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Full Length Article

Dual impact of digitalization on the carbon emissions of Yangtze River Delta urban agglomerations in China: A spatiotemporal perspective

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ABSTRACT

Digital transformation, as a recent trend in socioeconomic development, is considered as a critical pathway for urban carbon reduction because of its potential to increase productivity and energy efficiency. However, few studies have explored the relationship between urban digitalization and carbon emissions (CE). Therefore, this study systematically analyzed the spatiotemporal distribution and interaction mechanism between digitalization and CE in the Yangtze River Delta (YRD) urban agglomerations of China during 2006–2020 based on a multidimensional indicator system, including digitalization industry level, digitalization application level, and urban green digitalization willingness. The findings revealed that both digitalization and CE in the YRD exhibit a significant and synchronously evolving "core-periphery" spatial pattern. Core cities generated substantial positive spillover effect on periphery cities through technology diffusion and policy demonstration, advancing both regional digitalization and the collaborative governance of CE. However, digitalization had dual impact on CE. On the one hand, it promoted the reduction of CE by enhancing energy efficiency, optimizing industrial structures, and promoting the application of green technologies. On the other hand, the expansion of digital infrastructure introduced a potential risk of increased energy consumption. Therefore, targeted policy recommendations are proposed to facilitate the coordination of environmental sustainability and digitalization in the YRD. This study provides empirical support and policy insights for advancing the coordinated development of regional digital transformation and green low-carbon initiatives.

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1. Introduction

Rapid urbanization, a core driver of global economic growth, simultaneously leads to the rapid increase of greenhouse gas emissions (Dong et al., 2019; Xiang et al., 2023), thereby exacerbating global warming and its associated environmental risks (Jin et al., 2022; Huang et al., 2023). As one of the world's largest carbon emitter, China faces particularly severe emission reduction pressure under the constraints of the "dual carbon" goals (Yang et al., 2022; Zhang et al., 2023b; Yuan et al., 2024). Therefore, digital technology is considered a key tool for resolving the conflict between economic growth and carbon emissions (CE), but its mechanism of action remains highly debated. On the one hand, digital technology provides new pathways for carbon reduction by optimizing energy management, reshaping industrial models, and reducing spatiotemporal constraints. On the other hand, the energy consumption and "rebound effect" of digital industry, as well as the resulting spatial expansion and digital divide, may weaken its environmental benefits (Salahuddin and Alam, 2015; Zheng et al., 2023; Li and Zhou, 2024; Ma et al., 2025). Systematically analyzing the complex impact of digitalization on CE, especially its spatiotemporal heterogeneity, the mechanism of action, and policy synergy effects at the urban agglomeration scale, has become the core challenge of current research.

Urban digitalization, through information and communication technology (ICT), reconstructs urban resource allocation and governance models. The relationship between digitalization and CE can be explored from multiple dimensions. First, urban agglomerations, as the spatial carriers of digitalization and CE, exhibit dynamic interaction characteristics in their evolutionary patterns. Existing research indicates a nonlinear relationship between the diffusion of digital infrastructure and the spatiotemporal differentiation of CE within urban agglomerations (Balogun et al., 2020; Chen, 2022; Yang et al., 2022), but how interregional technology spillovers, factor flows, and policy differences influence this process requires further in-depth investigation. Second, the digitalization-driven industrial transformation has a dual impact on CE. Digitalization promotes the low-carbon transformation of energy-intensive industries through intelligent manufacturing and energy system optimization (Kjaer et al., 2018; Usman et al., 2021), but the energy demand of the digitalization industrial chain's upstream (e.g., chip manufacturing and data centers) may create new emission hotspots (Yang et al., 2022), and its net effect needs to be further verified in conjunction with regional industrial structures and energy endowments. Third, the emission reduction potential of digitalization application scenarios varies significantly. For example, remote work and intelligent transportation can reduce direct CE (Usman et al., 2021), whereas e-commerce and logistics digitalization may indirectly increase emissions due to the expansion of consumption scale (Salahuddin and Alam, 2015; Zheng et al., 2023), which highlights the importance of defining technology applications and system boundaries. Fourth, the synergy mechanism between digital policies and carbon reduction goals remains unclear. Although China has implemented regional digital strategies such as "Eastern Data and Western Computing", a quantitative evaluation framework is still lacking regarding how policy tools balance digital economic development and carbon reduction goals.

On the basis of the issues mentioned above, this study systematically proposes the following questions: (1) what dynamic patterns did digitalization and CE exhibit in the Yangtze River Delta (YRD) urban agglomerations of China during 2006–2020? (2) how do digitalization and CE interact during different stages of urban development in different regions and what are the driving mechanisms behind this interaction? and (3) how can the synergy path of digital policy design and carbon neutrality goals be optimized? Therefore, this paper systematically assessed the spatiotemporal evolution patterns of digitalization and CE, as well as their interaction mechanisms in the YRD urban agglomerations during 2006–2020, using spatial analysis methods and spatial econometric models. The research results will contribute to the government's formulation of digital transformation and low-carbon development policies, the optimization of regional resource allocation, and the achievement of the Sustainable Development Goals (SDGs).

2. Literature review

2.1. Spatiotemporal evolution patterns of digitalization and carbon emissions (CE)

Scholars have primarily focused on the spatial distribution of CE in cities or villages (Rong et al., 2020; Song et al., 2020; Yang et al., 2022; Zhang and Li, 2022; Wei et al., 2024). In terms of digitalization, several scholars found that digital economy alters the spatial structure of urban growth by either concentrating in a central area or spreading

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toward borders (Dadashpoor and Yousefi, 2018). This implies that the distribution of the digital economy is influenced by geographical elements (Liu et al., 2022a). Moreover, researchers analyzed the spatiotemporal characteristics of urban digitalization, revealing a greater degree of industrial spatial agglomeration in eastern China (Liu et al., 2022b) and a "concentration in central areas and dispersal in periphery areas" distribution pattern of the information technology (IT) enterprise, with a notable suburbanization trend (Aranya, 2008). Furthermore, scholars have investigated the spatial impact of digitalization on other factors. For example, they examined regional inequality issues by analyzing the spatiotemporal pattern of digitalization (Liu et al., 2024) and explored whether digital technology can affect the spatiotemporal evolution characteristics of traditional financial activities (Zhang et al., 2023a).

In recent years, with the increasing emphasis on environmental governance, scholars have begun to focus on the interaction between the spatiotemporal evolution characteristics of digitalization and CE. For example, some scholars reported that digitalization has a positive impact on the reduction of CE through spillover effect (Liu et al., 2022a). However, other scholars discovered that urban digitalization, if not effectively managed, can increase CE (Zhang et al., 2022b). Additionally, by analyzing the spatiotemporal evolution patterns of low-carbon development and digital economy levels in different provinces, researchers reported that digital economy can, to a certain extent, drive regional low-carbon development (Zhang et al., 2022a).

However, prior studies have generally neglected the spatiotemporal evolution of digitalization and CE in urban agglomerations. With the advancement of urbanization, urban agglomerations have emerged as the primary contributors to CE, posing significant challenges to reducing CE (Sharifi et al., 2023). Although the development of urban digitalization creates new opportunities for carbon reduction, the lack of effective regionally coordinated development policies may lead to higher CE, placing the primary responsibility for carbon reduction on urban agglomerations (Li and Wang, 2022; Yu et al., 2023). Therefore, it is necessary to analyze the spatiotemporal evolution patterns of digitalization and CE in urban agglomerations to provide feasible strategies for reducing CE (Hu et al., 2023).

2.2. Impact of digitalization on CE

2.2.1. Impact of digital-driven industrial transformation on CE

In recent years, digital technology has been essential in facilitating the modification and enhancement of urban industrial structures (Zhou et al., 2013; Zhu et al., 2019; Chang et al., 2023; Cui and Zhuang, 2025). By increasing government green subsidies and promoting technological progress, digital transformation can mitigate CE in manufacturing industry, making it vital for achieving "carbon peak and carbon neutrality" goals (Zhang et al., 2024). However, as urban industries continue to transform and upgrade with the promotion of digital technologies, some urban industries may experience increasing energy demand and rebound effect (Xie et al., 2024). In particular, digital infrastructure construction consumes high levels of resources (Ma et al., 2023), which leads to urban digitalization level showing an increasing and then decreasing pattern at certain stages (Zhang et al., 2024). Therefore, it is essential to thoroughly analyze the impact of urban digital transformation on CE.

2.2.2. Impact of digitalization application on CE

With the rapid advancement of urban digitalization, some scholars have begun to analyze how digitalization application affects CE. Initially, some scholars contended that digital economy is capable of reducing CE by altering the nature of products, generating new value, optimizing the allocation of factors, and providing enterprises with new competitive advantages (ElMassah and Mohieldin, 2020; Shang et al., 2023). Simultaneously, the widespread application of digital technologies in daily public life has increased the efficiency of resident participation in environmental monitoring, thus increasing the openness and transparency of environmental information (Sun and Hu, 2021). Therefore, some scholars have adopted greener behaviors (Yang et al., 2022; Long et al., 2023). The application of digital technologies can also generate spillover effects, reducing CE in both local and neighboring regions (Liu et al., 2022a).

2.2.3. Impact of digital policies on CE

With respect to the digital policies implemented by local governments, current research suggests that urban digitalization and the penetration of digital governance into the field of production have provided a new management system for society (Zeng and Yang, 2023), and that the degree of digitalization in government

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environmental governance and the completeness of environmental regulations have a significant impact on CE (Zhao et al., 2023). Additionally, some scholars believed that encouraging the construction of digital infrastructure such as telecommunication infrastructure systems can generate network spillover effects, breaking down spatiotemporal barriers between cities and villages, as well as promoting green technology innovation and the reduction of CE by enhancing the level of informatization (Tang et al., 2021).

In summary, previous research on the relationship between digitalization and CE has often focused on the macro level or single-industry level, with few detailed investigations of multiple indicators and dimensions. Most studies have emphasized the impact of a single dimension of digitalization on CE, lacking a multidimensional framework for comprehensively evaluating the impact of digital industry, digital application, and policy willingness on CE. Second, the existing studies have revealed a potential nonlinear relationship between digitalization and CE, but the underlying mechanisms have not been fully explained, and the role of policy guidance in digitalization transformation has not been thoroughly explored. Furthermore, it is necessary to further investigate the influence of digitalization in individual and organizational behavior at different development stages, as well as the specific paths and mechanisms by which it affects CE. Therefore, this study aims to fill these research gaps by systematically analyzing the spatiotemporal evolution of digitalization and CE, as well as their interaction mechanisms. Finally, this study can provide theoretical and practical guidance for achieving a balance between digitalization and environmental sustainability.

3. Data and methods

3.1. Study area

This study chose the YRD as the research area (Fig. 1), which is the largest urban agglomeration in China. The YRD is situated in the eastern coastal region of China, covering an area of 211,700 km^2 and including 37 prefecture-level cities, 3 provincial capitals, and 1 municipality. However, the YRD makes a significantly greater contribution to CE in China, amounting to an estimated 20.00% of the total CE, but covering just 3.70% of China's total land area. The YRD is also a pioneer in urban digitalization of China, with relatively rapid urban development, necessitating urgent coordination issues between digitalization and CE.

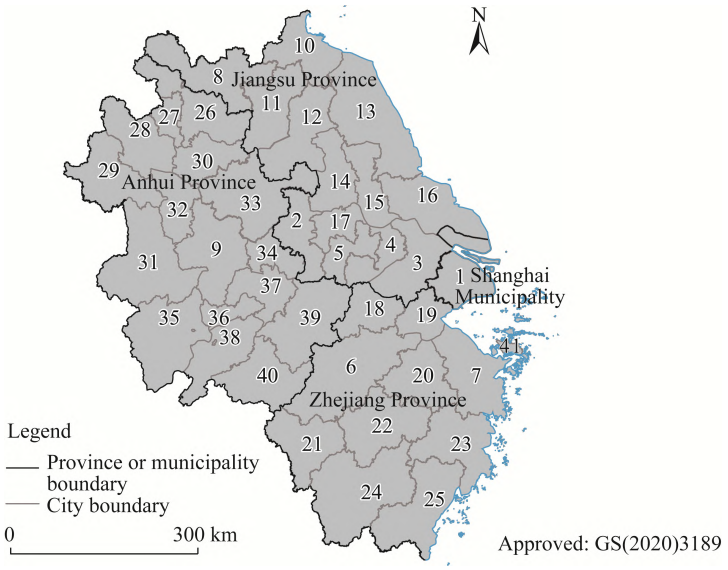


Fig. 1. Overview of the study area. Note that the figure is based on the standard map (GS(2020)3189) of the Map Service System (http://bzdt.ch.mnr.gov.cn/download.html) marked by the Ministry of Natural Resources of the People's Republic of China, and the boundary of the standard map has not been modified. 1, Shanghai Municipality; 2, Nanjing City; 3, Suzhou City (Jiangsu Province); 4, Wuxi City; 5, Changzhou City; 6, Hangzhou City; 7, Ningbo City; 8, Xuzhou City; 9, Hefei City; 10, Lianyungang City; 11, Suqian City; 12, Huai'an City; 13, Yancheng City; 14, Yangzhou City; 15, Taizhou City (Jiangsu Province); 16, Nantong City; 17, Zhenjiang City; 18, Huzhou City; 19, Jiaxing City; 20, Shaoxing City; 21, Quzhou City; 22, Jinhua City; 23, Taizhou City (Zhejiang Province); 24, Lishui City; 25, Wenzhou City; 26, Suzhou City (Anhui Province); 27, Huaibei City; 28, Bozhou City; 29, Fuyang City; 30, Bengbu City; 31, Lu'an City; 32, Huainan City; 33, Chuzhou City; 34, Maanshan City; 35, Anqing City; 36, Tongling City; 37, Wuhu City; 38, Chizhou City; 39, Xuancheng City; 40, Huangshan City; 41, Zhoushan City. The abbreviations are the same in the following figures.

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3.2. Data sources

The data include digitalization and socioeconomic indicators and CE in the YRD from 2006 to 2020. The digitalization and socioeconomic indicators are primarily sourced from the China Statistical Yearbook (National Bureau of Statistics, 2007–2021a), China Statistical Yearbook on Science and Technology (National Bureau of Statistics, 2007–2021b), China Internet Development Report (https://www. cnnic.com.cn/IDR/ReportDownloads/), and other relevant publications. The CE data were compiled from the China City Greenhouse Gas Working Group (CCG) database (http://www.cityghg.com/) and the Data Resources of the Carbon Dioxide Map (https://www.ipe.org.cn/index.html), as well as public data from various city governments. The CE data covered all direct emissions within the administrative areas of the YRD and indirect emissions from electricity purchased by cities or municipality from external sources.

3.3. Methods

3.3.1. Selection of digitalization indicators

Previous research has demonstrated that a single indicator cannot comprehensively reflect the level of urban digitalization, while comprehensive indicators can not only reflect the degree and breadth of digitalization, but also assess the penetration and effect of digitalization in the economy and society (Yang et al., 2022). Therefore, comprehensive indicators have been widely used in recent years. For example, some scholars have attempted to define and measure the digital economy from different perspectives, such as dividing it into core, narrow, and broad layers (Bukht and Heeks, 2017) or focusing on Internet development and digital finance (Pan et al., 2022). This study established a comprehensive indicator system for evaluating the impact of digitalization on CE, which combines multiple digitalization indicators, such as telecommunications output, long-haul fiber optic cable line density, digital industry talent, Internet application, mobile Internet application, and digital inclusive finance index (Tang et al., 2021). The comprehensive indicator system provided a more comprehensive assessment of the impact of digitalization on the economy and society.

Second, in terms of the policy background, China's major strategic actions typically require government policy guidance supplemented by market practices to achieve decisive results (Li et al., 2022a; Zhang et al., 2023b). Therefore, when selecting digitalization-related indicators, this study specifically considered local government awareness and policy support for green digitalization, particularly focusing on the policy orientation of government support for technological innovation and green technology. Finally, this study selected 4 indicators: environmental regulation, the degree of government emphasis on digital transformation, the degree of government support for technological innovation, and the degree of government support for green technology. These indicators reflect the policy orientation and implementation capabilities of local governments in promoting green digitalization transformation. In addition, China has guided economic development through 5-a plans, which include major national construction projects, key economic proportions, and long-term goals and directions. From 2006 to 2020, spanning 3 planning cycles, digitalization gradually rose from an embryonic stage to a national strategy, and its position in national policy gradually consolidated. These 3 stages are highly representative and valuable for research.

To better assess the overall impact of digitalization, this study combined multiple sub-indicators of the above dimensions to form a comprehensive digitalization indicator. This allows the research to more comprehensively and accurately reflect the digitalization development level in the YRD, avoiding the limitation of single-dimensional analysis.

3.3.2. Evaluation of the digitalization indicator system

In summary, this paper integrated theoretical and policy backgrounds to construct a comprehensive evaluation system for the digital economy during 2006–2020, including 3 digitalization dimensions: digitalization industry level, digitalization application level, and urban green digitalization willingness.

These 3 dimensions are interconnected, jointly reflecting the depth and breadth of digitalization development, and contribute to a comprehensive assessment of the impact of digitalization on CE. Digitalization industry level provides foundational support (Xiao et al., 2024), digitalization application level reflects the penetration of technology (Ma et al., 2025), and urban green digitalization willingness reveals the driving force of government policies (Xie and Wu, 2024). By integrating these 3 dimensions, this study can more accurately reveal how digitalization transformation interacts with CE while driving economic development, thereby overcoming the limitation of single-dimensional analysis and enhancing the understanding of the impact mechanism of digitalization on CE. Furthermore, this paper selected the control variables including economic structure, development level, lifestyle, infrastructure construction, and foreign economic ties based on the existing literature to

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improve the accuracy of research results (Li and Liao, 2022; Liu et al., 2022a; Bai et al., 2023; Xie et al., 2024). The selection and description of variables are shown in Table 1.

Table 1
Selection and description of indicators and sub-indicators.

Indicator	Sub-indicator	Description	Reference	Unit
Digitalization industry level	Telecommunications output	Total volume of telecommunications services per capita	Yang et al. (2022); Zhang et al. (2022c); Bai et al. (2023)	10^4 CNY
	Long-haul fiber optic cable line density	Ratio of the length of long-distance fiber optic cable line to the area of the administrative region	Yang et al. (2022)	km/km^2
	Digital industry talent	Percentage of employees in computer services and software	Yang et al. (2022); Zhang et al. (2022c); Bai et al. (2023)	%
Digitalization application level	Internet application	Internet users per 100 persons	Yang et al. (2022); Zhang et al. (2022c); Xie et al. (2024)	%
	Mobile Internet application	Cell phone subscribers per 100 persons	Zhang et al. (2022c); Bai et al. (2023); Xie et al. (2024)	%
	Digital inclusive finance index	Digital finance digitization index	Liu et al. (2022a); Zhang et al. (2022c); Xie et al. (2024)	-
Urban green digitalization willingness	Environmental regulation	Percentage of investment in environmental pollution control in the gross domestic product (GDP)	Schnebelin et al. (2021); Wen et al. (2022)	%
	Government digital awareness	Digital word frequency of government reports	Giest (2017); Su et al. (2020); Xie and Wu (2024)	-
	Science and technology focus	Percentage of science spending in the GDP	Tang et al. (2021); Liu et al. (2022a)	%
	Level of green technology	Percentage of green inventions among the total annual inventions filed in the region	Yang et al. (2022); Bai et al. (2023)	%

Note: -, dimensionless.

3.3.3. Data processing and analysis steps

The data processing and analysis involve 3 steps: building the database, exploring the spatiotemporal evolution patterns, and uncovering the influencing mechanisms (Fig. 2).

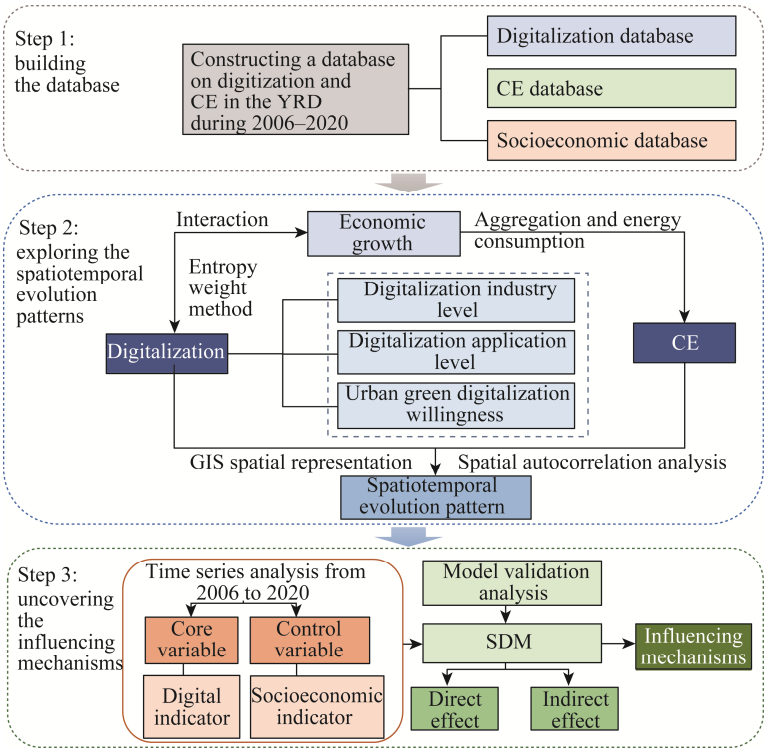


Fig. 2. Analytical framework. CE, carbon emissions; YRD, Yangtze River Delta; SDM, spatial Durbin model; GIS, Geographic Information System.

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(1) Building the database. The first step involves the establishment of a comprehensive database encompassing 40 cities and 1 municipality within the YRD, spanning from 2006 to 2020. This database was meticulously categorized into 3 primary data domains: CE, digitalization indicators, and socioeconomic indicators. It was constructed to gain a holistic understanding of the complex interplay among digitalization indicators, CE, and socioeconomic indicators in the YRD. This comprehensive database laid the groundwork for subsequent analyses and modeling efforts, enabling a deeper exploration of the impact mechanisms of digitalization on CE.

(2) Exploring the spatiotemporal evolution patterns of digitalization and CE. Weights are assigned using the entropy weight method (Li et al., 2022b), and the entropy weight can be calculated as follows:

$$D_j = \sum_{i=1}^{n} X_{ij} W_i , \tag{1}$$

where D_j represents the digitalization level of city j; i is the number of variable; n is the total number of variables; X represents the digitalization variable; and W_i represents the entropy weight of the i^{th} variable, varying from 0 to 1, which can be expressed as follows:

$$W_i = \frac{1 - E_i}{n - \sum_{i=1}^{n} E_i} , \tag{2}$$

where E_i represents the expectation of the amount of information in each variable, which can be expressed as follows:

$$E_i = -\ln(m)^{-1} \sum_{j=1}^{m} P_{ij} \ln P_{ij} , \tag{3}$$

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} , \tag{4}$$

where m refers to the number of cities and municipality; P serves as the probability value in the entropy calculation; and Z_{ij} represents the indicator after normalization, which can be calculated as follows:

$$Z_{ij} = \begin{Bmatrix} \dfrac{X_{ij} - \min(X_{1j}, \cdots, X_{nj})}{\max(X_{1j}, \cdots, X_{nj}) - \min(X_{1j}, \cdots, X_{nj})}, & X > 0 \\ \dfrac{\max(X_{1j}, \cdots, X_{nj}) - X_{ij}}{\max(X_{1j}, \cdots, X_{nj}) - \min(X_{1j}, \cdots, X_{nj})}, & X < 0 \end{Bmatrix}, \tag{5}$$

where X_{ij} is a decision matrix with n variables and m cities, which can be expressed as follows:

$$X_{ij} = \begin{Bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{Bmatrix}. \tag{6}$$

(3) Uncovering the influencing mechanisms. In this step, we used the spatial Durbin model (SDM) to analyze the influence mechanism between digitalization and CE. The SDM can identify the direct impact of digitalization on CE and their spatial spillover effects, and it is suitable for spatiotemporal dynamic analysis of the panel data. In contrast, although geographically weighted regression (GWR) can depict local spatial differences, it has difficulty in capturing global spillover effect and is not suitable for panel data (Brunsdon et al., 1998; Gao et al., 2022). The spatial lag model (SLM) is mainly used to analyze the spatial dependence of the dependent variable, but it cannot identify the spatial spillover effects of the independent variables, which limits the characterization of the cross-regional impact of digitalization. Although the spatial error model (SEM) can handle the autocorrelation of spatial errors, it cannot directly identify the spatial spillover effect of digitalization on CE. Therefore, the SDM not only considers the spatial effects of the dependent and independent variables, but also depicts the spillover effects of policies and technologies between regions, which is suitable for this study. The formula for the SDM is as follows:

$$\gamma = \rho W\gamma + \beta X + WX\theta + \varepsilon, \tag{7}$$

where γ is the CE of each city or municipality (t); ρ is the lag coefficient; β is the explanatory variable coefficient; θ is the spatial spillover coefficient, which denotes the spatial interaction between the explanatory variables; and ε is the perturbation term. Direct and indirect effects are important analytical results of the SDM. Compared with

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geographical distance matrices or economic weight matrices, the spatial weight matrix used in this study is an adjacency matrix, which can more directly characterize the spatial interactions among cities or municipality within a region and provide stable measures of spatial effects in the estimation of the SDM and SLM. This approach avoids model bias introduced by the subjective setting of weight functions.

4. Results

4.1. Spatiotemporal distribution of CE in the YRD

CE in the YRD region showed an overall increasing trend and displayed regional disparities during 2006–2020. CE has increased from 1167.83×10^6 t in 2006 to 1864.38×10^6 t in 2020 in the YRD, with a growth rate of 59.65%. Specifically, high-emission regions were concentrated mainly in Shanghai Municipality and its surrounding cities, which have high levels of economic development (Fig. 3). Additionally, these high-emission regions gradually spread to other cities, forming a spatial pattern of "main core+multiple centers". Shanghai Municipality was the main core, and Nanjing, Suzhou (Jiangsu Province), Wuxi, Changzhou, Hangzhou, Ningbo, Xuzhou, and Hefei cities were secondary cores. This pattern is highly consistent with the layout of metropolitan region in the YRD, reflecting the "core-periphery" spatial pattern of CE.

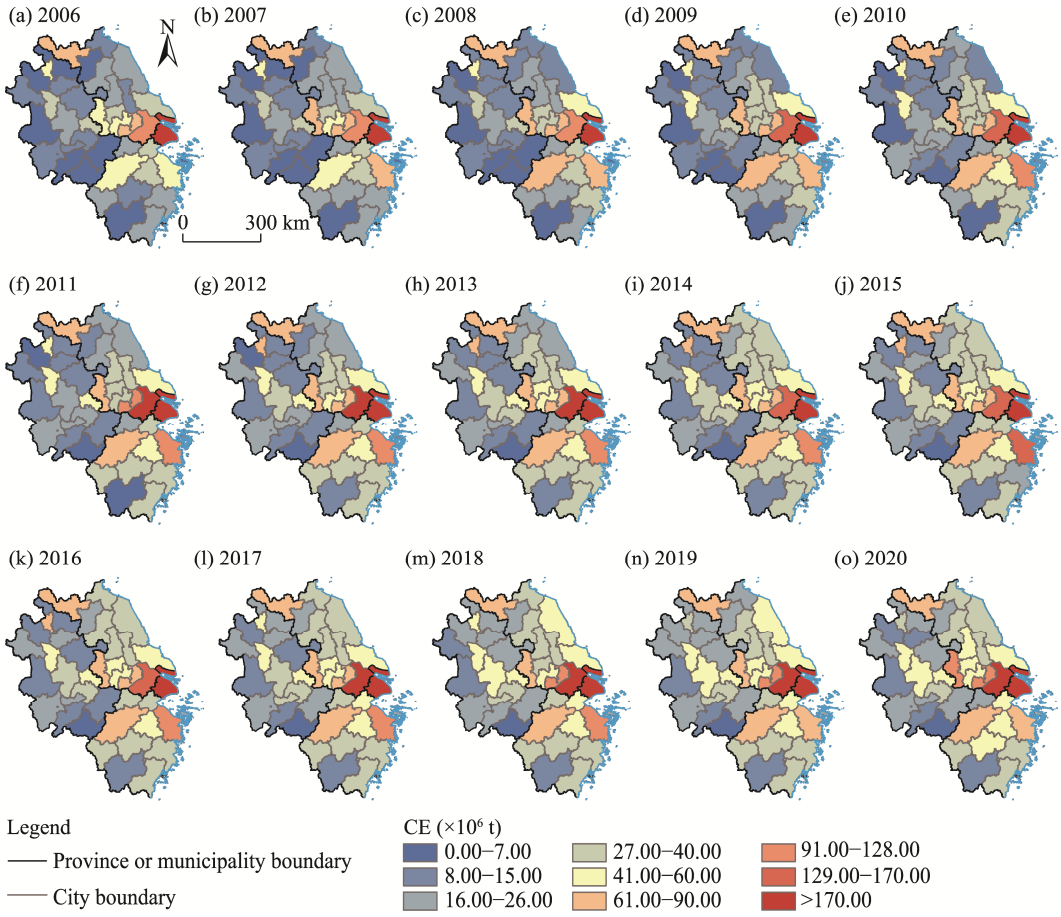


Fig. 3. Spatiotemporal distribution of CE in the YRD during 2006–2020 (a–o). Note that the figure is based on the standard map (GS(2020)3189) of the Map Service System (http://bzdt.ch.mnr.gov.cn/download.html) marked by the Ministry of Natural Resources of the People's Republic of China, and the boundary of the standard map has not been modified.

This paper conducted spatial autocorrelation analysis to further explore the spatiotemporal distribution patterns and evolution characteristics of CE in the YRD. The results showed that the global Moran's I values for each year were positive, and the Z values have passed the 95% significance test (Table 2), indicating that the interaction between regions in the YRD was strong during 2006–2020 and the spatial concentration of CE between regions was strong.

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Table 2
Moran's I and *Z* values for carbon emissions (CE) in the Yangtze River Delta (YRD) during 2006–2020.

Year	Moran's I	*Z* value	Year	Moran's I	*Z* value
2006	0.181***	2.591	2014	0.142*	1.855
2007	0.191***	2.686	2015	0.102	1.388
2008	0.195***	2.648	2016	0.157**	2.039
2009	0.213***	2.663	2017	0.183***	2.328
2010	0.205**	2.542	2018	0.231***	2.877
2011	0.192**	2.424	2019	0.244***	2.980
2012	0.175**	2.219	2020	0.192**	3.357
2013	0.159**	2.053			

Note: Z value was used to measure the difference between an observed value and the overall mean. ***, $P<0.01$ level; **, $P<0.05$ level; *, $P<0.10$ level.

However, the Moran's I and *Z* values showed a downward trend from 2006 to 2015 and even failed the significance test in 2015, before gradually rising again. This phenomenon reflected the phased evolution of the spatial agglomeration of CE, which is closely related to national strategies and policy implementation in China.

During 2006–2015, the YRD was affected by multiple factors, such as the national low-carbon development strategy, industrial structure adjustment, and "The Twelfth Five-Year Plan" energy conservation and carbon reduction targets. High-carbon industries gradually shifted to the central and western regions or economically underdeveloped regions of the YRD, reducing regional differences and leading to the decline of CE in spatial autocorrelation. During this process, there were differences in the development of various cities and municipality within the YRD. Shanghai Municipality, and Nanjing and Hangzhou cities have taken the lead in industrial upgrading, energy-saving technology promotion, and digital transformation, whereas some other cities (e.g., Hefei and Wuxi) that rely on traditional manufacturing still follow a high-carbon development model, weakening the spatial agglomeration of CE. In addition, owing to the continuous deepening of energy conservation and carbon reduction policies at the national and local levels after 2010 (such as carbon trading pilots and binding indicators for energy consumption per unit of GDP), the implementation process of the low-carbon policies in some cities lagged behind, leading to an increase in regional differences in policy effects and further reducing the spatial correlation of CE. Moreover, the year 2015 was a critical transition period for industrial structure adjustment in the YRD. The exit of traditional high-energy-consuming industries and the layout of emerging low-carbon industries were not fully synchronized, leading to a brief trend of decentralization in CE.

After 2016, the rebound in Moran's I value reflected the impact of the YRD integration national strategy, the deepening of the "13th Five-Year Plan" low-carbon development policies, and regional coordinated development. The "YRD Regional Integrated Development Plan Outline" was released in 2018, further promoting regional industrial cooperation and factor flow, strengthening economic ties between regions, and enhancing the synergistic effect of policies, such as energy structure adjustment, low-carbon technology promotion, and green transportation development. The spatial agglomeration of CE has once again strengthened. In addition, with the implementation of green finance, carbon market trading, and "dual control" policies for energy consumption, the low-carbon development paths of cities and municipality in the YRD have gradually converged. Advanced low-carbon technologies and digital governance methods have gradually spread from core cities to surrounding cities, gradually balancing the spatial distribution of regional CE. This trend reflects the shift from decentralized to coordinated regional low-carbon development, indicating the dynamic evolution of CE under the guidance of national strategies and policies.

In summary, the evolution of CE in the YRD not only reflects the dynamic adjustment of the regional internal economic structure and industrial layout, but also indicates the profound impact of national strategies and policies on regional development. In the future, under the guidance of the "dual carbon" goal and regional coordinated development strategies, the YRD is expected to further optimize the spatial pattern of CE and provide a demonstration for achieving green and low-carbon development.

4.2. Digitalization level and its spatiotemporal evolution in the YRD

4.2.1. Spatiotemporal evolutionary characteristics of the digitalization industry level, digitalization application level, and urban green digitalization willingness

Digitalization industry level initially concentrated in Shanghai Municipality and then expanded to surrounding

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cities (such as Suzhou (Jiangsu Province) and Hangzhou cities), forming a dual-core pattern (Fig. 4a–d). Spatiotemporal distribution of the digitalization industry level reflected the spatiotemporal distribution of CE. In 2006, Shanghai Municipality (0.70), and Suzhou (0.52), Hangzhou (0.38), Wuxi (0.33), and Nanjing (0.31) cities led at digitalization industry level. By 2020, the top 5 cities of digitalization industry level were Shanghai Municipality (1.00), and Hangzhou (0.58), Suzhou (Jiangsu Province; 0.52), Nanjing (0.44), and Xuzhou cities (0.41). The economic strength and digitalization infrastructure of Shanghai Municipality spurred this growth. Subsequently, the industrial development in Suzhou, Hangzhou, Nanjing, Hefei, and Xuzhou cities was integrated with the industry chain of Shanghai Municipality, promoting the development of centralized and diffused digital industries. This development extended from coastal cities to inland cities. This progression reflected the dynamic process of digital industrial transformation and the characteristics of integrated and complementary development in the YRD.

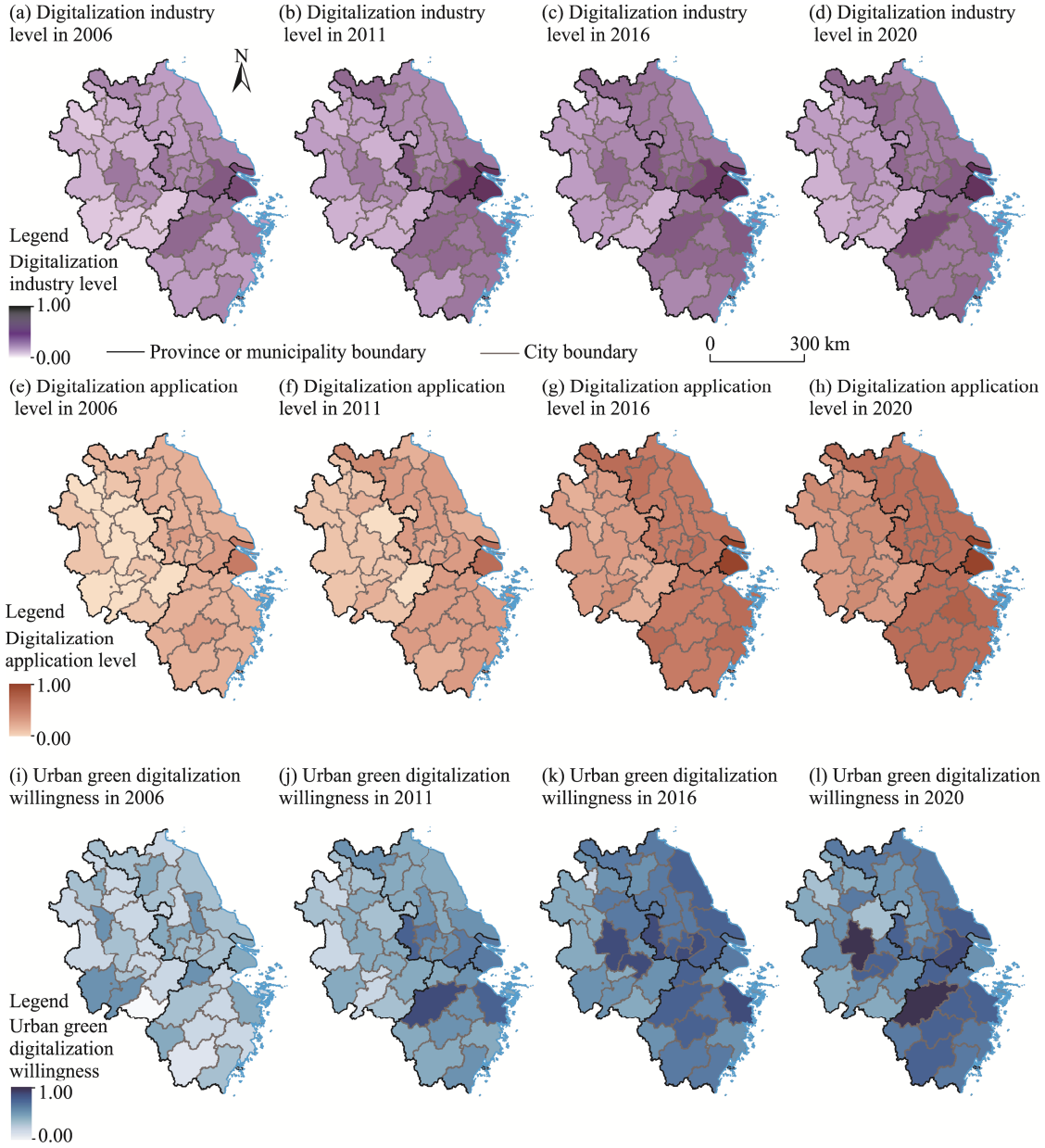


Fig. 4. Digitalization industry level in 2006 (a), 2011 (b), 2016 (c), and 2020 (d); digitalization application level in 2006 (e), 2011 (f), 2016 (g), and 2020 (h); and urban green digitalization willingness in 2006 (i), 2011 (j), 2016 (k), and 2020 (l) in the YRD. Note that the figure is based on the standard map (GS(2020)3189) of the Map Service System (http://bzdt.ch.mnr.gov.cn/download.html) marked by the Ministry of Natural Resources of the People's Republic of China, and the boundary of the standard map has not been modified.

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Shanghai Municipality also led in terms of digitalization application level (Fig. 4e–h). From 2006 to 2020, digitalization application level in Shanghai Municipality continuously improved, with the digitalization application level values increasing from 0.42 to 1.00. This improvement of digitalization application level has spread to Jiangsu and Zhejiang provinces, demonstrating a significant spillover effect. This process has not only strengthened the leading position of Shanghai Municipality in the YRD's economy, but also promoted the overall improvement of digitalization application level in the YRD. By 2020, Shanghai Municipality, and Jiangsu and Zhejiang provinces exhibited similar digitalization application level, whereas Anhui Province showed a significant gap with them. This revealed uneven development due to geographical, economic, and developmental disparities. Coastal cities, benefiting from stronger foundations, readily adopted digitalization. Despite proximity, the integration of the digitalization application level of Anhui Province with that of the YRD's core regions remained limited.

During 2006–2009, governments and markets of the YRD recognized the importance of urban green digitalization willingness, initiating digital transformation plans. After 2010, Shanghai Municipality, and Hangzhou, Nanjing, Ningbo, Suzhou (Jiangsu Province), and Wuxi cities showed an increase in green digitalization willingness, forming a multicenter pattern (Fig. 4i–l). After 2015, urban green digitalization willingness of Hefei City surged. By 2020, Hefei and Hangzhou cities, as well as the Su-Xi-Chang region have showed a high urban green digitalization willingness, demonstrating a diversifying and dynamic regional trend.

4.2.2. Spatial cluster analysis of the digitalization industry level, digitalization application level, and urban green digitalization willingness

From Figure 5 we observed significant differences in the digitalization process of the YRD during 2006–2020. Shanghai Municipality and its surrounding cities have developed their digital industries rapidly, becoming the core strength within the YRD. In 2020, the digitalization industry level of Shanghai Municipality reached near saturation and further expanded into parts of Zhejiang and Jiangsu provinces. This phenomenon reflects the concentrated development trend of the information technology and digital industry sectors in the YRD, demonstrating the leading position of these regions in the global digital economy.

In terms of digitalization application level (Fig. 4e–h), Shanghai Municipality has consistently maintained a leading position, and over time, the digitalization application level of Hangzhou and Nanjing cities has also gradually developed. By 2020, the penetration rate of digitalization application level in parts of Jiangsu and Zhejiang provinces has significantly increased, indicating that these regions have achieved relatively significant results in promoting digital economic transformation. However, the relatively remote central and western regions of the YRD still maintained lower digitalization application level, appearing as more obvious blue and gray areas. This result showed the regional differences in digitalization application level, reflecting the imbalance in technology penetration and application popularization between central cities and peripheral regions.

Spatial cluster analysis of urban green digitalization willingness further revealed the differences in promoting sustainable development and green digitalization in the YRD (Fig. 5i–l). Shanghai Municipality and Hangzhou City have continuously strengthened their green digitalization willingness. In 2020, green digitalization willingness was particularly prominent, indicating that Shanghai Municipality and Hangzhou City have strong policy support and market demand in promoting green and low-carbon transformation. In contrast, inland and less developed regions presented a significant gap in urban green digitalization willingness, revealing an imbalance in environmental awareness and green development promotion efforts across the YRD. This difference indicated that although the overall digitalization level of the YRD is gradually improving, the promotion of green digitalization still faces significant regional challenges, requiring policy and innovation to drive the green digitalization transformation of more inland cities.

4.3. Interaction mechanism between digitalization and CE in the YRD

4.3.1. Impact of digitalization on CE

The impact of digitalization on CE varied in the YRD across different periods (Table 3). In the initial budding period of digitalization (2006–2010), because cities were undergoing exploratory planning and construction, digitalization industry level, digitalization application level, and urban green digitalization willingness did not significantly correlate with CE. From 2011 to 2015, only urban green digitalization willingness had a significant negative direct effect on CE, with a weight of –0.0198, whereas the other digitalization indicators were not significant. This indicated that during this period, the digital construction of various cities and municipality gradually became

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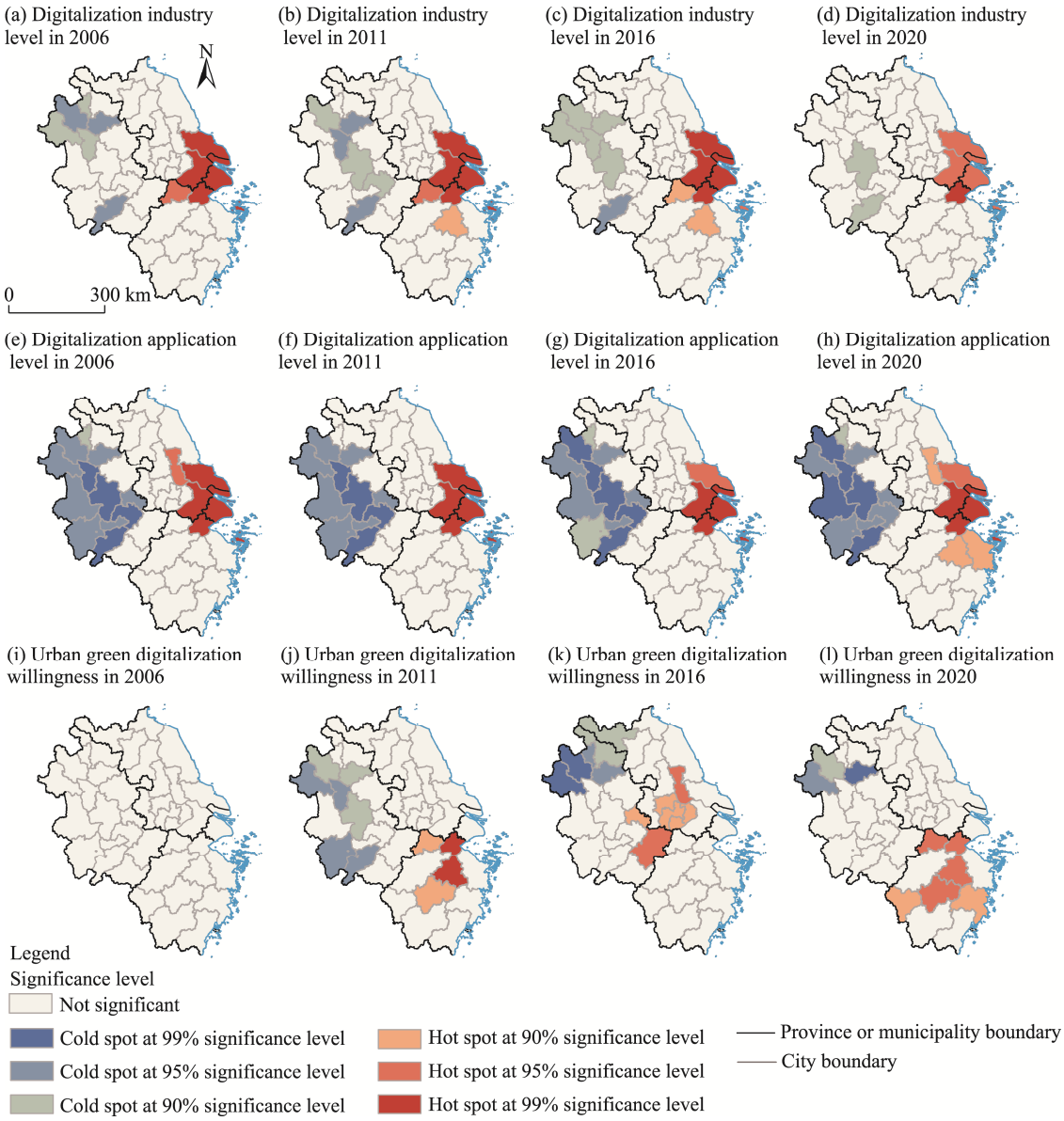


Fig. 5. Spatial cluster analysis of digitalization industry level in 2006 (a), 2011 (b), 2016 (c), and 2020 (d); spatial cluster analysis of digitalization application level in 2006 (e), 2011 (f), 2016 (g), and 2020 (h); and spatial cluster analysis of urban green digitalization willingness in 2006 (i), 2011 (j), 2016 (k), and 2020 (l) in the YRD. Note that the figure is based on the standard map (GS(2020)3189) of the Map Service System (http://bzdt.ch.mnr.gov.cn/download.html) marked by the Ministry of Natural Resources of the People's Republic of China, and the boundary of the standard map has not been modified.

systematic and standardized. The stronger the inclination of governments toward green digitalization construction, the greater the likelihood of leading to a decrease in CE within the city. This situation also demonstrated the positive guiding role of government policies in the coordinated development of digitalization and greening. From 2016 to 2020, digitalization industry level exhibited a significant negative indirect effect on CE, with a weight of –0.7600. This finding suggested that during this period, the development of digital industries within a city effectively reduced CE in neighboring cities. However, both the direct and indirect effects of digitalization application level were positive, with weights of 0.3350 and 0.7580, respectively. This implied that in the later stages of urban agglomeration development, while the promotion of digitalization applications and technologies can enhance production efficiency and resource utilization, this process is inherently energy intensive. Simultaneously, the improvement of digitalization application level has stimulated economic growth, leading to an increase in CE. Although these economic activities became more efficient through digitalization, the overall energy consumption continued to rise.

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Table 3
Direct and indirect effects of digitalization indictors on CE in the YRD during different periods.

Indicator	Direct effect			Indirect effect		
	2006–2010	2011–2015	2016–2020	2006–2010	2011–2015	2016–2020
Digitalization industry level	0.0047	0.0197	–0.1870	–0.0589	–0.0058	–0.7600**
Digitalization application level	–0.0111	–0.0039	0.3350**	–0.0005	0.0306	0.7580**
Urban green digitalization willingness	–0.0066	–0.0198**	0.0105	0.0184	–0.0223	0.1230

Note: **, $P<0.05$ level.

4.3.2. Influencing mechanisms of digitalization on CE

We conducted a detailed spatial econometric analysis of all sub-indicators at digitalization industry level, digitalization application level, and urban green digitalization willingness (Tables 4 and 5) to further investigate the influence mechanisms. The direct effect analysis revealed that the impact of urban digitalization on CE dynamically changes over different periods (Table 4). Telecommunication output, science and technology focus, and the level of green technology were negatively correlated with CE in the YRD during 2006–2010, with the weight values of –0.0555, –0.0423, and –0.0134, respectively. This suggested that during this period, a higher level of urban telecommunication development, greater emphasis on science and technology, and the wider application of green technologies contributed to the improvement of production efficiency and energy use efficiency, thereby reducing CE.

Table 4
Direct effect of digitalization on CE in the YRD across different periods.

Indicator	Sub-indicator	Weight value		
		2006–2010	2011–2015	2016–2020
Digitalization industry level	Telecommunications output	–0.0555*	0.0050	0.2640**
	Long-haul fiber optic cable line density	–0.0190	0.0481***	–0.0159
	Digital industry talent	0.0130	0.0013	–0.1350*
Digitalization application level	Internet application	0.1090	–0.0189	0.2960
	Mobile Internet application	–0.0410	0.0116	0.1110
	Digital inclusive finance index	–0.2120	0.0130	–0.3200
Urban green digitalization willingness	Environmental regulation	–0.0046	–0.0021	0.0571
	Government digital awareness	0.0283	–0.0097*	–0.0592
	Science and technology focus	–0.0423*	–0.0287	–0.0091
	Level of green technology	–0.0134*	–0.0306**	–0.1210

Note: ***, $P<0.01$ level; **, $P<0.05$ level; *, $P<0.10$ level.

Table 5
Indirect effect of digitalization on CE in the YRD across different periods.

Indicator	Sub-indicator	Weight value		
		2006–2010	2011–2015	2016–2020
Digitalization industry level	Telecommunications output	0.0987	0.0248	–0.0281
	Long-haul fiber optic cable line density	–0.0057	0.0368	–0.4390***
	Digital industry talent	–0.0418*	0.0003	–0.1120
Digitalization application level	Internet application	–0.0427	–0.0489	–2.5190**
	Mobile Internet application	0.1240	–0.0076	0.2190
	Digital inclusive finance index	–0.6750	0.0432	3.2840***
Urban green digitalization willingness	Environmental regulation	0.0081	–0.0082	–0.0193
	Government digital awareness	–0.0186	–0.0426**	0.2620***
	Science and technology focus	0.0910*	–0.0364	0.1520
	Level of green technology	0.0219	0.0190	0.0443

Note: ***, $P<0.01$ level; **, $P<0.05$ level; *, $P<0.10$ level.

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However, the impacts of various factors on CE were quite diverse in the urban digitalization process. On the one hand, long-haul fiber optic cable line density was positively correlated with CE, with a weight value of 0.0481, indicating that the early and middle-stage construction and expansion of digital industries and infrastructure led to the increase of energy consumption and CE. On the other hand, government digital awareness and the level of green technology were negatively correlated with CE, with weight values of –0.0097 and –0.0306, respectively. This suggested that despite the rapid pace of urban digital construction, the positive attitude of the government toward digitalization promoted energy efficiency and reduced CE. Thus, while promoting digitalization, the government has taken effective measures to guide and promote green development, thereby offsetting some of CE caused by the increase of infrastructure construction.

From 2016 to 2020, telecommunications output was positively correlated with CE, with a weight value of 0.2640, indicating that although the development of telecommunications industry helps to increase productivity and promote high-quality development, the rapid expansion and technological upgrading of this industry within a certain period may lead to the increase of CE. This reflected that while pursuing digital transformation, how to balance development needs with environmental protection is a key issue that needs to be addressed.

The indirect effect of a city's digitization on the CE of neighboring cities were dynamic and can vary over time (Table 5). From 2006 to 2010, digital industry talent was negatively correlated with CE in neighboring cities, with a weight value of –0.0418, which indicated that an increase in the number of digital industry talent in this city would lead to a decrease in the CE of neighboring cities. However, science and technology focus was positively correlated with CE in neighboring cities, with a weight value of 0.0910, suggesting that government's support for science and technology indirectly led to an increase in CE in neighboring cities. The above analysis indicates that the development of the digital industry and government's support for science and technology policies may trigger the reconfiguration of resources and industries, thereby affecting CE in surrounding areas.

From 2011 to 2015, government digital awareness was negatively correlated with CE in neighboring cities, with a weight value of –0.0426. This finding, combined with direct effect analysis, indicated that during this period, increasing digital awareness of the government reduced CE not only in its own city but also in its neighboring cities.

From 2016 to 2020, government digital awareness and digital inclusive finance index were positively correlated with CE in neighboring cities, with weight values of 0.2620 and 3.2840, respectively. This suggested that as the digitalization process of the government develops, more services and activities have shifted online, thus enhancing the attractiveness of city and leading to the outward transfer of some high-carbon industries. This process increased CE in neighboring cities. Moreover, mobile Internet application and long-haul fiber optic cable line density were negatively correlated with CE in neighboring cities, with weight values of –2.5190 and –0.4390, respectively. This reflected that the popularization of mobile Internet application and the construction of efficient information transmission infrastructure promotes energy use efficiency and increases remote work and online services, thereby reducing reliance on physical transportation and CE.

5. Discussion

5.1. Uneven development of digitalization and its impact on CE

5.1.1. "Core-periphery" spatial pattern of digitalization in the YRD: the coexistence of coordinated and uneven development

The analysis of spatiotemporal evolution patterns of digitalization reveals a distinct "core-periphery" spatial pattern in the digitalization process of the YRD (Fig. 6). This model comprises multiple core cities (e.g., Shanghai Municipality, and Hangzhou, Nanjing, and Suzhou (Jiangsu Province) cities) and peripheral cities, with the latter relying on the former for resources and markets. The core cities have spearheaded the digital wave, driving the digitalization process of surrounding cities (e.g., Jiaxing, Huzhou, and Zhenjiang cities) and forming a spatial pattern of diffusion from the core cities to the periphery cities. On the one hand, the "core-periphery" spatial pattern has fostered regional integration and coordinated development. Multiple core cities, together with their surrounding peripheral cities, constitute a comprehensive spatial system, enhancing urban management and service efficiency within the region, strengthening intercity connections and exchanges, and promoting the integrated development of the economy, society, and culture. On the other hand, the unevenness of digitalization process within the region, particularly the development gap between coastal and inland cities (Fig. 5), poses challenges. Coastal cities, with their geographical advantages, economic strength, and openness, generally have more apparent advantages in digital transformation, whereas inland cities face challenges, such as insufficient infrastructure, talent shortages, and inadequate funding. This unevenness not only affects the coordinated development of the regional economy, but also presents challenges to achieving the SDGs.

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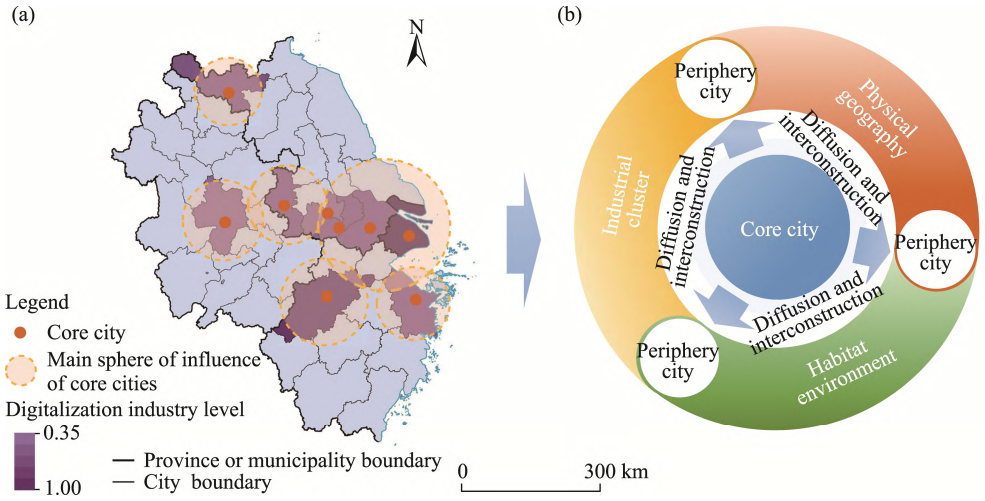


Fig. 6. "Core-periphery" spatial pattern of digitalization industry level in the YRD in 2020 (a) and spatial subsystems formed by the "core-periphery" spatial pattern (b). Note that the Figure 6a is based on the standard map (GS(2020)3189) of the Map Service System (http://bzdt.ch.mnr.gov.cn/download.html) marked by the Ministry of Natural Resources of the People's Republic of China, and the boundary of the standard map has not been modified.

5.1.2. Simultaneous spatiotemporal evolution of digitalization industry level and CE

The spatial distribution and evolutionary trends of digitalization industry level and CE in the YRD exhibit a certain degree of synchronization, which can be reflected from 2 main aspects. First, CE is concentrated in some core cities, where the level of digital development is also relatively high. This leads to a situation where regions with higher CE also maintain a higher level of digitalization, whereas regions with lower CE also have a lower level of digitalization (Figs. 7 and 8). Second, the diffusion trend of regional CE is generally consistent with the diffusion trend of digitalization level during 2006–2020. The diffusion trend from central cities to peripheral cities reveals the diffusion effect of increasing economic activity and the promotion of technology application on the regional environment. This synchronous development reflects a complex phenomenon, with the rise of digitalization industry level, the corresponding energy demand and CE spread simultaneously. Digitalization can indeed reduce CE to a certain extent (Zheng et al., 2023), but compared with economic and industrial development, the carbon reduction effect of digitalization is relatively limited (Du and Wang, 2024). It cannot fully offset the additional CE brought by economic and social development.

5.2. Complex interaction mechanisms between digitalization and CE

5.2.1. Dual influencing mechanism of digitalization on CE

The relationship between digitalization and CE clearly has a dual impact at different stages. On the one hand, digital technologies promote carbon reduction by improving energy efficiency and driving green innovation (Liu et al., 2023); on the other hand, the large-scale construction of digital infrastructure and data transmission demands also brings increasing emission pressure. The paradox lies in the fact that the efficiency gains of digitalization are accompanied by a rigid growth in energy demand, and its net effect depends on the synergy between technological pathways and energy structures.

The growth of telecommunications output has promoted the popularization of low-carbon technologies, such as remote communication and digital offices. Increasing emphasis on science and technology priorities has accelerated the research and development of energy-saving technologies, while the improvement of the level of green technology has highlighted the significant contribution of digitalization to green innovation. The direct effects of telecommunication output, science and technology focus, and the level of green technology on CE show that the emission reduction effect in the early stage of digitalization is achieved mainly through technological innovation and remote communication substitution effect (Table 4).

With the rapid expansion of digital infrastructure from 2011 to 2020, its role in increasing CE has become increasingly prominent. The increase of long-haul fiber optic cable line density reflects the impact of increasing data traffic on energy demand. From 2011 to 2015, the direct effect of long-haul fiber optic cable line density (0.0481) showed that although information infrastructure can improve economic efficiency, high energy consumption begins

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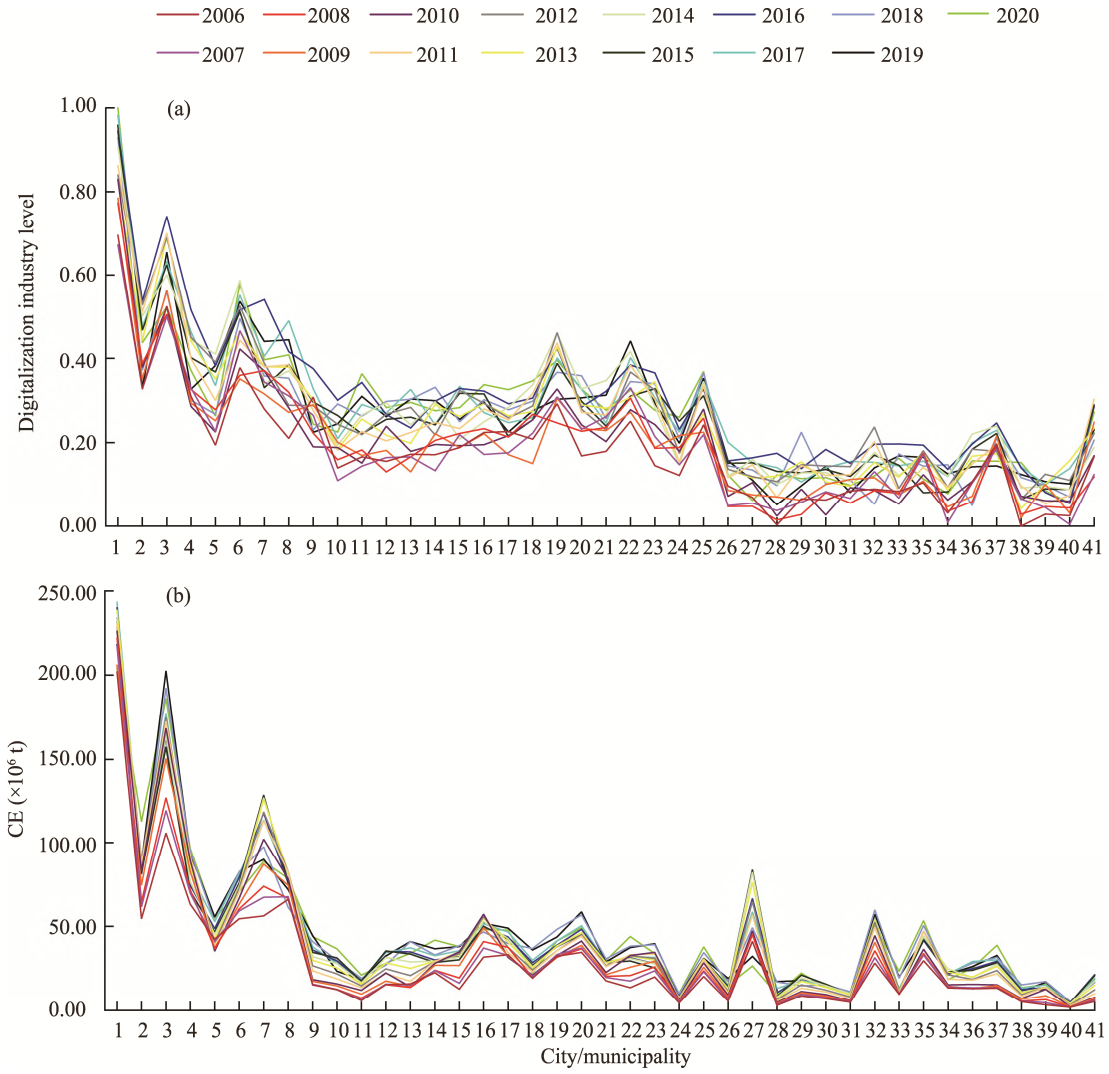


Fig. 7. Distribution of digitalization industry level (a) and CE (b) in the YRD during 2006–2020.

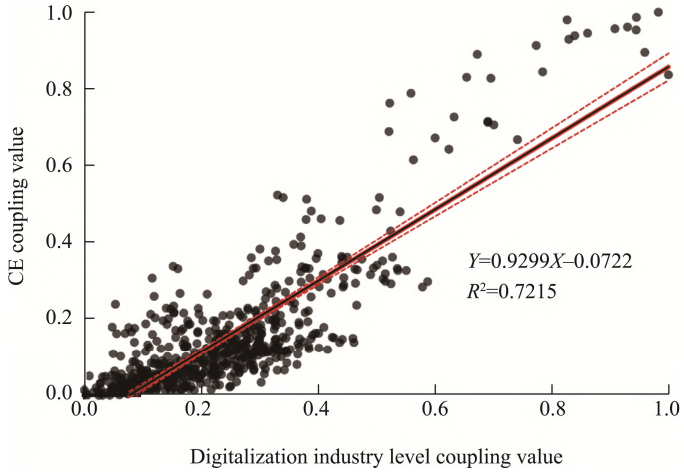


Fig. 8. Distribution of digitalization industry level coupling value and CE coupling value in the YRD.

to positively promote CE (Table 4). During 2016–2020, the direct and indirect effects of the digitalization application level (0.3350 and 0.7580, respectively) further indicated that although the economic and social penetration rate of digitalization has brought significant development dividends, it has also led to increasing energy

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consumption and CE (Table 3).

Mechanistically, the positive impact of digitalization on CE mainly occurs through technological progress and industrial optimization. The expansion of telecommunication industry has promoted the development of remote offices, intelligent manufacturing, digital finance, and other models, reducing the energy consumption of traditional offline economic activities. The application of technologies, such as smart grids, intelligent transportation, and low-carbon buildings promoted by the increase of emphasis on science and technology focus has improved energy utilization efficiency. In addition, the improvement of the level of green technology proves that digitalization can promote clean energy technology innovation, such as the intelligent scheduling of new energy sources (wind and solar power), improving the overall utilization rate.

At the same time, the negative impact of digitalization mainly comes from the demand for infrastructure and data energy. The increase of long-haul fiber optic cable line density reflects a surge in demand for data storage and transmission, and infrastructure construction requires a large amount of electricity support. Online consumption, logistics distribution, and various smart terminal devices also continue to increase energy consumption, and even a "carbon emission rebound effect" occurs in some industries in the short term. Therefore, while digitalization promotes economic growth, it also urgently needs to control emissions by improving the energy utilization efficiency of the telecommunication industry, promoting the low-carbon transformation of data centers, and strengthening green technology integration. Governments and enterprises should also jointly introduce more targeted policies and regulatory measures, such as digital carbon footprint monitoring, intelligent power dispatch, and green data storage, to stabilize or reduce CE while developing the digital economy.

5.2.2. Spatial spillover effect of digitalization on CE

Research shows that digitalization not only affects local CE, but also has significant indirect effects on CE in neighboring cities through channels, such as talent flow, policy demonstrations, and technology dissemination (Niu et al., 2024; Sun and Chen, 2025). The emission reduction effect of digitalization involves geographical penetration. For example, core cities drive technology diffusion through digital industry talent flow, whereas second- and third-tier cities rely on policy formulation. The essence is a dual-track mechanism of "market-driven" and "government-driven": the former relies on technology spillover, and the latter depends on institutional learning. However, it is necessary to be vigilant about the digital divide widening regional CE differences—developed regions reduce local emissions through technology monopolies but may transfer high-carbon industries to marginal areas, resulting in hidden carbon leakage.

From Table 5 we can see that digital industry talent (–0.0418) was significantly negatively correlated with CE in surrounding cities during 2006–2010. Government digitalization awareness (–0.0426) was significantly negatively correlated with CE in surrounding cities during 2011–2015, indicating that digitalization can promote the synergistic improvement of regional economy and environment through cross-regional talent and knowledge spillover. Further analysis revealed that there are differences in the digital spillover effects of different types of cities. Core cities have gathered more high-end software and computer talent, and their flow to surrounding areas can drive technology diffusion and industrial optimization, thereby promoting the reduction of CE in neighboring cities. In contrast, government digitalization awareness can better affect policy learning and management improvement in second- and third-tier cities, helping to enhance regional low-carbon governance capacity. Overall, the impact of digitalization to CE in neighboring cities mainly occurs through talent flow effect, policy demonstration effect, and technology spillover effect. Therefore, local governments should attach importance to the regional synergy of digitalization, build platforms for mutually beneficial technology sharing and policy docking, and extend digital applications from core cities to surrounding cities, thereby achieving carbon reduction goals at a larger scale.

5.2.3. Role of government in advancing digitalization and reducing CE

The implementation of active green policies and guidance by government during the digital transformation process can effectively reduce CE. From 2016 to 2020, urban green digitalization willingness was negatively correlated with CE (–0.1870; Table 3). During 2011–2015, government digital awareness and the level of green technology were negatively correlated with CE (Tables 4 and 5), indicating that the green awareness of urban government in digital construction has a positive impact on the reduction of CE. After 2011, the digital construction of the YRD gradually became systematic and standardized, and the government promoted digital transformation to reduce CE. By formulating and implementing policies and standards oriented towards green development, the government can not only guide carbon reduction during the digitalization process, but also promote sustainable

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development by optimizing energy structure and promoting green technologies. Therefore, the government needs to adjust its role according to the stage of digitalization. In the early stage, it should guide the direction of technology through green standards such as the level of green technology. In the mid-term, it needs to strengthen supervision to curb the energy lock-in effect of digital infrastructure. The key contradiction lies in balancing short-term economic benefits and long-term low-carbon costs (Yan et al., 2025). For example, the YRD has converted digital dividends into carbon productivity gains through policy coordination (Yan et al., 2023), but it is necessary to avoid "green digitalization" becoming a policy gimmick of technological optimism.

5.3. Policy implications

This study proposes the following policy approaches to address the aforementioned dual impact and spatial spillover effects, and enhance the linkage between digitalization and the reduction of CE (Fig. 9).

First, the standards for the green construction and operation of digital infrastructure should be improved. Given that digital infrastructure is both an important source of increasing digitalization and can reduce CE through improving energy efficiency, we should start with the entire lifecycle from design to operation and formulate construction specifications for green communication networks and low-energy data centers. Combining the analysis of these 2 mechanisms, we should focus on the improvement of energy efficiency and the control of CE while expanding infrastructure and promoting the deep integration of the ICT industry and green technologies.

Second, the government should promote the deep application of digital technologies in key fields and optimize regional coordinated development according to local conditions. Combining the discussion of spatial spillover effects, it can be concluded that core cities and surrounding cities need to establish joint mechanisms to promote the flow and sharing of talent and technology in the YRD. Focus should be placed on supporting the digital transformation of fields, such as smart transportation, green buildings, and smart grids. It is necessary to encourage second- and third-tier cities to establish policy linkage mechanism for digital governance and low-carbon transformation based on their actual situations, and to reduce the regional digital divide between regions through policy learning and technology diffusion.

Third, the government's overall planning and regulatory role in digital low-carbon transformation should be strengthened. The government should continue to improve financial incentives to encourage enterprises to research,

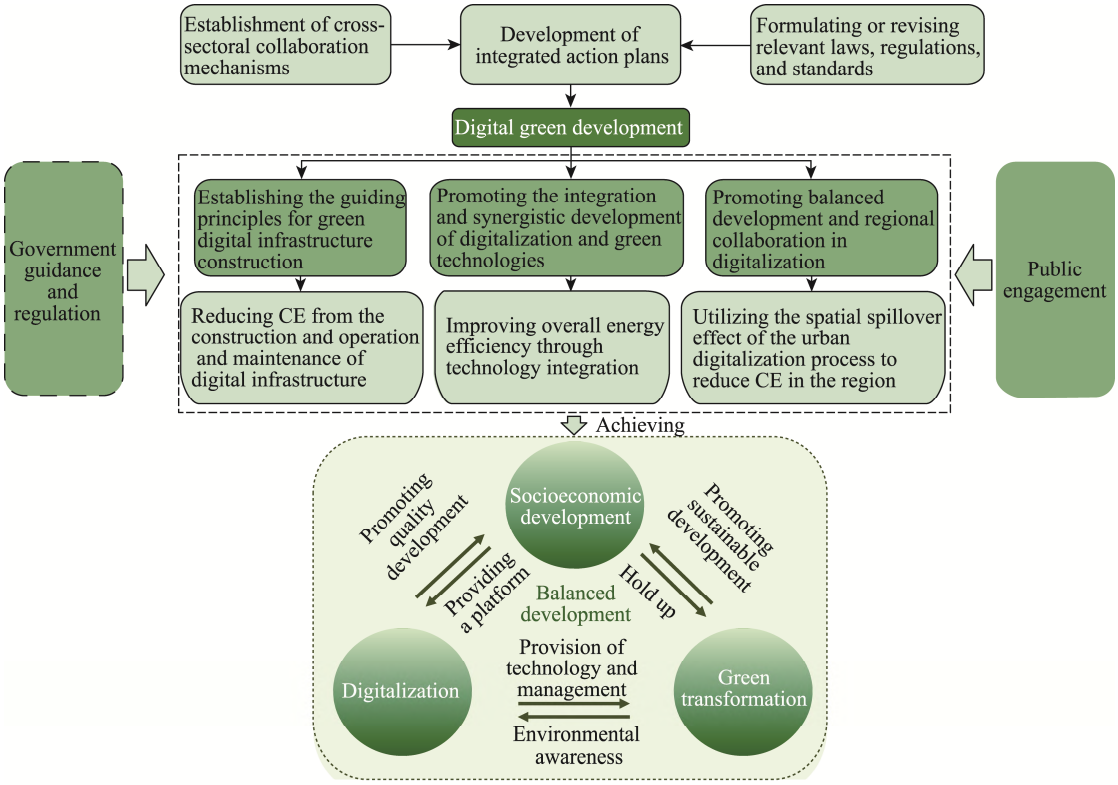


Fig. 9. Logical framework of policy recommendation.

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develop, and apply green digitalization technologies. For high-energy-consuming industries, stricter energy efficiency standards and digital transformation requirements should be established, and digital monitoring methods should be introduced to achieve precise management and real-time scheduling of CE. Through legislation and public policy leverage, industrial structure upgrade and energy structure optimization can be guided to ensure that digitalization not only serves economic development, but also effectively promotes the emission reduction goals.

Finally, this study uses the YRD as an example, other regions should flexibly draw on the above policy implementations according to their own digital development levels and industrial structure characteristics. Cities with relatively complete digital infrastructure can take the lead in exploring the application of cutting-edge digital technologies in emission reduction and play a leading role in regional coordination. However, cities with lower digital development levels should prioritize improving infrastructure and technical talent reserves to ensure the accessibility and effectiveness of digitalization in reducing CE. The government's institutional design and market guidance are crucial in this process, and the policy system needs to be continuously improved in terms of the compatibility and coordination of digitalization and low-carbon development to provide replicable and scalable experience for other regions.

6. Conclusions

This study focused on the spatiotemporal evolution characteristics of digitalization and CE in the YRD from 2006 to 2020, and systematically investigated the influence mechanisms of digitalization on CE across different spatial patterns, development stages, and policy environments. By constructing a multidimensional indicator, which encompasses digitalization industry level, digitalization application level, and urban green digitalization willingness, and combining spatiotemporal analysis with spatial econometric models, this research revealed the complex interactive logic between digitalization and CE in the YRD. Finally, this study provides empirical support and policy insights for achieving the coordinated development of regional digitalization transformation and green low-carbon development.

The study revealed that both digitalization and CE exhibit a distinct "core-periphery" spatial pattern in the YRD, highly overlapping with existing metropolitan area development axes, reflecting a coupled relationship in their spatial evolution. Core cities with higher levels of digitalization (such as Shanghai Municipality, and Hangzhou and Nanjing cities) drive the digitalization progress of surrounding cities through technology diffusion and policy demonstration effects while also promoting the collaborative improvement of regional CE management. The impact of digitalization on CE is dualistic. On the one hand, it reduces CE by enhancing energy efficiency, optimizing industrial structures, and promoting the application of green technologies. On the other hand, it also brings the risk of increasing emission due to the expansion of digital infrastructure and the growth of energy consumption. Digitalization has significant spatial spillover effect, especially under the mechanisms of talent mobility and institutional guidance, which can influence the performance of CE in neighboring cities of the YRD. The government plays a crucial regulatory role in the digital green transition, with its green intention and institutional guarantee significantly enhancing the effectiveness of carbon reduction through digitalization.

Despite the preliminary exploration in terms of theoretical construction and empirical analysis, this study still has certain limitations. First, limited by data availability, the timeframe of this paper ends in 2020, not yet encompassing the new changes brought by the accelerated evolution of digital technologies in recent years. Second, this study is based on macro-level panel data of urban agglomerations, which may not fully capture the dynamic relationship between digitalization and CE at the micro level. Third, the multidimensional indicator of the research still needs to be optimized. Furthermore, considering the regional differences in the economic development levels, industrial structures, and energy consumption patterns of different cities, the impact of digitalization on CE may exhibit regional characteristics. Future research can overcome these limitations by expanding the research scope, implementing in-depth analysis methods, and enriching data sources to provide more actionable policy recommendations for the coordinated advancement of the Digital China and "carbon peaking-carbon neutrality" goals.

Authorship contribution statement

WEI Meng: methodology, validation, investigation, formal analysis, investigation, data curation, visualization, and writing - original draft; RU Lifei: methodology, validation, and formal analysis; CAI Zhi: writing - review & editing, conceptualization, methodology, writing - review & editing, supervision, and project administration; and

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MA Minda: writing - review & editing. All authors approved the manuscript.

Ethics statement

Ethics approval was obtained from the Digital City Planning Ethics Committee of the Nanjing University, China. In addition, the participants provided their informed consent to participate in this study.

Declaration of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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