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Research on the Boundary of Spatial Spillover Effect of Carbon Emissions in the Digital Economy

-- Analysis based on the Yangtze River Delta Urban Network

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Abstract

The rapid rise of the digital economy has provided a new path for carbon emission reduction in the Yangtze River Delta urban agglomeration. The spatial spillover effect of carbon emissions brought about by it, along with its boundary characteristics, can directly affect the actual effectiveness of collaborative emission reduction across the entire urban agglomeration. This paper focuses on the boundary issues of the spatial spillover effect of digital economy carbon emissions, using the Yangtze River Delta urban network as the main research scenario. By reviewing relevant theoretical knowledge and current development status, we successfully identified three core issues: blurry spillover boundary definition, fragmented transmission mechanisms, and ineffective collaborative governance. During the research process, we found that the spatial spillover of digital economy carbon emissions in the Yangtze River Delta exhibits three distinct characteristics: geographical distance attenuation, network hierarchy differentiation, and institutional boundary constraints. However, existing research and practical work have not accurately delineated these spillover boundaries or achieved effective control. Based on this current situation, this paper constructs a three-dimensional boundary definition framework encompassing "geography-network-institution", and proposes optimization strategies to smooth technology, industry, and energy transmission mechanisms and upgrade the cross-regional collaborative governance system. This provides a theoretical basis and practical path for the Yangtze River Delta urban agglomeration to achieve collaborative carbon emission reduction relying on the digital economy, and also offers valuable references for the digital low-carbon transformation efforts of other urban agglomerations across the country.

Keywords

Digital Economy; Carbon Emissions; Spatial Spillover Effect; Boundary Research; Yangtze River Delta Urban Network.

1. Introduction

In the context of the deep integration of the "dual carbon" goals and the integrated development strategy of the Yangtze River Delta, the digital economy, as the core force driving economic transformation, is profoundly changing the carbon emission pattern within the region. The Yangtze River Delta urban agglomeration is a highland for the development of China's digital economy and a pioneering region in carbon emission reduction efforts. Cities have formed a very close network connection through the interconnection of digital infrastructure, collaborative cooperation in industrial chains, and the diffusion of technological innovation. The impact of the digital economy on carbon emissions is no longer confined to a single city, but will form cross-regional transmission through spatial spillover effects. On the one hand, this

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spillover effect creates a rare opportunity for the Yangtze River Delta urban agglomeration to break administrative barriers and achieve coordinated carbon emission reduction. On the other hand, due to the uncertainty of the spillover boundaries, it brings many challenges to carbon emission reduction governance.

Existing research on the relationship between the digital economy and carbon emissions mostly focuses on the direct impact of the digital economy on carbon emissions and the spatial spillover characteristics at the macro level, rarely incorporating the perspective of urban networks to deeply analyze the boundary issues of spillover effects [1]. The Yangtze River Delta urban network exhibits a hierarchical structure of "core-periphery", with the core cities having a significantly higher level of digital economy development than the peripheral cities. This development disparity results in distinct boundary characteristics of spatial spillover of digital economy-related carbon emissions in multiple dimensions, including geographical scope, network connectivity, and institutional constraints [2]. At the current stage, the Yangtze River Delta region faces numerous challenges in utilizing the digital economy to promote carbon emission reduction: the spillover boundaries cannot be precisely identified, the transmission pathways of effects are not sufficiently smooth, and there is a lack of coordination in cross-regional governance. These issues not only limit the positive spillover effects of the digital economy on emission reduction but also affect the overall effectiveness of collaborative carbon emission reduction among the Yangtze River Delta urban agglomeration [3].

Based on this current situation, this paper takes the Yangtze River Delta urban network as the analytical framework, focusing on the boundary issues of the spatial spillover effect of digital economy carbon emissions. It identifies the core dilemmas that currently exist and then constructs an optimization strategy system that is tailored to the characteristics of the Yangtze River Delta urban network. By clarifying the boundary logic and transmission rules of spatial spillover of digital economy carbon emissions, we have solved the practical problem of regional collaborative carbon emission reduction, thereby helping the Yangtze River Delta urban agglomeration achieve high-quality development of the digital economy and the "dual carbon" goals in a win-win situation. At the same time, it can also provide some valuable references for other urban agglomerations in China to explore the path of collaborative digital low-carbon development.

2. Identification of Core Issues

In the Yangtze River Delta (YRD) urban network, the boundary definition of the spatial spillover effect of digital economy carbon emissions has become significantly blurred. Most existing related research focuses on a single dimension of geographical distance, failing to fully consider the superimposed impacts of the "core-periphery" urban network structure and administrative institutional barriers in the YRD. This leads to a lack of precise delineation of the three boundaries: geography, network, and institution [4]. On the geographical level, the radiation effect of the digital economy on carbon emission reduction is not boundless and randomly diffusing. However, there is currently a lack of systematic identification of the differentiated geographical spillover radii between core and peripheral cities in the YRD. The effective radiation range of core cities and the specific mechanism of "spillover sinks" formation in peripheral cities have not been clearly revealed [5]. On the network level, the emission reduction spillover effect of the digital economy is achieved through network connections formed by transportation links between cities, interconnection of digital infrastructure, and correlation of industrial chains. However, the effective spillover range is currently not defined in conjunction with the connectivity degree of the urban network, and the differences in spillover intensity between core and peripheral nodes are generally overlooked. On the institutional level, significant barriers exist in various aspects such as digital economy-related

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policies, carbon emission reduction standards, and market access in the three provinces and one city of the YRD. These barriers have formed insurmountable institutional spillover boundaries, impeding the joint construction of cross-regional digital infrastructure and the interconnection and sharing of carbon data. This results in a noticeable "fault" phenomenon in the emission reduction spillover effect of the digital economy at administrative boundaries [6].

The transmission mechanism of spatial spillover of carbon emissions from the digital economy has exhibited significant fragmentation. The digital economy achieves emission reduction spatial spillover through three pathways: green technology innovation, industrial structure upgrading, and energy efficiency improvement. However, the hierarchical differentiation problem in the Yangtze River Delta (YRD) urban network has caused significant blockages in the transmission links [7]. The spillover of green technology exhibits a "circle-layer locking" characteristic. Due to the shortcomings in human capital and industrial foundation of peripheral cities, the core cities' technologies related to industrial internet energy conservation and digital carbon monitoring cannot be effectively inherited. As a result, the effect of technological emission reduction is confined to the core circle and difficult to radiate to a broader scope. In the process of industrial linkage, the division of labor in the industrial chain driven by the digital economy also harbors the risk of "high-carbon transfer". Core cities will transfer high-energy consumption links to peripheral cities, which can reduce local carbon emissions. However, due to the lagging digital transformation efforts in peripheral cities, the overall carbon emissions reduction of the entire urban agglomeration is not achieved, ultimately resulting in a "locally positive, overall imbalanced" spillover effect. In terms of energy interconnection, the construction of the smart energy system in the YRD is constrained by regional market segmentation and inconsistent infrastructure standards. Cross-city collaborative scheduling is also not smooth enough, and the spillover effect of energy efficiency improvement brought by the digital economy empowerment has not been effectively utilized. This also restricts the spatial spillover effect brought by the optimization of energy consumption structure [7].

The current carbon emission reduction governance system in the Yangtze River Delta has become severely disconnected from the characteristics of carbon emissions spillover in the digital economy. At the cross-regional level, there is currently no unified framework for low-carbon governance of the digital economy. Differences in policy standards among the three provinces and one city have made it impossible to clearly delineate the responsibility for emission reduction in cross-regional projects. These policy barriers have also offset some of the positive effects of emission reduction spillover in the digital economy. In the multi-level governance process, the policy coordination among the national, provincial, and municipal levels is not sufficient. National-level strategies have not been implemented in practical work in conjunction with the specific characteristics of the Yangtze River Delta urban network, and local-level governance has not fully considered the impact of spatial spillover effects. This has led to a lack of cross-regional collaborative planning for initiatives such as digital infrastructure construction [4]. At the level of governance tools, traditional administrative means still dominate. The construction of cross-city carbon data sharing platforms and carbon footprint tracing systems for digital economy projects is lagging behind, making it impossible to accurately monitor the path and intensity of spillover. Relevant governance measures also lack specificity, further exacerbating the difficulties faced in managing spillover effects [8].

3. Optimization Strategy: System Reconstruction based on Boundary Control and Collaborative Governance

Accurately defining the three-dimensional boundaries of spatial spillover of carbon emissions in the digital economy is an important prerequisite for effective control. In terms of

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geographical boundary control, we should, based on the relevant laws of geographical distance attenuation and combined with empirical analysis results, clarify differentiated carbon emission reduction radiation radii of 150 kilometers for core cities and 80-100 kilometers for node cities in the Yangtze River Delta. Within the radiation radius, we should focus on promoting the joint construction of digital infrastructure and the sharing of green technologies. Outside the radiation radius, the emphasis should be on enhancing the digital infrastructure capabilities of peripheral cities and cultivating secondary spillover nodes, in order to address the issue of "spillover sinkholes" [9]. In terms of network boundary identification, we should rely on the degree of transportation connectivity between cities, the degree of interconnection of digital infrastructure, and the degree of correlation in the industrial chain to construct a city network correlation matrix. Areas such as the G60 Science and Technology Innovation Corridor and the industrial innovation belt along the Shanghai-Nanjing route should be designated as core spillover network areas. At the same time, we should improve the digital infrastructure and industrial chain docking of peripheral cities, incorporating more peripheral nodes into effective spillover networks, thereby expanding the scope of positive spillovers [10]. In terms of institutional boundary removal, the Yangtze River Delta Integration Demonstration Zone should take the lead in establishing a coordination mechanism for digital economy and carbon emission reduction policies, unifying the accounting standards for carbon emissions from projects and the promotion catalogues for green technologies, promoting the integrated development of the Yangtze River Delta carbon market, clarifying responsibilities for cross-regional emission reduction, avoiding "carbon leakage", and establishing a joint approval channel for cross-regional projects to reduce institutional transaction costs [11].

The key to unleashing positive effects lies in smoothing the transmission mechanism of spatial spillovers from digital economy carbon emissions. In terms of technological spillovers, relying on the Yangtze River Delta National Technology Innovation Center, we should establish green digital technology research and development bases in core cities, set up technology transformation centers in node cities, and also establish technology assistance funds to support cooperation between research institutions in peripheral cities and core cities. This will help build a cascade diffusion system of "core research and development - node transformation - peripheral application", completely breaking the problem of "circle lock-in". In terms of industrial linkage, based on the division of labor pattern of the Yangtze River Delta industrial chain, we should promote core cities to focus on high-end segments of the digital economy, encourage node cities to carry out low-carbon transformation of traditional manufacturing, and facilitate peripheral cities to develop low-carbon supporting services. This will form a digital low-carbon collaborative development model across the entire industrial chain. Additionally, we need to build a carbon emission monitoring platform for the industrial chain to implement cross-sector carbon footprint tracing, thereby avoiding the risk of "high-carbon transfer". In terms of energy interconnection, we should create a cross-city smart energy collaborative dispatching platform, integrate clean energy and energy storage resources, carry out pilot projects for cross-city virtual power plants in key areas, unify standards for smart energy infrastructure, and rely on technologies such as 5G and the Internet of Things to achieve data interconnection between core and peripheral cities, thereby building an efficient low-carbon energy system empowered by digital technology.

Upgrading the collaborative governance system is a crucial guarantee for adapting to the spillover characteristics of carbon emissions in the digital economy. In terms of cross-regional governance, it is necessary to establish a low-carbon development alliance for the digital economy led by multiple departments from three provinces and one city. This alliance should have a professional committee to coordinate governance-related work, establish a joint prevention and control mechanism, set up special funds, and promote cross-regional collaborative emission reduction efforts. In terms of multi-level governance, it is necessary to

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formulate differentiated implementation plans based on the national dual-carbon strategy and the characteristics of the Yangtze River Delta urban network. These plans should clarify the development goals and governance tasks of cities at different levels, achieving precise alignment between national strategies, regional characteristics, and local implementation. In terms of digital governance, it is necessary to rely on the integrated data center of the Yangtze River Delta to build a comprehensive monitoring platform, integrate cross-regional data resources, and utilize big data, artificial intelligence, and other technologies to accurately identify the paths and intensity of spillovers. The platform should be enhanced with functions such as carbon footprint tracing and emission reduction effect evaluation, and digital twin technology should be promoted to simulate policy effects, making governance decisions more intelligent and scientific.

4. Conclusion

As the core driving force for the green and low-carbon transformation of the Yangtze River Delta, the digital economy brings about a spatial spillover effect of carbon emissions that exhibits multiple characteristics such as geographical distance attenuation, network hierarchy differentiation, and institutional boundary constraints. On the one hand, this characteristic provides an important path for the Yangtze River Delta urban agglomeration to achieve the "dual carbon" goals through collaborative emission reduction. On the other hand, it also poses a series of practical challenges to the urban agglomeration's carbon emission reduction efforts, including vague boundary definition, poor mechanism transmission, and insufficient governance coordination. Based on the structural characteristics of the Yangtze River Delta urban network, this paper systematically identifies the core issues of spatial spillover of digital economy carbon emissions in three dimensions: boundary, mechanism, and governance. It also clarifies the inherent logic between these three dimensions and constructs an optimization strategy system that is mutually supportive and collaborative, focusing on three dimensions: precise control of three-dimensional boundaries, smooth empowerment of three major transmission mechanisms, and upgrading of the three-tier governance system.

As the core agglomeration area for China's digital economy development and a pioneer region in carbon emission reduction efforts, the Yangtze River Delta (YRD) region's governance practices regarding the spatial spillover effects of digital economy carbon emissions not only relate to the achievement of its own "dual carbon" goals but also hold significant demonstrative value for the coordinated development of urban agglomerations nationwide. With the continuous deepening of the integration process in the YRD and the iterative upgrading of digital economy technologies, the boundary characteristics, transmission pathways, and governance needs of spatial spillovers of digital economy carbon emissions will undergo dynamic changes in the future. We also need to further combine the dynamic evolution characteristics of urban networks and employ more precise empirical methods to continuously track and analyze these changes. Simultaneously, the implementation effectiveness of cross-regional collaborative governance mechanisms and the application efficiency of digital governance tools also require continuous optimization and improvement based on actual practical progress. Only by basing ourselves on the essential characteristics of the YRD urban network, accurately grasping the dynamic changes of spillover boundaries, unblocking key bottlenecks in effect transmission, and constructing a collaborative governance system that can adapt to the development of the digital economy, can we fully unleash the positive spillover effects of digital economy carbon emissions on emission reduction, achieve a win-win situation for high-quality development of the YRD's digital economy and carbon emission reduction goals, and provide replicable and scalable practical experience for the digital low-carbon transformation of other urban agglomerations in China.

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