The Expansion of High-Tech Zone Development and Regional Carbon Emissions: A Synergistic Exploration of Spatial Heterogeneity and Environmental Justice

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Abstract
This study investigates the spatial relationship between the development scale of High-tech Industrial Development Zones (HTDZs) and regional carbon emissions in China. Using data from 168 national HTDZs, we construct a development index via the entropy method, and employ coupling coordination and multi-scale geographically weighted regression (MGWR) models to assess regional disparities and spatial heterogeneity. Results reveal that while advanced HTDZs achieve higher output with lower emissions, underdeveloped zones face disproportionate carbon burdens due to limited capacity. The findings highlight significant spatial injustice and carbon responsibility shifts. Policy recommendations include region-specific green support systems, emission coordination mechanisms, and enhanced governance. This research provides a scientific basis for promoting low-carbon, equitable, and high-quality development in China's HTDZs.

1 Introduction

Against the backdrop of intensifying global climate change, the notion of a "green transition" has emerged as a central agenda for governments and academic communities worldwide. Addressing global warming and achieving sustainable development are no longer optional choices but have become pressing imperatives for all nations (Liu et al., 2023). In this context, the restructuring and upgrading of economic systems, coupled with effective carbon emission control, have become core tasks for contemporary and future national policymaking and regional governance (Kong et al., 2021). As the world's largest developing country and the top emitter of carbon dioxide, China has put forward the "dual carbon" goals—peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. This ambitious commitment not only reflects China's proactive stance in global climate governance but imposes new internal demands for realizing high-quality development while significantly reducing greenhouse gas emissions and improving resource efficiency. Guided by these targets, China now finds itself at a critical juncture—pursuing both economic modernization and green transformation in tandem. High-tech Industrial Development Zones (HTDZs), which are specialized economic zones characterized by intensive knowledge capital and open institutional environments, play a pivotal role in this transformation (Wang et al., 2023). Leveraging policy incentives such as tax exemptions and R&D subsidies, HTDZs have become incubators of technological innovation and industrial upgrading. Today, they are strategically embedded in China's national innovation system and hold a prominent position in both the global division of labor and the domestic trajectory of green transition (Hua et al., 2023).

High-tech Industrial Development Zones (HTDZs), which are specialized economic zones characterized by intensive knowledge capital and open institutional environments, play a pivotal role in this transformation (Chen & Liu, 2022). Leveraging policy incentives such as tax exemptions and R&D subsidies, HTDZs have become incubators of technological innovation and industrial upgrading. Today, they are strategically embedded in China's national innovation system and hold a prominent position in both the global division of labor and the domestic trajectory of green transition (Wang & Feng, 2021). With this broader transition underway, the role of HTDZs as the frontier of technological innovation and economic restructuring is undergoing profound change. Since the 1990s, HTDZs in China have expanded rapidly due to policy support, concentrated resource allocation, and capital agglomeration. They have evolved into central nodes in the national innovation network, driving regional economic growth, technological advancement, and structural upgrading (Li et al., 2025). By 2024, China had established 178 national-level HTDZs, widely distributed across eastern, central, and western regions, forming high-tech clusters represented by Zhongguancun in Beijing, Zhangjiang in Shanghai, and the Optics Valley in Wuhan (Yan et al., 2024). However, as HTDZs continue to scale up and their industrial structures grow increasingly complex, their associated carbon emissions have come under closer scrutiny. The rapid expansion of these zones has inevitably brought about rising energy consumption and resource depletion, making them significant contributors to regional carbon emissions. This issue becomes more pronounced in the context of unbalanced regional development and unequal industrial specialization (Zhong et al., 2024). Significant disparities have emerged across regions in terms of HTDZs' development levels, emission reduction capacities, and green governance models—differences that not only affect the overall effectiveness of carbon mitigation but also raise fundamental concerns of environmental justice.

Existing research on the relationship between HTDZ development and carbon emissions has primarily focused on technological innovation, energy efficiency, or reductions in carbon intensity (Wang et al.; Wang et al., 2022; Li et al., 2025). These studies often presume that HTDZs inherently contribute to low-carbon development. Yet from a broader and long-term perspective, this assumption is contestable. While HTDZs are indeed rooted in high-tech, knowledge-intensive industries that generate green spillover effects, they may also exhibit the classic "three-high" pattern—high input, high energy consumption, and high emissions—during their early development phases (Zhao et al., 2025). This is particularly true for zones located in resource-dependent cities or areas with a narrow industrial base, where the creation of HTDZs may exacerbate rather than alleviate the regional carbon burden. Furthermore, as the model of "enclave economy" and interregional industrial division deepens, some HTDZs have outsourced carbon-intensive and polluting segments of their production chains to smaller cities or rural peripheries, effectively engaging in "carbon leakage." This spatial outsourcing of environmental burden underscores not only the trade-off between economic growth and ecological protection but also deeper concerns about equity in regional development and the fair distribution of environmental responsibilities (Pan et al., 2024). While scholars have examined HTDZs' contributions to green transition—emphasizing innovation-driven growth, resource efficiency, or improvements in green total factor productivity—many studies overlook spatial heterogeneity and environmental equity dimensions (Ouyang et al., 2024; Liu et al., 2025). Despite these insights, few studies have examined the uneven spatial impacts of HTDZ expansion on carbon emissions, particularly within the framework of environmental justice (Kaya, 2021). Existing analyses often rely on administrative comparisons (e.g., across provinces or municipalities) rather than focusing on functional zones like HTDZs. Given the vast disparities in policy support, institutional capacity, and market access among HTDZs across China's regions, the lack of zone-level spatial analysis represents a major research gap (Luo et al., 2024). Moreover, although environmental justice has gained recognition in international climate discourse, its application to China's spatial development policies and HTDZ expansion remains nascent, especially in terms of empirical quantification. These spatial and developmental asymmetries may give rise to several problems: the outsourcing of emission responsibilities, the entrenchment of technological divides, and the externalization of ecological costs—all of which could compromise the overall fairness and effectiveness of China's decarbonization efforts.

In this context, clarifying the relationship between the expansion of HTDZ development scales and regional carbon emissions is both theoretically and practically significant. Theoretically, this paper integrates the perspectives of coupling coordination theory, spatial heterogeneity, and environmental justice. Coupling coordination theory emphasizes the interactive dynamics between development and emissions systems. Spatial heterogeneity theory underscores the non-uniformity of economic, social, and ecological systems across geographic units, challenging the one-size-fits-all policy approach. Environmental justice theory adds a normative dimension—arguing that the burdens and benefits of environmental outcomes must be equitably distributed and that mismatches between responsibility and capacity undermine social cohesion and policy legitimacy.

Guided by these frameworks, this study investigates 168 national-level HTDZs in China. It adopts a multi-method approach combining the entropy method, multi-scale geographically weighted regression (MGWR), and coupling coordination models to analyze the spatial coupling between HTDZ development and carbon emissions. Specifically, the study seeks to answer the following questions: (1) Does the expansion of HTDZs inevitably lead to increased regional carbon emissions? (2) Are there systematic spatial differences in the coupling and coordination between HTDZ development and carbon emissions? (3) Does HTDZ expansion exacerbate regional disparities in carbon responsibility, and does it raise concerns related to environmental justice? (4) How can policy be designed to ensure a synergistic relationship between high-quality development and low-carbon transition?

Compared with existing literature, this paper offers several contributions. First, it shifts the analytical focus from macro-level provinces or cities to HTDZs as functional spatial units, filling a critical research gap. Second, it employs a two-step empirical strategy—first measuring development-emissions coupling using a coordination model, then identifying spatial heterogeneity using MGWR—thus enhancing explanatory power. Third, it extends the debate beyond efficiency to fairness by assessing the spatial inequities in emission burdens and developmental opportunities. Ultimately, the study aims to inform China's "dual carbon" strategy by offering differentiated policy recommendations for HTDZs, thereby enhancing both the environmental effectiveness and social equity of the green transition.

2. Data and Methods

2.1 Overview of the study area

By 2024, Chinese HTDZs have evolved from "policy lowlands" into "innovation highlands," occupying a pivotal position in global scientific innovation and the international division of labor. As of that year, there were 178 national-level HTDZs across the country, with development scale, industrial configuration, and global influence reaching globally leading standards. The geographic coordinates of these HTDZs were extracted via Baidu Maps based on their official listings. The spatial distribution of HTDZs in China currently follows a distinct "east-strong, west-weak" pattern, with the highest-output zones predominantly located in more economically advanced cities such as Beijing, Shanghai, Guangzhou, and Chengdu. In recent years, several HTDZs have begun to undergo deep transitions toward smart, green development (Figure 1). For example, Beijing's Zhongguancun HTDZ has positioned itself as a national hub for green technology research and demonstration, promoting low-carbon development through breakthroughs in renewable energy, hydrogen power, and energy storage technologies. The Zizhu HTDZ in Shanghai, capitalizing on the ecological resources of Minhang District, is exploring carbon sink trading mechanisms by quantifying the value of ecological products through urban greening and ecological restoration projects to support corporate carbon neutrality. Chengdu HTDZ is currently building a zero-carbon industrial park, equipped with a full life-cycle carbon footprint management platform to monitor and reduce emissions throughout the production chain. Meanwhile, Urumqi HTDZ in Xinjiang is experimenting with carbon emission statistics and monitoring platform to strengthen data governance for regional decarbonization.

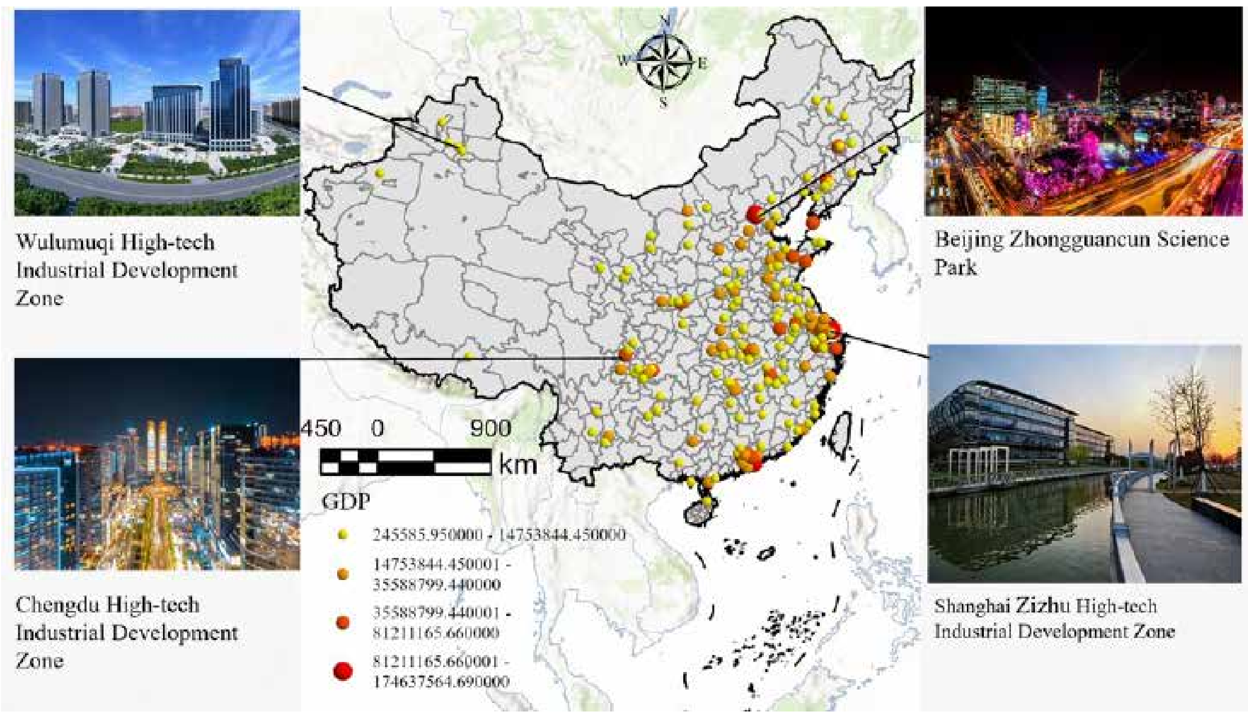

Figure 1 Overview of the study area

2.2 Research Methods

2.2.1 Entropy value method

We used relevant data from the high-tech zone and used the entropy method to calculate the index of investment, gross domestic product (GDP), technical income and export volume, and summarized it into the high-tech zone development scale index. The entropy method has the characteristics of objective weighting, comparability and flexibility. The calculation steps are as follows:

The first step involved standardizing the data by removing the units. The variable y_{ij} represents the data after the dimension was removed.

$$x'_{ij} = \frac{x - x_{min}}{xmin_{max}} \quad (1)$$

$$y_{ij} = \frac{x'_{ij}}{\Sigma x'_{ij}}, (0 \le y_{ij} \le 1) \quad (2)$$

The second step involved calculating the entropy value (e_j), the differentiation index (g_i), and the weight (w_j) for each indicator.

$$e_j = -k\Sigma_{y_{ij}} \ln y_{ij} \quad (3)$$

$$k = \frac{1}{\ln m} \quad (4)$$

$$g_j = 1 - e_j \quad (5)$$

$$w_j = \frac{g_j}{\Sigma g_j} \quad (6)$$

The third step involved calculating the index (c_{ij}) for the j-th indicator of the i-th HTDZ, based on the weights (w_j) of each indicator and the standardized matrix $y=\{y_{ij}\}$.

$$c_{ij} = w_j \times x'_{ij} \quad (7)$$

The fourth step involved summing up the index (c_{ij}) for each indicator to obtain the scale index (c_i) for each HTDZ.

$$c_i = \sum c_{ij} \quad (8)$$

2.2.2 Kernel density

To assess the spatial agglomeration or dispersion of HTDZ development, this study employed kernel density estimation (KDE)—a non-parametric statistical method widely used in ArcGIS to estimate spatial probability distributions. Kernel density values reflect the local intensity of industrial activity and spatial clustering. KDE provides critical insight into spatial hotspots, aiding the identification of dense innovation hubs and peripheral underdeveloped areas.

2.2.3 Coupling Coordination Model

To evaluate the degree of interaction and coordination between HTDZ development and carbon emissions, this study applied a coupling coordination model. Coupling degree is an index that quantifies the interaction intensity between two or more subsystems, indicating whether their evolution is synergistic or antagonistic. However, coupling degree alone may not capture the holistic coordination status due to dynamic inconsistencies among variables across regions. Hence, a comprehensive coupling coordination index was constructed to reflect the balance between economic development and environmental pressure. The formula is as follows:

$$\begin{cases} C = 2\sqrt{H_1H_2/(H_1+H_2)^2} \\ T = xH_1 + yH_2 \\ D = \sqrt{CT} \end{cases} \quad (9)$$

where C is the degree of coupling. H_1H_2 are the normalized values of the selected elements 1 and 2, respectively. D is the coupling coordination degree $D \in (0, 1)$. and the coupling coordination degree is measured in the range of 0 to 1, which is divided into equal intervals at 0.1 intervals. From low to high, they are extremely dysbiscus, severe imbalance, moderate dissonance, mild dissonance, near dissonance, reluctant coordination, primary coordination, intermediate coordination, good coordination and good coordination. T is the harmonic coefficient of elements 1 and 2. x and y represent the weights of elements 1 and 2 respectively.

2.2.4 MGWR

MGWR is a spatial regression model developed on the basis of traditional global regression models (Ordinary Least Squares, OLS) and Geographically Weighted Regression (GWR) (Yin et al., 2024; Zhang et al., 2023). It is designed to explore the geographically varying relationships between dependent/response variables and independent/explanatory variables. The traditional OLS model does not account for potential spatial dependence and spatial heterogeneity among various influencing factors in research, which can lead to biased estimates. To address this spatial non-stationarity, the GWR model is employed. While GWR extends the OLS model by allowing local variations in relationships, it still suffers from a limitation: it uses a single bandwidth value for all variables across different regions, which may oversimplify spatial processes. MGWR improves upon the classical GWR model by incorporating spatially stationary variables, enabling each influencing factor to have its own unique bandwidth value. This enhancement makes the model estimates more accurate and reliable by better capturing the multiscale nature of spatial relationships.

$$y_i = \sum_{k=1}^{m} \alpha_k X_{ik} + \sum_{k=n+1}^{n} \beta_k(\mu_i, v_i) X_{ik} + \varepsilon_i \tag{10}$$

α_k is the global variable regression coefficient. β_k is the local variable regression coefficient. X_{ik} is the kernel density of the kth influencing factor in the i-th selection unit. (μ_i, v_i) is the coordinates of the i-th selection unit. ε_i is the random perturbation term of the i-th selection unit.

2.3 Data source

Development indicators for HTDZs include zone name, construction area, number of employees, enterprise count, GDP, technological revenues, and export volume. Construction area data were extracted from the Torch Statistical Yearbook, while the remaining economic indicators were sourced from the China Statistical Yearbook on Science and Technology. Carbon emissions data were obtained from the Emissions Database for Global Atmospheric Research database (EDGAR), allowing for the integration of environmental metrics into economic analysis (https://edgar.jrc.ec.europa.eu/).

3 Spatial characteristics of the development of HTDZs

3.1 Analysis of spatial heterogeneity in HTDZs

Geographically, the study divides China into seven macro-regions: North China, Central China, East China, South China, Northwest China, Northeast China, and Southwest China. The results reveal significant interregional disparities in the scale indices of HTDZs (Figure 2). Investment and technological scale indices vary substantially across regions, while export indices show relatively smaller disparities. GDP scale indices exhibit relatively uniform distributions across the regions. Geospatial analysis of China's HTDZs reveals persistent regional disparities in developmental patterns. Northern regions, particularly the Beijing-Tianjin-Hebei metropolitan cluster in North China and the Yangtze River Delta in East China, exhibit significantly greater input intensity and technological sophistication, manifested through concentrated capital allocation and dominant R&D expenditure profiles. In contrast, southern regions demonstrate distinctive export superiority, with the Pearl River Delta in South China and urban agglomerations in Central China achieving elevated export volumes attributed to strategic coastal logistics advantages and deep integration within global industrial value chains. Innovation resources display a pronounced north-south bifurcation, characterized by northern HTDZs' command over strategic research infrastructure, while export activities adopt a dual-peak coastal-inland distribution. Coastal zones dominate high-value electronics trade through maritime accessibility, whereas inland clusters specialize in equipment manufacturing, reflecting the spatial articulation of China's dual development strategy that simultaneously cultivates indigenous innovation capacity and promotes export-oriented economic expansion.

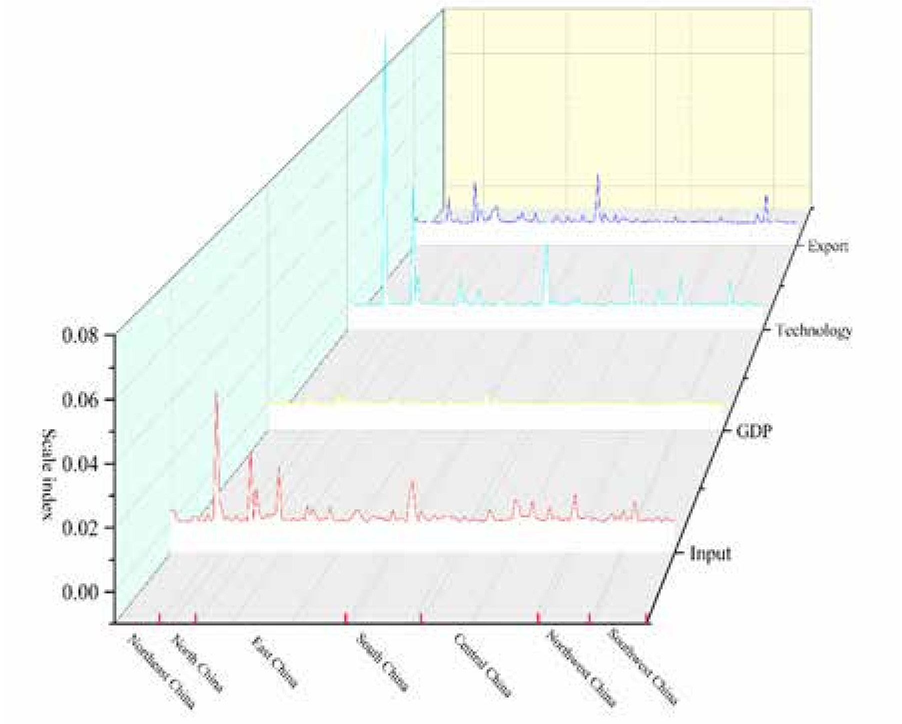

Figure 2 Heterogeneity of HTDZs

3.2 Distribution characteristics of the scale index of HTDZs
Aggregating the standardized indices of investment, technology, GDP, and exports yields a composite development scale index for each HTDZ (Figure 3). Kernel density analysis of these indices shows a "polycentric" spatial structure. Core development clusters are located in Beijing, Shanghai, and Guangzhou, which align closely with the Beijing-Tianjin-Hebei (Jing-Jin-Ji), Yangtze River Delta, and Pearl River Delta city clusters. Secondary peaks appear in Wuhan (Central China), Chengdu (Southwest China), and Xi'an (Northwest China), reflecting the radiating influence of national central cities. In contrast, HTDZs in Northeast China, parts of Northwest China, and much of Southwest China exhibit relatively low development scale values. The limited number of core clusters highlights persistent regional imbalances. While this polycentric configuration strengthens competitiveness in leading regions, it also risks marginalizing peripheral areas into a state of "low-end lock-in," where development stagnates without targeted intervention. Thus, policy mechanisms are urgently needed to enhance interregional factor mobility and collaborative governance.

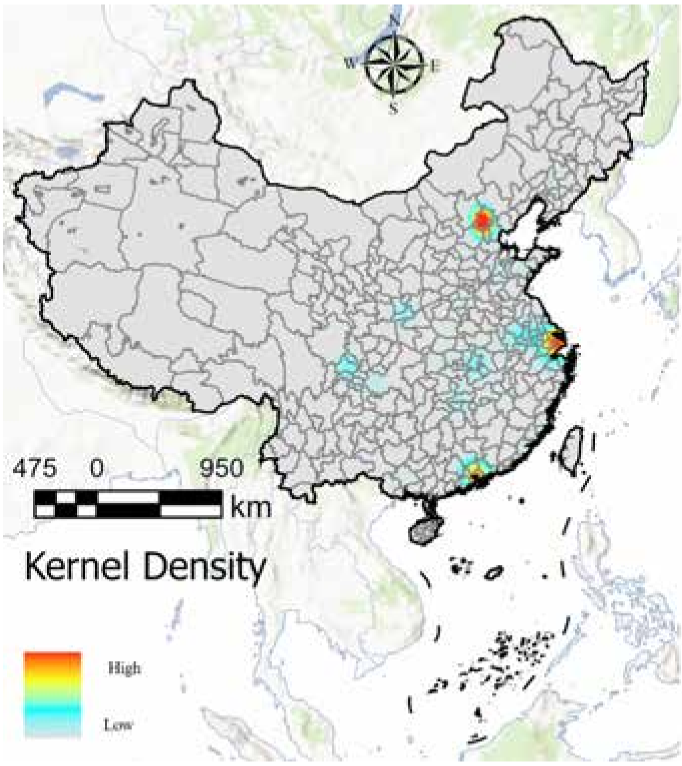

Figure 3 Results of kernel density analysis

4 Analysis of the synergistic nature of HTDZ development and carbon emissions

4.1 Differences between regional HTDZ development and carbon emissions

A significant spatial disparity also emerges in the relationship between economic output and carbon emissions across HTDZs. As shown in Figure 4, HTDZs in East and South China generate higher GDP contributions but maintain comparatively moderate carbon emission intensities, positioning them as low-carbon leaders. In contrast, HTDZs in Northwest and North China yield lower GDP outputs yet face disproportionately high carbon intensities. These findings suggest a spatially unjust distribution of emission burdens—where certain regions enjoy greater economic benefits with lower environmental costs, while others shoulder higher emissions despite lesser development returns. This spatial injustice is exacerbated by several structural mechanisms. First, leading HTDZs in the East often offload carbon-intensive segments—such as metal processing or chemical intermediates—to HTDZs in the Central and Western regions through vertical industrial disintegration. Despite this outsourcing, carbon emissions are still accounted for at the production end, effectively separating environmental responsibility from economic gain. Second, HTDZs in the Central-East region are at the forefront of green R\&D, particularly in hydrogen energy and nuclear fusion, whereas many Western HTDZs still rely on carbon-intensive technologies such as gas-fired boilers. This results in a technology divide and hinders cross-regional transition capabilities.

Third, due to spatial mismatches in policy tools and administrative capacity, HTDZs in core urban regions receive disproportionately higher subsidies for clean energy adoption, further increasing the carbon reduction burden on less-developed HTDZs.

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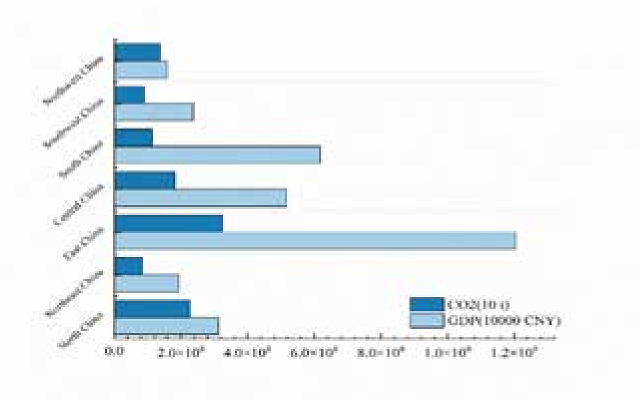

Figure 4 Output value and carbon emission of HTDZs in different regions

4.2 Coupling and coordination analysis of HTDZs and carbon emissions

To enhance the precision of measurement, this study constructed evenly spaced geographic sampling points across the national territory, calculating the micro-regional coupling coordination between HTDZ development and carbon emissions. The results indicate that overall coordination levels remain low nationwide (Figure 5). Nevertheless, relatively better coupling performance is observed in Southeastern China, coastal regions, central urban areas, and selected cities in the Southwest and Northeast. In contrast, most other regions remain in a state of serious imbalance.

These spatial disparities confirm the presence of pronounced environmental justice issues in the coordination between HTDZ development and carbon emissions. Specifically, the division of industrial labor has led to the transfer of high-carbon activities to less-developed regions without commensurate policy compensation or technology support. Meanwhile, institutional and fiscal privileges continue to concentrate in developed HTDZs, thereby deepening the structural disadvantage of others.

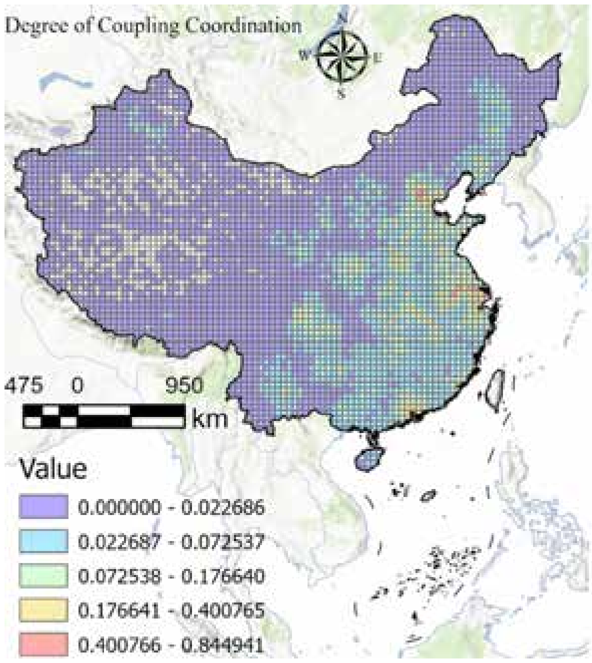

Figure 5 Coupling coordination analysis

4.3 Analysis of the impact of the development of HTDZs on regional carbon emissions

The spatial distribution of HTDZs' influence on regional carbon emissions shows significant spatial differences (Figure 6). The impact is strongest in the central-eastern regions, particularly in the Yangtze River Delta, where HTDZs are large in scale and equipped with advanced low-carbon technologies. Western regions, especially Tibet and Xinjiang, show a weak linkage between HTDZ development and regional emissions, largely due to their reliance on electricity exports and limited local green energy consumption. In these provinces, products such as electrolytic aluminum and polysilicon have high carbon footprints, and despite being powered by renewable energy, the "green electricity is exported, while carbon is retained." In the rest of the country, the influence of HTDZs on regional carbon emissions is statistically insignificant—likely due to the offsetting effect between moderate development scales and incomplete decarbonization measures.

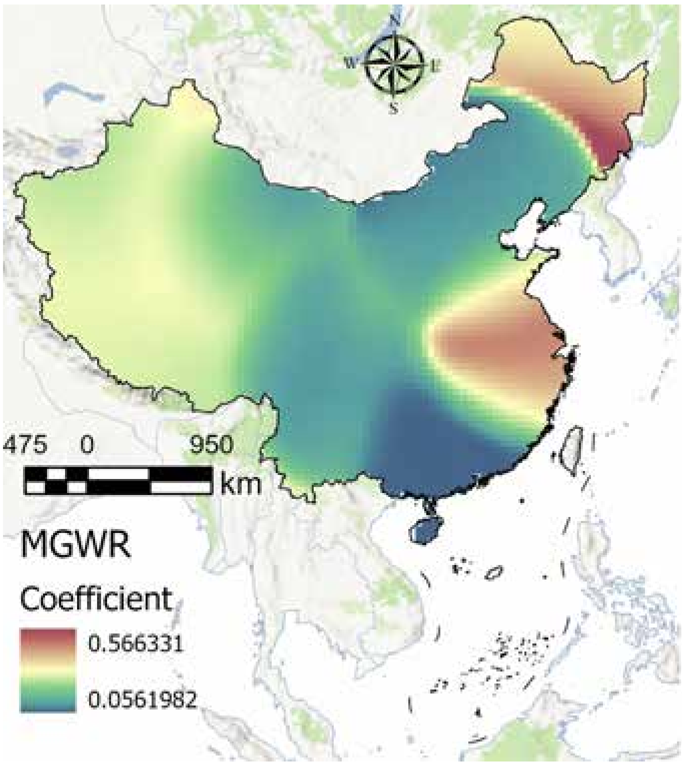

Figure 6 Mgwr model results

5 Conclusions and Recommendations

5.1 Conclusions

This study, guided by the dual perspectives of spatial heterogeneity and environmental justice, systematically investigates the complex relationship between the expansion of high-tech development zones (HTDZs) and regional carbon emissions in China. The main conclusions are as follows:

1. HTDZ development exhibits significant spatial disparities. HTDZs in eastern China—especially those located in major urban clusters such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta—are far ahead in terms of investment scale, technological capabilities, and economic output. These areas demonstrate a distinct "polycentric" development pattern. In contrast, HTDZs in central, western, and northeastern China remain at relatively low development levels, highlighting regional imbalances.

2. The relationship between HTDZ development and carbon emissions is spatially heterogeneous. Zones with larger development scales tend to benefit from advanced technologies and managerial efficiencies, resulting in higher resource productivity and lower carbon intensity—exemplifying a "high-output, low-emission" pattern. In contrast, underdeveloped HTDZs often face technological and financial constraints that hinder low-carbon transitions, leading to a "low-output, high-emission" outcome

3. The coupling coordination between development and emissions remains generally weak, though with clear regional variation. Coastal and economically advanced regions exhibit stronger coordination between HTDZ development and carbon emission reduction. However, most central and western HTDZs—particularly those in resource-dependent areas—display low coupling coordination, revealing a mismatch between economic growth and environmental sustainability. This reflects a deeper issue of spatial environmental injustice.

4. Environmental justice concerns are becoming increasingly prominent. Some HTDZs in developed eastern regions transfer carbon-intensive production segments to less-developed central and western zones, resulting in a "carbon responsibility shift." Meanwhile, access to clean energy R\&D and policy resources is highly concentrated in a few core regions. Peripheral zones, with limited capacity for green transition, are left with disproportionate emission burdens, exacerbating regional inequality.

5.2 Recommendations

In response to the pronounced spatial heterogeneity and environmental inequality observed between HTDZ expansion and regional carbon emissions, we propose the following four policy directions to promote greener, more equitable, and more coordinated development.

Develop regionally differentiated support systems for green development. The stark differences in HTDZ development across eastern, central, and western China render uniform policy approaches ineffective. Eastern HTDZs should continue to play a leading role in green innovation and technology diffusion, setting national standards. At the same time, targeted support mechanisms—including fiscal transfers, talent attraction programs, and technical assistance—must be established to assist HTDZs in the central and western regions. For example, a "paired assistance" model could be adopted to facilitate the transfer of green technologies from eastern to western HTDZs, bridging the technological divide and preventing carbon lock-in.

Establish cross-regional carbon emission coordination and burden-sharing mechanisms. To address issues such as carbon leakage and the retention of high emissions in underdeveloped areas, it is essential to develop mechanisms for cross-regional coordination of emission responsibilities. A shift from production-based to consumption-based or life-cycle carbon accounting would allow for more equitable attribution of emissions. Simultaneously, a multi-level carbon compensation system should be introduced—where regions that absorb high-carbon industries receive fiscal incentives and ecological compensation—to foster a synergistic and fair reduction framework.

Enhance the modern governance capacity of HTDZs in green transition. Many HTDZs currently lack robust systems for carbon data collection and green governance. We recommend accelerating the development of integrated platforms for data acquisition, monitoring, and governance to improve the digital management of emissions. A multi-stakeholder governance model—engaging governments, enterprises, research institutions, and the public—should be constructed. Emphasis should be placed on green industry entry thresholds, carbon performance evaluations, and public transparency to ensure effective policy implementation and emission reduction accountability.

Promote the synergy between green finance and technological innovation. Green finance is a critical enabler for HTDZs' transition toward sustainability. Financial instruments such as green credit, green bonds, and carbon markets should be leveraged to incentivize investments in renewable energy, environmental protection, and low-carbon technologies. Moreover, the innovation–application–diffusion chain must be accelerated by establishing green incubators and demonstration projects to facilitate the commercialization of green technologies and enhance the green production capacity of enterprises within HTDZs.

5.3 Limitations and prospects

This study proposed an empirical framework and policy recommendations from the perspective of environmental justice regarding the relationship between the expansion of high-tech zone development scales and regional carbon emissions. However, it still has the following limitations. The MGWR model used in this paper revealed spatial differences in the impact of high-tech zone development on carbon emissions but lacked causal identification methods to uncover the dynamic mechanisms of the influence pathways. Future research could incorporate econometric methods such as regression discontinuity, difference-in-differences, and event studies to explore the mediating or moderating effects of factors like policy interventions and technological investments in the "development-emissions" relationship. The current environmental justice analysis primarily focuses on spatial comparisons between carbon emissions and development imbalances, lacking further delineation of social group disparities. Subsequent research could integrate micro-level survey data and socioeconomic variables to construct a more comprehensive environmental equity assessment framework, enabling more precise identification of environmental risks faced by disadvantaged regions and populations.

Future studies should focus on a comprehensive analysis framework of "multi-scale, multi-actor, and multi-path," enhancing the integration of data accuracy, mechanism identification, and social equity. This would provide stronger theoretical support and decision-making references for achieving the synergistic goals of regional carbon neutrality and environmental equity.

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