Measurement of Green Development Level and Spatial Convergence of Prefecture-level Cities in the Yellow River Basin (Postprint)

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Abstract

Green development serves as a critical initiative for advancing ecological protection and high-quality development in the Yellow River Basin. This study examines 81 prefecture-level cities in the Yellow River Basin from 2006 to 2021, constructing a comprehensive evaluation index system based on the logic and internal mechanisms of green development. Employing the entropy weight method, kernel density estimation, β convergence model, and other methodologies, we investigate the green development level, distribution characteristics, and spatial convergence of prefecture-level cities in the basin. The findings reveal: (1) The green development level of prefecture-level cities in the Yellow River Basin demonstrates an upward trend, with a developmental pattern of "downstream > midstream > upstream" emerging across reaches, and significant inter-city disparities. (2) Kernel density curves exhibit uneven peak distribution, narrowing bandwidth, and right-skewed tails, indicating imbalanced green development levels, where certain prefecture-level cities achieve notably higher levels with substantial gaps from others. (3) Both the entire basin and its three major reaches display significant absolute β-convergence and conditional β-convergence in green development levels, with convergence velocities following an "upstream > midstream > downstream" trajectory. Furthermore, differentiated spatial spillover effects characterize the convergence process across the three reaches. These conclusions hold important practical significance for enhancing green development levels among prefecture-level cities and promoting coordinated basin-wide development.

Full Text

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Measurement and Spatial Convergence of Green Development Levels in Prefecture-Level Cities of the Yellow River Basin

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Abstract: Green development represents a critical approach for advancing ecological protection and high-quality development in the Yellow River Basin. This study examines green development patterns across 81 prefecture-level cities in the Yellow River Basin from 2006 to 2021. Based on the logical framework and internal mechanisms of green development, we constructed a comprehensive evaluation index system and employed the entropy weight method, kernel density estimation, and β convergence models to analyze development levels, distribution characteristics, and spatial convergence. Our analysis revealed three key findings: (1) Temporal and spatial patterns: Green development levels across prefecture-level cities in the Yellow River Basin demonstrated consistent improvement throughout the study period. A clear spatial gradient emerged with downstream regions outperforming midstream areas, which in turn surpassed upstream regions. Significant differences persist between individual prefecture-level cities. (2) Distribution characteristics: Kernel density analysis showed uneven peak distribution with a narrow width and pronounced right tail extension, indicating a substantial imbalance in green development levels. Some cities have achieved notably high green development levels, creating significant gaps compared to other urban centers in the basin. (3) Convergence dynamics: Both absolute β convergence and conditional β convergence were statistically significant across the entire basin and within the three major river sections. Convergence rates followed an "upstream > midstream > downstream" progression. Additionally, differentiated spatial spillover effects were observed in green development levels across the three major convergence processes. These findings offer valuable insights for enhancing green development levels in prefecture-level cities throughout the Yellow River Basin and promoting coordinated regional development strategies that address the identified spatial disparities.

Keywords: level of green development; statistical measurement; distribution characteristics; spatial convergence; Yellow River Basin

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Since the reform and opening up, the Yellow River Basin has achieved remarkable economic growth by leveraging its abundant energy resources, though this progress has inevitably placed unprecedented pressure on the local ecological environment. The basin's complex topography, substantial elevation changes, and east-west span across multiple climate zones render its ecosystems extremely sensitive and vulnerable to external disturbances. With rapid socio-economic development, environmental problems have become increasingly prominent, including water pollution, land degradation, and biodiversity loss. The interplay of natural and anthropogenic factors poses severe challenges to high-quality development in the Yellow River Basin. In 1989, British environmental economist Pierce first introduced the concept of "green development" in his book *Blueprint for a Green Economy*, emphasizing that economic development should not come at the cost of environmental pollution. The Organisation for Economic Co-operation and Development (OECD) defines green development as promoting economic growth while ensuring that natural assets continue to provide essential resources and ecological services for human well-being. The World Bank views green development as an environmentally friendly and socially inclusive development model. As understanding of the relationship between economic activity and resource-environment systems deepens, green development has acquired new connotations: pursuing high efficiency, low pollution, and low energy consumption while maintaining economic growth, representing a sustainable development model that balances social equity.

Regarding the measurement of green development, scholars have employed different research methods, indicator selection criteria, and study scopes. Methodologically, some researchers have constructed DEA models incorporating inputs, desirable outputs, and undesirable outputs to measure green development efficiency. Others have focused on building comprehensive evaluation index systems based on green development concepts, such as frameworks derived from the conceptual connotations of green development. Indicator selection has primarily emphasized economic growth, industrial upgrading, clean production, and green innovation. Most studies have concentrated on national or industry levels, with limited attention to the city level. For the Yellow River Basin specifically, existing research has examined green development efficiency at the provincial level and in sectors such as agriculture, industry, and manufacturing, generally finding that green development efficiency is not high but rising, with significant regional disparities. Some scholars have constructed index systems to analyze green development levels at the provincial and agricultural levels, revealing continuously improving levels with an east-west gradient.

In summary, scholars have conducted in-depth discussions on green development issues, providing a solid theoretical foundation for subsequent research. This paper's marginal contributions are reflected in three aspects: First, based on the logic and internal mechanisms of green development in the Yellow River Basin, we construct a comprehensive evaluation index system using a "Foundation-Dynamics-Results" process framework to measure green development levels. Second, existing studies have paid limited attention to green development at the city level. As cities serve as hubs for population, industry, transportation, and infrastructure, and rapid urban development exacerbates resource and environmental problems, research at the city level is highly practical. Therefore, this study focuses on prefecture-level cities. Third, existing research has found that green development levels in the Yellow River Basin are rising with significant inter-sectional differences and varying improvement speeds. However, few scholars have examined the evolution of gaps in green development levels. Clarifying this issue is crucial for promoting coordinated basin development. This paper employs β convergence models to test whether green development levels among prefecture-level cities in the Yellow River Basin exhibit convergence effects, providing references for policy formulation.

1.1 Study Area Overview

The Yellow River originates from the northern foothills of the Bayan Har Mountains on the Qinghai-Tibet Plateau and flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong before emptying into the Bohai Sea. Since Sichuan's river system primarily belongs to the Yangtze River and its tributaries, with the Yellow River only flowing through Aba and Garzê prefectures, and considering the integrity of geographical units and administrative regions, this study examines 81 prefecture-level cities in the Yellow River Basin. Taking into account the basin's natural boundaries, we delineate the cities included in each river section: downstream, midstream, and upstream [Figure 1: see original paper].

1.2 Data Sources

Green patent and environmental attention data come from CNRDS. $PM_{2.5}$ concentration data are from Dalhousie University in Canada, while other data are from the *China City Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, and provincial/municipal statistical yearbooks and bulletins. Missing data for individual indicators were interpolated using linear interpolation. In 2019, the State Council merged Laiwu City into Jinan City. Given our study period of 2006–2021, we adopt the 2019 administrative map but only count Jinan City's data for 2019–2021.

1.3 Research Methods

1.3.1 Entropy Weight Method

We employ the entropy weight method for objective weighting. The calculation steps are as follows:

Step 1: Standardize indicators.
For positive indicators:

$$X'_{ij} = \frac{X_{ij} - \min(X_{nj})}{\max(X_{nj}) - \min(X_{nj})}$$

For negative indicators:

$$X'_{ij} = \frac{\max(X_{nj}) - X_{ij}}{\max(X_{nj}) - \min(X_{nj})}$$

where X_{ij} is the value of indicator j for city i; X'_{ij} is the standardized result; $\max(X_{nj})$ and $\min(X_{nj})$ are the maximum and minimum values, respectively; $i = 1, 2, 3, \ldots, n$; and $j = 1, 2, \ldots, m$.

Step 2: Calculate the proportion of indicator j for city i (P_{ij}):

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}}$$

Step 3: Calculate the information entropy of indicator j (e_j):

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} P_{ij} \ln(P_{ij})$$

Step 4: Determine indicator weights (w_j):

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)}$$

Step 5: Calculate the comprehensive green development level score for each prefecture-level city (GDL_i):

$$GDL_i = \sum_{j=1}^{m} w_j X'_{ij}$$

1.3.2 Kernel Density Estimation

To understand the distribution characteristics of green development levels in Yellow River Basin prefecture-level cities, we employ kernel density estimation:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{X_i - \bar{X}}{h}\right)$$

where $f(x)$ is the probability density function; n is the total number of prefecture-level cities; h is the bandwidth; K is the kernel function; X_i is the sample observation; and $\bar{X}$ is the mean of observations.

1.3.3 β Convergence Model

To examine whether development gaps in green development levels among Yellow River Basin prefecture-level cities are narrowing, we adopt β convergence models. The following equations represent absolute β convergence and conditional β convergence models. Absolute β convergence emphasizes unconditional catch-up effects—whether cities with lower green development levels can grow faster and eventually converge to a common steady state without considering other factors. Conditional β convergence examines conditional catch-up effects after accounting for socio-economic differences among prefecture-level cities.

The spatial Durbin model is specified as:

$$\ln\left(\frac{GDL_{i,t+1}}{GDL_{i,t}}\right)=\alpha+\beta\ln(GDL_{i,t})+\rho\sum_{j=1}^{n}W_{ij}\ln(GDL_{j,t})+\gamma\sum_{j=1}^{n}W_{ij}X_{jt}+\delta X_{it}+\mu_i+\nu_t+\varepsilon_{it}$$

where $\ln(GDL_{i,t+1}/GDL_{i,t})$ is the green development growth rate of city i in year t; β is the convergence coefficient—when significantly negative, it indicates convergence; ρ is the spatial autocorrelation coefficient reflecting spatial interactions; W_{ij} is the spatial weight matrix; γ is the control variable coefficient; X_{it} represents control variables; α is the intercept; μ_i and ν_t are city and year fixed effects; and ε_{it} is the random disturbance term.

1.4 Index System Construction

Green development at the city level involves coordinating the relationship between environmental protection and economic development to promote urban growth with minimal resource and environmental consumption, emphasizing ecological civilization and livable city construction. Green development is a dynamic and interactive process: solid foundational conditions provide necessary prerequisites and generate momentum for green development; strong driving forces facilitate implementation of green practices and policies, yielding better development outcomes; these outcomes in turn reinforce the foundation, creating a positive feedback loop. Implementing green development requires considering the interrelationships and synergistic effects among foundation, dynamics, and results to form a coordinated development path that ensures long-term effectiveness and sustainability. This paper constructs a "Foundation-Dynamics-Results" process framework to clarify the logic and internal mechanisms of green development at the city level [Figure 2: see original paper].

Green Development Foundation: Implementing green development requires favorable foundational conditions. Cities possess production, living, and ecological attributes, necessitating simultaneous consideration of economic development, green living, and resource foundations. Economic development emphasizes coordinated efficiency in scale, benefits, and structure, measured by GDP, per capita GDP growth rate, and tertiary industry share. Water, gas, and public bus availability reflect both basic livelihoods and green lifestyle promotion, measured by water coverage, gas coverage, and buses per 10,000 people. Water resources and urban space constrain development, measured by total water supply, comprehensive water production capacity, and population density.

Green Development Dynamics: Green development emphasizes quality and sustainability, requiring driving force support. Environmental protection facilities enhance urban cleanliness and promote environmental awareness, serving as foundational drivers measured by public toilet numbers, wastewater treatment plants, and sanitation vehicles. Green innovation, with its dual characteristics of environmental protection and innovation, is a direct driver measured by green invention patents, green utility model patents, and their respective shares of total patents. Government investment in science and education and high-level human capital generate leverage effects as endogenous drivers, measured by science/technology expenditure share, education expenditure share, and university students per 10,000 people.

Green Development Results: Green development pursues harmonious coexistence between humans and nature. The Yellow River Basin emphasizes ecological priority and conservation, manifested in resource conservation, clean production, and ecological livability. Resource conservation focuses on reducing consumption of water, energy, and construction land, measured by water consumption intensity, energy consumption intensity, and construction land area per unit GDP. Clean production aims to reduce waste emissions, particularly industrial "three wastes" in this industrially dominated basin, measured by industrial wastewater, SO_2, and smoke/dust emission intensities. Ecological livability involves reducing smog, increasing greening, and improving urban environments, measured by $PM_{2.5}$ concentration, built-up area green coverage, and waste/wastewater treatment rates.

Drawing on existing research and following principles of scientific rigor, comprehensiveness, accuracy, and data availability, we construct a comprehensive green development evaluation index system using the "Foundation-Dynamics-Results" framework .

2.1 Green Development Level Measurement Results

Due to space limitations, we report only the 2021 results for Yellow River Basin prefecture-level cities . The analysis reveals: (1) **Basin-wide analysis:** The mean green development level is 0.283 with an average annual growth rate of 1.75%, indicating relatively low but slowly rising green development levels across the basin, demonstrating positive progress. (2) **Sectional analysis:** Downstream regions lead with a mean of 0.343 and growth rate of 1.81%; midstream regions follow with 0.292 and 1.81%; upstream regions trail with 0.232 and 1.66%, forming a "downstream > midstream > upstream" pattern. Green development levels correlate closely with natural environment, economic development, industrial structure, and infrastructure. Downstream regions benefit from convenient transportation and higher economic development, enabling greater resource allocation to green development and successful industrial restructuring toward high-tech and service industries. Midstream regions are transitioning from traditional to green industries, with cities like Taiyuan and Luoyang renovating heavy industries while cultivating emerging green sectors, though their green development levels remain below downstream areas due to ongoing transformation. Upstream regions, characterized by fragile plateaus and mountains, limited economic development, and resource-based/traditional agriculture-pastoral industries, face greater environmental impacts from extraction and extensive production methods, resulting in lower green development levels and slower improvement. (3) **City-level analysis:** All cities improved, but inter-city differences are substantial. Wuwei and Tongchuan lag with means of 0.183 and 0.196 and slow growth rates of 1.23% and 0.71%, respectively. Jinan and Qingdao lead with means of 0.473 and 0.468 and rapid growth of 2.88% and 3.01%. Xi'an has surged with a mean of 0.421 and the fastest growth rate of 4.73%. These disparities reflect that cities in early industrialization prioritize GDP growth, while more developed cities emphasize green sustainability. Wuwei and Tongchuan suffer from poor natural environments, water scarcity, and resource-dependent/high-energy-consumption industries, limiting green growth. Qingdao and Jinan, with robust economies, allocate more resources to green development and ecological civilization, with Qingdao recognized as China's most ecologically competitive city. Xi'an has prioritized green development through policy documents clarifying environmental responsibilities and vigorously developing new energy vehicles, rapidly accelerating its green transformation.

2.2 Distribution Characteristics of Green Development Levels

We analyze kernel density estimation curves for the entire basin and three major sections from 2006–2021 [Figure 3: see original paper].

2.2.1 Basin Level

Distribution position: The curve's center shifts rightward annually, indicating overall rising green development levels across the basin. **Distribution shape:** The main peak fluctuates in height with modest width changes, suggesting that while concentration levels vary, the distribution range remains relatively stable. **Distribution extension:** The right tail indicates some cities have significantly higher green development levels. Over time, this tail extends and broadens, showing that gaps between high-performing cities and others are widening, though this also reflects green development potential.

2.2.2 Regional Level

Distribution position: All three curves shift rightward significantly, confirming substantial improvements in upstream, midstream, and downstream regions. **Distribution shape:** In midstream regions, the main peak rises continuously, indicating increasing concentration, while width narrows significantly, showing reduced dispersion. These changes suggest lower-level cities are developing rapidly while higher-level cities consolidate their gains. In upstream and downstream regions, the peak first declines then rises, indicating a shift from dispersion to concentration. Narrowing width from "broad-flat" to "sharp-narrow" patterns shows decreasing dispersion and gradually narrowing inter-city gaps. **Distribution extension:** Midstream and downstream regions exhibit pronounced right tails that extend annually, indicating some cities (e.g., Xi'an, Taiyuan, Qingdao, Jinan) have achieved high green development levels while most remain concentrated at lower levels.

2.3 Spatial Convergence of Green Development Levels

Following Shao Shuai et al., we construct geographic adjacency and geographic distance weight matrices and select a spatiotemporal fixed-effects spatial Durbin model for convergence analysis. In the conditional β convergence model, we include environmental attention, financial development, government self-sufficiency, social security, and industrialization level as control variables .

Convergence analysis: Both absolute and conditional β convergence coefficients are negative and significant at the 1% confidence level across the entire basin and all sections, indicating that cities with lower green development levels grow faster than high-level cities, eventually converging toward a common level. **Convergence speed:** The rate follows an "upstream > midstream > downstream" pattern, likely because upstream regions have weaker green development foundations and greater convergence potential, enabling faster improvement under identical policy and resource inputs. **Spatial spillover effects:** Upstream regions show no significant spatial autocorrelation (ρ), indicating that cities reach stable states independently. Midstream regions show significant negative spatial spillover effects only under the geographic distance matrix, suggesting cautious interpretation is needed. Downstream regions exhibit significant negative spatial spillover effects under both matrices, indicating that local green development improvements may disadvantage neighboring cities through resource competition. This negative spillover suggests insufficient effective cooperation and low collaborative advancement among Yellow River Basin cities, warranting strengthened complementary cooperation and win-win development models.

3.1 Conclusions

(1) **Green development levels:** Prefecture-level cities in the Yellow River Basin show growth momentum but remain relatively low overall. The three regions form a "downstream > midstream > upstream" pattern. Inter-city differences are significant with clear polarization: Jinan and Qingdao consistently lead with rapid growth, Wuwei and Tongchuan lag with slow growth, and Xi'an has surged rapidly. (2) **Distribution characteristics:** Basin-wide concentration fluctuates but distribution range remains stable. Midstream regions show increasing concentration and decreasing dispersion, indicating balanced development. Upstream and downstream regions alternate between concentration and dispersion with decreasing dispersion, gradually narrowing overall inter-city gaps. Midstream and downstream right tails extend annually, showing some cities have achieved substantial green development improvements. (3) **Spatial convergence:** Significant absolute and conditional β convergence exists basin-wide and across all sections, demonstrating clear catch-up trends in low-level regions. Convergence speed follows "upstream > midstream > downstream." Spatial spillover effects vary by section: upstream shows no spillover; midstream shows negative spillover only under distance matrix;

downstream shows negative spillover under both matrices.

3.2 Recommendations

(1) **Differentiated strategies by city:** The Yellow River Basin should consolidate existing green development achievements and improve policies for sustainability. Strategies must avoid "one-size-fits-all" approaches and adapt to local conditions based on industrial structure, resource endowments, and development stages. Upstream regions should focus on ecological restoration, ecological agriculture-pastoralism, and clean energy; midstream regions should accelerate green transformation of traditional industries and build green industrial systems; downstream regions should enhance resource efficiency and prioritize emerging green industries based on advanced manufacturing and urbanization. (2) **Enhanced cooperation:** High-level cities should lead basin-wide green development through radiation effects. Given downstream regions' advantages, they should organize experience-sharing activities with midstream and upstream regions to promote coordinated development, narrow gaps, and achieve overall improvement. High-level cities should provide replicable experiences and develop green city clusters while avoiding resource siphoning effects. (3) **Policy support:** Policies should account for convergence trends and speeds, increasing support and resource allocation for low-level regions to accelerate catch-up. Local governments should promote effective inter-regional cooperation through improved ecological compensation mechanisms and integrated environmental standards, fostering healthy competition and reducing negative spatial spillovers to achieve coordinated green development across the basin.

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