The pain of breathing: how does haze pollution affect urban innovation?

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Abstract
In China, innovation plays an important role in achieving economic development with green growth, but innovation activities are inhibited by the spread of haze pollution (also called smog). Using panel data on 265 cities in China at the prefectural level from 2001 to 2018, 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, replace variables, 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 are mainly attributed to production efficiency, willingness to consume, and entrepreneurial activity. Third, the inhibitory effect of haze pollution on innovation has a spatial spillover effect. Fourth, among the different regions in China, the most serious inhibitory effect of haze pollution on innovation is in the central region, while that of the eastern and western regions is insignificant. Moreover, across diverse Chinese cities, the significant inhibitory effects of haze pollution on innovation are mainly in cities that are abundant in natural resource. Accordingly, the efficient management of haze pollution is a critical prerequisite and effective guarantee for increasing urban innovation, such as promoting clean energy, strengthening technological innovation, and improving human capital.

Keywords Haze pollution · Spatial correlation · Urban innovation

JEL Classification K32 · O13 · O31 · R11

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. Several non-Chinese athletes wore masks to participate in the Beijing Summer Olympics held in 2008. That year, the US Embassy began to post daily updates on the airborne fine particulate matter (PM2.5) in Beijing. In 2012, China began to include PM2.5 in its air quality indicators. At the beginning of 2013, central and eastern China had an incidence of large-scale haze pollution, and many cities developed air pollution that was so thick that people could not see the sky. In 2013, according to the China Climate bulletin issued by the China Meteorological Administration, the average number of haze days in the central and eastern region reached 36, the highest level since 1961. Following the implementation of policies such as the Air Pollution Prevention and
Haze pollution has many causes, and various factors affect its severity. In China, particulate matter from human activity, such as transportation and burning coal, is the main source of haze pollution (Sun et al. 2014), and changes in climatic factors, such as the ground wind speed and relative humidity, can also expand the extent of haze pollution (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, strokes, and various types of cancer, and thus is also a cause of premature death (Xu et al. 2013; Sharma et al. 2020). Ma et al. (2021) find that if China could increase its PM2.5 environmental efficiency by 1%, respiratory disease mortality per 10,000 persons could be decreased by 2%. 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 to technological innovation, which is crucial for high-quality economic development in China. The impact of haze pollution on urban innovation is reflected mainly in the characteristics of enterprises and the labor force. As the foundation of microeconomics, enterprises are the front line and main focus of innovation, and high-quality labor and high-end technical talent are the leaders of urban innovation and undertake the main 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 (Chang et al. 2016; Xu et al. 2020). At the same time, it can also reduce the willingness of enterprises to innovate by reducing the frequency of consumption and regional economic vitality (Agarwal et al. 2020). 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 driving the willingness to adopt green consumption.

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 prefectural level and above. Moreover, production efficiency, willingness to consume, and entrepreneurial activity are the main channels of haze pollution that affect urban innovation.

The rest of the paper is structured as follows. The “Literature review” section is the literature review and proposes theoretical hypotheses based on a discussion of the relationship between haze pollution and urban innovation. The “Theoretical hypothesis” section describes our research, including the construction and measurement of the variables. The “Empirical equation” and “Empirical analysis” sections empirically investigate our theoretical hypotheses. The “Conclusion and policy implications” section offers our conclusions and makes corresponding policy recommendations.

Literature review

Researching the relationship between technological innovation and environmental pollution is an important and interesting topic that attracts many scholars.

One strand of the relevant studies focuses on the impact of technological innovation on environmental quality. From the perspective of developed countries, some studies hold that environmental innovation is an important driving force in reducing toxic gas emissions (Ahmad et al. 2021). Others also believe that innovation is an effective way to reduce carbon dioxide (CO₂) emissions at the national and regional levels in China (Yu and Du 2019).

However, some literature argues that the impact of innovation on environment is not always linear, especially in different types of regions (Chen et al. 2019; Dauda et al. 2019). For example, Dauda et al. (2019) believe that innovation reduces CO₂ emissions in the G6 countries but increases emissions in the Middle East, North Africa, and the BRICS (Brazil, Russia, India, China, and South Africa). Fan et al. (2020) demonstrate that in China the relationship between improvement in urban innovation and haze pollution takes an inverted U shape.

Meanwhile, other studies that focused on the Porter hypothesis concerning the effect of environmental pollution on technological innovation are generally at the microenterprise level and mainly explore whether environmental regulation promotes enterprise innovation and compensates for losses due to its cost. Based on different research samples, such as the 2181 enterprises in Ireland (Doran and Ryan 2016) and Dutch manufacturing enterprises (Van Leeuwen and Mohnen 2017), these scholars find that environmental oversight helps companies reduce pollutant emissions and achieve process innovation. Some papers use panel data on

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Chinese manufacturing enterprises or Chinese-listed firms. Unlike the above-mentioned studies, Zhu et al. (2019) find that different kinds of regulation have diverse effects on innovation, i.e., voluntary regulations help to improve technological innovation, but compulsory regulations do not have a significant effect. Meanwhile, the impact of environmental regulation on innovation also depends on the extent of competitiveness in industries (Zhuge et al. 2020). Furthermore, some papers find that haze pollution can stimulate urban innovation (Zhao et al. 2021a), the opposite of our findings.

In the existing literature, in previous discussions on the relationship between environmental pollution and technological innovation, the latter is usually regarded as the “cause,” and 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. In addition, extant studies usually use sulfur oxides (SOx) or nitrogen oxides (NOx) to represent air pollution (Lin et al. 2021), and little research pays attention to smog pollution, which is measured by PM2.5. However, even when PM2.5 is employed, few studies focus on innovation in prefectural-level cities (Zhu and Lee 2021). Notably, although Zhao et al. (2021a) have investigated the relationship between haze pollution and urban innovation, their conclusion deviates from the facts and our understanding. Therefore, it is necessary and urgent to reexamine and clarify the relationship between these two variables.

Unlike the aforementioned literature, we use data on 265 cities at the prefectural level in China from 2001 to 2018, adopt PM2.5 as a measurement of haze pollution, and employ total patents granted to measure a city’s innovation level. Moreover, we find that, like the pain of breathing, haze pollution can inhibit urban innovation.

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 affects urban innovation through the channel of production efficiency. Production efficiency is usually regarded as a representation of innovation performance (Saunila et al. 2020), and improving productivity can significantly affect innovation incentive and innovation motivation. According to the externality theory, the negative externality caused by haze pollution reduces production efficiency, whether in the agricultural sector (Graff Zivin and Neidell 2012; Graff Zivin and Neidell 2014), the service sector (Chang et al. 2019), or the manufacturing sector (Chang et al. 2016), and the higher the productivity, the stronger the producers’ response to haze pollution (He et al. 2019). They inhibit urban innovation on the production side. The main reason is that haze pollution not only causes a risk of respiratory tract infection, increasing health costs and health risks (Zeng et al. 2019), but also damages the emotional health and cognitive ability of producers, thus inhibiting their production efficiency (Xu et al. 2020), and the health of producers is an important guarantee of labor productivity (Arshad et al. 2015).

Second, haze pollution has an impact on urban innovation by affecting urban residents’ willingness to consume. According to the theory of market demand inducing innovation, consumption can drive innovation in services and products (Howells 2004), and large-scale consumption can drive market competition, leading to process innovation, management innovation, and product innovation (Desmet and Parente 2010). Although haze pollution raises consumer demand for purchasing anti-haze products and green appliances (Yang et al. 2020), more importantly, severe haze weather encourages people to increase the duration of staying at home and reduce the frequency of leaving their homes in order to avoid harm to their health (Agarwal et al. 2020; Yi et al. 2020), which tends to depress demand for catering, retail, tourism, and other activities. It reduces the vitality of a city’s consumption and innovation (Sun et al. 2019; Liu et al. 2021; Tian et al. 2021).

Finally, haze pollution acts on urban innovation by inhibiting entrepreneurial activity. According to the theory of innovation and entrepreneurship, because of their flexible management pattern and acute market sensitivity, the individual business and private enterprises are regarded as the main drivers and executors of innovation (De Massis et al. 2016). However, stagnation in their entrepreneurial activity is not conducive to innovation (Naudé and Nagler 2018). This is mainly because strict environmental regulation has high entrepreneurial costs, which weakens enthusiasm for entrepreneurship (Kong and Qin 2021; Gu et al. 2021) and affects investment efficiency (Zhang et al. 2019). At the same time, if entrepreneurs are often exposed to haze pollution, it not only damages their normal cognitive ability and behavior but also evokes adverse emotions, such as anxiety and depression, which inhibit the development of entrepreneurial and innovation activity (Buoli et al. 2018; Guo et al. 2021).

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 production efficiency, willingness to consume, and entrepreneurial activity.

**Empirical equation**

**Specification**

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

\[
\ln \text{innovation}_{it} = \alpha_0 + \alpha_1 \ln \text{haze}_{it} + \alpha_2 \ln \text{finance}_{it} + \alpha_3 \ln \text{fdi}_{it} + \alpha_4 \ln \text{rd}_{it} + \alpha_5 \ln \text{edu}_{it} + \alpha_6 \ln \text{regulation}_{it} + \alpha_7 \ln \text{weather}_{it} + \delta_i + \epsilon_{it}
\]

where innovation is urban innovation, haze is haze pollution, finance is financial revenue, fdi is foreign direct investment, rd is technology expenditure, edu is the education level, regulation is environmental regulation, weather is weather conditions including humidity, temperature, rain, and sunshine, \(\delta_i\) is time-fixed effects, \(\epsilon_i\) is random disturbances, \(i\) is a city, and \(t\) is the year. Because of concerns about data stationarity and the elimination of heteroskedasticity, all variables are calculated by natural logarithm.

**Variables**

The explained variable, innovation, which is comprised of technology, management, and policy innovations (Nam and Pardo 2011), is measured by total patents granted (Jinji et al. 2015). Figure 1 shows that in China, the average level of urban innovation between 2001 and 2018 is imbalanced.

The core explanatory variable, haze, is measured by the 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 imbalanced as well, and the heaviest haze pollution is concentrated in the region of Beijing-Tianjin-Hebei in North China.

Among the control variables, financial revenue (lnfinance) is measured by the ratio of local general budgetary revenue to the gross domestic product (GDP); foreign direct investment (lnfdi) is measured by the ratio of FDI to GDP; science and technology expenditure (lnrd) is measured by the ratio of science and technology expenditure in the general local budget to GDP; the education level (lnedu) is measured by the proportion of education expenditure in the general local budget. Additionally, weather conditions (lnweather) are measured by the percentage of average relative humidity, average temperature, hourly precipitation, and hours of sunshine. Following Chen et al. (2018), we measure environmental regulation (lnregulation) by the ratio of total words in environment-related sentences in the work report.
Fig. 2 The spatial distribution of haze pollution in China

Table 1 Descriptive statistics

| Variables         | P25   | P50   | P75   | Mean  | St. dev. | Min.  | Max.  | t-value | Obs. |
|-------------------|-------|-------|-------|-------|----------|-------|-------|---------|------|
| ln innovation     | 4.7875| 6.0426| 7.4239| 6.1643| 1.8695   | 0.6931| 11.8475| 227.301 | 4752 |
| ln finance        | 3.3828| 3.7189| 4.0450| 3.6710| 0.4869   | 1.1415| 4.7016 | 520.5766| 4768 |
| ln fdi            | −3.1687| −2.8197| −2.5333| −2.8972| 0.5737   | −7.0926| −1.4271| −348.753| 4769 |
| ln rd             | −5.3155| −4.3392| −3.5704| −4.5544| 1.3940   | −11.3306| −0.8477| −224.458| 4720 |
| ln edeu           | −5.7616| −5.0352| −4.2893| −5.0262| 1.0439   | −15.5303| −1.5758| −332.493| 4769 |
| ln regulation     | −1.9191| −0.7161| −1.5479| −1.7518| 0.3635   | −15.5875| −0.7046| −332.814| 4769 |
| ln humidity       | −1.3042| −0.8594| −0.5102| −0.9514| 0.6178   | −4.0456| 0.7066 | −98.8835| 4123 |
| ln temperature    | 4.1271| 4.2485| 4.3307| 4.2160| 0.1553   | 3.5918| 5.2090| 1871.515| 4753 |
| ln rain           | 2.5014| 2.7788| 2.9014| 2.6432| 0.4629   | −2.5257| 3.2958| 393.169 | 4742 |
| ln sunshine       | 6.3238| 6.8084| 7.2177| 6.7363| 0.6622   | 0.6932| 9.4982| 699.3538| 4727 |
| ln productivity   | 7.3879| 7.5646| 7.7538| 7.5449| 0.2767   | 5.5094| 8.0965| 1865.046| 4679 |
| ln consumer       | −1.2141| −1.0503| −0.8621| −1.0293| 0.4324   | −10.3786| 1.7353| −163.993| 4746 |
| ln entrepreneurship| −0.7131| −0.2784| 0.1372| −0.3108| 0.6774   | −4.2457| 2.8415| −31.3625| 4674 |

by city $i$ in year $t$ to the total words in the work report by city $i$ in year $t$.

The data mainly come from the *China Statistical Yearbook* and *China City Statistical Yearbook*. Notably, in the section on the “mechanism test,” production efficiency (ln productivity) is measured by the ratio of the total industrial output above a designated size to the number of industrial enterprises above a designated size (IEADS), willingness to consume (ln consumer) is measured by the ratio of retail sales to regional GDP, and entrepreneurial activity (ln entrepreneurship) is measured by the ratio of the number of urban private employees and individual business to the number of employees in urban firms at the end of the period.

All the descriptive statistics are reported in Table 1.

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1 Following Chen et al. (2018), we use Python to select all sentences in the government work report that contain the following keywords: environment (huanjing), energy consumption (nenghao), pollution (wuran), emissions reduction (jianpai), and environmental protection (huanbao) as environment-related sentences.

2 We are willing to share our dataset in Excel format with those who wish to replicate the results of this study.
Before constructing the regressions, we test whether multicollinearity exists between the variables. Table 2 shows that the variables have little multicollinearity.

Meanwhile, in Table 3, 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.

### Empirical analysis

#### 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 $-0.3837$, which is significant at a level of 1%. Columns (2) to (5) demonstrate the regression results with control variables added one by one. According to the baseline regression results reported in column (5), the influence coefficient of haze pollution on urban innovation is $-0.3672$, which is significant at the 1% 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 ($\ln fdi$) and the education level ($\ln edu$), which is consistent with our expectations. In column (10) of Table 4, the education level has an impact on urban innovation of $-0.0789$ at a significance level of 1%, which means that the education level has a negative effect on urban innovation.

#### Table 2: Multicollinearity test

| Variables       | VIF  | 1/VIF |
|-----------------|------|-------|
| lninnovation    | 3.5400 | 0.2828 |
| lnhaze          | 3.4700 | 0.2879 |
| lnfinance       | 3.3200 | 0.4287 |
| lnfdi           | 2.0700 | 0.4826 |
| lnr            | 1.5500 | 0.6432 |
| lnedu           | 1.5100 | 0.6601 |
| lnregulation    | 1.5000 | 0.6616 |
| lnhumidity      | 1.4500 | 0.6905 |
| lntemperature   | 1.3600 | 0.7332 |
| lnrain          | 1.1400 | 0.8798 |
| lnsunshine      | 3.5400 | 0.2828 |

#### Table 3: Variance inflation factor test

| Variables | VIF  | 1/VIF |
|-----------|------|-------|
| lninnovation | 3.5400 | 0.2828 |
| lnhaze      | 3.4700 | 0.2879 |
| lnfinance   | 3.3200 | 0.4287 |
| lnfdi       | 2.0700 | 0.4826 |
| lnr         | 1.5500 | 0.6432 |
| lnedu       | 1.5100 | 0.6601 |
| lnregulation | 1.5000 | 0.6616 |
| lnhumidity  | 1.4500 | 0.6905 |
| lntemperature | 1.3600 | 0.7332 |
| lnrain      | 1.1400 | 0.8798 |
| lnsunshine  | 3.5400 | 0.2828 |

1.99
Table 4  Regression results based on panel data in the fixed-effects model

|        | (1)     | (2)     | (3)     | (4)     | (5)     | (6)     | (7)     | (8)     | (9)     | (10)    |
|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| lnhaze | −0.3837*** | −0.3769*** | −0.3710*** | −0.2752*** | −0.2793*** | −0.3401*** | −0.3384*** | −0.3577*** | −0.3578*** | −0.3672*** |
|        | (0.0756) | (0.0762) | (0.0760) | (0.0678) | (0.0682) | (0.0730) | (0.0729) | (0.0728) | (0.0728) | (0.0731) |
| lnfinance | 0.0626 | 0.0718* | 0.0744** | 0.0673* | 0.0429 | 0.0428 | 0.0400 | 0.0394 | 0.0399 |
|        | (0.0392) | (0.0387) | (0.0371) | (0.0378) | (0.0518) | (0.0519) | (0.0517) | (0.0518) | (0.0518) |
| lnfdi | 0.0133 | 0.0120 | 0.0115 | 0.0107 | 0.0107 | 0.0109 | 0.0109 | 0.0103 | 0.0123 |
|        | (0.0137) | (0.0129) | (0.0128) | (0.0128) | (0.0137) | (0.0137) | (0.0137) | (0.0138) | (0.0139) |
| lnrd | 0.2124*** | 0.2134*** | 0.2347*** | 0.2340*** | 0.2333*** | 0.2328*** | 0.2334*** |
|        | (0.0263) | (0.0264) | (0.0315) | (0.0314) | (0.0313) | (0.0315) | (0.0320) |
| lnedu | −0.0413 | −0.0797*** | −0.0794*** | −0.0792*** | −0.0792*** | −0.0797*** | −0.0789*** |
|        | (0.0287) | (0.0288) | (0.0287) | (0.0286) | (0.0286) | (0.0286) | (0.0283) |
| lnregulation | 0.0669*** | 0.0668*** | 0.0654*** | 0.0657*** | 0.0665*** | 0.0669*** |
|        | (0.0235) | (0.0225) | (0.0234) | (0.0234) | (0.0234) | (0.0234) |
| lnhumidity | 0.0937 | 0.0855 | 0.0601 | 0.1785 |
|        | (0.2151) | (0.2145) | (0.2266) | (0.2454) |
| lntemperature | −0.0657 | −0.0523 | −0.0100 |
|        | (0.1239) | (0.1240) | (0.1260) |
| lnrain | 0.0208 | 0.0019 |
|        | (0.0316) | (0.0294) |
| lninsunshine | −0.2032** |
|        | (0.0921) |
| lninnovation | 6.0650*** | 6.2821*** | 6.3846*** | 7.1608*** | 7.0709*** | 7.3612*** | 6.9539*** | 7.2221*** | 7.1467*** | 8.2507*** |
|        | (0.2776) | (0.2946) | (0.2949) | (0.3107) | (0.3173) | (0.3326) | (0.9578) | (1.0241) | (1.0239) | (1.4550) |
| Year effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 4752 | 4751 | 4702 | 4702 | 4066 | 4066 | 4066 | 4055 | 4048 | 3997 |
| R² | 0.8864 | 0.8866 | 0.8877 | 0.8966 | 0.8955 | 0.8955 | 0.8955 | 0.8961 | 0.8958 | 0.8953 |

*, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at city level are in parentheses.
It might be that although the proportion of educational expenditure in China has grown in recent years, the quality of education has not improved. It is still the case that college graduates are insufficient for meeting market demand. At the same time, the development of local enterprises in China erodes multinational corporations' profits or market share, so it threatens FDI. Therefore, FDI adopts a strategy of inhibiting the R&D of local enterprises, which hinders its spillover effect and adversely affects improvement in urban innovation capabilities and the development of high-tech industries.

### Considering endogeneity

Because of the potential bidirectional 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 adopt a shift-share design to construct a Bartik instrumental variable (IV) in order to eliminate endogeneity (Bartik 1991). Because the Bartik IV is based on the initial share, it is related to haze pollution, but has nothing to do with other factors affecting urban innovation. Following Zhao et al. (2021b), it is constructed as follows.

\[
haze_{ijt} = haze_{ijt0} \left(1 + g_{jt}\right)
\]

where \(haze_{ijt}\), called the Bartik IV, is haze pollution in city \(i\) in province \(j\) in year \(t\), \(haze_{ijt0}\) is the initial haze pollution in city \(i\) in province \(j\) in year \(t_0\), \(g_{jt}\) is the rate of change in haze pollution in province \(j\) in year \(t\).

Accordingly, 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. After we control for time-fixed effects, we find that the impact of haze pollution on urban innovation is still significantly negative. That is, the regression result that worsening haze pollution inhibits urban innovation is robust.

### Robustness checks

#### Replacing variables

In order to check the robustness of our results, we adopt the methodology of replacing key variables in regressions.

First, we replace haze pollution (\(\text{lnhaze}\)) by sulfur dioxide emissions (\(\text{lnSO}_2\)). The results reported in column (1) of Table 6 show that the coefficient of \(\text{lnSO}_2\) on urban innovation (\(\text{lninnovation}\)) is significantly negative at a statistical level of 1%, which is consistent with our expectation.

Second, we replace the dependent variable, i.e., total patents granted by the amount of invention patents granted (\(\text{lninnovation}_1\)) and the urban innovation index (\(\text{lninnovation}_2\)). The data on the urban innovation index come from the "FIND Report on City and Industrial Innovation in
China (2017)" (Kou and Liu 2017). Columns (2) and (3) in Table 6 show the results after replacing the interpreted variable. They demonstrate that the impact of haze pollution on innovation is still negative at the 1% level of statistical significance, which implies that the regression results are robust. Additionally, besides the proportion of education expenditure (lnedu), there are other indicators which can reflect the education level. Hence, we employ the weighted years of education (lnedu) and the number of college students per 10,000 people (lnedu2) to replace the proportion of education expenditure (lnedu). The regression results are reported in columns (4) and (5) of Table 6, which show that haze pollution still has a significantly negative impact on urban innovation.

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 lninnovation in Table 1 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 1 to 99%, and the regression results are reported in Table 7. The impact of haze pollution on urban innovation is still significantly negative, which means that our regression results are robust.

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 (Jiang et al. 2020). 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. Before conducting this analysis, we need to identify whether urban innovation is applicable to the spatial econometric model. Spatial autocorrelation can be measured by Global Moran’s I and Geary’s C. According to Table 8, the Global Moran’s I values of lninnovation are all greater than 0 and significant at the 5% level at least, while the Geary index C values of lninnovation are all less than 1 and also significant at the 10% level at least. This implies that, significantly and positively, spatial autocorrelation is found across cities in China.

Haze pollution in China is influenced not only by geographic factors but also by economic factors. As seen in Figure 2, more severe haze pollution is found in more developed regions, such as North China and East China. Therefore, we construct an economic distance matrix to test the relationship between haze pollution and urban innovation further, as follows.

\[
W_{ij} = W^d_{ij} \text{diag} \left( \frac{Y_1}{\bar{Y}}, \frac{Y_2}{\bar{Y}}, \ldots, \frac{Y_n}{\bar{Y}} \right)
\]

\[
W^r_{ij} = \frac{W^e_{ij}}{\sum_j W^e_{ij}}, i \neq j
\]

where \(W^d_{ij}\) is the economic distance matrix; \(W^e_{ij}\) is the geographic distance matrix; \(W^r_{ij}\) is the standardized economic distance matrix; \(\bar{Y} = \sum_{i=1}^{n} Y_i / \sum_{i=1}^{n} \sum_{t=1}^{m} t_i \) is the mean of real GDP per capita of city \(i\), and \(\bar{Y} = \sum_{i=1}^{n} \sum_{t=1}^{m} Y_i / \sum_{i=1}^{n} \sum_{t=1}^{m} t_i \) is the mean of real GDP per capita of all cities.

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3 Notes: The “innovation index” covers 680 national economic industries of four-digit code in 338 cities from 2001 to 2016. All these industries are authorized for invention patent. Following Pakes and Schankerman (1984), Kou and Liu (2017) constructed the “innovation index” based on the micro invention patent authorized by China National Intellectual Property Administration. More detail and the data can be available at https://kouzonglai.blog.caixin.com/archives/176063.

4 According to the Chinese education system, schooling consists of 6 years of primary school, 3 years of junior secondary school, 3 years of senior secondary school, and 4 years of college. Hence, we calculate the education level as follows. \(Y = (X_1*6 + X_2*9 + X_3*12 + X_4*16) / X\), where \(Y\) is the weighted years of education, \(X_1, X_2, X_3, X_4\), and \(X\) is population aged 6 and over, primary school, junior secondary school, senior secondary school, and college and higher level, respectively. \(X\) is population aged 6 and over (sample survey) (person).
Accordingly, we employ a spatial Durbin model (SDM), a spatial autoregression model (SAR), and a spatial error model (SEM). The coefficients of haze pollution are reported in Table 9, and they are all significantly negative.

After considering the likelihood rate (LR), goodness of fit ($R^2$), and Akaike information criterion (AIC), we select SDM as the model in our analysis. It shows that the direct and indirect effects of haze pollution on innovation are

| Year | Moran’s I | Geary’s C | Year | Moran’s I | Geary’s C |
|------|-----------|-----------|------|-----------|-----------|
|      | Spatial economic-geographic matrix | Spatial economic-geographic matrix | Moran’s I | Geary’s C | Moran’s I | Geary’s C |
| 2001 | 0.227*** | 0.731*** | 2010 | 0.264*** | 0.689*** |
| 2002 | 0.233*** | 0.732*** | 2011 | 0.258*** | 0.697*** |
| 2003 | 0.257*** | 0.709*** | 2012 | 0.247*** | 0.703*** |
| 2004 | 0.245*** | 0.721*** | 2013 | 0.218*** | 0.732*** |
| 2005 | 0.258*** | 0.706*** | 2014 | 0.234*** | 0.719*** |
| 2006 | 0.273*** | 0.689*** | 2015 | 0.223*** | 0.732*** |
| 2007 | 0.267*** | 0.684*** | 2016 | 0.217*** | 0.736*** |
| 2008 | 0.276*** | 0.671*** | 2017 | 0.205*** | 0.749*** |
| 2009 | 0.250*** | 0.703*** | 2018 | 0.192*** | 0.762*** |

* *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

| (1) | (2) | (3) |
|-----|-----|-----|
| $\ln(\text{innovation})$ | $\ln(\text{innovation})$ | $\ln(\text{innovation})$ |
| $\ln(\text{haze})$ | $-0.2515***$ | $-0.4298***$ | $-0.1870***$ |
| | $(0.0696)$ | $(0.0564)$ | $(0.0636)$ |
| $\rho$ | $0.6894***$ | $0.7917***$ | |
| | $(0.0197)$ | $(0.0178)$ | |
| $\lambda$ | $0.1702***$ | $0.1743***$ | $0.1725***$ |
| | $(0.0101)$ | $(0.0107)$ | $(0.0106)$ |
| $\sigma^2_e$ | $0.3209***$ | $-0.5015***$ | - |
| | $(0.0717)$ | $(0.0657)$ | |
| $\text{LR}_{\text{Direct}}$ | $1.3814***$ | $-1.5610***$ | - |
| | $(0.2850)$ | $(0.2134)$ | |
| $\text{LR}_{\text{Total}}$ | $1.7023***$ | $2.0625***$ | - |
| | $(0.3017)$ | $(0.2648)$ | |
| Control variables | Yes | Yes | Yes |
| Observations | 4752 | 4752 | 4752 |
| $R^2$ | 0.8319 | 0.7505 | 0.4074 |
| AIC | 5543.748 | 5818.402 | 6060.412 |
| Likelihood-ratio test | LR chi2(10) = 294.65 | LR chi2(10) = 536.66 |
| (Assumption: SAR nested in SDM) | Prob > chi2 = 0.0000 | Prob > chi2 = 0.0000 |

* *, **, 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.
significantly negative at the level of 10%, indicating that haze pollution in a region not only directly inhibits local innovation but also has an indirectly negative impact on the innovation level of adjacent regions. Moreover, the absolute value of the spatial spillover effect is greater than the direct effect. This implies that haze pollution in other regions has a greater inhibitory effect on local innovation, which not only demonstrates that it is reasonable to use spatial econometrics but also confirms our hypothesis.

Mechanism test

Investigating the mechanism in which haze pollution affects urban innovation is of great significance in clarifying the relationship between these two variables. Following Gao and Zheng (2020) and Ma and Ruzic (2020), this section conducts empirical tests based on the three mechanisms described above, namely, production efficiency, willingness to consume, and entrepreneurial activity (Fan et al. 2020; Zhao et al. 2021a). The regression results are reported in Table 10.

First, Table 10 shows that the effect of haze pollution on production efficiency is $-0.4581$ at the 1% significance level. This means that haze pollution can inhibit urban innovation through the channel of reducing producer productivity. As an important factor of production, producers, especially high-end technical employees, always consider and care about the urban environment in which they work and live (Jiang et al. 2020; Zhao et al. 2021a). However, haze pollution can significantly worsen air quality, and widespread haze pollution slows down the flow of workers and reduces labor reserves (Xue et al. 2021). Additionally, haze pollution can significantly worsen air quality, and widespread haze pollution slows down the flow of workers and reduces labor reserves (Xue et al. 2021). Therefore, haze pollution can significantly worsen air quality, and widespread haze pollution slows down the flow of workers and reduces labor reserves (Xue et al. 2021).

Second, the coefficient of haze pollution on willingness to consume is $-0.4592$, which is significant at the 1% level. This means that haze pollution can significantly reduce urban innovation by weakening willingness to consume. The main reason is that if consumers encounter haze when they go outside, they are more likely to stay home, rather than engage in outdoor activities. In this case, business activities can be gradually be 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 (Desmet and Parente 2010; Eizenberg 2014).

Third, the effect of haze pollution on entrepreneurial activity is $-0.1704$, which is significant at the 1% level. It seems that haze pollution has a significantly negative impact on entrepreneurial activity and further reduces support for urban innovation. Poor air quality due to haze pollution does not create beneficial environmental conditions for production and business by enterprises, and the decrease in market demand also forces them to reduce transactions or even shut down to avoid more losses (Buoli et al. 2018; Guo et al. 2021). Additionally, aerosol particles, i.e., the main substance in haze pollution, have a serious impact on traffic conditions and discourage logistics and commercial activity (De Massis et al. 2016). Hence, haze pollution can inhibit innovation through the channel of hindering entrepreneurial activity.

Further discussion

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

First, based on the classification standard of the National Bureau of Statistics of China, we divide the 265 cities at the

| Table 10  Mechanism test |
|-------------------------|
| (1) Inproductivity | (2) Innovation | (3) Inconsumer | (4) Innovation | (5) Inentrepreneurship | (6) Innovation |
| lnhaze | $-0.2296^{***}$ | $-0.4592^{***}$ | $-0.1704^{**}$ |
| (0.0526) | (0.0446) | (0.0713) |
| lnproductivity | 1.0898*** | 0.4961*** |
| (0.0651) | (0.1009) |
| lnconsumer |  |  |
| lnentrepreneurship | 0.3963*** |
| (0.0533) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Years effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 3842 | 3828 | 4006 | 3991 | 3936 | 3921 |
| $R^2$ | 0.6135 | 0.7613 | 0.1235 | 0.6414 | 0.2223 | 0.6436 |

* *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are in parentheses
prefectural 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 a significant inhibitory effect on innovation in the central region (−0.5279), while in the eastern region and the western region the effect is insignificant. The reason is as follows. Eastern China has a higher level of economic development, better infrastructure, and a better environment for talent incubation than the central and western regions. Consequently, the environmental regulations in the eastern region are stricter and the effects of haze governance are better. As a result, the inhibitory effect of haze pollution on innovation in the eastern region is insignificant. As seen in Figure 2, many high-pollution cities are in the central region, which makes it difficult to carry out innovation projects and causes a greater loss of human capital due to the threat of haze pollution (Feng and Yuan 2021; Zhao et al. 2021a). It, in turn, poses a more serious obstacle to improvement in innovation. Therefore, in the central region, haze pollution has a significantly suppressive effect on its innovation ability. Because of its backward economic development and insufficient innovation vitality, haze pollution in the western region has a relatively small impact on local innovation.

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 0.5656 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 −0.2344, which is less than that of resource-based cities. 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 smaller.

### Conclusion and policy implications

Based on the PM2.5 concentration data and the urban innovation indicators on 265 prefectural-level cities in China from 2001 to 2018, 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, replacing variables, excluding extreme outliers, and taking spatial correlation into consideration. This is because haze pollution inhibits urban innovation mainly through the channels of production efficiency, willingness to consume, and entrepreneurial activity. Meanwhile, in terms of the different regions, haze pollution has a significant inhibitory effect on innovation in the central region. Additionally, this effect applies to resource-based cities but is less severe in non-resource-based cities.

Considering the importance of innovation and the severity of pollution, management of the haze pollution is an urgent matter 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. We should also attempt to eliminate backward production capacity and highly polluting industries and develop cleaner production and a circular economy. Second, we should realize that prevention of pollution at the front end

|                      | (1) ln\(innovation\) | (2) ln\(innovation\) | (3) ln\(innovation\) | (4) ln\(innovation\) | (5) ln\(innovation\) |
|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
|                      | East                 | Center               | West                 | Resource             | Non-Resource         |
| ln\(haze\)           | −0.2566 (0.1613)     | −0.5279*** (0.1046)  | 0.0280 (0.1303)      | −0.5656*** (0.1022)  | −0.2344** (0.0942)   |
| Control variables    | Yes                  | Yes                  | Yes                  | Yes                  | Yes                  |
| Years effects        | Yes                  | Yes                  | Yes                  | Yes                  | Yes                  |
| Observations         | 1510                 | 1448                 | 1039                 | 1526                 | 2471                 |
| \(R^2\)              | 0.9004               | 0.9048               | 0.9131               | 0.8684               | 0.9157               |

*, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at city level are in parentheses.
is more important than treatment at the back end and treat technological innovation as an engine for promoting efficient ways to control haze. Meanwhile, we should also realize the importance of protecting the environment and try to promote a green way of life. Third, it is necessary to construct a joint prevention and control mechanism for interregional haze pollution. Through an effective haze reduction approach of cost sharing and technology sharing among regions, the haze reduction responsibilities of each region need to be clarified, in order to avoid the “tragedy of the commons." 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. We should do our utmost to raise the quality of education and give full play to the positive role of talents in technological innovation, productivity improvement, and environmental protection.

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