

The Impact of Urban Compactness on Carbon Emission Performance in the Yellow River Basin: A Postprint

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Abstract

Under the national “dual carbon” goals, moderate compactness represents the optimal choice for green, low-carbon, and high-quality development of cities in the Yellow River Basin. Taking 77 prefecture-level cities in the Yellow River Basin as examples, this study constructs a multi-dimensional comprehensive evaluation index system and employs the entropy weight method, comprehensive weighted summation model, kernel density estimation, bivariate spatial autocorrelation analysis, Geographically and Temporally Weighted Regression (GTWR) model, and Geodetector to analyze the impact of urban compactness on carbon emission performance from 2005 to 2021. The results show that: (1) Both urban compactness and carbon emission performance in the Yellow River Basin improved slightly from 2005 to 2021, exhibiting spatial distribution patterns of “low in the upper and middle reaches, high in the lower reaches” and “low in the middle reaches, high in the upper and lower reaches,” respectively. (2) The correlation between urban compactness and carbon emission performance demonstrated significant spatiotemporal variations, predominantly manifesting as negative spatial correlation, with an increasing number of cities exhibiting such negative correlation; cities showing positive spatial correlation were mainly located in the middle and lower reaches. (3) Land use compactness and population compactness had relatively significant negative impacts on carbon emission performance; the negative impact of land use compactness weakened, while that of population compactness strengthened in the upper and middle reaches but weakened in the lower reaches; economic compactness and traffic compactness mainly exerted positive impacts, though areas with negative impacts of traffic compactness increased in both the upper and lower reaches. (4) Interactions between urban compactness and other socioeconomic factors enhanced their impacts on carbon emission performance, with various factors synergistically influencing carbon emission performance, among which the synergy

between economic compactness and energy consumption level had the greatest impact. In the future, the basin should promote coordinated development of economic growth, social welfare improvement, and low-carbon emission reduction by implementing differentiated urban compact development strategies tailored to local conditions, optimizing industrial structure, enhancing urbanization quality, strengthening low-carbon technology innovation, and reinforcing dynamic regulation of urban compactness.

Full Text

Abstract

Under the framework of China's "dual carbon" goals, moderately compact urban development represents the optimal pathway for achieving green, low-carbon, and high-quality growth in the Yellow River Basin. This study examines 77 prefecture-level cities, constructing a comprehensive evaluation index system across multiple dimensions. Using the entropy weight method, comprehensive weighted summation model, kernel density estimation, bivariate spatial autocorrelation analysis, spatiotemporal geographically weighted regression (GTWR) model, and geographical detector, we analyze the impacts of urban compactness on carbon emission performance in the Yellow River Basin from 2005 to 2021. The results show: (1) Both urban compactness and carbon emission performance increased slightly during 2005–2021, exhibiting spatial patterns of "lower in upper/middle reaches, higher in lower reaches" for compactness and "lower in middle reaches, higher in upper/lower reaches" for carbon emission performance. (2) The correlation between urban compactness and carbon emission performance displayed significant spatiotemporal heterogeneity, with most cities showing negative spatial correlation that increased over time; cities with positive spatial correlation were concentrated in the middle and lower reaches. (3) Land use compactness and population compactness had notable negative effects on carbon emission performance, with the negative impact of land use compactness weakening over time, while population compactness showed enhanced negative effects in upper/middle reaches but weakening effects in the lower reaches. Economic and transportation compactness mainly exerted positive influences, though areas with negative transportation compactness effects increased in both upstream and downstream regions. (4) The combined influence of urban compactness with other socioeconomic factors enhanced impacts on carbon emission performance, with synergistic effects among all factors. The interaction between economic compactness and energy consumption levels demonstrated the strongest effect. Moving forward, the basin should implement differentiated urban compact development strategies tailored to local conditions, optimize industrial structures, improve urbanization quality, strengthen low-carbon technology innovation, and enhance dynamic regulation of urban compactness to promote coordinated development among economic growth, social welfare improvement, and low-carbon emission reduction.

Keywords: urban compactness; carbon emission performance; impact effect; interaction effect; Yellow River Basin

1 Data and Methods

1.1 Study Area

The Yellow River Basin comprises nine provinces/autonomous regions: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. The terrain descends from west to east, with natural geographic boundaries at Tuoketuo County in Inner Mongolia (upper-middle reach demarcation) and Taohuayu in Zhengzhou, Henan (middle-lower reach demarcation). Following existing research [?, ?, ?], this study uses the natural river basin as the foundation, considering administrative unit integrity, regional economic connectivity, and data availability. After removing prefecture-level cities with severe data gaps, we identified 77 prefecture-level cities as research subjects. The upper reaches include 24 cities in Qinghai, Gansu, Ningxia, and Inner Mongolia, characterized as ecologically fragile high-cold and arid regions with numerous mountains and canyons, poor transportation, limited development, and relatively slow economic growth. The middle reaches include 18 cities in Shaanxi and Shanxi, dominated by loess landforms with severe soil erosion. The lower reaches include 35 cities in Henan and Shandong, primarily plains with dense populations, convenient transportation, and the most economically developed areas in the basin.

1.2 Data Sources

Socioeconomic data primarily derive from the *China Urban Construction Statistical Yearbook*, *China City Statistical Yearbook*, provincial/municipal statistical yearbooks, and national economic and social development statistical bulletins. Missing data were supplemented using interpolation methods. Chinese urban data have three statistical scopes: entire municipality, municipal districts, and built-up areas. To comprehensively reflect urban functions and considering data availability, this study uses the entire municipality scope. Carbon emission data were obtained from the open-source inventory provided by the Global Environmental Research Center (ODIAC2022), with $1 \text{ km} \times 1 \text{ km}$ GeoTIFF format data processed accordingly [?]. Following administrative adjustments where Laiwu City was merged into Jinan in 2019, we consolidated Laiwu's data into Jinan's for pre-2019 periods to ensure continuity and comparability.

1.3 Methods

1.3.1 Kernel Density Estimation Kernel density estimation is a representative non-parametric method for analyzing non-equilibrium data distributions [?]. This study uses Stata 15.1 software to plot kernel density curves for urban compactness and carbon emission performance, examining dynamic evolution

trends through curve position, peak shape, and extension. The kernel density estimate is calculated as:

$$f(x) = \frac{1}{Mh} \sum_{i=1}^M K\left(\frac{x-x_i}{h}\right)$$

where $f(x)$ represents the probability density at point x , M is the sample size, h is the bandwidth, K is the kernel function, and x_i is the i th sample observation value.

1.3.2 Bivariate Spatial Autocorrelation Bivariate spatial autocorrelation analysis describes spatial association patterns among multiple variables [?, ?]. *The spatial interaction and coupling characteristics can be reflected by the Bivariate Moran's Index (I_{xy})*, calculated as:

$$I_{xy} = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(y_j - \bar{y})}{S^2 \sqrt{\sum_{i=1}^n \sum_{j=1}^n w_{ij}^2}}$$

where I_{xy} is the bivariate Moran's index, w_{ij} is the inverse distance spatial weight between spatial units i and j , x_i and y_j are attribute values for units i and j , \bar{x} and \bar{y} are means, S^2 is sample variance, and n is the number of spatial units.

1.3.3 Spatiotemporal Geographically Weighted Regression (GTWR) Model The GTWR model effectively captures spatiotemporal relationships between dependent and independent variables [?]. Regression parameters vary with spatiotemporal location, revealing spatiotemporal differences in how independent variables affect the dependent variable. The formula is:

$$CEP_j = \theta_0(t_j) + \sum_{k=1}^p \theta_k(t_j) x_{jk} + \varepsilon_j$$

where CEP_j is the dependent variable for city j , j represents the sample, t_j denotes latitude, longitude, and temporal coordinates, $\theta_k(t_j)$ is the regression coefficient for the k th independent variable, x_{jk} is the k th independent variable, and ε_j is the random error term.

1.3.4 Geographical Detector The geographical detector is a statistical method for exploring spatial differentiation and analyzing driving factors [?, ?]. The q value represents detection results, calculated as:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$$

where $q \in [0, 1]$, N is total number of cities, σ^2 is variance of driving factors, N_h and σ_h^2 are sample size and variance for the h th driving factor. By comparing the q value after bivariate interaction with single-factor q values, we can determine interaction type and direction (Table 1).

1.4 Theoretical Analysis

1.4.1 Relationship Between Urban Spatial Form and Carbon Emission Performance

Cities are complex giant systems serving as primary spatial carriers for population, land, and industry [?]. Carbon emission performance integrates spatial, social, and economic dimensions, representing the efficiency of factor inputs and desired outputs. Reducing emission scale and intensity advances the “dual carbon” goals, but ultimate objectives focus on improving development quality and living standards under resource and environmental constraints [?]. Carbon emission performance is deeply influenced by urban spatial form and internal elements, with urban form exhibiting lock-in effects on urban operations [?]. *Urban spatial form can be characterized by scale, centrality, compactness, complexity, and fragmentation [?], "centric" and "polycentric" cities influence transportation and energy demand through functional agglomeration, regional distances, indirectly influencing travel choices and industrial production [?].*

Higher urban form complexity increases commuting distances and mobility, positively affecting emissions. Greater fragmentation disperses daily activities, increasing infrastructure demands and extra energy consumption, thereby reducing carbon emission performance. Industrial structure upgrading promotes low-carbon sustainable transformation [?]. *Technological innovation improves energy efficiency [?].* Population quality influences energy consumption patterns while providing intellectual support for low-carbon innovation. Urbanization indirectly affects carbon emission performance through economic development scale and mode [?]. Government policies directly impact carbon emission performance, with interactions among factors creating further direct or indirect effects (Figure 1 [Figure 1: see original paper]). Relatively high-density and high-intensity development represents the appropriate “compact” spatial form characteristic of low-carbon cities, but excessive density adversely affects urban energy consumption. In ecologically fragile regions with significant inter-city differences like the Yellow River Basin, exploring moderate and differentiated compact development models will better facilitate sustainable development.

1.4.2 Mechanism of Urban Compactness Impact on Carbon Emission Performance

Urban compactness is one of the most commonly used indicators for measuring urban spatial form [?]. *Carbon emission performance derives from environmental performance (see original paper). Intensive land use optimizes production and living spaces, improving commuting efficiency and land conflicts and increases production/living energy consumption. Low compactness requires broader space for* Increased population compactness brings scale effects, improving shared facility utilization rates, public transport 分担率, and energy efficiency for lighting/heating, promoting economic/social benefits and emission reductions.

However, excessive density exacerbates resource consumption and traffic congestion, while insufficient density reduces public service facility efficiency [?]. *Economic development provides capital support for urban construction. High economic agglomeration promotes emission, high - energy - consumption in industries and enhancing low - carbon development levels. Low economic density results in weak urban construction and low investment returns.* However, redundant road construction affects traffic efficiency. Low road network coverage reduces traffic accessibility and logistics rates while limiting public transport operation, strengthening demand for private vehicles and generating excessive energy consumption [?].

1.5 Indicator Construction

1.5.1 Urban Compactness Following existing research [?, ?, ?, ?], this study constructs a comprehensive evaluation index system for Yellow River Basin urban compactness based on principles of scientificity, systematicness, comprehensiveness, typicality, and data availability (Table 2). The calculation formula is:

$$Y = \sum_{i=1}^m A_i \sum_{j=1}^n B_{ij} X'_{ij}$$

where Y represents Yellow River Basin urban compactness or human development index, A_i is the weight of the i th primary indicator, B_{ij} is the weight of the j th secondary indicator under the i th primary indicator, m and n are numbers of primary and secondary indicators, and X'_{ij} is the standardized value.

1.5.2 Carbon Emission Performance Following existing studies [?, ?], this study defines carbon emission performance as maximizing socio-economic welfare output while minimizing carbon emissions. We construct a comprehensive carbon emission performance index from economic and welfare perspectives, incorporating non-market welfare outputs at the social level. The calculation formula is:

$$CEP = \frac{CEE + CSE}{2}$$

$$CEE = \frac{GDP}{CE}$$

$$CSE = \frac{YHDI}{CE}$$

where CEP is the comprehensive carbon emission performance index, CEE is carbon economic performance, CSE is carbon welfare performance, CE is

carbon emissions, GDP is gross domestic product, and $YHDI$ is the regional urban human development index.

Life expectancy, education level, and income level constitute the Human Development Index (HDI) developed by the United Nations Development Programme [?]. *Since city-level life expectancy data are difficult to obtain and significantly influenced by medical standards,* then apply the entropy weight method to determine indicator weights [?], and finally use the comprehensive weighted summation model to calculate Yellow River Basin urban compactness and human development index.

2 Results

2.1 Spatiotemporal Evolution Characteristics

2.1.1 Temporal Evolution Using box plots and kernel density estimation, we examine temporal dynamic evolution characteristics. From 2005 to 2021, both urban compactness and carbon emission performance increased slightly in the Yellow River Basin, with regional differences in compactness narrowing while differences in carbon emission performance expanded (Figure 3 [Figure 3: see original paper]). The kernel density curves for urban compactness shifted rightward continuously, while carbon emission performance curves first shifted leftward with rising peaks, then shifted rightward with declining peaks. During 2005–2012, rapid urbanization drove population and economic agglomeration in built-up areas, accelerating compactness growth. However, population growth and extensive early-stage economic development caused substantial increases in energy-related carbon emissions, significantly reducing carbon emission performance before recovering alongside improved economic and social benefits. During 2012–2021, manufacturing upgrades and reduced demand for low-skilled labor gradually slowed urbanization and compactness growth rates. Meanwhile, increasingly integrated regional industrial division and overall improvements in economic, social, and environmental benefits accelerated carbon emission performance growth.

2.1.2 Spatial Evolution Using ArcGIS 10.8 software, we classified urban compactness and carbon emission performance into five levels to examine spatial evolution characteristics. Due to space limitations, only 2005, 2012, and 2021 are visualized. Urban compactness showed a spatial pattern of “lower in upper/middle reaches, higher in lower reaches” from 2005–2021, with declining trends in the lower reaches and rising trends in the upper/middle reaches (Figure 4 [Figure 4: see original paper]). High and relatively high compactness values concentrated in downstream areas, particularly in provincial capitals. Shandong and Henan provinces, with relatively favorable natural conditions, attracted substantial population agglomeration and development investment before 2005. Construction of the Shandong Peninsula and Central Plains urban agglomerations further promoted factor concentration, while stricter land policies in eastern regions maintained high compactness values. In recent years, policy regulation has weakened compactness in Shandong. Low compactness areas

were concentrated in upper/middle reaches of Gansu, Ningxia, and Shaanxi—ecologically fragile arid/semi-arid regions and Loess Plateau areas with historically slow socioeconomic development and low urbanization levels.

Carbon emission performance exhibited a “lower in middle reaches, higher in upper/lower reaches” pattern (Figure 4 [Figure 4: see original paper]). High and relatively high performance concentrated in upstream Gansu and downstream Shandong, while low values appeared in midstream Shanxi/Shaanxi and downstream Shandong. Upstream cities had small economies, low urbanization levels, and strong environmental policy impacts, resulting in low emission intensity and paradoxically high performance. Downstream regions experienced massive emissions from dense populations, land expansion, and traffic congestion, but high economic/social benefits maintained relatively high performance. Midstream resource-dependent cities had high manufacturing shares with energy-intensive, low-end industries, producing large emissions while lagging economically and socially, resulting in low carbon emission performance.

2.2 Spatiotemporal Correlation Between Urban Compactness and Carbon Emission Performance

To investigate spatiotemporal correlation, we calculated bivariate Moran’s indices using Geoda software and generated LISA cluster maps (Figure 5 [Figure 5: see original paper]). From 2005–2021, high-high and low-low clusters dominated, with high-low clusters increasing in Inner Mongolia and Shanxi, indicating growing negative spatial correlation between urban compactness and carbon emission performance in the Yellow River Basin. The negative impact of excessive compactness on carbon emission performance became increasingly prominent in upper/middle reaches. Low-high clusters concentrated in Henan, suggesting some downstream cities had insufficient compactness to leverage positive compact development effects. Cities with positive spatial correlation were concentrated in middle/lower reaches. High-high clusters appeared in Henan, while low-low clusters appeared in Shanxi (declining in number). By 2021, Shandong showed low-low clusters, indicating positive correlation in middle/lower reaches where insufficient compactness in some Shandong cities failed to promote carbon emission performance.

2.3 Impact Effects of Urban Compactness on Carbon Emission Performance

Using carbon emission performance as the dependent variable and urban compactness indicators plus control variables as explanatory variables, we constructed regression models to examine impact effects and mechanisms. Control variables include energy consumption level, industrial structure, technological progress, population quality, urbanization level, and government participation, measured by per capita carbon emissions, ratio of tertiary to secondary industry, R&D expenditure as percentage of GDP, university students per 10,000 people, urban population percentage, and per capita local budget expenditure.

2.3.1 GTWR Model Goodness-of-Fit Test Using Stata 15.1 for multicollinearity testing ($VIF < 5$), all variables showed no collinearity. We constructed OLS, GWR, and GTWR models in ArcGIS 10.8, with GTWR showing the best fit (Table 4).

2.3.2 GTWR Model Results To visualize spatiotemporal differences, we mapped regression coefficients for compactness indicators and control variables using ArcGIS 10.8.

Urban Compactness Indicators: Land use compactness shifted from mixed positive/negative to predominantly positive effects (Figure 6 [Figure 6: see original paper]). Negative effect zones were concentrated in upper/middle reaches but decreased as ecological improvements enhanced positive effects. Population compactness showed consistently negative effects, intensifying in upper/middle reaches but weakening downstream, indicating that environmental performance degradation from crowding exceeded benefits from improved compactness. Economic compactness had uniformly positive effects, particularly pronounced upstream, where economic agglomeration benefits improved environmental performance under national strategies and environmental policies. Transportation compactness showed mostly positive effects, but negative effect zones increased in upstream/downstream areas, reflecting excessive road network construction beyond environmental carrying capacity in fragile upstream regions and reduced transport efficiency from high-density redundant construction in downstream areas.

Control Variables: Energy consumption level had uniformly negative effects, with high-value zones in middle/lower reaches. Industrial structure had predominantly negative effects, also concentrated in middle/lower reaches and intensifying, reflecting the need for structural adjustment. Population quality showed increasing negative effects upstream but weakening negative effects in middle/lower reaches, as higher education diversified material demands and energy consumption, though clean energy consumption patterns gradually emerged. Technological progress and government participation had positive effects, especially in middle/lower regions. Urbanization shifted from positive to negative dominance, with negative effects intensifying in middle reaches and Henan province, though weakening in Shandong.

2.3.3 Interaction Detection Results To examine interactive effects between urban compactness and other factors, we first analyzed single-factor explanatory power using factor detection (Table 5). Ranked by intensity: energy consumption level, urbanization level, economic compactness, government participation, population quality, population compactness, industrial structure, transportation compactness, land use compactness, and technological progress.

Interaction detection revealed two interaction types: nonlinear enhancement and dual-factor enhancement (Table 1). All interactions showed enhanced explanatory power compared to single factors (1%–32% for single factors vs. 9%–

45% after interaction) (Figure 8 [Figure 8: see original paper]). The interaction between economic compactness and energy consumption level showed the highest q value, explaining carbon emission performance changes. Economic compactness promotes spatial structure optimization and reduces traffic energy consumption while accelerating industrial upgrading and eliminating high-energy-consumption enterprises, creating synergistic effects that dominate spatial differentiation in Yellow River Basin carbon emission performance.

3 Discussion

Our findings show that carbon emission performance during 2005–2021 exhibited a “lower in middle reaches, higher in upper/lower reaches” pattern, indicating that more economically developed regions may have lower carbon emission performance than less-developed areas—a conclusion consistent with Wang et al. [?]. We also found that upstream, middle, and downstream regions showed particularities under ecological environmental constraints, with regional differences widening. As ecological quality improved, positive effects of urban compactness on carbon emission performance became prominent, indicating that ecological protection and improvement will remain fundamental for high-quality development in the Yellow River Basin. Compared with previous studies, this research focuses on the Yellow River Basin with its large number of cities and significant environmental and developmental stage differences. Using GTWR and geographical detector methods, we examine spatiotemporal heterogeneity and interactive effects, enriching existing research and providing references for differentiated urban and land use planning and emission reduction policies.

Notably, urban compactness impacts on carbon emission performance are diverse, complex, and dynamic. Although we constructed a comprehensive index system from economic, social, and natural dimensions, data limitations restricted indicator comprehensiveness. The study scale focused on cities, neglecting micro-scale analysis at county or grid levels, limiting local pattern identification. Future research should improve evaluation index systems, refine study scales, and conduct comprehensive cross-scale comparative analyses to ensure conclusions better reflect regional realities.

4 Conclusions and Recommendations

4.1 Conclusions

From 2005–2021, urban compactness and carbon emission performance in the Yellow River Basin showed slight increases but different temporal changes: (1) During 2005–2012, urban compactness grew rapidly while carbon emission performance first declined significantly then recovered. (2) During 2012–2021, compactness growth slowed while carbon emission performance accelerated. Spatially, urban compactness showed “lower in upper/middle reaches, higher in lower reaches,” while carbon emission performance showed “lower in middle

reaches, higher in upper/lower reaches,” with compactness regional differences narrowing and carbon emission performance differences widening.

The correlation between urban compactness and carbon emission performance showed significant spatiotemporal heterogeneity. Most cities exhibited negative spatial correlation, increasing over time. Cities with positive correlation concentrated in middle/lower reaches. Excessive compactness in upper/middle reaches increasingly negatively impacted carbon emission performance, while some downstream cities had insufficient compactness to leverage positive effects.

Impacts of urban compactness and other socioeconomic factors on carbon emission performance showed clear spatiotemporal heterogeneity. Land use compactness had negative effects in upper/middle reaches that decreased as ecological improvements enhanced positive effects basin-wide. Population compactness had consistently negative effects, intensifying in upper/middle reaches but weakening downstream. Economic compactness had uniformly positive effects, especially upstream. Transportation compactness had mostly positive effects, but negative effect zones increased in upstream/downstream areas. Among control variables, energy consumption had uniformly negative effects; industrial structure and population quality had predominantly negative effects, though population quality’s positive effects emerged in middle/lower reaches; technological progress and government participation had mostly positive effects; urbanization shifted from positive to negative dominance, with negative effects intensifying in middle reaches and Henan but weakening in Shandong.

Interactions between urban compactness indicators and other factors showed dual-factor enhancement and nonlinear enhancement types, with significantly strengthened impacts compared to single factors. Urban compactness synergistically affected carbon emission performance with energy consumption, urbanization, government participation, population quality, industrial structure, and technological progress. The interaction between economic compactness and energy consumption dominated carbon emission performance changes.

4.2 Recommendations

Based on these findings, we propose the following policy recommendations to promote coordinated low-carbon emission reduction, economic growth, and social welfare improvement in the Yellow River Basin:

1. **Implement differentiated urban compact development strategies** tailored to local conditions. Given unbalanced and insufficient development and significant ecological differences, upstream regions should prioritize ecological protection while seeking economic development, particularly slowing population and transportation compactness growth. Some ecologically sound cities may appropriately increase land use and economic compactness. Middle reaches should regulate urban scale, prioritize revitalizing existing and inefficient land, and improve economic/social benefits per unit land area. Downstream regions should optimize transport net-

works in Shandong and guide rational population distribution in Henan to promote multi-factor synergy.

2. **Optimize industrial structure.** Industrial structure had predominantly negative effects, especially in middle/lower reaches. Cities should accelerate industrial upgrading based on local foundations and functions, developing characteristic advantageous industries. Strengthen energy use supervision for high-emission enterprises and industries, promote industrial transfer, gradually eliminate high-energy-consumption enterprises, and develop clean energy, intelligent manufacturing, and other green emerging industries to increase their share in urban economies.
3. **Improve urbanization quality.** Urbanization involves multi-dimensional subsystems of land, population, and economy. Middle/upper reaches should optimize urban spatial structure and function combinations during expansion, use urban space intensively and efficiently, reduce environmental impacts, strengthen low-carbon consumption awareness, promote clean energy use, and coordinate land, population, and economic urbanization.
4. **Strengthen low-carbon technology innovation.** Technological progress is the main driver for improving carbon emission performance. Governments should increase investment in green low-carbon technology R&D, cultivate key innovation talents in low-carbon materials and energy, break information barriers among innovation entities, promote inter-regional cooperation, and guide the market toward more complete low-carbon technology innovation systems.
5. **Enhance dynamic regulation of urban compactness.** Moderate compactness is key to green high-quality development. Low-carbon city construction should emphasize ecological environmental responses, strengthening dynamic regulation. Focus on intensifying land use and transport compactness coordination with energy consumption levels in urbanization processes, highlighting energy consumption and carbon emission evaluations in new land development and infrastructure projects. Fully leverage government participation while scientifically pre-assessing synergistic or antagonistic interactions between urban compactness and other factors to improve policy coherence.

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Note: Figure translations are in progress. See original paper for figures.

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