of resources and geographical location. Strikingly, our study has revealed that the digital economy exacerbates the urban carbon decoupling situation in neighboring regions through the siphoning effect.

The structure is as follows: Part two comprises a literature review, and part three presents a research hypothesis. Part four includes the dataset, sample set, and model set. Part five analyzes the empirical results while part six concludes and discusses the findings.

Literature review

Literature review of the digital economy and carbon emission. Scholars' research on the relationship between the digital economy and carbon emissions mainly focuses on the following content: First, some scholars believe that the digital industry belongs to the industry with low energy density and low energy consumption increment (Romm, 2002). The dematerialization effect, decarbonization, and demobilization of the digital economy inhibit consumption-based carbon emissions (Alam and Murad, 2020; Ma et al. 2022). The digital economy reduces carbon emissions through industrial progress and energy consumption optimization, environmental governance, and innovation (Hao et al. 2022; Wang et al. 2022b; Wu et al. 2023; Zhang et al. 2022); it reduces the intensity of carbon emissions by improving innovation, increasing the proportion of clean energy consumption, upgrading industrial structure, improving energy utilization efficiency, and improving environmental regulation efficiency, and total factor productivity (Wang et al. 2022a; Wang and Zhong, 2023; Yan et al. 2022; Zhong et al. 2022); improves carbon emission efficiency by reducing energy consumption (Lyu et al. 2023), suppressing factor mismatch (Ge et al. 2022), technological innovation, reducing energy consumption intensity, and improving urban productivity (Zhao et al. 2022). The digital economy can reduce carbon emissions through spatial effects (Wang et al. 2022; Yi et al. 2022). Second, some scholars believe the digital economy increases carbon emissions (Dong et al. 2022; Zhang et al. 2022). The main reasons are that the digital economy has increased the demand for energy-intensive computers (Ma et al. 2022), and their use and disposal have increased the pressure on the environment (Houghton, 2015; Mickoleit, 2010). The surge in the number of digital centers has increased energy consumption and pollution (Jahangir et al. 2021). Third, some scholars also believe the digital economy and carbon emissions present an inverted U-shaped (Cheng et al. 2023; Li and Wang, 2022; Xiang et al. 2022), N-shaped (Zhang et al. 2022), inverted N-shaped (Hao et al. 2022), and other nonlinear relations (Wu et al. 2022).

In summary, scholars currently evaluate the impact of the digital economy on carbon emissions primarily through total emissions, intensity, and efficiency. However, a consensus on this issue has not been reached yet. There is a lack of literature utilizing decoupling theory to examine the relationship between the digital economy and carbon emissions. Previous research on carbon decoupling and the digital economy has predominantly employed provincial data from China (Lu and Chen, 2022; Zhong et al. 2022) and has neglected urban data. No literature has explored the spatial effects of the digital economy on carbon emissions decoupling. Using decoupling theory, this article analyzes the direct and spatial impact of the digital economy on carbon emissions decoupling in 281 Chinese cities, addressing the limitations of previous research.

Literature review of the decoupling theory. The concept of decoupling originates from physics, where it signifies the loss of correlation between two or more physical quantities. The OECD first introduced the decoupling theory to describe the disconnection between economic growth and resource consumption or environmental pollution, i.e., the decoupling of economic growth from these factors. In 2002, the OECD devised the decoupling index and decoupling factor to compare changes between the final and base years to clarify whether there was any decoupling in the economic system during that period. If the decoupling factor is positive and nearly 1, it is absolute decoupling, depicting environmental variables associated with economic development remaining stable or decreasing. If the decoupling factor is positive and near 0, it is relative decoupling, where both economic growth and environmental variables change positively, but the rate of change of the latter is lower. If the decoupling factor is 0 or negative, there is no decoupling. Based on the OECD measurement method, Hasan Rüstemoğlu concluded that Germany achieved an absolute decoupling of its GDP and carbon emissions from 1990 to 2015 (Rüstemoğlu, 2019). However, Tapio argues that this classification oversimplifies complex changes and tends to overstate some weaker ones. To address this limitation, Tapio introduced Tapio's decoupling indicator system, which classifies decoupling into three main categories and eight subcategories, illustrated in Fig. 1. Tapio's decoupling indicator is valued for its comprehensive nature and its independence from a base period selection. Consequently, scholars extensively employ this indicator to analyze the carbon emissions decoupling (de Freitas and Kaneko, 2011; Jiang and Li, 2017; Chen et al. 2023; Gao et al. 2021; Huang and Guo, 2022; Huang et al. 2022; Huo et al. 2021; Wang and Han, 2021; Zhao and Li, 2018). Previous researchers have utilized Tapio's decoupling indicator to examine the decoupling of carbon emissions in various regions and industries (Amir et al. 2023; Chen et al. 2023; Dong et al. 2021; Hua et al. 2023; Jiang et al. 2018; Huo et al. 2021; Liu et al. 2022; Wei et al. 2022). They have also analyzed the impact of factors such as financial development, household income, Sino-US trade, urbanization, carbon emission trading policies, labor and investment, urbanization, industrialization, and trade openness on carbon emissions decoupling (Huo et al. 2021, Wang and Han, 2021; Duan et al. 2022; Huang and Guo, 2022; Lyu et al. 2022; Wang and Jiang, 2020; Wang et al. 2018; Wang et al. 2023; Wang and Zhang, 2021).

In summary, there's limited literature on the link between the digital economy and carbon emissions decoupling. Some scholars, based on provincial data in China, propose that the digital economy initially aids decoupling, yet this effect weakens over time due to industrial structure mediation and positive regulation from network centrality. However, existing studies lack quantity,

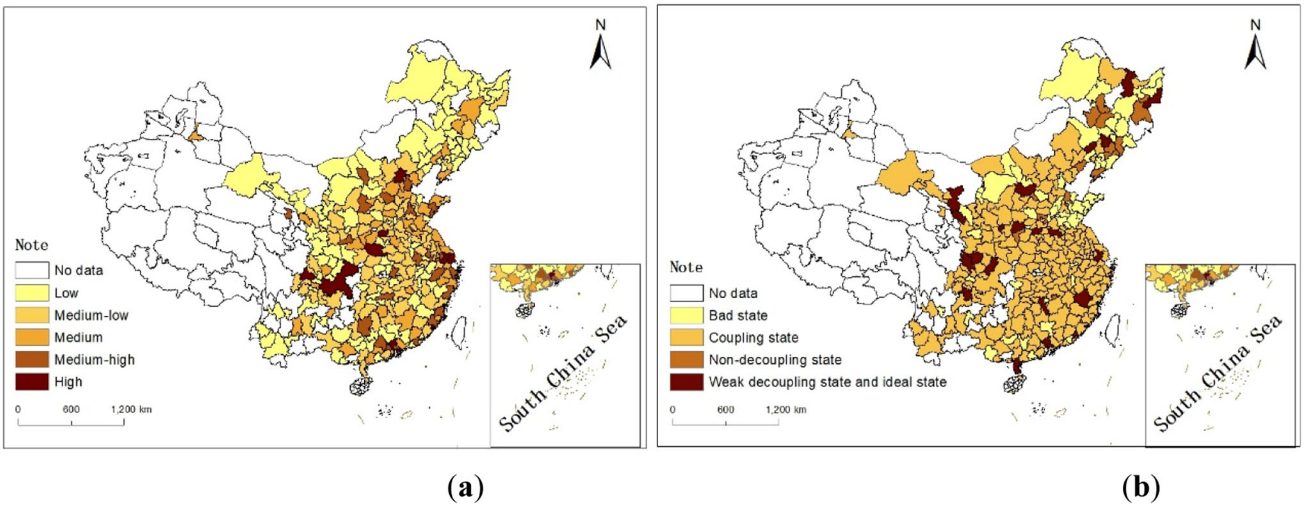

Fig. 1 Spatial distribution. a Spatial distribution of urban digital economy in 2019; **b** The spatial distribution of urban carbon decoupling in 2019.

depth, and comprehensiveness, and often omit city-level data. They also overlook Tapio's decoupling indicator classification. The spatial impact of the digital economy on carbon decoupling is underexplored, despite the rise of new economic geography. Carbon emission involves externality, necessitating spatial considerations. Scholars employ spatial econometric models to study specific factors' spatial correlation with carbon emissions (Li and Fan, 2023; Lin et al. 2023; Liu et al. 2023; Long et al. 2020). Nonetheless, the spatial impact of the digital economy on carbon emissions decoupling lacks research.

Research hypothesis

Digital economy and carbon decoupling. This article believes that the digital economy will promote the decoupling of urban economic growth and carbon emissions from four aspects. From a technological progress standpoint, the digital economy has the potential to drive green technological advancements and enhance pollution control measures (Wurlod and Noailly, 2018). Following Davidow's law, initial-generation products can automatically capture 50% of the market share upon entering the market. To expand their market presence, enterprises increase their investment in innovation, leading to higher innovation output. Notably, green innovation and environmental innovation are crucial outcomes of innovation and play a significant role in achieving emission reduction (Liu et al. 2022; Zhang et al. 2021; Zhang et al. 2017). Hence, this study asserts that the digital economy can effectively reduce emissions and facilitate the decoupling of urban carbon emissions by fostering advancements in green innovation.

From an energy standpoint, the digital economy has the potential to lower energy intensity, decrease the costs associated with renewable energy utilization (Moyer and Hughes, 2012), increase the share of non-fossil energy sources, and optimize industrial structure (Wang et al. 2021). Furthermore, it can enhance the efficiency of energy allocation across the upstream and downstream sectors (Yan et al. 2016), reduce energy intensity, and foster a conducive environment for green growth (Ulucak, 2020). As a result, this study posits that the digital economy can effectively reduce the intensity of urban carbon emissions and facilitate decoupling by curtailing energy consumption, improving energy efficiency, and promoting the transformation and upgrade of energy structures.

From an economic growth standpoint, scholars argue that the advancement of the digital economy facilitates the alignment of product and service supply and demand, lowers transaction costs (Romm, 2002), and can result in more efficient production methods and enhanced productivity (Moyer and Hughes, 2012). In addition, the digital economy promotes dematerialization effects (Liang, 2021), thereby reducing material production and consumption and curbing the demand for high-carbon-emitting products, both directly and indirectly (Akimoto et al. 2022). We think that the digital economy has improved production efficiency and reduced information asymmetry through big data. Through accurate prediction of market demand, enterprises have made accurate production and sales and improved the matching efficiency between supply and demand. Meanwhile, the digital economy promotes the growth rate of marginal returns of various factors by adding new data as the production factor and reforming and restructuring the traditional production factors, which amplifies and superimposes economic growth. Therefore, the digital economy promotes urban carbon decoupling through economic growth effect and efficient use of resources.

From a regulation perspective, smartphone applications can enhance the accountability of public agricultural extension services by enabling real-time remote supervision. Consequently, this leads to a reduction in both the cost and time needed for regulation (Namyenya et al. 2022). Therefore, digital technology can integrate various social entities, including platforms, businesses, consumers, and governments, into the carbon emission governance system. This expansion enhances the scope, methods, and scenarios of environmental oversight, thereby contributing to the development of a collaborative, multi-agent framework for green governance. Simultaneously, the digital economy aids governments in establishing integrated ecological environment perception systems and expediting the implementation of intelligent monitoring systems for carbon emissions.

Based on the above analysis, we put forward the research hypothesis:

H1: The digital economy can promote the decoupling of urban economic growth and carbon emissions.

Digital economy, space effect and carbon decoupling. Spatial effects include the spillover effect and the siphoning effect. The spillover effect means something drives the development of things around it. In economics, the siphoning effect refers to a city with an advantageous position that can attract various resources from a city with a relatively inferior position. The siphoning effect may cause cities with advantages to be more competitive while cities with relative disadvantages are more disadvantaged. Digitalization and carbon emissions have significant spatial spillover effects (Fang et al. 2022; Liu et al. 2021). However, no scholars have examined whether the digital economy affects the decoupling of neighborhood carbon emissions from economic growth. This article argues that the digital economy can have both spillover and siphon effects on carbon emissions decoupling in neighborhoods.

First, the digital economy facilitates decoupling through spillover effects. It helps establish cross-regional industrial chains and industry-university research platforms (Yang et al. 2021; Fang et al. 2022). Technological spillovers from the industrial chain promote the green transformation of neighborhoods (Handfield et al. 2005). In addition, industry-university research platforms contribute to the adoption of green technology across regions (Fang et al. 2022). Thus, this article concludes that the digital economy generates technology and learning spillovers, actively promoting the decoupling of carbon emissions in neighborhoods.

In addition, it is often overlooked in the existing literature that the digital economy can also hinder the decoupling of carbon emissions in neighborhoods through the siphoning effect. The digital economy facilitates the construction of digital infrastructure and urban management, attracting high-quality resources from neighboring areas (Xu and Sun, 2021). According to Colin Clark, income differences primarily determine population mobility. In the context discussed in this article, the digital economy's ability to bring efficient production methods and productivity improvements attracts high-quality talent to regions with robust digital economy development (Moyer and Hughes, 2012). As a result, the digital economy intensifies the concentration and convergence of high-quality resources (Luo et al. 2022), thereby enhancing the factor structure of cities (Duggal et al. 2007). However, it is precisely because regions with strong digital economy development lure high-quality resources from neighboring areas that a considerable amount of these valuable resources is depleted within the neighborhoods. This, in turn, hampers the sustainable development of the neighborhood's economy and leads to increased carbon emissions. Thus, this article argues that the development of the digital economy can also suppress the decoupling of carbon emissions in neighborhoods through the siphoning effect.

Therefore, this article proposes the following competitive hypothesis:

H2: The digital economy deteriorates the surrounding carbon decoupling state through the siphoning effect.

H3: The digital economy improves the surrounding carbon decoupling through spillover effects.

Methods

Benchmark model setting. We set up the following linear regression model to test the relationship between the digital economy and carbon decoupling:

$$tapioc_{it} = \alpha_0 + \alpha_1 dec_{it} + \sum \alpha X_{it} + u_i + v_t + \mu_{it} \tag{1}$$

In the above formula, i represents the city; t represents the year; $tapioc_{it}$ represents the state of urban carbon decoupling; dec_{it} represents the urban digital economy;α_0, X, u, v and μ represent constant term, control variables, individual effect, time effect, and random error. To ensure the reliability of the results, we control the city-fixed and year-fixed effects and adopt robust standard error to mitigate the disturbance.

The setting of the spatial measurement model. We have established a spatial econometric economic model to explore the spatial effect of the digital economy on carbon decoupling:

$$\begin{aligned} tapioc_{it} &= \alpha_0 + \rho W \mathrm{tapioc}_{it} + \alpha_1 dec_{it} + \varphi_1 W dec_{it} + \alpha_2 X_{it} \\ &+ \sum \varphi W X_{it} + u_i + v_t + \mu_{it} \mu = \lambda W \mu + \varepsilon \end{aligned} \tag{2}$$

Among them, ρ and W represent the spatial autocorrelation coefficient and spatial weight matrix. φ_1, φ, and λ are the coefficient of the interaction term between the core explanatory variable, control variable, random disturbance term, and the spatial weight matrix. Equation (2) is the spatial Dubin model (SDM) to examine the spatial effects. When the spatial Dubin model meets certain conditions, it can be simplified into the spatial lag model (SLM) and spatial error model (SEM).

Variable selection

Explained variable. Firstly, calculating total carbon emissions of cities (CO_2), which can be divided into three components:

(1) Carbon emissions from urban electricity (c_1):
Calculate these emissions by multiplying social electricity consumption by the baseline emission factor of the regional power grid.

(2) Carbon emissions from urban thermal energy (c_2):
Urban thermal energy relies on steam and hot water heating, often from raw coal. Calculate emissions by multiplying total urban steam and hot water heating by the raw coal emission coefficient and thermal efficiency value, then dividing by the average low calorific value of raw coal. A thermal efficiency value of 70% is used.

(3) Carbon emissions from urban manufactured gas, natural gas, and liquefied petroleum (c_3):

$$C_3 = petroleum \times M + natural\_gas \times Q \tag{3}$$

In this case, *petroleum* and M represent the supply volume and carbon emission coefficient of artificial manufactured gas and natural gas, respectively, while *natural_gas* and Q represent the supply volume and carbon emission coefficient of liquefied petroleum, respectively. Calculating carbon emissions for each component allows us to determine the total urban carbon emissions (CO_2).

Secondly, calculate the carbon decoupling index for each city using Tapio's (2005) decoupling index system (Tapio, 2005).

$$T_{it} = \frac{\Delta co_2^{it} / co_2^{i,t-1}}{\Delta gdp^{it} / gdp^{i,t-1}} = \frac{\left(co_2^{it} - co_2^{i,t-1}\right) / co_2^{i,t-1}}{\left(gdp^{it} - gdp^{i,t-1}\right) / gdp^{i,t-1}} \tag{4}$$

In the formula provided, i represents city, and t represents time. According to Tapio's classification, the decoupling status includes strong growth decoupling, weak growth decoupling, strong recession decoupling, weak recession decoupling, growth non-decoupling, recession non-decoupling, growth coupling, and recession coupling.

Next, when we consider the inclusion of the eight decoupling states in the explained variables, the econometric model becomes complex, and these states present pros and cons (Mi and Zhao, 2022). In growth decoupling, a smaller growth rate in carbon emissions signifies a more favorable urban decoupling status. Conversely, in recession-type decoupling, a greater reduction in carbon emissions corresponds to an improved city decoupling state. The most optimal scenario arises from robust urban economic growth coupled with decreased carbon emissions. On the contrary, recession-strong-decoupling indicates the least desirable circumstances. Thus, the ranking of decoupling states aligns as follows: weak growth decoupling > non-decoupling in growth > growth coupling, weak decline decoupling > non-decoupling in decline > decline coupling. With the increase (decrease) in positive (negative) economic growth rates, carbon emission growth rates decrease, forming a symmetrical optimization path for recession and growth decoupling. In conclusion, according to the optimal sequencing of decoupling, this paper re-induces five states and constructs the interpreted variable (*tapioc*). We divide the urban carbon decoupling state into the ideal state (strong growth decoupling, *tapioc* = 4), weak decoupling state (weak growth decoupling, recession weak decoupling, *tapioc* = 3), non-decoupling state (growth non-decoupling, recession non-decoupling, *tapioc* = 2), coupling state (growth coupling, recession coupling, *tapioc* = 1), and bad state (strong recession decoupling, *tapioc* = 0). To mitigate the influence of base period changes on results, this research employs data from the previous year as the base period for urban carbon decoupling calculation. Table 1 illustrates the diverse urban carbon emissions decoupling types and the structure of dependent variables in this study.

Core explanatory variables. The measurement methods of the digital economy mainly include the national economic accounting method, satellite account, index method, etc. The index method is real-time, flexible, innovative, and can systematically reflect the national or regional digital economy. So, we study the impact of the digital economy on urban carbon decoupling, which is more suitable for using the index method. Regarding Zhao et al. (2020), we measure the urban digital economy from the proportion of Internet users, mobile phone users, information transmission and technology services employment, the total number of telecommunications services per capita, and the urban digital inclusive financial index.

Control variables. Some scholars believe that technological innovation in the information industry will raise carbon emission intensity (Wang et al. 2021). Technology expenditure reflects the level of emphasis and support for technology, and general technology expenditure is positively correlated with regional technology levels. The IPAT model, STIRPAT extended model, and LMDI model all acknowledge the influence of population and technology on the environment (Dietz and Rosa, 1997). Hence, this article includes technology expenditure and regional population size as control variables.

Table 1 Types of urban carbon emission decoupling.

Decoupling type		Carbon dioxide growth rate	Economic growth rate	Decoupling index range	Variable setting
Decoupling	Growth strong decoupling	−	+	$T < 0$	$tapioc = 4$
	Growth weak decoupling	+	+	$0 < T < 0.8$	$tapioc = 3$
	Recession weak decoupling	−	−	$T > 1.2$	$tapioc = 3$
Negative decoupling	Recession coupling	−	−	$0 < T < 0.8$	$tapioc = 1$
	Recession strong decoupling	+	−	$T < 0$	$tapioc = 0$
	Growth coupling	+	+	$T > 1.2$	$tapioc = 1$
Coupling	Growth non-decoupling	+	+	$0.8 < T < 1.2$	$tapioc = 2$
	Recession non-decoupling	−	−	$0.8 < T < 1.2$	$tapioc = 2$

"+" represents positive change, and "−" represents negative change.

Government expenditure can impact urban carbon emissions. According to some scholars, an increase in total government spending in the short term can result in higher carbon dioxide emissions (Galinato and Galinato, 2016). The overall impact of government expenditure on total carbon emissions is positive, as the negative direct impact is offset by positive indirect effects (Adewuyi, 2016). Therefore, this article selects government expenditure as a control variable.

Human capital has the potential to influence urban carbon emissions. Some scholars argue that enhancing human capital can contribute to the reduction of carbon emissions (Bano et al. 2018; Sheraz et al. 2021). ICT capital enhances carbon emission efficiency by facilitating the accumulation of human capital (Xu et al. 2022). In addition, the impact of human capital on carbon emissions differs before and after the turning point of the Environmental Kuznets Curve (EKC) (Wang et al. 2023). Hence, this article considers human capital as a control variable.

Finance can indeed impact the levels of urban carbon emissions (Ali et al. 2022; Zhang et al. 2022). Considering the influence of urban finance on the extent of decoupling urban carbon emissions, this article considers urban financial development as the control variable.

Based on this, the control variables selected in this paper are as follows: ① Science and technology expenditure(*tech*). This paper adopts the proportion of scientific expenditure in the general budget of local finance to measure urban scientific and technological expenditure. ② Government intervention (*gov*). This paper uses the proportion of expenditure in the general budget of local finance to GDP as a measure of government intervention. ③ Human capital (*human*). Measure human capital in cities by the proportion of education expenditure to GDP. ④ Population (*lnp*). We use the logarithm of the population at the end of the year to measure the size of the urban population. ⑤ Financial development (*fa*). We use the ratio of the balance of loans from financial institutions at the end of the year to the city's current GDP to measure the financial development.

Data source. Social electricity consumption, artificially manufactured gas and natural gas supply, liquefied petroleum gas, the proportion of internet users, mobile phone users, information transmission and technology services deployment, the total number of telecommunications services per capita, science and technology expenditure, government intervention, human capital, population, financial development, etc., are obtained from the China Urban Statistical Yearbook. Heat data is sourced from the China Urban Construction Statistical Yearbook. The baseline emission factors of the regional power grid are obtained from the official website of the Ministry of Ecology and Environment. The average low calorific value and carbon emission coefficient of raw coal are derived from the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. We have chosen the time frame spanning from 2012 to 2019 for our analysis. Some incomplete data are processed by interpolation. Table 2 presents the descriptive statistics of all variables.

Table 2 Descriptive statistics of variables.

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Tapioc	2248	1.6988	1.3553	0.0000	4.0000
Dec	2248	1.8229	2.4169	0.0353	30.6314
Tech	2248	0.0168	0.0169	0.0007	0.2118
Gov	2248	0.2047	0.1034	0.0441	0.9174
Human	2248	0.0354	0.0183	0.0076	0.1486
Lnp	2248	5.8979	0.6850	2.9857	8.1362
Fa1	2248	1.0188	0.6180	0.1200	9.5567

Result

Spatial distribution and agglomeration

Space distribution. Figure 1a illustrates the predominant distribution of the low-level digital economy in the northeast and northwest regions, while the high-level digital economy is concentrated in the Southeast Coast and municipalities directly under the Central Government. In Fig. 1b, which displays the spatial arrangement of urban carbon decoupling in 2019 with 2018 as the base year, it becomes apparent that cities with unfavorable carbon decoupling status are primarily situated in Northeast China and North China. It is notable that the majority of cities currently do not exhibit decoupling.

Space agglomeration. Following the first law of Geo-economics, cities in closer proximity exhibit heightened mutual influence. Thus, we employ a normalized inverse distance spatial weight matrix to scrutinize spatial correlations. By utilizing Matlab-R2017a, we compute the inverse distance spatial weight matrix following travel standardization. As displayed in Table 3, the global Moran's I index for urban carbon decoupling utilizing the inverse distance matrix exceeds 0 and is significant during 2013–2018. That signifies a positive spatial correlation in urban carbon decoupling across most years. In addition, Table 3 demonstrates that the global Moran's I index for the urban digital economy surpasses 0 and is significant, indicating a favorable spatial correlation. Consequently, spatial analysis becomes crucial for examining the interaction between the digital economy and urban carbon decoupling.

Next, this paper uses the LISA agglomeration diagram to analyze the agglomeration types of the digital economy and urban carbon decoupling. These patterns encompass four types: high-high (H-H), high-low (H-L), low-high hollow (L-H), and low-low (L-L) types (Wu et al. 2023).

Figure 2A shows that the H-H type concentration area of the digital economy mainly includes the Southeast Coast. The L-L type is distributed in Northeast China, Gansu, and Yunnan. Figure 2B shows the LISA cluster diagram of China's urban carbon decoupling in 2019. The results show that the L-H type of urban carbon decoupling is mainly distributed in Gansu and Shanxi of China, and the L-L type is mainly concentrated in Shandong, Hebei, and Inner Mongolia Autonomous Region.

Benchmark regression results. In Column (1) of Table 4, the coefficient of the urban digital economy is 0.083 and significant at the 1% level. Columns (2) to (4) are the benchmark regression results after adding the control variables. In column (4), the coefficient of the digital economy is 0.074, which is statistically significant at the 1% level. Table 4 shows that the digital economy has improved urban carbon decoupling. Therefore, this paper verifies hypothesis 1 and posits that the digital economy has improved urban carbon decoupling by reducing information asymmetry, precision production, and sales, increasing output, promoting urban green development, and strengthening environmental governance.

Robust test

Add missing variables. We further test the robustness of the benchmark regression by increasing the logarithm of actual output (*lnrgdp*), foreign investment (*fdi*), urbanization level (*urb*), energy structure (*es*), and industrialization level (*ind*) that may affect urban carbon decoupling as control variables in the benchmark regression model. In Column (1) of Table 5, the coefficient of the digital economy is 0.076 and significant after adding control variables. The result means that the digital economy still improves the carbon decoupling status.

Table 3 Global Moran Index.

	Urban carbon decoupling			Urban digital economy		
Year	**I**	**Z**	***P* value**	**I**	**Z**	***P* value**
2012	−0.0065	−0.4235	0.6719	0.0398	6.5557	0.0000
2013	0.0068	1.5043	0.1325	0.0434	7.1165	0.0000
2014	0.0258	4.2485	0.0000	0.0381	6.3069	0.0000
2015	0.0149	2.6751	0.0075	0.0278	4.7681	0.0000
2016	0.0271	4.4290	0.0000	0.0282	5.1159	0.0000
2017	0.0232	3.9499	0.0001	0.0388	6.4293	0.0000
2018	0.0751	11.3974	0.0000	0.0340	5.6239	0.0000
2019	−0.0078	−0.6228	0.5334	0.0187	3.3821	0.0007

Interaction fixed effect. The interactive fixed effects model fully considers multidimensional shocks and different reactions, which can better reflect the authenticity of specific problems. Therefore, we next use the interaction fixed effect of individuals and time to test robustness. After adding the interactive fixed effect, column (2) in Table 5 shows the coefficient of the digital economy is 0.069 and significant at the 5% level. This finding suggests that the digital economy can significantly improve the urban carbon decoupling status, which verifies hypothesis 1.

Excluding municipalities directly under the Central Government. Municipalities under the Central Government generally have large built-up areas, a large population, and an important position in politics, economy, science, and culture. Therefore, it's political particularity may impact the digital economy and urban carbon decoupling differently. So, after deleting Beijing, Shanghai, Chongqing, and Tianjin, we find the digital economy is 0.073 and significant at the 1% level. The finding further verifies hypothesis 1.

Eliminate relevant policies affecting carbon emissions. We conduct robustness tests by excluding provinces and cities involved in carbon trading. Table 5, column (5) shows that the digital economy is 0.082, significant at the significance level of 1%. The result means that the digital economy improves the urban carbon decoupling status. The robustness test verifies hypothesis 1.

Shrinkage treatment. We conducted a 1% tail reduction on the digital economy to prevent the impact of outliers on the research results. In Table 5, Column (5) shows that the digital economy after tail reduction is 0.087, significant at the significance level of 5%. The result means that the digital economy improves the urban carbon decoupling status. The robustness test verifies hypothesis 1.

Treatment of endogenous problems. We use the number of telephones per 100 people in 1995 as an instrumental variable

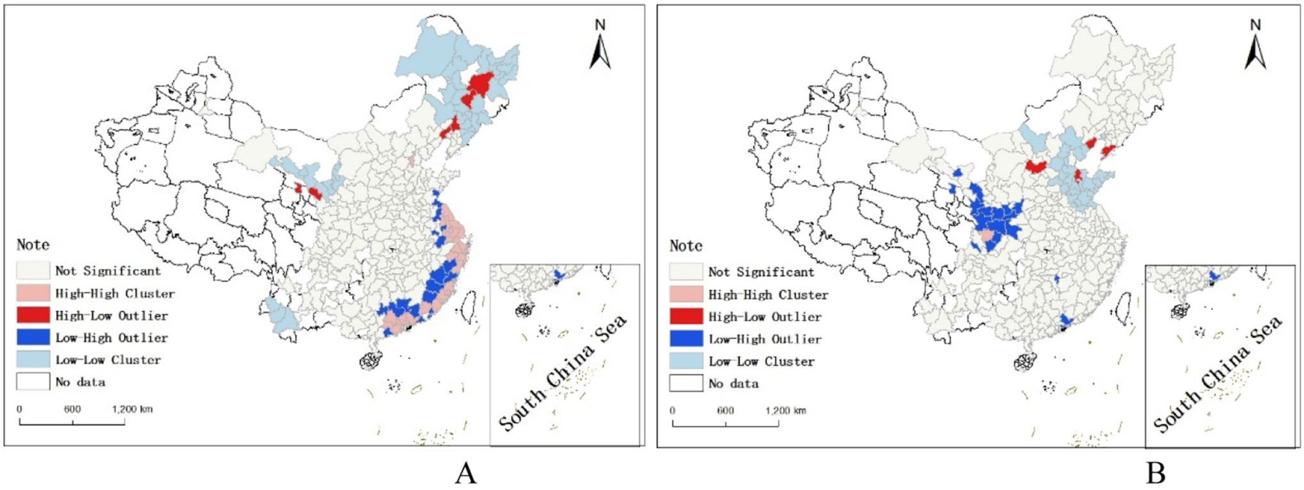

Fig. 2 LISA chart. A LISA chart of digital economy in 2019; **B** LISA chart of urban carbon decoupling in 2019.

estimation for endogenous analysis. This paper believes the number of telephones in 1995 is historical data, which will not affect the current carbon decoupling status and meet exogenous conditions. From the perspective of relevance, the telephone is an important communication device. The number of telephones provides resources for the digital economy. So, the number of telephones per 100 people in 1995 is related to the development of the digital economy. However, the digital economy evolved while the number of telephones per 100 people in 1995 remained constant. Therefore, we select the Interaction between the number of telephones per 100 people in 1995 and Internet users as the instrumental variable (iv). In Table 6, the first column shows that the is positively correlated with the digital economy. The result is consistent with the expectation.

The second column of Table 6 reports that the F statistic of the weak instrumental variable test with heteroscedasticity in the first stage is >10. Week identification test (Cragg-Donald Wald F statistic) = 366.252 is >16.38 at the 10% level. The *P* value of the Underidentification test is significant at the 1% level. Meanwhile, the digital economy is 0.152 and significant at 5%. Therefore, after considering the endogenous analysis, the digital economy can still improve the carbon decoupling status, confirming hypothesis 1.

Table 4 Benchmark regression results.

	(1) Tapioc	(2) Tapioc	(3) Tapioc	(4) Tapioc
Dec	0.083*** (3.284)	0.078*** (3.116)	0.075*** (2.936)	0.074*** (2.903)
Tech		4.338 (0.964)	3.565 (0.802)	3.546 (0.790)
Gov		−1.314 (−1.343)	−1.014 (−1.026)	−1.182 (−1.186)
Human		−14.513** (−2.196)	−16.247** (−2.438)	−17.189** (−2.547)
Lnp			1.003 (1.468)	1.031 (1.508)
Fa1				0.122 (1.629)
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
_cons	1.547*** (33.577)	2.266*** (9.103)	−3.629 (−0.905)	−3.852 (−0.959)
N	2248	2248	2248	2248
R2_a	0.1612	0.1666	0.1673	0.1676

* * and * * * represent significant at the statistical level of 5 and 1% respectively; Figures in brackets are statistical values of t.

Heterogeneity analysis

Heterogeneity of urban resource types. Urban resource endowment affects carbon emissions. This paper classifies the cities into non-resource-based and resource-based cities to test the Heterogeneity. In Table 7, the first column shows that the digital economy of non-resource-based cities is 0.079, significant at 1%. In the second column, the digital economy of resource-based cities is −0.024, which is negative but not statistically significant. So, the digital economy can improve the carbon decoupling level of non-resource-based cities, not yet resource-based cities.

We believe that a resource-based city takes the mining and processing of natural resources as the leading industry. Its industrial development is highly dependent on resources, and its ability to gather talent and innovation is weak, resulting in its slow development of green transformation and poor carbon decoupling capacity.

Regional heterogeneity. This paper divides the cities into eastern, central, and western cities to test the Heterogeneity. The third column of Table 7 shows that the eastern digital economy (dec) is 0.106, significant at the 5% level. The fourth column indicates that the coefficient of the digital economy in the central region is 0.062, which is significant at the level of 10%. The fifth column suggests that the coefficient of the digital economy in Western China is −0.032, which is negative but not statistically significant. Therefore, the digital economy can improve the carbon decoupling level in eastern and central cities, but not yet in western cities. We believe that the digital economy in the eastern and central cities is developing better, enabling the development of traditional industries through digital technology and improving the urban green development and decoupling status. However, the digital economy in Western cities is poor, the industrial structure is unreasonable, and the dependence on resources is strong, which leads to the small impact of the digital economy on carbon decoupling in Western cities.

Research on spatial effect. Table 3 and Fig. 2 show that urban carbon decoupling has a positive spatial correlation and the

Table 5 Robustness test.

	(1) Tapioc	(2) Tapioc	(3) Tapioc	(4) Tapioc	(5) Tapioc
Dec	0.076*** (2.890)	0.069** (2.111)	0.073*** (2.590)	0.082*** (3.109)	0.087** (2.149)
Tech	3.367 (0.740)	7.483** (2.073)	3.606 (0.801)	−2.416 (−0.519)	3.476 (0.777)
Gov	−3.373*** (−3.023)	−0.789 (−0.726)	−1.271 (−1.274)	−1.885* (−1.890)	−1.174 (−1.179)
Human	−12.206 (−1.547)	−19.845*** (−2.793)	−16.474** (−2.439)	−16.754** (−2.561)	−17.254** (−2.557)
Lnp	0.890 (1.284)	1.027 (1.618)	1.024 (1.492)	0.211 (0.295)	1.010 (1.467)
Fa1	0.107 (0.895)	0.100 (1.110)	0.127* (1.690)	0.134* (1.819)	0.122 (1.631)
Fdi	25.679 (1.321)				
Urb	−0.131*** (−4.133)				
Es	2.406** (2.387)				
Ind	1.343 (1.448)				
City	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
_cons	2.888 (0.640)	−3.849 (−1.028)	−3.784 (−0.942)	1.226 (0.293)	−3.743 (−0.927)
N	2118	2248	2216	1880	2248
R2_a	0.1836		0.1675	0.1779	0.1670

*, * * and * * * represent significant at the statistical level of 10, 5 and 1% respectively; Figures in brackets are statistical values of t.

characteristics of spatial aggregation. Therefore, it is necessary to use spatial econometric models to analyze the spatial effects of the digital economy on urban carbon decoupling.

Table 8 shows the results of the LM test, the Hausman test, the LR test, and the Wald test. Meanwhile, Elhorst (2010) suggested that if the results of the LM test support any one or two of the SEM and the SAR, we need to use the SDM to estimate (Elhorst, 2010). According to Table 8 and Elhorst (2010), we should use the spatial Durbin model to analyze the spatial relationship between the digital economy and carbon emissions decoupling (Elhorst, 2010).

In Table 9, models (1), (2), and (3) are the regression results of the spatial weight matrix of inverse distance, economic distance, and the nested weight matrix of geographical and economic distance. After considering the spatial effect, the coefficients of the model (1)–model (3) digital economy (dec) are all positive and significant at the 5% level. The result shows that the digital economy can still improve the city's carbon decoupling status after considering the spatial effect. Models (1)–(3) show that rho is positive and significant at a 1% significance level. Therefore, the carbon decoupling status of the surroundings positively impacts this city's carbon decoupling status.

Meanwhile, we also found that the digital economy with close geographical distance, economic distance, and economic, geographical distance can reduce the carbon decoupling of the city. This result shows that the digital economy can worsen the carbon decoupling status of the surroundings through the siphoning effect. We believe that regions with a well-developed digital economy can attract high-quality resources from the surrounding, further enhancing the potential for local economic development and enhancing the emission reduction advantages. As a result, where the digital economy is developing well, it strengthens its carbon decoupling status but worsens the carbon decoupling status of the surroundings. Therefore, Hypothesis 2 holds.

Table 6 Treatment of endogenous problems.

	(1) Dec	(2) Tapioc
Iv	0.015*** (8.885)	
Dec		0.152** (2.140)
Tech	−2.805 (−0.756)	12.496*** (2.744)
Gov	−0.926* (−1.777)	0.163 (0.139)
Human	2.391 (0.639)	−29.375*** (−3.368)
Lnp	0.375 (0.664)	0.502 (0.787)
Fa1	0.109 (1.195)	0.180 (1.405)
City	Yes	Yes
Year	Yes	Yes
_cons	−1.062 (−0.321)	0.870 (0.301)
N	1768	1768
R2_a	0.8945	0.1665

*, * * and * * * represent significant at the statistical level of 10, 5 and 1% respectively; Figures in brackets are statistical values of t.

Discussion

This study aims to examine the correlation between the digital economy and the decoupling of carbon emissions in 281 Chinese cities from 2012 to 2019. Our findings reveal an imbalanced distribution of digital economy development and carbon emissions decoupling among Chinese cities, showing a spatial agglomeration phenomenon. The conclusion aligns with previous research in the field. For example, Kang et al. (2016) observed a spatial imbalance in China's carbon emissions (Kang et al. 2016). In addition, Tang et al. (2021) highlighted variations in the development level of China's digital economy among different cities (Tang et al. 2021).

Our research indicates that the digital economy holds significant promise not only in advancing human progress, bridging the digital divide, and fostering social development but also in driving the decoupling of urban carbon emissions. Consequently, the digital economy plays a pivotal role in facilitating sustainable economic, social, and environmental growth. Its development aligns with the United Nations' sustainable development goals and aids the Chinese government in achieving harmonized progress in digitization and environmental sustainability (Wu and Zhu, 2022). Policymakers can leverage the digital economy to reduce emissions and achieve high-quality economic development.

Furthermore, we also examined the role of urban heterogeneity in the digital economy and carbon emissions decoupling. Policymakers can develop targeted policies to foster the digital economy and decouple carbon emissions in these areas. For instance, there is a concentration of regions with inadequate decoupling of carbon emissions in Northeast and North China, with many of these areas also being L-L agglomeration zones. As a result, these locations represent crucial and challenging areas for carbon emission control. It is imperative to swiftly transform the existing, unsustainable industrial structure and introduce green

Table 7 Heterogeneity analysis.

	(1) Tapioc	(2) Tapioc	(3) Tapioc	(4) Tapioc	(5) Tapioc
Dec	0.079*** (3.014)	−0.024 (−0.309)	0.106** (2.288)	0.062* (1.927)	−0.032 (−0.560)
Tech	14.168*** (2.850)	−8.728** (−2.435)	8.915 (1.086)	4.503 (0.664)	−10.321** (−2.244)
Gov	−1.727 (−1.021)	−0.611 (−0.527)	−2.426 (−0.860)	0.044 (0.027)	−2.577** (−2.094)
Human	−14.147* (−1.686)	−25.646*** (−2.693)	−7.542 (−0.457)	−30.827** (−2.348)	−20.029** (−2.389)
Lnp	2.220** (2.092)	−0.153 (−0.167)	2.475 (1.219)	−0.203 (−0.225)	2.842** (2.199)
Fa1	0.081 (0.343)	0.148* (1.920)	0.211 (0.728)	0.075 (0.609)	0.181*** (2.669)
City	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
_cons	−11.504* (−1.802)	3.721 (1.272)	−13.357 (−1.096)	3.682 (0.694)	−12.762* (−1.744)
N	1352	896	904	864	480
R2_a	0.1843	0.1555	0.1403	0.1890	0.2166

*, * * and * * * represent significant at the statistical level of 10, 5 and 1% respectively; Figures in brackets are statistical values of t.

development initiatives such as digital transformation to invigorate the economy. To further accelerate the decoupling of carbon emissions, we actively encourage non-resource-based cities and those in the Middle East to enhance their digital economy development. Our focus is on promoting digital technology and smart city solutions to attract investments, drive innovation, improve resource efficiency, and reduce carbon emissions.

Interestingly, our research reveals that the digital economy can suppress neighborhood carbon emissions decoupling due to the siphoning effect, a novel finding given the absence of spatial Durbin models in existing literature exploring the relationship between the digital economy and carbon emissions decoupling. That highlights the need for urban managers to address imbalanced development in the digital economy and reasonably plan its growth to ensure high-quality development while minimizing carbon emissions in neighborhoods.

Conclusion and recommendations

Scholars primarily examined the digital economy's effects on total, intensity, and efficiency of carbon emissions. However, few have analyzed its impact on carbon emissions decoupling. This article innovatively utilizes Chinese urban data to explore both the spatial distribution and characteristics of the digital economy and carbon emission decoupling. It further investigates the direct impact, heterogeneity, and spatial effects of the digital economy on carbon emission decoupling. Key findings include:

(1) The digital economy's lower level mainly concentrates in the northeast and northwest regions, while the higher level is predominant in municipalities directly under the Central Government and the Southeast Coast.
(2) Cities facing challenges in carbon decoupling are primarily found in Northeast China and North China, with most cities still lacking decoupling progress.
(3) A positive spatial correlation exists between the digital economy and urban carbon decoupling.
(4) The Southeast Coast stands out as the H-H concentration area for the digital economy. Conversely, the L-L category extends across Northeast China, Gansu, and Yunnan. Gansu and Shaanxi host the L-H type for urban carbon decoupling, while Shandong, Hebei, and the Inner Mongolia Autonomous Region witness significant L-L cluster concentrations.
(5) Through empirical study, the digital economy's positive impact on urban carbon decoupling is verified, with results consistently supported by robustness tests.
(6) Heterogeneity analysis reveals significant enhancements in urban carbon decoupling by the digital economy in non-resource-based cities, particularly those located in the central and eastern regions.
(7) The carbon decoupling status of surrounding areas positively affects this city's decoupling progress. Moreover, our findings indicate that a closely aligned geographical, economic, and economic-geographical proximity of the digital economy can mitigate the city's carbon decoupling. This dynamic implies a spatial spillover effect on urban carbon emissions decoupling. However, it's important to note that the digital economy can also exacerbate carbon decoupling challenges in surrounding regions through the siphoning effect.

Based on these findings, we propose the following recommendations: To begin with, the uneven development of the digital economy across China poses a risk of widening the digital divide. To mitigate this, we recommend bolstering digital infrastructure and literacy in less-developed regions, such as the Northeast and

Table 8 Space effect test.

Test	Statistic	Df	*P* value
LM-error	2945.4540	1	0.0000
Robust LM-error	43.3430	1	0.0000
LM-lag	2907.4330	1	0.0000
Robust LM-lag	5.3230	1	0.0210
Hausman	27.9800	6	0.0001
LR-lag	23.8300	6	0.0006
LR-error	17.7800	6	0.0068
Wald-lag	23.7800	6	0.0006
Wald-error	17.7300	6	0.0069

Table 9 Spatial econometric regression results.

	(1) Tapioc	(2) Tapioc	(3) Tapioc
Dec	0.073** (2.471)	0.068** (2.182)	0.069** (2.232)
Tech	0.345 (0.104)	0.771 (0.227)	0.232 (0.068)
Gov	−2.947*** (−2.685)	−0.908 (−0.870)	−1.868* (−1.754)
Human	−15.565** (−2.290)	−16.017** (−2.314)	−13.409* (−1.907)
Lnp	0.567 (0.957)	1.039* (1.694)	0.757 (1.243)
Fa1	0.116 (1.357)	0.122 (1.355)	0.103 (1.168)
Wx:			
Dec	−0.497** (−2.203)	−0.219** (−2.167)	−0.388*** (−4.219)
Tech	56.881* (1.872)	−2.070 (−0.297)	5.057 (0.740)
Gov	20.661*** (3.442)	7.200*** (2.651)	7.622*** (3.150)
Human	8.998 (0.337)	−16.857 (−1.081)	−16.464 (−1.115)
Lnp	0.740 (0.160)	1.051 (1.024)	1.831* (1.877)
Fa1	−1.444* (−1.960)	−1.176*** (−3.607)	−0.677*** (−2.931)
Spatial:			
Rho	0.844*** (22.109)	0.373*** (11.804)	0.400*** (13.376)
Variance:			
Sigma2_e	1.284*** (33.451)	1.437*** (33.299)	1.406*** (33.259)
N	2248	2248	2248
R2_a			

*, * * and * * * represent significant at the statistical level of 10, 5 and 1% respectively; Figures in brackets are statistical values of t.

West, to ensure equitable digital access nationwide. Secondly, carbon emission decoupling varies among Chinese cities, posing particular challenges in the northeast and north. Addressing this necessitates tailored emission reduction policies, technical assistance, and robust enforcement of stringent environmental measures. The positive agglomeration effects observed in both the digital economy and carbon decoupling underscore the potential for cross-regional economic policies and environmental interventions. Moreover, the digital economy not only drives economic growth but also enhances urban carbon decoupling. Our research underscores the need for tailored strategies to foster urban digital economies and curb carbon emissions, promoting a balanced development of digitalization and environmental sustainability for robust economic progress. Notably, in non-resource-based cities, especially in the central and eastern regions, the digital economy has played a pivotal role in advancing urban carbon decoupling. This phenomenon is attributed to China's structural challenges. To address this, the paper advocates for comprehensive system reforms, the establishment of a unified market, seamless digital resource flow within the market, leveraging digital technology to boost traditional industries, nurturing emerging sectors, and ultimately fostering shared prosperity among residents. Furthermore, regions with mature digital economies exhibit a Matthew effect, where stronger areas attract premium resources, potentially impeding carbon emission decoupling in neighboring regions. To counteract this trend, we propose proactive measures by the Chinese government to channel high-quality human and material resources to underdeveloped digital economy areas. That can be achieved through initiatives like rural revitalization, facilitating new urbanization projects, bridging the digital divide, and ensuring widespread digital service accessibility in daily life and work.

Limitations and future directions. An innovative aspect of this study is its examination of the spatial distribution and traits of the digital economy and carbon emission decoupling. Furthermore, it explores the direct influence, diversity, and spatial impacts of the digital economy on carbon emission decoupling, utilizing data from Chinese cities. This investigation is a novel endeavor. Our findings illustrate that leveraging the digital economy not only spurs economic and societal transformation but also enhances urban carbon emission decoupling. Consequently, integrating the digital economy can foster economically, socially, and environmentally sustainable progress, aligning with the United Nations 2030 Agenda for Sustainable Development. Naturally, governments should remain attentive to the digital divide and the potential siphon effect associated with the digital economy.

This paper has limitations: Firstly, it does not account for the global outbreak of COVID-19 in 2020. The measures taken by China to combat the pandemic, such as restrictions on gatherings, work suspension, business shutdowns, and city closures, have impacted urban carbon emissions and may have affected the empirical results of this study. Future research should consider including data from the epidemic period to analyze its impact on the empirical findings. Secondly, this paper primarily focuses on the spatial distribution and agglomeration of decoupling between the digital economy and carbon emissions, as well as their relationship and spatial effects. However, it does not analyze the underlying mechanisms of their interaction. Therefore, further exploration is needed to understand the mediation and regulatory mechanisms between the two factors.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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References

Adewuyi AO (2016) Effects of public and private expenditures on environmental pollution: A dynamic heterogeneous panel data analysis. Ren Sustain Energy Rev 65:489–506. https://doi.org/10.1016/j.rser.2016.06.090

Akimoto K, Sano F, Oda J (2022) Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions. Technol Forecasting Soc Change 174:121311. https://doi.org/10.1016/j.techfore.2021.121311

Alam MM, Murad MW (2020) The impacts of economic growth, trade openness and technological progress on renewable energy use in organization for economic co-operation and development countries. Ren Energy 145:382–390. https://doi.org/10.1016/j.renene.2019.06.054

Ali R, Rehman MA, Rehman RU, Ntim CG (2022) Sustainable environment, energy and finance in China: evidence from dynamic modelling using carbon emissions and ecological footprints. Environ Sci Pollut Res 29(52):79095–79110. https://doi.org/10.1007/s11356-022-21337-0

Amir I, Tang X, Jahangir S, Yang Y, & Rasool SF (2023). Decoupling mechanism of industry carbon emissions, carbon intensity and economic growth in Pakistan. Indoor Built Environ. https://doi.org/10.1177/1420326X231159586

Bano S, Zhao Y, Ahmad A, Wang S, Liu Y (2018) Identifying the impacts of human capital on carbon emissions in Pakistan. J Cleaner Prod 183:1082–1092. https://doi.org/10.1016/j.jclepro.2018.02.008

Chen Q, Wang Q, Zhou D, & Wang H (2023). Drivers and evolution of low-carbon development in China?s transportation industry: An integrated analytical approach. Energy, 262. https://doi.org/10.1016/j.energy.2022.125614

Cheng Y, Zhang Y, Wang J, & Jiang J (2023). The impact of the urban digital economy on China's carbon intensity: Spatial spillover and mediating effect. Resourc Conserv Recycling, 189. https://doi.org/10.1016/j.resconrec.2022.106762

de Freitas LC, Kaneko S (2011) Decomposing the decoupling of CO2 emissions and economic growth in Brazil. Ecol Econ 70(8):1459–1469. https://doi.org/10.1016/j.ecolecon.2011.02.011

Dietz T, Rosa EA (1997) Effects of population and affluence on CO2 emissions. Proc Natl Acad Sci USA 94(1):175–179. https://doi.org/10.1073/pnas.94.1.175

Dong F, Hu M, Gao Y, Liu Y, Zhu J, & Pan Y (2022). How does digital economy affect carbon emissions? Evidence from global 60 countries. Sci Total Environ 852. https://doi.org/10.1016/j.scitotenv.2022.158401

Dong J, Li C, & Wang Q (2021). Decomposition of carbon emission and its decoupling analysis and prediction with economic development: A case study of industrial sectors in Henan Province. J Cleaner Product 321. https://doi.org/10.1016/j.jclepro.2021.129019

Duan X, Li X, Tan W, & Xiao R (2022). Decoupling relationship analysis between urbanization and carbon emissions in 33 African countries. Heliyon, 8(9). https://doi.org/10.1016/j.heliyon.2022.e10423

Duggal VG, Saltzman C, Klein LR (2007) Infrastructure and productivity: An extension to private infrastructure and it productivity. J Econ 140(2):485–502. https://doi.org/10.1016/j.jeconom.2006.07.010

Elhorst JP (2010) Applied spatial econometrics: raising the bar. Spatial Econ Analy 5(1):9–28. https://doi.org/10.1080/17421770903541772

Fang Z, Razzaq A, Mohsin M, Irfan M (2022) Spatial spillovers and threshold effects of internet development and entrepreneurship on green innovation efficiency in China. Technol Soc 68:101844. https://doi.org/10.1016/j.techsoc.2021.101844

Galinato GI, Galinato SP (2016) The effects of government spending on deforestation due to agricultural land expansion and CO2 related emissions. Ecol Econ 122:43–53. https://doi.org/10.1016/j.ecolecon.2015.10.025

Gao C, Ge H, Lu Y, Wang W, & Zhang Y (2021). Decoupling of provincial energy-related CO2 emissions from economic growth in China and its convergence from 1995 to 2017. J Cleaner Product 297. https://doi.org/10.1016/j.jclepro.2021.126627

Ge W, Xu Y, Liu G, Shen B, Su X, Liu L, … Ran Q (2022). Exploring the Impact of the Digital Economy on Carbon Emission Efficiency Under Factor Misallocation Constraints: New Insights From China. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.953070

Handfield R, Sroufe R, Walton S (2005) Integrating environmental management and supply chain strategies. Business Strategy Environ 14(1):1–19. https://doi.org/10.1002/bse.422

Hao X, Wen, S, Li Y, Xu Y, & Xue Y (2022). Can the digital economy development curb carbon emissions? Evidence from China. Front Psychol 13. https://doi.org/10.3389/fpsyg.2022.938918

Houghton JW (2015). ICT, the environment, and climate change. Int Encyclopedia Digital Commun Soc 1–13. https://doi.org/10.1002/9781118767771.wbiedcs015

Hua J, Gao J, Chen K, & Li J (2023). Driving Effect of Decoupling Provincial Industrial Economic Growth and Industrial Carbon Emissions in China. Int J Environ Res Public Health, 20(1). https://doi.org/10.3390/ijerph20010145

Huang J, & Guo L (2022). Research on the impact of financial development in different regions on the decoupling of carbon emissions from economic growth. Energy Environ. https://doi.org/10.1177/0958305X221107341

Huang W, Shahbaz M, & Li H (2022). Decomposition and Decoupling of Regional Carbon Emissions: A Case of the Yangtze River Delta in China. J Glob Inform Manag *30*(6). https://doi.org/10.4018/JGIM.306269

Huo T, Ma Y, Yu T, Cai W, Liu B, & Ren H (2021). Decoupling and decomposition analysis of residential building carbon emissions from residential income: Evidence from the provincial level in China. Environ Impact Assess Rev 86. https://doi.org/10.1016/j.eiar.2020.106487

International Energy Agency. (2022). World Energy Outlook 2022. https://www.oecd-ilibrary.org/energy/world-energy-outlook-2022_3a469970-en

Jahangir MH, Mokhtari R, Mousavi SA (2021) Performance evaluation and financial analysis of applying hybrid renewable systems in cooling unit of data centers–A case study. Sustain Energy Technol Assess 46:101220. https://doi.org/10.1016/j.seta.2021.101220

Jiang R, Li R (2017) Decomposition and Decoupling Analysis of Life-Cycle Carbon Emission in China's Building Sector. Sustainability 9(5):793. https://doi.org/10.3390/su9050793

Jiang R, Zhou Y, & Li R (2018). Moving to a Low-Carbon Economy in China: Decoupling and Decomposition Analysis of Emission and Economy from a Sector Perspective. Sustainability, 10(4). https://doi.org/10.3390/su10040978

Kang Y-Q, Zhao T, Yang Y-Y (2016) Environmental Kuznets curve for CO2 emissions in China: A spatial panel data approach. Ecol Indicators 63:231–239. https://doi.org/10.1016/j.ecolind.2015.12.011

Li W, Fan Y (2023) Influence of green finance on carbon emission intensity: empirical evidence from China based on spatial metrology. Environ Sci Pollut Res 30(8):20310–20326. https://doi.org/10.1007/s11356-022-23523-6

Li Z, & Wang J (2022). The Dynamic Impact of Digital Economy on Carbon Emission Reduction: Evidence City-level Empirical Data in China. J Cleaner Product 351. https://doi.org/10.1016/j.jclepro.2022.131570

Liang H (2021) Research on the advantages of digital publishing economy under the low-carbon environmental concept. Fresenius Environ Bullet 30(7 A):9551–9557. https://doi.org/10.3390/ijerph20064931

Lin Z, Liao X, Yang Y (2023) China's experience in developing green finance to reduce carbon emissions: from spatial econometric model evidence. Environ Sci Pollut Res 30(6):15531–15547. https://doi.org/10.1007/s11356-022-23246-8

Liu J, Duan Y, Zhong S (2022) Does green innovation suppress carbon emission intensity? New evidence from China. Environ Sci Pollut Res 29(57):86722–86743. https://doi.org/10.1007/s11356-022-21621-z

Liu J, Yang Q, Ou S, & Liu J (2022). Factor decomposition and the decoupling effect of carbon emissions in China's manufacturing high-emission subsectors. Energy, 248. https://doi.org/10.1016/j.energy.2022.123568

Liu Q, Wu S, Lei Y, Li S, Li L (2021) Exploring spatial characteristics of city-level CO2 emissions in China and their influencing factors from global and local perspectives. Sci Total Environ 754:142206. https://doi.org/10.1016/j.scitotenv.2020.142206

Liu X, Jin X, Luo X, & Zhou Y (2023). Quantifying the spatiotemporal dynamics and impact factors of China's county-level carbon emissions using ESTDA and spatial econometric models. J Cleaner Product 410. https://doi.org/10.1016/j.jclepro.2023.137203

Long R, Gan X, Chen H, Wang J, & Li Q (2020). Spatial econometric analysis of foreign direct investment and carbon productivity in China: Two-tier moderating roles of industrialization development. Resourc Conserv Recycling, 155. https://doi.org/10.1016/j.resconrec.2019.104677

Lu Y, & Chen X (2022). Digital economy, new-type urbanization, and carbon emissions: Evidence from China. Environ Prog Sustain Energy. https://doi.org/10.1002/ep.14045

Luo K, Liu Y, Chen P-F, Zeng M (2022) Assessing the impact of digital economy on green development efficiency in the Yangtze River Economic Belt. Energy Econ 112:106127. https://doi.org/10.1016/j.eneco.2022.106127

Lyu B, Ni W, Ostic D, Yu H, & Qureshi NA (2022). Can Carbon Trading Policy Promote China's Decoupling of Carbon Emission From the Perspective of Technology-Driven Innovation? Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.893947

Lyu K, Yang S, Zheng K, & Zhang Y (2023). How Does the Digital Economy Affect Carbon Emission Efficiency? Evidence from Energy Consumption and Industrial Value Chain. Energies, 16(2). https://doi.org/10.3390/en16020761

Ma Q, Khan Z, Tariq M, IŞik H, & Rjoub H (2022). Sustainable digital economy and trade adjusted carbon emissions: Evidence from China's provincial data. Econ Research-Ekonomska Istrazivanja, 1–17. https://doi.org/10.1080/1331677X.2022.2028179

Mickoleit A (2010). Greener and smarter: ICTs, the environment and climate change. OECD Green Growth Papers. https://doi.org/10.1787/22260935

Mi MJC, Zhao ZX (2022) Industrial agglomeration and carbon decoupling of enterprise exports. J Int Trade 477(09):17–34. https://doi.org/10.13510/j.cnki.jit.2022.09.001

Moyer JD, Hughes BB (2012) ICTs: do they contribute to increased carbon emissions? Technol Forecasting Soc Change 79(5):919–931. https://doi.org/10.1016/j.techfore.2011.12.005

Namyenya A, Daum T, Rwamigisa PB, Birner R (2022) E-diary: a digital tool for strengthening accountability in agricultural extension. Inform Technol Dev 28(2):319–345. https://doi.org/10.1080/02681102.2021.1875186

ODCC. (2022). Data centre arithmetic carbon efficiency white paper. https://www.odcc.org.cn/index.html

Romm J (2002) The internet and the new energy economy. Resourc Conserv Recycling 36(3):197–210. https://doi.org/10.1080/02681102.2021.1875186

Rüstemoğlu H (2019) Factors affecting Germany's green development over 1990–2015: a comprehensive environmental analysis. Environ Sci Pollut Res 26(7):6636–6651. https://doi.org/10.1007/s11356-019-04132-2

Sheraz M, Xu D, Ahmed J, Ullah S, Ullah A (2021) Moderating the effect of globalization on financial development, energy consumption, human capital, and carbon emissions: evidence from G20 countries. Environ Sci Pollut Res 28(26):35126–35144. https://doi.org/10.1007/s11356-021-13116-0

Speth JG, Zinn D (2008) Bridge at the Edge of the World. Yale University Press, New Haven, CT, https://hrcak.srce.hr/ojs/index.php/socijalna-ekologija/article/download/18550/10121/65989

Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Crucifix M (2018) Trajectories of the Earth System in the Anthropocene. Proc Natl Acad Sci 115(33):8252–8259. https://doi.org/10.1073/pnas.1810141115

Tang L, Lu B, Tian T (2021) Spatial correlation network and regional differences for the development of digital economy in China. Entropy 23(12):1575. https://doi.org/10.3390/e23121575

Tapio P (2005) Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Policy 12(2):137–151. https://doi.org/10.1016/j.tranpol.2005.01.001

Ulucak R (2020) How do environmental technologies affect green growth? Evidence from BRICS economies. Sci Total Environ 712:136504. https://doi.org/10.1016/j.scitotenv.2020.136504

United Nations (2015) Transforming our World: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda

Wang J, Dong K, Dong X, Taghizadeh-Hesary F (2022a) Assessing the digital economy and its carbon-mitigation effects: The case of China. Energy Econ 113:106198. https://doi.org/10.1016/j.eneco.2022.106198

Wang J, Dong K, Dong X, & Taghizadeh-Hesary F (2022b). Assessing the digital economy and its carbon-mitigation effects: The case of China. Energy Econ 113. https://doi.org/10.1016/j.eneco.2022.106198

Wang J, Luo X, Zhu J (2022) Does the digital economy contribute to carbon emissions reduction? A city-level spatial analysis in China. Chinese J Popul Resourc Environ 20(2):105–114. https://doi.org/10.1016/j.cjpre.2022.06.001

Wang L, Chen Y, Ramsey TS, Hewings GJ (2021) Will researching digital technology really empower green development? Technol Soc 66:101638. https://doi.org/10.1016/j.techsoc.2021.101638

Wang L, Chen Y, Ramsey TS, & Hewings GJD (2021). Will researching digital technology really empower green development? Technol Soc 66. https://doi.org/10.1016/j.techsoc.2021.101638

Wang Q, & Han X (2021). Is decoupling embodied carbon emissions from economic output in Sino-US trade possible? Technol Forecasting Soc Change 169. https://doi.org/10.1016/j.techfore.2021.120805

Wang Q, & Jiang R (2020). Is carbon emission growth decoupled from economic growth in emerging countries? New insights from labor and investment effects. J Cleaner Product 248. https://doi.org/10.1016/j.jclepro.2019.119188

Wang Q, Su M, Li R (2018) Toward to economic growth without emission growth: The role of urbanization and industrialization in China and India. J Cleaner Product 205:499–511. https://doi.org/10.1016/j.jclepro.2018.09.034

Wang Q, Wang L, Li R (2023) Trade protectionism jeopardizes carbon neutrality-Decoupling and breakpoints roles of trade openness. Sustain Product Consump 35:201–215. https://doi.org/10.1016/j.spc.2022.08.034

Wang Q, & Zhang F (2021). The effects of trade openness on decoupling carbon emissions from economic growth e Evidence from 182 countries. J Cleaner Product 279. https://doi.org/10.1016/j.jclepro.2020.123838

Wang Q, Zhang F, & Li R (2023). Revisiting the environmental kuznets curve hypothesis in 208 counties: The roles of trade openness, human capital, renewable energy and natural resource rent. Environ Res 216. https://doi.org/10.1016/j.envres.2022.114637

Wang X, & Zhong M (2023). Can digital economy reduce carbon emission intensity? Empirical evidence from China's smart city pilot policies. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-26038-w

Wei L, Jia G, Xu X, & Zhao L (2022). Construction and Application of Relationship Model between Development of Mining Industry and Carbon Emission of

Energy Consumption. Adv Civil Eng 2022. https://doi.org/10.1155/2022/5143501

Wu R, Hua X, Peng L, Liao Y, & Yuan Y (2022). Nonlinear Effect of Digital Economy on Carbon Emission Intensity-Based on Dynamic Panel Threshold Model. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.943177

Wu YA, Peng BY, & Lao YH (2023). The Emission Reduction Effect of Financial Agglomeration under China's Carbon Peak and Neutrality Goals. Int J Environ Res Public Health, 20(2). https://doi.org/10.3390/ijerph20020950

Wu & Zhu (2022). Digitalisation and greening synergies for high quality development. http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/images/2022-01/04/05/KJRB2022010405.pdf

Wurlod J-D, Noailly J (2018) The impact of green innovation on energy intensity: An empirical analysis for 14 industrial sectors in OECD countries. Energy Econ 71:47–61. https://doi.org/10.1016/j.eneco.2017.12.012

Xiang X, Yang G, & Sun H (2022). The Impact of the Digital Economy on Low-Carbon, Inclusive Growth: Promoting or Restraining. Sustainability, 14(12). https://doi.org/10.3390/su14127187

Xu Q, Zhong M, & Cao M (2022). Does digital investment affect carbon efficiency? Spatial effect and mechanism discussion. Sci Total Environ 827. https://doi.org/10.1016/j.scitotenv.2022.154321

Xu Z, & Sun T (2021). The Siphon effects of transportation infrastructure on internal migration: Evidence from China's HSR network. Appl Econ Lett 28(13):1066–1070. https://doi.org/10.1080/13504851.2020.1796913

Yan J, Zhao T, Kang J (2016) Sensitivity analysis of technology and supply change for CO2 emission intensity of energy-intensive industries based on input–output model. Appl Energy 171:456–467. https://doi.org/10.1016/j.apenergy.2016.03.081

Yan X, Deng Y, Peng L, & Jiang Z (2022). Study on the impact of digital economy development on carbon emission intensity of urban agglomerations and its mechanism. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-24557-6

Yang R, Che T, Lai F (2021) The Impacts of production linkages on cross-regional collaborative innovations: The role of inter-regional network capital. Technol Forecasting Soc Change 170:120905. https://doi.org/10.1016/j.techfore.2021.120905

Yi M, Liu Y, Sheng MS, & Wen L (2022). Effects of digital economy on carbon emission reduction: New evidence from China. Energy Policy, 171. https://doi.org/10.1016/j.enpol.2022.113271

Yu Z, Liu S, & Zhu Z (2022). Has the Digital Economy Reduced Carbon Emissions?: Analysis Based on Panel Data of 278 Cities in China. Int J Environ Res Public Health 19(18). https://doi.org/10.3390/ijerph191811814

Zhang J, Lyu Y, Li Y, Geng Y (2022) Digital economy: An innovation driving factor for low-carbon development. Environ Impact Assess Rev 96:106821. https://doi.org/10.1016/j.eiar.2022.106821

Zhang J, Yu H, Zhang K, Zhao L, & Fan F (2021). Can Innovation Agglomeration Reduce Carbon Emissions? Evidence from China. Int J Environ Res Public Health 18(2). https://doi.org/10.3390/ijerph18020382

Zhang L, Mu R, Zhan Y, Yu J, Liu L, Yu Y, & Zhang J (2022). Digital economy, energy efficiency, and carbon emissions: Evidence from provincial panel data in China. Sci Total Environ 852. https://doi.org/10.1016/j.scitotenv.2022.158403

Zhang W, Zhu Z, Liu X, Cheng J (2022) Can green finance improve carbon emission efficiency? Environ Sci Pollut Res 29(45):68976–68989. https://doi.org/10.1007/s11356-022-20670-8

Zhang Y-J, Peng Y-L, Ma C-Q, Shen B (2017) Can environmental innovation facilitate carbon emissions reduction? Evidence from China. Energy Policy 100:18–28. https://doi.org/10.1016/j.enpol.2016.10.005

Zhao M-M, Li R (2018) Decoupling and decomposition analysis of carbon emissions from economic output in Chinese Guangdong Province: A sector perspective. Energy Environ 29(4):543–555. https://doi.org/10.1177/0958305X17754253

Zhao S, Zhang Z, Liang SS (2020) Digital economy, entrepreneurship, and high-quality economic development: empirical evidence from urban china. J Manag World 36(10):65–76. https://doi.org/10.19744/j.cnki.11-1235/f.2020.0154

Zhao X, Dong Y, & Gong X (2022). The Digital Economy and Carbon Productivity: Evidence at China's City Level. Sustainability, 14(17).https://doi.org/10.3390/su141710642

Zhong K, Fu H, & Li T (2022). Can the digital economy facilitate carbon emissions decoupling? an empirical study based on provincial data in China. Int J Environ Res Public Health 19(11). https://doi.org/10.3390/ijerph19116800

Zhong S, Shen H, Niu Z, Yu Y, Pan L, Fan Y, & Jahanger A (2022). Moving towards Environmental Sustainability: Can digital economy reduce environmental degradation in China? Int J Environ Res Public Health 19(23). https://doi.org/10.3390/ijerph192315540

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Competing interests

The authors declare no competing interests.

Additional information

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