The Pain of Breathing: How Does Haze Pollution Affect Urban Innovation?

wei feng (weifeng717719@126.com)
Southeast University https://orcid.org/0000-0002-1557-6200
hang yuan
Southeast University

Research Article

Keywords: haze pollution, urban innovation, spatial correlation, mechanism

Posted Date: September 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-750306/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on January 28th, 2022. See the published version at https://doi.org/10.1007/s11356-021-18279-4.

Abstract

Innovation plays an important role in achieving green-growth economic development in China, while the spread of haze pollution (also called smog) inhibits innovation activities. Using panel data on 265 cities at the prefecture level in China from 2001 to 2016, this paper investigates the relationship between haze pollution and urban innovation. The conclusions are as follows. First, haze pollution has a significant inhibitory effect on urban innovation. After we consider endogeneity, eliminate extreme values, and incorporate spatial correlation, we find that the negative impact of haze pollution on urban innovation still exists. Second, the channels through which haze pollution affects urban innovation can mainly be attributed to population density, the size of the home market, and economic activity. Third, among the different regions in China, the inhibitory effect of haze pollution on innovation is the most serious in the eastern region, followed by the central and western regions. Moreover, across diverse Chinese cities, the significant inhibitory effects of haze pollution on innovation are mainly in cities that are not provincial capitals and resource-based cities. Accordingly, efficient management of haze pollution is a critical prerequisite and effective guarantee for improving urban innovation.

JEL codes: K32; O13; O31; R11

1. Introduction

China's efforts to become a modern power are strongly supported by the implementation of an innovation-driven development strategy. Technological innovation provides favorable conditions for green growth in China's economy and plays an irreplaceable role in reducing pollutant emissions and increasing the value added of products. However, it is still undeniable that air pollution, represented by haze pollution (also called smog), not only damages human health but also casts a shadow over urban innovation activities.

Haze pollution results from an accumulation of particulate matter all year round, which limits the environment's carrying capacity with a subsequent human impact. At the beginning of 2013, a large-scale haze pollution incident occurred in central and eastern China, and many cities developed air pollution that was so heavy that people could not see the sky. Therefore, 2013 is regarded as first year of haze pollution in China. In recent years, the air quality level has improved due to policies such as the "Air Pollution Prevention and Control Action Plan" and the "Three-Year Action Plan for Winning the Blue-Sky War." In these policies, imposing pollution punishment and rewarding environmental protection are adopted. However, according to the recent environmental bulletin, as of 2018, more than half the cities had not yet reached the ambient air quality standards, and the outlook for overall air quality in China is still not encouraging.

Haze pollution has many causes, and various factors affect its severity. In China, singular matter from human activity, such as transportation and burning coal, is the main source of haze pollution (Sun et al., 2017), and changes in climatic factors, such as the ground wind speed and relative humidity, can also spread the extent of haze pollution (Ding and Liu, 2014; Wang and Chen, 2016). The main human effect of haze pollution is its negative impact on health. Specifically, haze pollution causes respiratory ailments, cardiovascular disease, cerebrovascular, and various types of cancer and thus is also a cause of premature death (Nel and André, 2005; Rückerl et al., 2006; Xu et al., 2014). Silva et al. (2013) find that 1.3 million to 3 million people die of cardiopulmonary diseases related to the amount of airborne particulate matter 2.5 (PM2.5). In addition, haze pollution can also seriously affect transportation by reducing road visibility (Zhang et al., 2014), cause economic losses by increasing health-care expenditures in local and nearby provinces (Zeng and He, 2019), and affect financial markets by increasing investor pessimism and reducing the willingness to engage in transactions (Zhang et al., 2017).

Air pollution, characterized by haze pollution, is likely to be harmful for technological innovation, which is crucial for high-quality economic development in China. The impact of haze pollution on urban innovation is reflected mainly in characteristics of enterprises and the labor force. As the foundation of microeconomics, enterprises are the front line and main locus of innovation, and high-quality labor and high-end technical talent are the “vanguards” of urban innovation who undertake core technical tasks. Haze pollution inhibits the innovation ability and production efficiency of workers by affecting their emotional cognition and creative thinking, thus depressing the enterprise’s innovation activities (Lavy et al., 2014; Chang et al., 2016). Meanwhile, it can also reduce the willingness of enterprises to innovate by reducing the frequency of consumption and regional economic vitality. However, from another perspective, the need for pollution control, personal protection, medicine, and health care caused by haze pollution can also have a positive effect on innovative technologies. For example, people’s perception of haze pollution can play a positive role in promoting green consumption willingness.

So, what role does haze pollution play in urban innovation? How does haze pollution affect urban innovation? In this paper, we explore the impact of haze pollution on urban innovation and find that in China haze pollution has a significant inhibitory effect on urban innovation in cities at the prefecture level and above. Moreover, population density, the home market size, and economic activity are the main channels of haze pollution that affect urban innovation.

The rest of our paper is structured as follows. Section 2 is literature review and proposes theoretical hypotheses based on a discussion of the relationship between haze pollution and urban innovation. Section 3 describes our research, including construction and measurement of the variables. Section 4 empirically investigates our theoretical hypotheses. The last section offers our conclusions and makes corresponding policy recommendations.

2. Literature Review

Most of the relevant studies that research the relationship between technological innovation and environmental pollution focus on the impact of technological innovation on environmental quality. Yu and Xu (2019) construct a panel-corrected standard error (PCSE) model and conclude that innovation can reduce emissions of carbon dioxide (CO_2) and significantly improve the efficiency of emissions reduction at the national and regional levels. Liu (2018) uses the nuclear density method and finds that technological innovation not only reduces regional haze pollution but also indirectly drives improvement in haze pollution in neighboring provinces through knowledge spillover effects. Yu and Du (2019) focus on China’s current economic new normal and find that when economic growth slows, innovation is an effective way to reduce CO_2 emissions. From a global perspective, Carrión-Flores and Innes (2010) show that environmental innovation is an important driving force in reducing toxic gas emissions in US manufacturing. Dauda et al. (2019) believe that innovation reduces CO_2 emissions in the G6 countries but increases emissions in the Middle East, North Africa, and the BRICS (Brazil, Russia, India, China, and South Africa). Ahmad et al. (2019) use data on 26 member countries of the Organization for Economic Cooperation and Development (OECD) and demonstrate that the positive impact of innovation is beneficial for raising environmental quality. In addition, based on data on 283 Chinese cities, Fan et al. (2020) demonstrate that the relationship between improvement in urban innovation and haze pollution takes an inverted U shape.

Meanwhile, studies focused on the Porter hypothesis concerning the effect of environmental pollution on technological innovation are generally at the micro-enterprise level and mainly explore whether environmental regulation promotes enterprise innovation and compensates for losses due to its cost. Based on panel data on Chinese manufacturing, Yu et al. (2017) claim that a threshold exists in the change rate of environmental regulation intensity, and at this threshold technological and management innovation in industries is not promoted by environmental regulation. Zhu et al. (2019) use panel data on Chinese industrial enterprises and find that voluntary regulation helps to improve the technological innovation efficiency of provincial industrial enterprises, but compulsory regulation does not have a significant effect. Additionally, De and Pereira (2010) show that in Brazil environmental oversight promotes technological innovation in highly polluting industries. Based on the 2009 German Community Innovation Survey, Jens et al. (2011) find that current and expected environmental oversight helps companies reduce pollutant emissions and achieve process innovation. Doran and Ryan (2016) use data on 2,181 enterprises in Ireland and show that regulatory drivers can increase the likelihood of enterprises' participation in environmental innovation. Based on comprehensive data on Dutch manufacturing enterprises, Van and Mohne (2017) also demonstrate that regulations are important in environmental innovation. Zhao et al. (2021) explore the relationship between haze pollution and urban innovation, finding that haze pollution can stimulate urban innovation, which is the opposite of this study.

In the existing literature, we find that in previous discussions on the relationship between environmental pollution and technological innovation, the latter is usually regarded as the "cause," while improvement in environmental quality is often treated as the "effect." That is, the reverse effect of environmental pollution on technological innovation is relatively overlooked. Even where it concerns the environmental impact on innovation, the previous literature tends to verify the Porter hypothesis and focus on environmental regulation rather than the pollutants, which reflect the local environmental pollution conditions more directly. What's more, the samples regressed in previous studies are often at the micro-enterprise or provincial level, and little literature focuses on innovation in prefecture-level cities. In addition, previous studies often use Sulfur Oxide (SO_x) or Nitric Oxide (NO_x) to measure air pollution, and few focus on haze pollution measured in terms of the PM2.5 level. Notably, although Zhao et al. (2021) have investigated the relationship between haze pollution and urban innovation, their conclusion deviates from the fact and our cognition. Therefore, it is necessary and urgent to reexamine and clarify the relationship between these two variables.

Unlike the aforementioned literature, we utilize the data on 265 cities at the prefecture level in China from 2001 to 2016, and adopt PM2.5 as a measurement of haze pollution and employ the urban innovation index to measure the innovation level of a city. Moreover, we robustly find that like the pain of breathing, haze pollution can inhibit urban innovation.

3. Theoretical Hypothesis

To clarify the relationship between these two variables, combined with the existing literature and current conditions, we discuss the mechanisms of haze pollution that affect urban innovation and propose a corresponding theoretical hypothesis.

First, haze pollution can affect innovation vitality through population density. In a city, a decrease in population density means the loss of labor. Worsening air pollution affects the supply of labor (Hanna and Oliva, 2015). A poor atmospheric environment is one of the reasons for cross-regional migration, which is mainly driven by well-educated people (Chen et al., 2017), and serious air pollution can even intensify people's willingness to emigrate (Qin and Zhu, 2018). Generally speaking, a sufficient labor force is the guarantee of innovation, but haze pollution usually causes its loss. In areas threatened by haze pollution, the loss of urban population can be quite large, and workers migrate to other cities, which makes it difficult to provide sufficient a labor reserve for R&D and innovation at enterprises in operations, management, and logistics. In addition, haze pollution also causes a loss of human capital. High-quality labor and high-end technical talent are essential for technological innovation, and the accumulation of talented employees can make a positive contribution to regional technological innovation. Raising environmental quality is beneficial for promoting urban innovation ability by enhancing the concentration of high-quality innovative talents. These talented employees are more sensitive to air quality and when they begin to suffer "breathing pain" caused by haze pollution, they tend to create cross-regional outflow.

Second, haze pollution can affect innovation vitality through the size of the home market. A broader market means higher demand and fiercer competition. Changes in market demand and the need to adapt to competition are important driving forces behind enterprises' innovation. The theory of the home market effect demonstrates that when a country's home market demand is higher, its output and production efficiency are higher (Krugman, 1980). The home market size has a significantly positive impact on industrial innovation. For example, Blume-Kohout and Sood (2013) hold that, in the pharmaceutical industry, the home market size can increase the inputs to R&D expenditure and lead to further innovation. Larger trade volume and more diverse categories induced by the home market size can also create the potential for process innovation in products and management (Desmet and Parente, 2010). However, haze pollution reduces the scale of the local market and dampens the vitality of urban innovation. In the short term, haze pollution puts the regional economy at risk of shutting down. It is difficult for enterprises that suffer from reduced labor productivity and lower production to provide sufficient products to satisfy the local market scale. Because of the deterioration in emotional cognition and increasing duration of staying at home, consumer demand for products will also be greatly reduced, and industries such as tourism and catering services might be sluggish. In the long run, because of the damage to human health and labor productivity, haze pollution greatly increases population outflow and enterprise migration, which makes a city gradually lose its attractiveness. As a result, output and consumption are not be maintained, and the home market size might shrink sharply. Hence, innovation activities may be unsustainable.

Third, haze pollution can dampen innovation by affecting economic activity. Economic conditions can provide physical and human resource support for innovation. The prosperity from a city's economic activities reflects economic strength and sound infrastructure, which supports its ability to attract talented employees and generate ideas. Hence, high-quality economic activities, characterized by increasing returns, can effectively promote industrial development and urban innovation. However, it is undeniable that haze pollution can seriously hinder normal economic activities and greatly weaken regional economic vitality. Specifically, haze pollution can severely reduce the quality of economic activities because of the great damage to human capital and labor productivity. In addition, the medical and health expenditures caused by haze pollution have a negative impact on expansion in urban economic vitality as well. Meanwhile, the aerosol particles formed by haze pollution reduce visibility and hinder the normal development of transportation. Also, because haze pollution has deleterious respiratory effects, heavy haze pollution causes people to remain indoors at home more and reduce the frequency of their economic activities to avoid negative health effects, which reduces consumption and depresses business activities. Moreover, the production of foods and drugs, high-end chips, and precision instruments have strict environmental requirements, so when air pollution is serious, it is difficult to obtain a production environment that is in compliance, which can impede production activities. Therefore, the threat of haze pollution limits all kinds of economic activities, which then limit the ability to engage in innovation.

To sum up, we posit our theoretical hypothesis:

Haze pollution has an inhibitory effect on urban innovation. The higher the haze pollution is, the lower the urban innovation. The main channels through which haze pollution affects urban innovation are population density, the home market size, and economic activity.

4. Empirical Equation

4.1 Specification

We construct the following empirical equation to test this hypothesis, as follows:

$$lninnovation_{it} = \alpha_0 + \alpha_1 lnhaze_{it} + \alpha_2 lnedu_{it} + \alpha_3 lnfinance_{it} + \alpha_4 lnrd_{it} + \alpha_5 lnfdi_{it} + \delta_{it} + e_{it}$$

where innovation is urban innovation, haze is baze pollution, edu is the eduation level, finance is financial revenue, rd is technology expenditure, fdi is foreign direct investment, δ_{it} time-fixed effects, e_{it} is random disturbances, i is a city, and t is the year. Because of concerns about data stationarity and the elimination of heteroscedasticity, all variables are calculated by natural logarithm.

4.2 Variables

The explained variable, urban innovation, is derived from the "FIND Report on City and Industrial Innovation in China (2017)" (Kou and Liu, 2017).[1] Figure 1 shows that in China the average level of urban innovation between 2001 and 2016 is unbalanced. The core explanatory variable, haze pollution, is measured by PM2.5 concentration, which comes from the Social and Economic Data and Application Center (SEDAC) at Columbia University. Its spatial distribution, illustrated in Figure 2, is unbalanced as well, and the heaviest haze pollution is concentrated in the region of Beijing-Tianjin-Hebei in north China.

Among the control variables, the education level (ln*edu*) is measured by the proportion of education expenditure in the general local budget; financial revenue (ln*finance*) is measured by the ratio of local general budgetary revenue to the gross domestic product (GDP); science and technology expenditure (ln*rd*) is measured by the ratio of science and technology expenditure in the general local budget to GDP; and foreign direct investment (ln*fdi)* is measured by the ratio of FDI to GDP. The data mainly come from the *China Statistical Yearbook* and *China City Statistical Yearbook*. Notably, in the section on the "mechanism test," population density is measured by the population in an area of city land, and the home market size (ln*hms*) is calculated based on Hariss (1954), and data on city lighting (ln*light*) come from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) nighttime lighting.[2] All the descriptive statistics are reported in Table 1.[3]

Before constructing the regressions, we test whether multicollinearity exists between the variables. Table 2 shows that the variables have little multicollinearity.

Meanwhile, the value of the variance inflation factor (VIF) also indicates that the value of each variable's VIF is less than 10, which means that the regressions have no multicollinearity.

5. Empirical Analysis

5.1 Baseline Regression

We use haze pollution and urban innovation as the main variables and conduct the regressions with Stata 16.0. Based on the Hausman test, we adopt a fixed-effects model to conduct estimations. Table 4 reports the baseline regression results, in which column (1) shows that when no control variables are added, haze pollution has an impact on urban innovation of -0.1900, which is significant at a level of 5%. Columns (2) to (5) demonstrate the regression results with control variables added step by step. According to the baseline regression results reported in column (5), the influence coefficient of haze pollution on urban innovation is -0.1477, which is significant at the 5% level, which confirms our hypothesis and implies that worse haze pollution has a significant inhibitory effect on urban innovation. The reason is that haze pollution not only damages human health and affects production efficiency but also induces great losses in the research and development of technology-intensive products.

The regression results of the control variables are all significantly positive, except foreign direct investment (ln*fdi*), which is consistent with our expectations. In column (5) of Table 4, FDI has an impact of -0.0516 on urban innovation at a significance level of 1%, which means that FDI has a crowding-out effect on urban innovation. It might be that the development of local enterprises in China threatens FDI in that local enterprises will erode its profits or market share. Therefore, FDI adopts a strategy of inhibiting the R&D of local enterprises, which adversely affect improvement in urban innovation capabilities and the development of high-tech industries.

5.2 Considering Endogeneity

Because of the potential two-way causality between haze pollution and urban innovation (Yu and Du, 2019; Fan et al., 2020), based on the two-stage least squares (2SLS) method, we select the first-order lag term of haze pollution as an instrumental variable (IV) to overcome endogeneity (Fieler et al., 2018). The results are reported in column (1) in Table 5. We find that the *F*-statistic of the first-stage regression is greater than 10, which indicates that there are no weak IVs. To further check the robustness of our results, we employ a generalized method of moments (GMM) estimation to conduct the regressions again. In addition to difference-GMM, we also employ the system-GMM method to mitigate potential weak IV bias. Columns (2) and (3) show that the *p*-value of AR (1) is less than 0.05 whereas that of AR (2) is greater than 0.1, which indicates that first-order autocorrelation exists but not second-order autocorrelation in the regressions. Additionally, all the results of the Sargan test reject the null hypothesis that the IVs are overidentified, which means that the selection of IVs is reasonable. After we control for time-fixed effects, we find that the impact of haze pollution on urban innovation is still significantly negative regardless of whether the 2SLS, difference-GMM, or system-GMM method is used. That is, the regression result that worsening haze pollution inhibits urban innovation is robust.

5.3 Robustness Checks

5.3.1 Excluding Extreme Outliers

Samples for Beijing, Tianjin, Chongqing, and Shanghai are omitted because they have particular characteristics due to their special political status as municipalities, which are under the direct administration of the central government. Meanwhile, the standard deviation of ln*innovation* in Table 2 exceeds 1, which implies that there are extreme values. This causes bias in the regression results. Accordingly, to exclude extreme values, we retain a sample range of 5 percent to 95 percent, and the regression results are reported in Table 6. The impact of haze pollution on urban innovation is still significantly negative, which means that our regression results are robust.

5.3.2 Spatial Regression

As a concrete manifestation of air pollution, haze pollution is more susceptible to the influence of meteorological conditions, such as wind, because it is suspended in the air, which enables it to spread from one area to another (Chen et al., 2020; Jiang et al., 2021). Therefore, to identify the effect of haze pollution on urban innovation more clearly, we not only focus on the emissions of local pollutants but also include haze pollution in surrounding areas.

Accordingly, we adopt the methodology of spatial econometrics to conduct further regressions. We employ a spatial geographic matrix and a standardized geographic matrix as the spatial weight matrix and use a spatial Durbin model (SDM), a spatial autoregression model (SAR), and a spatial error model (SEM). The regression results are reported in Table 7, in which columns (1) to (3) are based on a spatial geographic matrix, while columns (4) to (6) are based on a standardized geographic matrix. Table 6 shows that no matter which kind of matrix or model is adopted, the effect of haze pollution on urban innovation is significantly negative, which is consistent with the baseline regression results and implies that even when spatial correlation is considered, our hypothesis is still confirmed.

5.4 Mechanism Test

Investigating the mechanism in which haze pollution affects urban innovation is of great significance for clarifying the relationship between these two variables. This section employs the mediating effect model (MacKinnon, 2008; Hayes, 2017) to conduct empirical tests based on the three mechanisms described above, namely, population density, the home market size, and economic activity (Fan et al., 2020; Zhao et al., 2021). The regression results are reported in Tables 8 to 10. Notably, in these tables, column (1) presents the result of the benchmark regression, column (2) shows the result of haze pollution on the mediating variable, and column (3) demonstrates the result of the mediating variable on urban innovation.

First, Table 8 shows that the effect of haze pollution on population density is -0.0217 at the 5 percent significance level. The coefficient of population density on urban innovation is 0.0253, which is not significant at least at the 10 percent level. However, the bootstrap test shows that the 95 percent confidence interval excludes 0, which means that a mediating effect exists (MacKinnon, 2008; Hayes, 2017). Hence, haze pollution can inhibit urban innovation through the channel of reducing population density. As an important factor of production, workers, especially high-end technical employees, always consider and care about the urban environment where they work and live (Jiang et al., 2021; Zhao et al., 2021). However, haze pollution can significantly worsen air quality, and widespread haze pollution slows down the flow of workers and reduces labor reserves. As a consequence, it seriously hinders innovation efficiency and makes it impossible to raise the level of urban innovation.

Second, based on the regression results in Table 9, the coefficient of haze pollution on the home market size is -0.0345, which is significant at the 1 percent level. Additionally, the effect of the home market size on urban innovation is 0.3062, which is not significant at least at the 10 percent. Nevertheless, the existence of a mediating effect is verified by the bootstrap test, which does not include 0 at the 95 precent confidence interval. Many studies show that an expansion in the home market size has a positive effect on urban innovation (Desmet and Parente, 2010; Eizenberg, 2014), and haze pollution can significantly reduce urban innovation by reducing the home market size. The harm of haze pollution on the home market size is reflected in the following two effects. First, haze pollution damages workers' health and emotional cognition and inhibits improvement in production efficiency, which makes it difficult for the quantity and quality of the products to meet the needs of the local market. Therefore, in the long run, it will induce the home market size to shrink and urban innovation to regress. Second, if consumers encounter haze when they go outside, they are more likely to stay at home, rather than engage in outdoor activities. In this case, business activities can be gradually depressed, and consequently the demand for goods will decline sharply, which leads to a dramatic decrease in the home market size and drive further stagnation in urban innovation.

Third, based on the regression results reported in Table 10, the effect of haze pollution on economic activity is 0.0320, which is insignificant at least at the 10 percent level, while the coefficient of economic activity on urban innovation is -0.3298, which is significant at the 5 percent level.[1] Similarly, we use a bootstrap test to confirm the existence of a mediating effect. The 95 percent CI excludes 0, which implies that haze pollution has a mediating effect on urban innovation. It seems that it is difficult for haze pollution to have a positive impact on economic activity or provide the necessary support for urban innovation. Poor air quality due to haze pollution does not create beneficial environmental conditions for production by enterprises, and the decrease in market demand also forces them to reduce production or even shut down to avoid more losses. Additionally, aerosol particles, i.e., the main substance in haze pollution, have a serious influence on traffic conditions and discourage travel and transportation by residents. Hence, haze pollution can inhibit innovation through the channel of hindering economic activity.

5.5 Further Discussion

Because of the heterogeneous characteristics of Chinese cities, we conduct a differentiated analysis by region (Fan et al., 2020; Jiang et al., 2021; Zhao et al., 2021).

First, based on the classification standard of the National Bureau of Statistics of China, we divide the 265 cities at the prefecture level and above into three regions: the east, the center, and the west. Table 11 reports the regression results, which show that haze pollution has the greatest inhibitory effect on innovation in the eastern region (-0.3800), followed by the central region (-0.3231), and the western region (-0.0823). The reason is as follows. The eastern region of China has a higher level of economic development and better infrastructure and talent incubation atmosphere than the central and western regions. The eastern region has more high-quality employees and stricter air quality requirements. Consequently, haze pollution causes a greater loss of human capital, which in turn poses a more serious obstacle to improvement in innovation. Moreover, even though the eastern region has sufficient innovation vitality, it difficult to carry out innovation projects under the threat of haze pollution. As a result, innovation in the eastern region is more sensitive to haze pollution. The central region is less attractive for high-quality employees engaged in innovation than the east, but more attractive than the west, so haze pollution has a secondary suppression effect on a region's innovation ability. Haze pollution has a relatively small impact on local innovation in the western region because of its insufficient innovation vitality and backward innovation level.

Second, we distinguish these 265 cities according to their resource abundance based on the *National Sustainable Development Plan for Resource-Based Cities (2013-2020)* issued by the State Council in 2013. The regression results are shown in Table 11. Haze pollution has an impact of -0.1924 on innovation in resource-based cities, which is greater than that of non-resource-based cities. This implies that the higher the haze pollution is, the lower the innovation level of resource-based cities is. The reason is as follows. Resource-based cities rely on abundant coal or other resources to engage in mining, transportation, and processing activities. As a consequence, over time, their environmental damage has been severe, and haze pollution has accumulated, which makes the environmental conditions worse and then gradually deteriorates, which seriously harms innovation. The negative effect of haze pollution on innovation in non-resource-based cities is not significant. Non-resource-based cities have a more suitable industrial structure than resource-based cities, and the contradiction between pollution and development is also smaller. Therefore, the inhibitory effect of haze pollution on innovation is insignificant.

6. Conclusion And Policy Implications

Based on the PM2.5 concentration data and urban innovation index on 265 prefecture-level cities in China, this study discusses the effect and mechanism of haze pollution on urban innovation. The main conclusions are as follows. In general, haze pollution has a significantly negative impact on urban innovation, and this result is robust even after considering endogeneity, excluding extreme outliers, and taking spatial correlation into consideration. This is because haze pollution inhibits urban innovation mainly through the channels of population density, the home market size, and economic activity. Meanwhile, in terms of the different regions, haze pollution has the greatest inhibitory effect on innovation in the eastern region, followed by the central and the western regions. Additionally, this effect applies to resource-based cities but is insignificant in non-resource-based cities.

Considering the importance of innovation and the severity of pollution, it is urgent to manage the haze pollution for the sake of innovation. In China, the huge level of pollution heightens the difficulty of pollution control. Hence, there is a long way to go in reducing haze pollution.

These conclusions lead us to propose some recommendations. First, we should strengthen the energy transformation in the coal-fired power industry and vigorously promote clean energy, such as solar energy and natural gas. Second, we should also realize that prevention of pollution at the front end is more important than treatment at the back end and treat technological innovation as an engine for promoting the efficient ways to control haze. Finally, the critical role of human capital and other elements in innovation activities needs to be recognized, and sufficient conditions for innovation with talent reserves and capital support need to be created.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The data that support the findings of this study is available on request from the corresponding author. The data is not publicly available for privacy and ethical restrictions.

Competing interests

The authors declare that they have no competing interests.

Funding

This research was funded by the Social Science Foundation of Jiangsu Province under Grant 20EYA003, and the Fundamental Research Funds for the Central Universities under Grant 2242021S20021 and 2242021K30005.

Authors' contributions

Wei Feng: Conceptualization, Design, Methodology, and Writing-original draft.

Hang Yuan: Software, Data curation, and Writing-original draft.

All authors read and approved the final manuscript.

Acknowledgements

This research was supported by the Social Science Foundation of Jiangsu Province (No. 20EYA003), and the Fundamental Research Funds for the Central Universities (No. 2242021S20021 and No. 2242021K30005).

Authors' information

Dr. Wei Feng is an associate professor at the school of Economics and Management, Southeast University, China. His research interests involve applied development topics like international trade, innovation, and environmental pollution. Dr. Feng has published a few papers in peer-reviewed journals like *China & World Economy, Growth and Change,* and in Chinese leading journals like *China Industrial Economics* and *China Soft Science*. Dr. Feng's contact details are as follows: Mail Address: Jingguan Building, Dongnandaxue Road 2, Jiangning District, Nanjing 211189, China, E-mail: weifeng717719@126.com.

Miss. Hang Yuan is a postgraduate at the school of Economics and Management, Southeast University, China. Her research fields are applied economics topics including international trade and industrial growth. Miss. Yuan can be contacted at: yuanhang006@126.com.

References

Ahmad M, Khan Z, Rahman Z U, et al. Can innovation shocks determine CO_2 emissions (CO_{2e}) in the OECD economies? A new perspective. Economics of Innovation and New Technology, 2019(1):1-21.

Blume-Kohout M E, Sood N. Market size and innovation: Effects of Medicare Part D on pharmaceutical research and development. Journal of Public Economics, 2013, 97(1):327-336.

Carrión-Flores C E, Innes R. Environmental innovation and environmental performance. Journal of Environmental Economics and Management, 2010, 59(1): 27-42.

Chang T, Graff Zivin J, Gross T, et al. The effect of pollution on worker productivity: Evidence from call-center workers in China. NBER Working Paper, 2016 (w22328).

Chen H, Wang H. Haze days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. Journal of Geophysical Research, 2015, 120(12): 5895-5909.

Chen S, Oliva P, Zhang P. The effect of air pollution on migration: Evidence from China. NBER Working Paper, 2017(w24036).

Chen W, Si W, Chen Z M. How technological innovations affect urban eco-efficiency in China: A prefecture-level panel data analysis. Journal of Cleaner Production, 2020, 270: 122479.

Dauda L, Long X, Mensah C N, et al. The effects of economic growth and innovation on CO_2 emissions in different regions. Environmental Science and Pollution Research, 2019, 26(15): 28-38.

De Azevedo A M M, Pereira N M. Environmental regulation and innovation in high-pollution industries: A case study in a Brazilian refinery. International Journal of Technology Management & Sustainable Development, 2010, 9(2): 133-148.

Desmet K, Parente S L. Bigger is better: Market size, demand elasticity, and innovation. International Economic Review, 2010, 51(2):319-333.

Ding Y, Liu Y. Analysis of long-term variations of fog and haze in China in recent 50 years and their relations with atmospheric humidity. Science China-Earth Sciences, 2014, 57(1): 36-46.

Doran J, Ryan G. The importance of the diverse drivers and types of environmental innovation for firm performance. Business Strategy and the Environment, 2016, 25(2): 102-119.

Eizenberg A. Upstream innovation and product variety in the US home PC market. Review of Economic Studies, 2014, 81(3): 1003-1045.

Fan F, Cao D, Ma N. Is improvement of innovation efficiency conducive to haze governance? Empirical evidence from 283 Chinese cities. International Journal of Environmental Research and Public Health, 2020, 17(17): 6095.

Fieler, A. C., Marcela, E., and Yi, X. D. Trade, quality upgrading, and input linkages: Theory and evidence from Colombia. American Economic Review, 2018, 108 (1): 109-146.

Hanna R, Oliva P. The effect of pollution on labor supply: Evidence from a natural experiment in Mexico City. Journal of Public Economics, 2015,100(122): 68-79.

Hayes, A. F. Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach. New York: Guilford Press, 2017.

Jiang X, Fu W, and Li G. Can the improvement of living environment stimulate urban innovation? Analysis of high-quality innovative talents and foreign direct investment spillover effect mechanism. Journal of Cleaner Production, 2020, 255(10): 120212.

Kou, Z. L., and Liu, X. Y. FIND Report on city and industrial innovation in China (2017). Fudan Institute of Industrial Development, School of Economics, Fudan University, 2017.

Krugman P. Scale economies, product differentiation, and the pattern of trade. American Economic Review, 1980, 70(5):950-959.

Lavy V, Ebenstein A, Roth S. The impact of short-term exposure to ambient air pollution on cognitive performance and human capital formation. NBER Working Paper, 2014 (w20648).

Lin D, Lu J, Liu X, et al. Returnee CEO and innovation in Chinese high-tech SMEs. International Journal of Technology Management, 2014, 65(1-4): 151-171.

Liu X. Dynamic evolution, spatial spillover effect of technological innovation and haze pollution in China. Energy & Environment, 2018, 29(6): 968-988.

MacKinnon, D. Introduction to Statistical Mediation Analysis. New York: Routledge, 2008.

Nel A. Air pollution-related illness: Effects of particles. Science, 2005, 308(5723): 804-806.

Qin Y, Zhu H. Run away? Air pollution and emigration interests in China. Journal of Population Economics, 2018, 31(1): 235-266.

Rückerl, R, Ibald-Mulli A, Koenig W, et al. Air pollution and markers of inflammation and coagulation in patients with coronary heart disease. Am J Respir Crit Care Med, 2006, 173(4):432-441.

Van Leeuwen G, Mohnen P. Revisiting the Porter hypothesis: an empirical analysis of green innovation for the Netherlands. Economics of Innovation and New Technology, 2017, 26(2): 63-77.

Xu P, Chen Y, Ye X. Haze, air pollution, and health in China. Lancet, 2013, 382(9910):2067-2067.

Yu Y, Du Y. Impact of technological innovation on CO2 emissions and emissions trend prediction on “new normal” economy in China. Atmospheric Pollution Research, 2019, 10(1): 152-161.

Yu H, You J, Liu H. Optimal environmental regulation intensity of manufacturing technology innovation in view of pollution heterogeneity. Sustainability, 2017, 9(7):1240-1240.

Yu Y, Xu W. Impact of FDI and R&D on China’s industrial CO2 emissions reduction and trend prediction. Atmospheric Pollution Research, 2019, 10(5): 1627-1635.

Zeng J, He Q. Does industrial air pollution drive health care expenditures? Spatial evidence from China. Journal of Cleaner Production, 2019,218(1): 400-408.

Zhang Y, Jiang Y, Guo Y. The effects of haze pollution on stock performances: evidence from China. Applied Economics, 2017, 49(23): 2226-2237.

Zhang Z, Wang J, Chen L, et al. Impact of haze and air pollution-related hazards on hospital admissions in Guangzhou, China. Environmental Science and Pollution Research, 2014, 21(6): 4236-4244.

Zhao C, Deng M, and Cao X. Does haze pollution damage urban innovation? Empirical evidence from China. Environmental Science and Pollution Research, 2021, 2(1): 1-16.

Zhu Y, Wang Z, Qiu S, et al. Effects of environmental regulations on technological innovation efficiency in China's industrial enterprises: A spatial analysis. Sustainability, 2019, 11(7): 1-19.

Tables

Table 1. Descriptive statistics

Variables	Mean	Standard deviation	Min.	Max.	t-value	Observations
ln*innovation*	-0.4468	1.9175	-4.6052	6.9673	-15.1626	4235
ln*haze*	3.4443	0.5579	0.6638	4.5093	401.9916	4240
ln*edu*	-1.7462	0.377	-15.5944	-0.7046	-301.627	4240
ln*finance*	0.1266	0.3883	-1.4059	2.2976	21.223	4240
ln*rd*	-4.9944	1.0139	-15.5383	-1.5758	-320.745	4240
ln*fdi*	-4.5077	1.364	-11.3071	-0.8477	-214.378	4208
ln*density*	5.77	0.8916	1.5476	9.3557	421.3534	4239
ln*hms*	15.3133	0.7639	12.8821	17.3335	1305.384	4240
ln*light*	1.3352	1.0858	-2.2818	4.043	72.0389	3432

Table 2. Multicollinearity test

Variables	ln*innovation*	ln*haze*	ln*edu*	ln*finance*	ln*rd*	ln*fdi*	ln*density*	ln*hms*	ln*light*
ln*innovation*	1.0000								
ln*haze*	0.2421	1.0000							
ln*edu*	-0.1284	0.0410	1.0000						
ln*finance*	0.3919	-0.1523	-0.1504	1.0000					
ln*rd*	0.6054	0.1750	-0.0075	0.1770	1.0000				
ln*fdi*	0.2795	0.2742	-0.2412	0.1000	0.2488	1.0000			
ln*density*	0.3924	0.5989	-0.0046	0.0332	0.2280	0.3924	1.0000		
ln*hms*	0.6203	0.4393	0.1451	0.0708	0.6162	0.2571	0.3716	1.0000	
ln*light*	0.5466	0.4265	-0.0897	0.1841	0.4007	0.4709	0.7295	0.4434	1.0000

Table 3. Variance inflation factor test

Variables	VIF	1/VIF
ln*haze*	1.82	0.5503
ln*edu*	1.08	0.9236
ln*finance*	1.16	0.8624
ln*rd*	1.74	0.5761
ln*fdi*	1.37	0.7273
ln*density*	2.76	0.3624
ln*hms*	2.01	0.4973
ln*light*	2.79	0.3588
	1.84	

Table 4. Regression results based on the panel data of fixed-effects model

	(1)	(2)	(3)	(4)	(5)
	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*
ln*haze*	-0.1900**	-0.1873**	-0.1920**	-0.1469**	-0.1477**
	(0.0762)	(0.0752)	(0.0748)	(0.0735)	(0.0732)
ln*edu*		0.1039**	0.1060**	0.0866*	0.0864*
		(0.0484)	(0.0497)	(0.0451)	(0.0474)
ln*finance*			0.2033*	0.2609**	0.2564**
			(0.1124)	(0.1013)	(0.1009)
ln*rd*				0.2417***	0.2425***
				(0.0336)	(0.0333)
ln*fdi*					-0.0516***
					(0.0157)
Constant	-1.5561***	-1.3626***	-1.3490***	-0.2637	-0.4833
	(0.2505)	(0.2780)	(0.2776)	(0.3159)	(0.3131)
Year effects	Yes	Yes	Yes	Yes	Yes
Observations	4235	4235	4235	4235	4203
R^2	0.8964	0.8970	0.8975	0.9075	0.9088

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

Table 5. Regression results based on the 2SLS and GMM methods

	(1)	(2)	(3)
	ln*innovation*	ln*innovation*	ln*innovation*
	2SLS	difference-GMM	system-GMM
ln*haze*	-0.1748*	-0.1263***	-0.0841***
	(0.0989)	(0.0305)	(0.0158)
l.ln*innovation*		1.0221***	1.0197***
		(0.0044)	(0.0043)
Control variables	Yes	Yes	Yes
Years effects	Yes	Yes	Yes
AR(1)		-7.71***	-7.64***
AR(2)		-0.22	-0.36
Sargan test		330.31	364.77
Observations	3941	3674	3938
R^2	0.9655	-	-

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

Table 6. Regression results excluding extreme values

	(1)	(2)
	ln*innovation*	ln*innovation*
	Excluding municipalities	Excluding extreme values
ln*haze*	-0.1502**	-0.2040**
	(0.0733)	(0.0857)
Control variables	Yes	Yes
Year effect	Yes	Yes
Observations	4139	3833
R^2	0.9078	0.9058

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

Table 7. Regression results based on the spatial econometrics model

	(1)	(2)	(3)	(4)	(5)	(6)
	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*
	SDM	SAR	SEM	SDM	SAR	SEM
	Spatial geographic matrix			Standardized geographic matrix		
ln*haze*	-0.1490**	-0.1399**	-0.1620**	-0.1468**	-0.1390**	-0.1597**
	(0.0741)	(0.0666)	(0.0727)	(0.0740)	(0.0666)	(0.0727)
ln*edu*	0.1059*	0.1126**	0.1051**	0.1058*	0.1126**	0.1049*
	(0.0564)	(0.0568)	(0.0598)	(0.0564)	(0.0567)	(0.0597)
ln*finance*	0.2452**	0.3244***	0.2647***	0.2440**	0.3236***	0.2630***
	(0.1017)	(0.0974)	(0.1022)	(0.1015)	(0.0974)	(0.1022)
ln*rd*	0.2496***	0.1673***	0.2637***	0.2494***	0.1672***	0.2637***
	(0.0349)	(0.0210)	(0.0363)	(0.0348)	(0.0210)	(0.0363)
ln*fdi*	-0.0562***	-0.0690***	-0.0712***	-0.0561***	-0.0690***	-0.0712***
	(0.0157)	(0.0168)	(0.0165)	(0.0157)	(0.0167)	(0.0165)
rho	0.9377***	0.9128***	0.9812***	0.9374***	0.9122***	0.9809***
	(0.0101)	(0.0169)	(0.0174)	(0.0102)	(0.0169)	(0.0065)

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses. SDM = spatial Durbin model. SAR = spatial autoregression model. SEM = spatial error model.

Table 8. Mechanism test based on population density

	(1)	(2)	(3)
	ln*innovation*	ln*density*	ln*innovation*
ln*haze*	-0.1477**	-0.0217**	-0.1473**
	(0.0732)	(0.0086)	(0.0730)
ln*density*			0.0253
			(0.1690)
Control variables	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes
Bootstrap (95 percent CI)	[0.2573, 0.3705]		
Mediation effect	-0.0006		
Contribution	0.3717%		
Observations	4203	4207	4202
R^2	0.9088	0.1065	0.9088

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses. CI = confidence interval.

Table 9. Mechanism test based on the home market size

	(1)	(2)	(3)
	ln*innovation*	ln*hms*	ln*innovation*
ln*haze*	-0.1477**	-0.0345***	-0.1371*
	(0.0732)	(0.0067)	(0.0731)
ln*hms*			0.3062
			(0.5798)
Control variables	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes
Bootstrap (95 percent CI)	[0.4028, 0.5184]		
Mediation effect		-0.0106	
Contribution		7.1523%	
Observations	4203	4208	4203
R^2	0.9088	0.9985	0.9089

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses. CI = confidence interval.

Table 10. Mechanism test based on economic activity

	(1)	(2)	(3)
	ln*innovation*	ln*light*	ln*innovation*
ln*haze*	-0.1477**	0.0320	-0.0740
	(0.0732)	(0.0320)	(0.0615)
ln*light*			-0.3298**
			(0.1277)
Control variables	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes
Bootstrap (95 percent CI)	[0.2188, 0.3008]		
Mediation effect		-0.0106	
Contribution		7.1453%	
Observations	4203	3406	3401
R^2	0.9088	0.7702	0.8831

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses. CI = confidence interval.

Table 11. Regression results based on the type of cities

	(1)	(2)	(3)	(4)	(5)
	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*	ln*innovation*
	East	Center	West	Resource	Non-Resource
ln*haze*	-0.3800**	-0.3231***	-0.0823*	-0.1924**	-0.0827
	(0.1757)	(0.1046)	(0.0488)	(0.0778)	(0.1175)
Control variables	Yes	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	1552	1535	1116	1677	2526
R^2	0.9291	0.909	0.9173	0.9000	0.9180

Notes: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses.

Figures

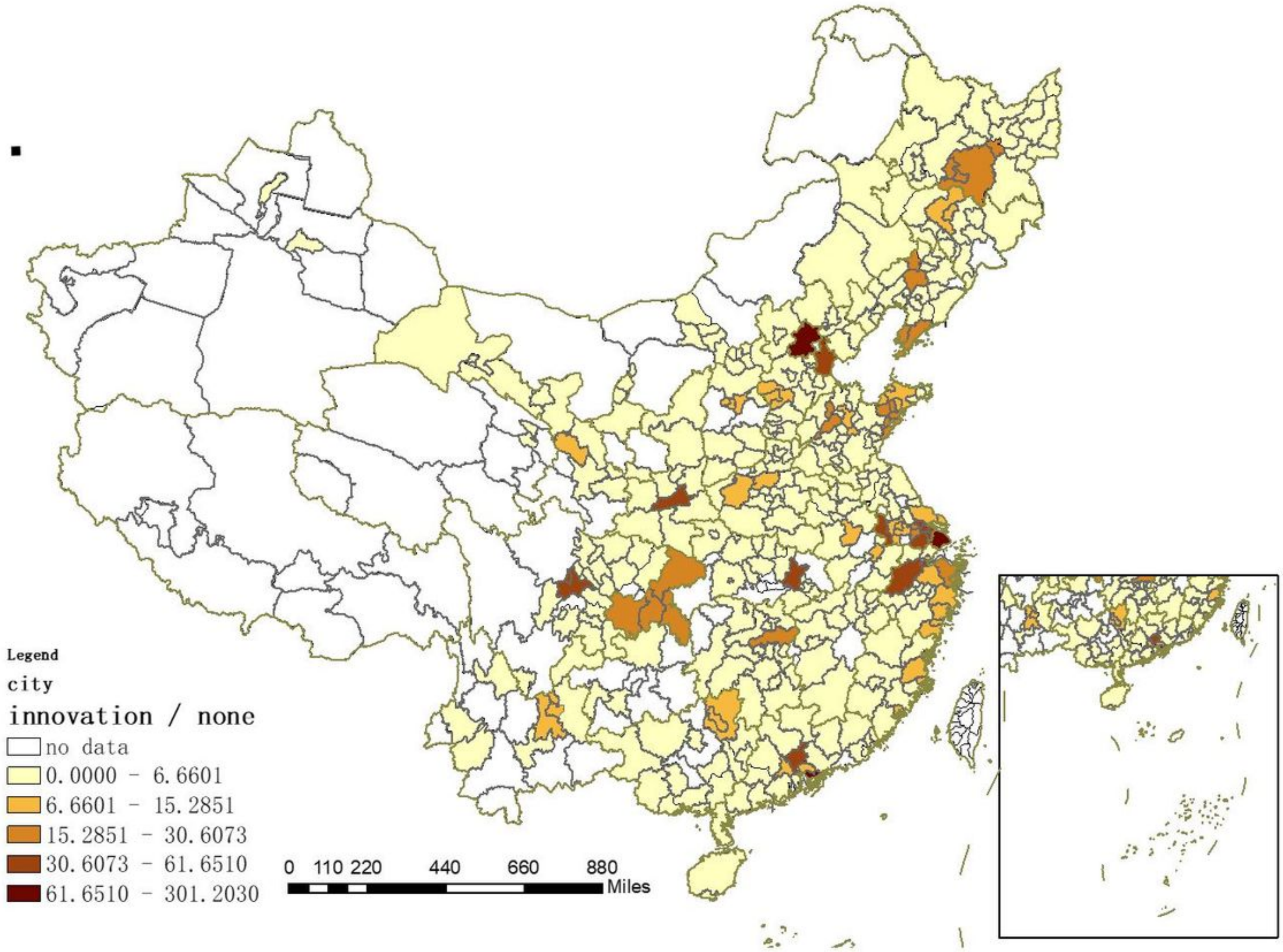

Figure 1

The spatial distribution of urban innovation in China

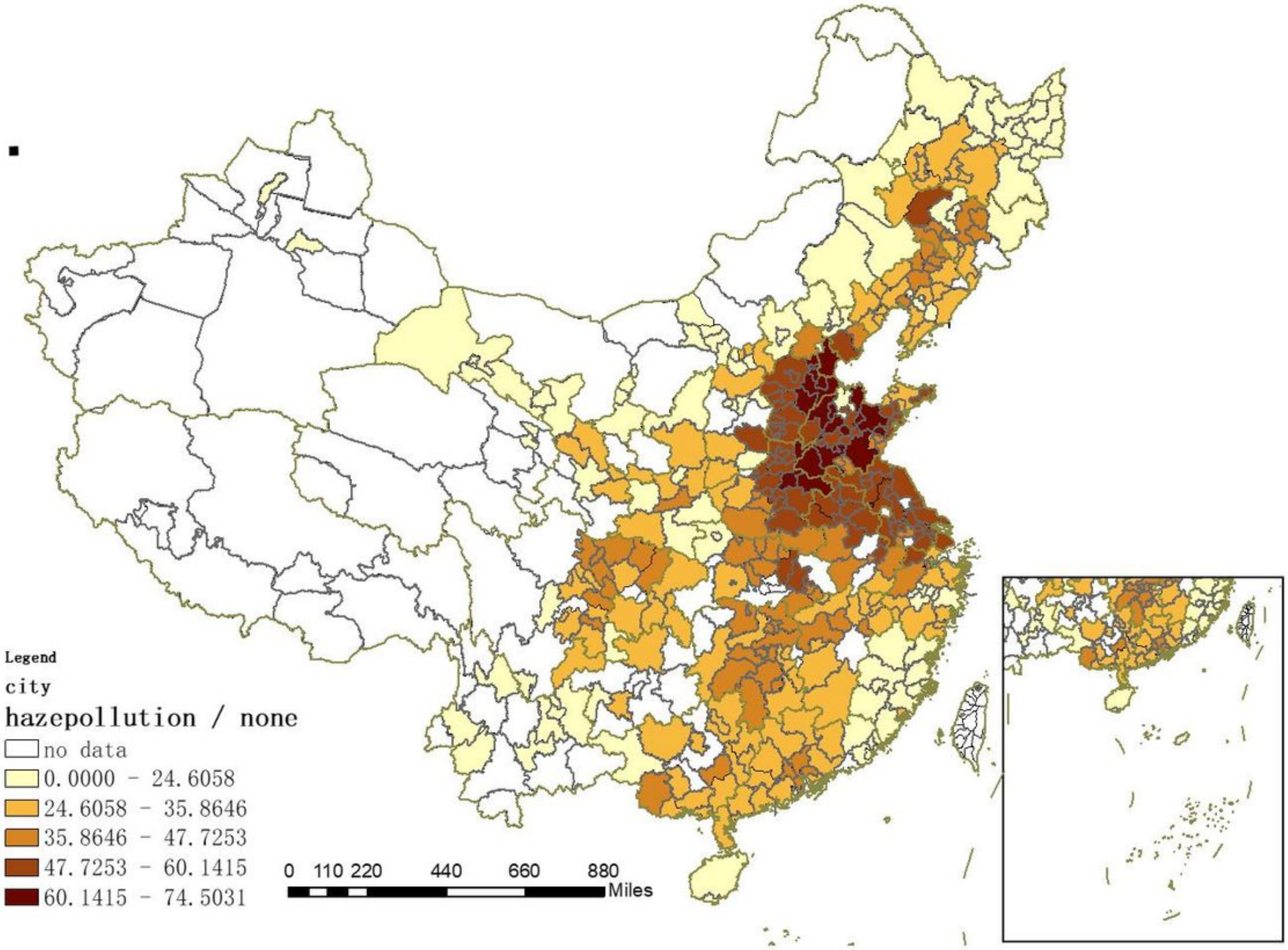

Figure 2

The spatial distribution of haze pollution in China