

## Spatiotemporal Evolution of PM<sub>2.5</sub> and Its Influencing Factors in the Five Major Urban Agglomerations of the Yellow River Basin: Postprint

**Authors:** Mu Shilei

**Date:** 2024-05-20T00:00:00+00:00

### Abstract

Taking the 82 cities within five major urban agglomerations in the Yellow River Basin as the study area, this research selected PM<sub>2.5</sub> data released by the China National Environmental Monitoring Centre from 2016 to 2020, and employed spatial autocorrelation, geographical detector, and geographically weighted regression methods to investigate the spatiotemporal distribution characteristics of PM<sub>2.5</sub> and the main driving factors of its spatial heterogeneity. The results indicate that: (1) The annual average PM<sub>2.5</sub> concentration generally exhibits an inverted ‘N’ pattern, while the seasonal average shows a periodic ‘U’-shaped pattern of first decreasing and then increasing. (2) In terms of spatial distribution, a gradient decreasing pattern from lower reaches > middle reaches > upper reaches of the Yellow River Basin has formed, with a gradual declining trend. (3) The evolution of PM<sub>2.5</sub> overall demonstrates a positively autocorrelated cluster distribution, with cluster types primarily being high-high, low-low, and low-high clusters. (4) In 2016 and 2020, physical geographical factors exhibited stronger driving forces on PM<sub>2.5</sub> spatial differentiation than socioeconomic factors, with interaction results showing two types: bi-factor enhancement or nonlinear enhancement. (5) By fitting the five factors with the greatest change in explanatory power identified through differentiation detection using the geographically weighted regression model, the negative effects of each factor on PM<sub>2.5</sub> pollution in the five major urban agglomerations continuously increased during the 5-year period, while positive effects showed a decreasing trend, with significant differences in spatial direction and intensity. The research results provide a reference basis for air pollution prevention and environmental regulation improvement in the five major urban agglomerations of the Yellow River Basin, promoting ecological protection and high-quality development of the Yellow River Basin.

## Full Text

# Spatiotemporal Evolution and Influencing Factors of PM<sub>2.5</sub> in the Five Urban Agglomerations of the Yellow River Basin

MU Shilei<sup>1</sup>, YANG Yuhuan<sup>2</sup>, Wuritaoketaohu<sup>1</sup>

<sup>1</sup>College of Ethnology and Anthropology, Inner Mongolia Normal University, Hohhot, Inner Mongolia 010022, China

<sup>2</sup>College of Urban and Environmental Sciences, Northwestern University, Xi'an 710127, Shaanxi, China

**Abstract:** This study examines 82 cities across five major urban agglomerations in the Yellow River Basin, utilizing PM<sub>2.5</sub> data published by the China National Environmental Monitoring Centre from 2016 to 2020. Spatial autocorrelation analysis, geographic detectors, and geographically weighted regression were employed to investigate the spatiotemporal distribution characteristics and primary driving factors of spatial heterogeneity in PM<sub>2.5</sub> concentrations. The results indicate: (1) The annual mean PM<sub>2.5</sub> concentration changed in an approximate inverted “N” shape, while seasonal mean concentrations exhibited a periodic “U” pattern of first decreasing then increasing. (2) Spatially, a gradient decreasing pattern formed from downstream to upstream regions of the Yellow River Basin, with an overall declining trend. (3) PM<sub>2.5</sub> evolution showed positive spatial autocorrelation and an aggregated distribution overall, with high-high, low-low, and low-high clustering types. (4) Natural geographical factors demonstrated stronger driving forces on PM<sub>2.5</sub> spatial differentiation than socioeconomic factors in both 2016 and 2020, with interaction results showing either bi-factor enhancement or nonlinear enhancement. (5) Geographically weighted regression modeling of the five most explanatory factors revealed that negative effects on PM<sub>2.5</sub> pollution have continuously strengthened while positive effects have declined, with significant differences in spatial direction and intensity.

**Keywords:** Yellow River Basin; PM<sub>2.5</sub>; urban agglomeration; ecological protection; high-quality development

## Introduction

The Yellow River Basin constitutes a crucial ecological security barrier in China, occupying a significant position in the “Two Screens and Three Belts” national ecological security strategic pattern. Known as China’s “Energy River Basin,” it serves as a vital base for energy, chemical, and raw material industries. The enormous coal-dominated energy consumption, while driving industrialization and urbanization, has exerted tremendous pressure on the ecological environment, with atmospheric pollution from industrial sources remaining particularly severe. Fine particulate matter (PM<sub>2.5</sub>) has become the primary pollutant causing heavy pollution weather, endangering public physical and mental health,

affecting people's sense of fulfillment regarding blue skies, and constraining ecological protection and high-quality development in the Yellow River Basin.

Extensive research has been conducted on environmental fine particulate matter both domestically and internationally. Regarding standards, the United States established national ambient air quality standards for PM<sub>2.5</sub> in 1997, with Spain, Canada, and other countries following suit. China incorporated PM<sub>2.5</sub> into its Environmental Air Quality Standards (GB3095-2012) in 2012, implemented nationwide in 2016, gradually aligning with international standards. Research on PM<sub>2.5</sub> characteristics has primarily analyzed chemical composition and spatial variability. Influencing factors mainly involve socioeconomic elements such as coal consumption, economic growth, urbanization, technological level, foreign trade, foreign direct investment, and vehicle emissions, as well as natural geographical factors including topography, temperature, precipitation, and vegetation cover index. Analytical methods have included spatial Durbin models, geographic detectors, geographically weighted regression, and STIRPAT models. Study areas have primarily focused on national, provincial, and municipal scales, with urban agglomerations receiving increasing attention. While research on the Yangtze River Economic Belt is abundant, studies on the Yellow River Basin remain relatively limited.

Regarding research progress on PM<sub>2.5</sub> spatiotemporal evolution and influencing factors in Yellow River Basin urban agglomerations, previous studies have primarily used standard deviation ellipses and spatial autocorrelation to reveal heterogeneity characteristics. Influencing factor studies have emphasized technological innovation's impact and spatial spillover effects. However, research has only covered partial urban agglomerations such as the Lanzhou-Xining and Guanzhong Plain urban agglomerations, or individual cities like Jinan, Taiyuan, and Lanzhou. Comprehensive studies examining the overall spatiotemporal evolution pattern of PM<sub>2.5</sub> across all five major urban agglomerations in the Yellow River Basin remain scarce, particularly multi-angle discussions of influencing factors.

This study addresses this gap by examining 82 cities across five major urban agglomerations in the Yellow River Basin using PM<sub>2.5</sub> data from 2016 to 2020. Integrating spatial autocorrelation, geographic detectors, and geographically weighted regression methods, we explore the spatiotemporal distribution characteristics, primary driving factors of spatial heterogeneity, and inter-factor coupling relationships. The findings provide decision-making support for atmospheric pollution prevention and environmental regulation improvement in the five major urban agglomerations, promoting ecological protection and high-quality development in the Yellow River Basin.

### 1.1 Study Area

This study selected five major urban agglomerations along the Yellow River from upstream to downstream: the Lanzhou-Xining Urban Agglomeration, the

Yellow River “Ji” Character Bay Metropolitan Circle, the Guanzhong Plain Urban Agglomeration, the Central Plains Urban Agglomeration, and the Shandong Peninsula Urban Agglomeration. The Lanzhou-Xining Urban Agglomeration, the first cross-provincial urban agglomeration in the upper Yellow River, serves as both a strategic barrier for national ecological security and an important growth pole supporting northwestern development. The Yellow River “Ji” Character Bay Metropolitan Circle possesses a robust energy industry, spanning parts of the upper Yellow River and the entire middle reaches, covering Ningxia, Inner Mongolia, Shaanxi, and Shanxi. The Guanzhong Plain Urban Agglomeration, centered on Xi’an, constitutes an important fulcrum of the Eurasian Land Bridge and a crucial gateway for western China facing central and eastern regions, spanning Gansu, Shaanxi, and Shanxi. The Central Plains Urban Agglomeration, located at the intersection of the Lianyungang-Lanzhou Railway and Beijing-Guangzhou Railway corridors within the national “Two Horizontal and Three Vertical” urbanization strategy, represents a critical hub of modern land transportation and an intermediate zone for China’s economic development advancing from east to west, covering Henan, Shanxi, Hebei, Shandong, Anhui, and other provinces. The Shandong Peninsula Urban Agglomeration covers the entire Shandong Province, connecting north and south internally and neighboring Japan and South Korea externally while linking to the Belt and Road Initiative, serving as the main maritime gateway of the Yellow River Basin.

## 1.2 Data Sources

PM2.5 data were obtained from the China National Environmental Monitoring Centre (<http://www.cnemc.cn>). Natural geographical factor data including topographic relief, vegetation cover index, and net primary productivity were sourced from the Chinese Academy of Sciences Resource and Environmental Science Data Center (<https://www.resdc.cn>). Temperature and precipitation data were obtained from the National Meteorological Science Data Center (<https://data.cma.cn>). Socioeconomic factor data including economic growth, urbanization, population size, industrial scale, technological innovation, energy efficiency, smoke and dust emissions, and urban greening rate were derived from the China City Statistical Yearbook. Public environmental concern data, measured by Baidu haze search index (2016-2020), were obtained from Baidu Index (<https://index.baidu.com>).

## 1.3 Methods

**1.3.1 Spatial Autocorrelation Global Moran’s I:** This measures the average similarity degree of PM2.5 between different spatially adjacent regions. For details, see reference [38].

**Local Moran’s I:** This measures the correlation between PM2.5 pollution in a region and its neighboring units. The calculation formula is:

$$I_i = \frac{x_i - \bar{x}}{S^2} \sum_{j=1}^m W_{ij}(x_j - \bar{x})$$

where  $I_i$  is the local Moran's index for city  $i$  in the Yellow River Basin urban agglomerations;  $\bar{x}$  is the mean value of all research units;  $n$  is the number of cities;  $m$  is the number of cities spatially adjacent to city  $i$ ;  $x_i$  and  $x_j$  are the PM2.5 values of cities  $i$  and  $j$  respectively;  $W_{ij}$  is the spatial weight matrix for neighboring cities  $i$  and  $j$ . When  $I_i > 0$ , it indicates positive spatial correlation ("high-high" or "low-low" association), while  $I_i < 0$  indicates negative spatial correlation ("high-low" or "low-high" association).

**1.3.2 Geographic Detector** The geographic detector is an analytical tool for detecting spatial differentiation patterns and influencing mechanisms. This study employed differentiation detection to measure the explanatory power of different driving factors on PM2.5 spatial differentiation, and interaction detection to identify the strength of interactive effects between different factors. For details, see reference [39].

**1.3.3 Geographically Weighted Regression** Geographically Weighted Regression (GWR), proposed by Brunson et al. in 1996, incorporates spatial heterogeneity and non-stationarity into regression analysis. It introduces location-based estimation of influencing factors, effectively capturing the non-stationary effects of various elements on PM2.5 pollution and describing how variable relationships change with spatial location. This study used GWR to examine the local spatial characteristics of PM2.5 influencing factors [40]. The calculation formula is:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^p \beta_k(u_i, v_i) X_{ik} + \varepsilon_i$$

where  $i$  is the observation unit;  $(u_i, v_i)$  are the geographic coordinates of the  $i$ th sample; parameter  $\beta$  is a function of  $u_i$  and  $v_i$ , meaning that the estimated parameters for any specific spatial location are obtained through local estimation and vary with geographic location;  $X_{ik}$  is the explanatory variable value for city  $i$ ;  $\beta_k(u_i, v_i)$  is the regression parameter for the  $k$ th variable at location  $(u_i, v_i)$ ;  $\beta_0(u_i, v_i)$  and  $\varepsilon_i$  are the intercept and random error term at location  $i$ , respectively.

## 2.1.1 Temporal Distribution Characteristics

Comparing the five urban agglomerations during China's 13th Five-Year Plan period (2016-2020), PM2.5 changes generally followed an inverted "N" shape, with seasonal mean changes showing a periodic "U" pattern of first decreasing then increasing. PM2.5 concentrations consistently declined from 2016 to 2019,

rebounded in 2020, then declined again, showing an overall gradual decreasing trend. Specifically, compared to 2016, the Lanzhou-Xining Urban Agglomeration decreased by  $35.14 \text{ g} \cdot \text{m}^{-3}$ , the Central Plains Urban Agglomeration by  $21.19 \text{ g} \cdot \text{m}^{-3}$ , the Guanzhong Plain Urban Agglomeration by  $19.42 \text{ g} \cdot \text{m}^{-3}$ , the Yellow River “Ji” Character Bay Metropolitan Circle by  $12.59 \text{ g} \cdot \text{m}^{-3}$ , and the Shandong Peninsula Urban Agglomeration by  $15.09 \text{ g} \cdot \text{m}^{-3}$ , representing an overall decrease of 20.7% during the 13th Five-Year Plan period. The 2020 rebound was attributed to weaker cold air activity, smaller average wind speeds, increased days with light winds, and fewer days with effective precipitation [41].

According to the Grade II standard ( $35 \text{ g} \cdot \text{m}^{-3}$ ) of the Environmental Air Quality Standard (GB3095-2012), only the Lanzhou-Xining Urban Agglomeration and the Yellow River “Ji” Character Bay Metropolitan Circle met the standard in 2020, while other urban agglomerations failed to comply in remaining years. Cities with notably elevated PM<sub>2.5</sub> included Linfen, Qingyang, Xi’an, and Baoji in the Guanzhong Plain Urban Agglomeration; Lüliang and Xinzhou in the Yellow River “Ji” Character Bay Metropolitan Circle; and Suzhou, Fuyang, Huaibei, and Bozhou in the Central Plains Urban Agglomeration. Cities with significantly reduced PM<sub>2.5</sub> included Jiyuan and Shangqiu in the Central Plains Urban Agglomeration; Jinzhong, Ulanqab, Datong, Alxa League, and Zhongwei in the Yellow River “Ji” Character Bay Metropolitan Circle; and Linxia Hui Autonomous Prefecture and Dingxi in the Lanzhou-Xining Urban Agglomeration.

Seasonal mean changes followed a “U” pattern, characterized by high concentrations in the first and fourth quarters and low concentrations in the second and third quarters [Figure 2: see original paper]. The peak occurred in the first quarter in the Lanzhou-Xining Urban Agglomeration at  $96.24 \text{ g} \cdot \text{m}^{-3}$ , while the trough appeared in the second quarter in the Shandong Peninsula Urban Agglomeration at  $17.15 \text{ g} \cdot \text{m}^{-3}$ . Overall, the Yellow River Basin urban agglomerations exhibited a seasonal pattern of high winter concentrations, low summer concentrations, and moderate spring and autumn levels. This pattern primarily results from the basin’s northern location, where winter’s cold, dry northwest winds necessitate coal heating, and low temperatures with weak winds create meteorological conditions conducive to pollutant accumulation.

### 2.1.2 Spatial Distribution Characteristics

The spatial distribution of PM<sub>2.5</sub> in the Yellow River Basin formed a gradient decreasing pattern from downstream to upstream regions. The five-year average PM<sub>2.5</sub> concentrations ranked from highest to lowest as: Shandong Peninsula Urban Agglomeration ( $235.14 \text{ g} \cdot \text{m}^{-3}$ ), Central Plains Urban Agglomeration ( $211.93 \text{ g} \cdot \text{m}^{-3}$ ), Guanzhong Plain Urban Agglomeration ( $194.22 \text{ g} \cdot \text{m}^{-3}$ ), Yellow River “Ji” Character Bay Metropolitan Circle ( $150.92 \text{ g} \cdot \text{m}^{-3}$ ), and Lanzhou-Xining Urban Agglomeration ( $125.93 \text{ g} \cdot \text{m}^{-3}$ ). This pattern reflects severe, large-scale contiguous pollution in downstream regions, particularly in the Central Plains and western Shandong Peninsula Urban Agglomerations. Except for the Guanzhong Plain Urban Agglomeration, all other urban

agglomerations showed gradually decreasing PM<sub>2.5</sub> trends, indicating effective atmospheric pollution prevention and control during the 13th Five-Year Plan period.

## 2.2 Spatial Autocorrelation Analysis

Using Moran's I as an indicator, spatial autocorrelation tests were conducted on PM<sub>2.5</sub> mean values for 2016 and 2020—the beginning and end of the 13th Five-Year Plan period. The results revealed significant spatial heterogeneity [Figure 3: see original paper]. The spatial distribution of PM<sub>2.5</sub> showed varying spatial autocorrelation across years but generally exhibited positive spatial autocorrelation and aggregated distribution. The global Moran's I values were all greater than 0 and passed significance tests at the 1% level. The Lanzhou-Xining Urban Agglomeration showed negative spatial autocorrelation, tending toward random distribution. Although the Yellow River “Ji” Character Bay Metropolitan Circle exhibited positive spatial autocorrelation and aggregated distribution, its Moran's I approached 0 in 2020, also showing a random distribution trend. The Guanzhong Plain, Central Plains, and Shandong Peninsula Urban Agglomerations all showed Moran's I values greater than 0, indicating positive spatial autocorrelation and aggregated distribution.

Local spatial autocorrelation further revealed regional differences in PM<sub>2.5</sub> distribution [Figure 4: see original paper]. The main clustering types were high-high, low-low, and low-high aggregations, with no high-low clustering observed. High-high clusters were primarily located in downstream regions, mainly in the Central Plains and western Shandong Peninsula Urban Agglomerations, representing long-term high-pollution areas. Low-low clusters were mainly located in the upper and middle reaches of the Lanzhou-Xining Urban Agglomeration and Yellow River “Ji” Character Bay Metropolitan Circle, representing stable air quality improvement zones. From 2016 to 2020, the high-pollution area continuously shrank, with 11 cities evolving from high-pollution to good air quality areas, though Huaibei City showed the opposite trend.

## 3.1 Differentiation Detection Analysis

Different factors exert varying degrees of influence on PM<sub>2.5</sub> spatial differentiation in the Yellow River Basin. Natural geographical factors include topographic relief, vegetation cover index, temperature, precipitation, and net primary productivity. Socioeconomic factors include economic growth, urbanization, industrialization, population size, industrial scale, technological innovation, energy efficiency, smoke and dust emissions, public environmental concern, and urban greening rate.

Differentiation detection using geographic detectors revealed that natural geographical factors showed stronger driving forces than socioeconomic factors in both 2016 and 2020. The most influential factors were net primary productivity ( $X_1$ ), topographic relief ( $X_2$ ), vegetation cover index ( $X_3$ ), population size

( $X_4$ ), and public environmental concern ( $X_5$ ). Net primary productivity ranked first in both years, as vegetation adsorbs PM2.5 through photosynthesis, representing a key component of the surface carbon cycle that effectively reduces atmospheric PM2.5 content and improves urban agglomeration environmental quality. Topographic relief, temperature, and vegetation cover index were also strong natural drivers. Topographic relief negatively correlates with PM2.5, as the complex terrain in central-western urban agglomerations hinders population and industrial agglomeration while blocking external PM2.5 pollution. In contrast, downstream urban agglomerations' flat terrain facilitates large-scale industrial activities but also enables PM2.5 diffusion. Topographic relief also affects surface wind speed and circulation fields, contributing to temperature inversion formation. During stable weather conditions with calm circulation, atmospheric boundary layer winds directly relate to heavy winter haze pollution in northern cities. Temperature affects PM2.5 both temporally (promoting pollutant dilution) and spatially (facilitating pollutant transformation and secondary pollutant formation). High vegetation cover benefits PM2.5 deposition, retention, adsorption, and absorption.

Among socioeconomic factors, population size was the dominant driver in 2016, while energy efficiency became dominant in 2020, though population size remained highly influential. As urban agglomerations expand, rapid population growth leads to increased energy consumption. With coal accounting for a large proportion of energy consumption in Yellow River Basin urban agglomerations, smoke and dust emissions increase accordingly. Public environmental concern effectively plays a constraining role in informal environmental regulations, forming a benign environmental governance structure involving government, enterprises, and the public.

### 3.2 Interaction Detection Analysis

Interaction detection using geographic detectors revealed that factor interactions showed either bi-factor enhancement or nonlinear enhancement, significantly improving explanatory power for PM2.5 spatial differentiation [Figure 5: see original paper]. In 2016, the top five interaction combinations were  $X_1 X_2$ ,  $X_1 X_3$ ,  $X_1 X_4$ ,  $X_1 X_5$ , and  $X_2 X_3$ . In 2020, they were  $X_1 X_2$ ,  $X_1 X_3$ ,  $X_1 X_4$ ,  $X_1 X_5$ , and  $X_2 X_4$ . All interaction effects between  $X_1$  (net primary productivity) and other factors exceeded their individual factor effects, consistent with  $X_1$ 's strongest individual influence. The interaction between  $X_1$  and  $X_2$  showed the highest explanatory power, indicating that when these two factors with obvious spatial differentiation interact, they significantly enhance PM2.5 spatial heterogeneity.

### 3.3 Geographically Weighted Regression Analysis

GWR modeling was applied to the five factors showing the greatest explanatory power changes in differentiation detection to analyze spatiotemporal differences in factor direction and intensity [Figure 6: see original paper].

**Socioeconomic factors:** Industrial scale ( $X_9$ ) and smoke and dust emissions ( $X_{12}$ ) are primary PM2.5 sources, showing consistently positive regression coefficients that enhance PM2.5 pollution. Energy efficiency ( $X_{11}$ ) showed increasingly negative effects spreading from the central Yellow River Basin outward, indicating initial achievements in green, low-carbon energy transition under the “dual carbon” goals. Urban greening rate ( $X_{14}$ ) exhibited a polarity reversal effect: in 2016, it significantly contributed to carbon sequestration in western cities but not eastern cities, whereas by 2020, eastern cities showed greater benefits from landscape improvements for carbon reduction due to favorable natural geographical conditions. Population size ( $X_4$ ) maintained positive coefficients overall, indicating that coal, soil dust, vehicle emissions, biomass burning, secondary sulfates, and nitrates remain major PM2.5 contributors.

**Natural geographical factors:** Net primary productivity ( $X_1$ ), topographic relief ( $X_2$ ), and vegetation cover index ( $X_3$ ) all showed negative effects on PM2.5 pollution across space, particularly in the Lanzhou-Xining Urban Agglomeration and Yellow River “Ji” Character Bay Metropolitan Circle, where their inhibitory effects were most pronounced.

#### 4.1 Conclusions

- (1) PM2.5 concentrations in the five major Yellow River Basin urban agglomerations generally followed an inverted “N” shape, showing an overall declining trend. Seasonal variations exhibited a “U” pattern, with high winter concentrations, low summer concentrations, and moderate spring and autumn levels.
- (2) Spatially, a gradient decreasing pattern formed from downstream to upstream regions. Except for the Guanzhong Plain Urban Agglomeration, all other urban agglomerations showed gradually decreasing PM2.5 trends, demonstrating effective atmospheric pollution prevention and control during the 13th Five-Year Plan period.
- (3) PM2.5 evolution showed varying spatial autocorrelation across years but generally exhibited positive spatial autocorrelation and aggregated distribution. Local spatial autocorrelation revealed that clustering types were primarily high-high, low-low, and low-high, with high-pollution areas continuously shrinking.
- (4) Differentiation detection using geographic detectors showed that natural geographical factors had stronger driving forces than socioeconomic factors in both 2016 and 2020. Interaction detection results demonstrated bi-factor enhancement or nonlinear enhancement.
- (5) GWR analysis of the five most explanatory factors revealed that negative effects on PM2.5 pollution have continuously strengthened while positive effects have declined, with significant spatial differences in direction and intensity.

## 4.2 Recommendations

The 20th Party Congress report proposed deepening environmental pollution prevention and control, continuously fighting the battle for blue skies, clear waters, and clean soil, and essentially eliminating heavy pollution weather. Although PM<sub>2.5</sub> in the Yellow River Basin continued improving during the 13th Five-Year Plan period, the industrial structure dominated by heavy chemicals, energy structure dominated by coal, and transportation structure dominated by roads have not fundamentally changed, making “dual carbon” goals challenging. The 14th Five-Year Plan period has entered deep waters for atmospheric pollution governance, with PM<sub>2.5</sub> control remaining a formidable task. The following recommendations are proposed:

- (1) Establish a cooperative mechanism for joint construction, prevention, control, and treatment of PM<sub>2.5</sub> pollution across the upper, middle, and lower Yellow River Basin. Develop tailored prevention policies based on different pollution emission sources in the five major urban agglomerations while enhancing inter-agglomeration division of labor, coordination, and integrated governance.
- (2) Build a pollution governance system led by government, with enterprise responsibility and citizen participation. Leverage government ecological functions to promote comprehensive green transformation through environmental regulations; utilize market mechanisms and public opinion supervision to strengthen corporate social responsibility; and enhance citizen awareness to create a social atmosphere of energy conservation and emission reduction.
- (3) Implement “dual carbon” goals through classified policies and precise advancement. The upstream Lanzhou-Xining Urban Agglomeration should promote green industrial transformation, prohibit high-energy-consumption and high-emission industries, and improve resource utilization. The mid-upstream Yellow River “Ji” Character Bay Metropolitan Circle should optimize its industrial structure and reduce coal consumption. The midstream Guanzhong Plain and downstream Central Plains Urban Agglomerations should optimize industrial layout and promote mandatory clean production in steel and chemical industries. The downstream Shandong Peninsula Urban Agglomeration should actively promote market-based trading of atmospheric pollution emission rights and explore cross-basin or national emission rights trading systems.
- (4) Continuously promote winter clean heating transformation across urban agglomerations, popularize centralized heating, and develop distributed new heating methods such as biomass energy to change the strong seasonal characteristics of PM<sub>2.5</sub> pollution.
- (5) Adhere to ecological priority and green development to build a “five-pole” development pattern in the Yellow River Basin. The five major urban

agglomerations serve as regional economic growth poles and primary carriers for population and productivity layout. Solid efforts should promote the Yellow River Basin as China's main battlefield for ecologically prioritized green development, facilitating rational factor flow and efficient agglomeration among the "five poles" to continuously fight and win the battle for blue skies. High-quality ecological environments should support high-quality development in the Yellow River Basin.

## References

- [1] Wang Liwei. Co-drawing a high-quality development picture of the Yellow River Basin[N]. Guangming Daily, 2021-10-16(5).
- [2] Huang Chengliang. Promoting ecological protection and high-quality development of the Yellow River Basin[J]. Red Flag Manuscript, 2022(8): 15-17.
- [3] Ministry of Ecology and Environment of the People's Republic of China. Ministry of Ecology and Environment reported the state of surface water and ambient air quality in December and from January to December 2021[EB/OL]. [2022-08-19]. [https://www.mee.gov.cn/ywdt/xwfb/202201/t20220131\\_968703.shtml](https://www.mee.gov.cn/ywdt/xwfb/202201/t20220131_968703.shtml).
- [4] Wang Zhenbo, Liang Longwu, Wang Xujing. Spatio-temporal evolution patterns and influencing factors of PM<sub>2.5</sub> in Chinese urban agglomerations[J]. Acta Geographica Sinica, 2019, 74(12): 2614-2630.
- [5] Yang Xinxing, Feng Lihua, Wei Peng. Air particulate matter PM<sub>2.5</sub> and its harm[J]. Frontier Science, 2012, 6(1): 22-31.
- [6] Zhu Yumin. New Air Quality Standard & PM<sub>2.5</sub>[J]. World Environment, 2012(1): 14-15.
- [7] Ministry of Ecology and Environment. Announcement on the issuance of the national environmental quality standard ambient air quality standard[EB/OL]. [2022-08-20]. [https://www.mee.gov.cn/gkml/hbb/bgg/201203/t20120302\\_224145.htm](https://www.mee.gov.cn/gkml/hbb/bgg/201203/t20120302_224145.htm).
- [8] Hao Jiming, Yin Weilun, Cen Kefa. Strategies and technical approaches for the prevention and control of atmospheric PM<sub>2.5</sub> pollution in China[M]. Beijing: Science Press, 2016.
- [9] Yang Hongbin, Zou Xudong, Wang Hongyu, et al. Study progress on PM<sub>2.5</sub> in atmospheric environment[J]. Journal of Meteorology and Environment, 2012, 28(3): 77-82.
- [10] Sun Y L, Zhuang G S, Tang A H, et al. Chemical characteristics of PM<sub>2.5</sub> and PM<sub>10</sub> in haze-fog episodes in Beijing[J]. Environmental Science & Technology, 2006, 40(10): 3148-3155.
- [11] Xiong Huanhuan, Liang Longwu, Zeng Zeng, et al. Dynamic analysis of PM<sub>2.5</sub> spatial-temporal characteristics in China[J]. Resource Science, 2017, 39(1): 136-146.

- [12] Pinto J P, Lefohn A S, Shadwick D S. Spatial variability of PM<sub>2.5</sub> in urban areas in the United States[J]. *Journal of the Air & Waste Management Association*, 2004, 54(4): 440-449.
- [13] Khan M M, Zaman K, Irfan D, et al. Triangular relationship among energy consumption, air pollution and water resources in Pakistan[J]. *Journal of Cleaner Production*, 2015, 112: 1375-1385.
- [14] Wang Keliang, Meng Xiangrui, Yang Baochen, et al. Regional differences and influencing factors of China's air pollution emission efficiency considering technological heterogeneity[J]. *China Population, Resources and Environment*, 2017, 27(1): 101-110.
- [15] Stern D I, Common M S, Barbier E B. Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development[J]. *World Development*, 1996, 24(7): 1151-1160.
- [16] Ma Limei, Zhang Xiao. The spatial effect of China's haze pollution and the impact from economic change and energy structure[J]. *China Industrial Economics*, 2014(4): 19-31.
- [17] Cardelino C A, Chameides W L. Natural hydrocarbons, urbanization, and urban ozone[J]. *Journal of Geophysical Research: Atmospheres*, 1990, 95(D9): 13971-13979.
- [18] Peng Diyun, Liu Chang, Zhou Yifan. Threshold effect of urbanization development on haze pollution in the Yangtze River Economic Belt: From the perspective of residents' consumption level[J]. *Finance and Economy*, 2015(8): 36-42.
- [19] Brimblecombe P. Air pollution in industrializing England[J]. *Journal of the Air Pollution Control Association*, 1978, 28(2): 115-118.
- [20] He Feng, Ma Dongdong. Association study between haze pollution and industrialization: An empirical study based on 74 cities in China[J]. *Soft Science*, 2015, 29(6): 110-114.
- [21] Walsh M P. PM<sub>2.5</sub>: Global progress in controlling the motor vehicle contribution[J]. *Frontiers of Environmental Science & Engineering*, 2014, 8(1): 1-17.
- [22] Yin Chengmei, He Jianjun, Yu Lijuan, et al. The impact of multi-scale meteorological conditions on PM<sub>2.5</sub> pollution over Ji'nan[J]. *Plateau Meteorology*, 2019, 38(5): 1120-1128.
- [23] Guan D B, Su X, Zhang Q, et al. The socioeconomic drivers of China's primary PM<sub>2.5</sub> emissions[J]. *Environmental Research Letters*, 2014, 9(2): 024010.
- [24] Kang Yu. The impact of trade openness on haze: A spatial econometric study based on China's provincial panel data[J]. *Economic Science*, 2016(1): 114-125.

- [25] Leng Yanli, Xian Guoming, Du Sizheng. Foreign direct investment and haze pollution: An empirical analysis based on China's provincial panel data[J]. *Journal of International Trade*, 2015(12): 74-84.
- [26] Small K A, Kazimi C. On the costs of air pollution from motor vehicles[J]. *University of California Transportation Center, Working Papers*, 1995(6): 7-32.
- [27] Zhou Qiao. Cause of the haze weather[J]. *China Population, Resources and Environment*, 2015, 25(Suppl.1): 211-212.
- [28] Wang Zhenbo, Liang Longwu, Wang Xujing. Spatio-temporal evolution patterns and influencing factors of PM2.5 in Chinese urban agglomerations[J]. *Acta Geographica Sinica*, 2019, 74(12): 2614-2630.
- [29] Xiong Huanhuan, Liang Longwu, Zeng Zeng, et al. Dynamic analysis of PM2.5 spatial-temporal characteristics in China[J]. *Resource Science*, 2017, 39(1): 136-146.
- [30] Wang Keliang, Meng Xiangrui, Yang Baochen, et al. Regional differences and influencing factors of China's air pollution emission efficiency considering technological heterogeneity[J]. *China Population, Resources and Environment*, 2017, 27(1): 101-110.
- [31] Ma Limei, Zhang Xiao. The spatial effect of China's haze pollution and the impact from economic change and energy structure[J]. *China Industrial Economics*, 2014(4): 19-31.
- [32] Peng Diyun, Liu Chang, Zhou Yifan. Threshold effect of urbanization development on haze pollution in the Yangtze River Economic Belt: From the perspective of residents' consumption level[J]. *Finance and Economy*, 2015(8): 36-42.
- [33] Wang Zhaohua, Zhang Ming. The effect of adsorbing fine particulate matter (PM2.5) by garden plants: A review[J]. *Chinese Journal of Ecology*, 2014, 33(9): 2558-2566.
- [34] Teng Tangwei, Chen Danhua, Hu Senlin. Spatial evolution and influencing factors of spatial agglomeration pattern of air pollution in the Yellow River Basin[J]. *Scientia Geographica Sinica*, 2021, 41(10): 1852-1861.
- [35] Wang Zhao, Yan Xiaobing. Temporal-spatial evolution of PM2.5 and driving factors in Yangtze River Delta urban agglomeration[J]. *Resources and Environment in the Yangtze Basin*, 2020, 29(7): 1497-1506.
- [36] Zhou Dong, Zhang Shuaiqian, Yan Jinwei, et al. Spatio-temporal distribution characteristics of PM2.5 and its influencing factors of the three urban agglomerations in the Yangtze River Economic Belt[J]. *Resources and Environment in the Yangtze Basin*, 2022, 31(4): 878-889.
- [37] Zhang Jun, Jin Zihan, Wang Yue, et al. Temporal and spatial evolution pattern of PM2.5 and its influencing factors in Guanzhong Plain urban agglomeration[J]. *Environmental Science*, 2022, 43(12): 5333-5343.

- [38] Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective[J]. *Acta Geographica Sinica*, 2017, 72(1): 116-134.
- [39] Lu Binbin, Ge Haimeng, Fang Chuanglin, et al. A review on geographically weighted regression[J]. *Geomatics and Information Science of Wuhan University*, 2020, 45(9): 1356-1366.
- [40] Liu Yong, Qin Kun, et al. The spatial-temporal characteristics and influencing factors of air pollution in Beijing-Tianjin-Hebei urban agglomeration[J]. *Acta Geographica Sinica*, 2018, 73(1): 177-191.
- [41] Hu Shulan, Hu Lin, Cheng Lu, et al. Low-level streamline field typing of heavy pollution weather of Guanzhong region in Shaanxi Province[J]. *Arid Land Geography*, 2022, 45(1): 122-130.
- [42] Huang Xiaogang, Shao Tianjie, Zhao Jingbo, et al. Influence factors and spillover effect of PM2.5 concentration on Fen-wei Plain[J]. *China Environmental Science*, 2019, 39(8): 3539-3548.
- [43] Liu Xiaojie, Wang Lili, He Bowen, et al. Spatio-temporal evolution and drivers of PM2.5 in the Yellow River Economic Belt[J]. *Resources and Environment in the Yangtze Basin*, 2022, 31(3): 647-658.
- [44] Li Heng, Han Yan. Analysis on the spatial-temporal evolution characteristics of PM2.5 and its influencing factors in the Yellow River Basin[J]. *World Regional Studies*, 2022, 31(1): 130-141.
- [45] Yang Xiaolin, Chen Yiyang, Li Yiling, et al. Research on the spatial-temporal heterogeneity and spatial spillover effects of urban PM2.5 in the Yellow River Basin[J]. *Resource Development & Market*, 2022, 38(10): 1208-1215, 1223.
- [46] Wang Jingjing, Cheng Yu. Impact of technological innovation on PM2.5 and its spatial spillover effect in the Yellow River Basin[J]. *China Population, Resources and Environment*, 2022, 32(9): 108-118.
- [47] Geng Jiachen, Shen Shi, Cheng Changxiu. Spatio-temporal evolution and the multi-scale socio-economic influencing mechanism of PM2.5 in the Yellow River Basin during China's 13th Five-Year Plan[J]. *Journal of Geo-information Science*, 2022, 24(6): 1163-1175.
- [48] Jia Zhuo, Qiang Wenli, Wang Yueju, et al. The spatial characteristics and spatial effect of industrial pollution agglomeration in Lanzhou-Xining Urban Agglomeration[J]. *Economic Geography*, 2020, 40(1): 68-75, 84.
- [49] Inner Mongolia Autonomous Region Statistics Bureau. Comparative analysis in the Yellow River "Ji" Character Bay Metropolitan Area[EB/OL]. [2023-05-13]. [http://tj.nmg.gov.cn/tjdt/fbyjd\\_{11654}/202204/t20220422\\_{2043235}.html](http://tj.nmg.gov.cn/tjdt/fbyjd_{11654}/202204/t20220422_{2043235}.html).
- [50] Cui Muhua. The relationship of coupling coordination between urbanization and ecological environment: A case of urban cluster in the Central Plains[J]. *Economic Geography*, 2015, 35(7): 72-78.

- [51] Wang Fuxi. Study on the quality measurement and coordinated development of population-land urbanization in Shandong Peninsula urban agglomeration[J]. *Scientia Geographica Sinica*, 2020, 40(8): 1345-1354.
- [52] Jiang Juanli, Yang Qingyuan, Zhang Zhongxun, et al. Spatial distribution pattern of intangible cultural heritage and tourism development in Chongqing[J]. *Economic Geography*, 2019, 39(6): 205-213.
- [53] Chinese Meteorological Society. Forests make Beijing “bluer” annually by reducing PM2.5 by hundreds of tons[EB/OL]. [2023-08-05]. [http://www.cms1924.org/WebPage/WebPageDetail\\_{{76}}{{123}}{2324}.aspx](http://www.cms1924.org/WebPage/WebPageDetail_{{76}}{{123}}{2324}.aspx).
- [54] Wu Libo, Yang Meimin, Sun Kege. Impact of public environmental attention on environmental governance of enterprises and local governments[J]. *China Population, Resources and Environment*, 2022, 32(2): 1-14.
- [55] Ji Jing, Wang Gang, Du Xilong, et al. Evaluation of adsorbing haze PM2.5 fine particulate matters with plants in Beijing-Tianjin-Hebei region in China[J]. *Scientia Sinica (Vitae)*, 2013, 43(8): 694-699.
- [56] Yang Chunxue, Kan Haidong, Chen Renjie. Research on level, composition, source and pollution characteristics of ambient fine particles in China[J]. *Journal of Environment and Health*, 2011, 28(8): 735-738, 753.
- [57] Liu Weijie, Hu Tianpeng, Mao Yao, et al. Characteristics and origin analysis of air pollution during the spring festival in Linfen, Fen-wei Plain[J]. *Environmental Science*, 2021, 42(11): 5122-5130.
- [58] Wang Lili, Liu Xiaojie, Li Ding, et al. Spatial-temporal characteristics and drivers of PM2.5 in the Yellow River Basin[J]. *Journal of Lanzhou University (Natural Sciences Edition)*, 2022, 58(4): 427-435, 442.
- [59] Meng Zhaoyang, Zhang Huaide, Jiang Xiaoming, et al. The characteristics of PM2.5 and its influencing factors during winter and spring in Taiyuan[J]. *Journal of University of Chinese Academy of Sciences*, 2007, 24(5): 648-656.
- [60] Wang Xin, Nie Yan, Chen Hong, et al. Pollution characteristics and source apportionment of PM2.5 in Lanzhou City[J]. *Environmental Science*, 2016, 37(5): 1619-1628.
- [61] Zhang Bihui, Wang Ruoqia. “Haze ash” continues to decrease, and the reason is geometric[N]. *China Meteorological News*, 2020-04-30(3).
- [62] He Bin, Yuan Xiaoling, Zhang Yuesheng. Spatio-temporal heterogeneity of driving factors of PM2.5 in Chinese cities[J]. *Statistics & Decision*, 2020, 36(22): 53-56.

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

*Source: ChinaXiv — Machine translation. Verify with original.*