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Special Section:
Atmospheric PM2.5 in China: indoor, outdoor, and health effects

Key Points:

- $PM_{2.5}$- and O_3-related mortality risks presented significant spatial heterogeneity
- Urbanization had effects on $PM_{2.5}$, O_3, and mortality associations in Beijing
- With the decrease in urbanization level, mortality risks exhibited upward trends

Supporting Information:

Supporting Information may be found in the online version of this article.

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Influence of Urbanization on the Spatial Distribution of Associations Between Air Pollution and Mortality in Beijing, China

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Abstract This study investigated the influence of urbanization on the intra-city spatial distribution of associations between air pollution and mortality in Beijing, China. First, we utilized the generalized additive model to establish the exposure-response associations of $PM_{2.5}$, O_3, with nonaccidental and cardiorespiratory mortality between urban and suburban areas. Second, we assessed district-specific air pollution-related mortality and analyzed how these associations were affected by the degree of urbanization. Finally, we analyzed the changes in air pollution-related mortality before and after the enforcement of the Air Pollution Prevention and Control Action Plan (referred to as the Action Plan). The effect estimates of $PM_{2.5}$ for nonaccidental mortality were 0.20% (95% CI: 0.12–0.28) in urban areas and 0.46% (95% CI: 0.35–0.58) in suburban areas per 10 μg/m^3 increase in $PM_{2.5}$ concentrations. The corresponding estimates of O_3 were 0.13% (95% CI: −0.04–0.29) in urban areas and 0.34% (95% CI: 0.12–0.56) in suburban areas per 10 μg/m^3 increase in O_3 concentrations; however, the difference between the estimates of O_3 in urban and suburban areas was not statistically significant. The district-specific results suggested that the estimated risks increased along with urban vulnerability levels for the effects of $PM_{2.5}$. Implementing the Action Plan reduced the mortality risks of $PM_{2.5}$, but the risks of O_3 increased in some districts. However, the difference in the estimates between the pre- and post-emission reductions was not statistically significant. Our study indicated that populations living in less urbanized areas are more vulnerable to the adverse effects of air pollution in Beijing, particularly for $PM_{2.5}$.

Plain Language Summary A large body of epidemiological studies has verified that exposures to air pollution are associated with increased mortalities, However, most studies were carried out considering the city as a whole, and evidence of the intra-city heterogeneity in air pollution-mortality associations is limited. In this study, we explored the influence of urbanization levels on the spatial distribution of exposure-response associations between $PM_{2.5}$, O_3, and mortality in Beijing, China. The results indicated significant spatial variations in $PM_{2.5}$-related mortality risks, which were lower in urban areas than in suburban areas. As the urbanization level decreased, the $PM_{2.5}$-related mortality risks in different districts increased. However, the O_3-related mortality risks were not significantly different. The spatial heterogeneity of air pollution-related mortality reflects health disparities during urbanization. Our study reveals the need for precise and varied air pollution management policies that take into account the levels of urbanization within the areas of application.

1. Introduction

Between 1978 and 2020, China experienced a rapid increase in the urban population, from 170 to 902 million, corresponding to an urbanization rate change from 17.9% to 63.9% (National Bureau of Statistics of China, 2022). By 2030, the urbanization rate and total urban population in China are projected to reach 71% and 1,070 million, respectively (Q. Chen et al., 2017). This trend can lead to several consequences for the health of China's population. There is no consensus on whether urbanization is more beneficial or detrimental to human health, but the common understanding is that the mechanisms underlying the impact on human health are complex. On the

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one hand, urbanization provides several advantages for city dwellers compared to their rural counterparts, thus offering opportunities for improving the well-being of residents. On the other hand, substantial health risks can be caused by economic growth and urbanization.

Air pollution resulting from the increased consumption of fossil fuels is the major concern of the urbanization process. Previous epidemiological studies have suggested that short- and long-term exposures to air pollution are associated with an increase in all-cause, cardiovascular, and respiratory-related mortalities (Apte et al., 2015; Brown et al., 2022; C. Liu et al., 2019; Sheehan et al., 2016). However, most studies were carried out considering the city as a whole, as opposed to accounting for the different parts of the city due to the inaccessibility of data. Owing to the spatial heterogeneity in air pollution exposure and intra-city disparity in socio-economic status, evaluating the city as a whole could underestimate the issues within urban subpopulations. Although few studies have estimated the health burden of air pollution induced by urbanization (Maji et al., 2020; Xie et al., 2016; Yim et al., 2019), their exposure-response parameters were derived from the published literature without consideration of the possible differences in exposure-response associations between air pollution and health outcomes at different urbanization levels. As such, the findings of these studies suggest that urbanization has exacerbated the health burden of air pollution, mainly driven by the higher pollutant concentrations and denser population in areas with higher urbanization. Clarifying the spatial distribution of exposure-response associations between health outcomes and air pollution depends on the disaggregated intra-urban health and air pollution data. Furthermore, several studies have investigated the urban–rural differences in the associations between air pollution and mortality. They found that the relative risks of air pollution-related mortality were generally higher in rural areas than in urban areas (Atkinson et al., 2012; Lin et al., 2022; Madrigano et al., 2015; Renzi et al., 2019; Zhao et al., 2021). These studies improved our knowledge of the mortality risks of air pollution exposure in rural areas. However, the spatial distribution of associations between air pollution and health outcomes within cities is rarely discussed. This topic is particularly important for sustainable urban development in developing countries, which are undergoing rapid urbanization but face inequality issues due to the unbalanced economic development levels.

To abate severe air pollution and secure public health, the State Council of China issued the Air Pollution Prevention and Control Action Plan (hereafter referred to as the Action Plan) on 10 September 2013. The Action Plan contains a series of stringent measures to achieve the overall improvement in national air quality and drastic reductions in heavily polluted days after 5 years of efforts, including multi-pollutant emission reduction, industrial structure optimization, technology transformation acceleration, and energy structure adjustment (State Council of China, 2013). With the successful implementation of the Action Plan, particulate matter with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) pollution has significantly ameliorated, leading to remarkable improvements in environmental air quality (Zhang et al., 2019). However, regional haze episodes still frequently occur during autumn and winter. At the same time, the problem of ground-level O_3 pollution has become increasingly prominent and has emerged as a new challenge for current emission control actions. The three-year moving average value of O_3 concentrations from 2015 to 2020 exhibited a steady rise (The Annual Report Working Group of Synergistic Roadmap for Carbon Neutrality and Clear Air in China 2021, 2021). Many studies have recorded appreciable health benefits of the enforcement of emission reduction plans (L. Han, Sun, Gong, et al., 2020; L. Han, Sun, He, et al., 2020; Huang et al., 2018); however, little is known about how the impacts associated with O_3 have changed.

As the capital of China and the second largest city in the country, Beijing metropolitan area had a population of 21.89 million in 2021, of which 87.5% was urban. In this study, taking Beijing as a typical example, we explored the influence of urbanization levels on the spatial distribution of exposure-response associations between $PM_{2.5}$, O_3, and mortality. Moreover, we analyzed changes in the $PM_{2.5}$- and O_3-related mortality risks caused by the implementation of the Action Plan. The findings are expected to provide beneficial evidence for developing targeted policies to protect vulnerable populations from air pollution, particularly against the backdrop of rapid urbanization and pollution by $PM_{2.5}$ and O_3 in China.

2. Materials and Methods

2.1. Data Collection

Daily mortality data for Beijing from 1 January 2013, to 31 December 2016, were obtained from the Chinese Center for Disease Control and Prevention. Based on the tenth revision of the International Classification of Diseases, we extracted the data on daily mortality from nonaccidental causes (codes A00–R99), respiratory diseases (codes J00–J98), and cardiovascular diseases (codes I00–I99). In addition, we classified the data by district according to residential addresses to obtain district-specific mortality records.

District-specific daily meteorological data, including average temperature and relative humidity, were obtained from the Beijing Municipality Meteorological Bureau (Figure S1 in Supporting Information S1). We utilized the data from the Chaoyang and Haidian stations to represent the weather conditions in the nearby Dongcheng and Xicheng districts because no meteorological monitoring stations were set there.

Air pollution data, including O_3 and $PM_{2.5}$ concentrations, were retrieved from the Beijing Municipal Ecological and Environmental Monitoring Center (BMEEMC). The BMEEMC made public real-time ground-level concentrations of primary air pollutants in 2013. A total of 35 monitoring stations were chosen across all districts of Beijing (Figure S1 in Supporting Information S1). The monitoring and quality control of air pollutant concentrations were strictly performed according to the ambient air quality standards (GB 3095–2012). $PM_{2.5}$ concentrations were based on the 24 hr average, and O_3 concentrations were based on the daily maximum 8 hr average (DMA8). Observations were averaged for districts with two or more stations.

2.2. Statistical Methods

2.2.1. Establishment of Urban Vulnerability Index

We included eight demographic and socio-economic variables to establish the urban vulnerability index, including the proportion of the urban population, the proportion of the population aged ≥65 years, the number of beds per 1,000 people, per capita disposable income, the proportion of the unemployed, average years of education, the proportion of illiteracy, and proportion of the population living alone. The first five indices, which are the average values of the corresponding variables, were obtained and calculated from the Beijing Regional Statistical Yearbooks from 2014 to 2017. The last three variables were obtained from the 2010 County-Level Population Census data.

First, we calculated Spearman's correlation coefficients among the eight vulnerability variables. We then used principal component analysis to limit the number of variables and create independent factors for inclusion in the vulnerability index, which has been used in previous studies to assess the heat vulnerability of populations in different parts of the study regions (Harlan et al., 2013; Reid et al., 2009). The original variables were dimensionally reduced using principal component analysis. The variables were normalized to a mean of 0 and a standard deviation of 1. The four variables that were negatively associated with the urban vulnerability levels (including the proportion of the urban population, the number of beds per 1,000 people, per capita disposable income, and average years of education) were multiplied by −1 to obtain positive variables. A Kaiser–Meyer–Olkin value of 0.659 and a P-value of Bartlett's sphericity test lower than 0.05 would indicate that the data met the criterion for factor analysis. A varimax rotation was used to minimize the number of original variables, load on any one factor, and increase the variation among factors, thus making these new factors more statistically independent than the original variables. We retained two factors based on a combined criterion of eigenvalues >1 and a total explained variance of >85%. Finally, the comprehensive evaluation scores were calculated to obtain the urban vulnerability index of each district. The principal component analysis was conducted using the IBM SPSS Statistics software (SPSS 22.0) (IBM Corporation, 2013).

2.2.2. Exposure-Response Associations Between $PM_{2.5}$, O_3, and Mortality

We utilized the generalized additive model (GAM) to estimate the associations of $PM_{2.5}$ and O_3 concentrations with mortality in Beijing. Relative to the total population, the number of daily deaths is generally assumed to be a small probability event that obeys the Poisson distribution. Thus, a logistic regression model was introduced to the GAM. The GAM can fit the exposure-response associations between air pollutants and mortality using nonlinear and linear additive forms. The effects of some potential confounders, including long-term trends, seasonal variations, and meteorological factors, can be adjusted using nonparametric smoothing functions in the GAM. The model is as follows:

$$\mathrm{Log}[E(Y_k)] = \alpha + \mathrm{DOW} + \beta X_k + s(\mathrm{time}, df) + s(\mathrm{Temp}_k, df) + s(\mathrm{RH}_k, df) + s(\mathrm{AP}_k, df)$$

where $E(Y_k)$ denotes the expected number of deaths on day k, α denotes the intercept, DOW denotes the indicator variable to adjust for the day of the week effect, β denotes the coefficients of exposure-response relationships of mortality risks associated with a 10 μg/m^3 increase in daily $PM_{2.5}$ and O_3 concentrations, X_k denotes the $PM_{2.5}$ and O_3 concentrations on day k, s denotes the smoothing spline function, time denotes the calendar time, df denotes the degrees of freedom, Temp_k and RH_k denote the mean temperature and relative humidity on day k, respectively, and AP_k denotes the air pollutant on day k. When the impacts of $PM_{2.5}$ were estimated, the effects of O_3 were adjusted by a spline function of 3*df*; alternatively, when the impacts of O_3 were estimated, the effects of $PM_{2.5}$ were adjusted by a spline function of 3*df*. A spline function with 7*df* for the time variable was used to control the long-term trend and seasonal variations in mortality data. Spline function with 3*df* for mean temperature and relative humidity was used to control their underlying impacts. Mortality risks associated with $PM_{2.5}$ and O_3 concentrations on the current day and over a lag of up to 6 days (lag0–lag6) were examined. The maximum estimations across the lag periods were chosen for further analysis.

The excess risk (ER) and the corresponding 95% confidence interval (CI) were used to quantify the mortality risks associated with a 10 μg/m^3 increase in $PM_{2.5}$ and O_3 concentrations, calculated using the following formulas:

$$\text{ER} = [\text{EXP}(\beta * 10) - 1] * 100\%$$

$$\text{ER 95\%CI} = [\text{EXP}((\beta \pm 1.96SE) * 10) - 1] * 100\%$$

where β denotes the coefficients of exposure-response associations between air pollution and mortality derived from the GAM. SE denotes the standard errors of β.

We tested whether the differences in the estimates between urban and suburban areas and between pre- and post-emission reduction periods were statistically significant using the following formula:

$$\left(\widehat{Q_1} - \widehat{Q_2}\right) \pm 1.96\sqrt{\widehat{\text{SE}_1}^2 + \widehat{\text{SE}_2}^2}$$

where $\widehat{Q_1}$ and $\widehat{Q_2}$ denote the estimated coefficients of exposure-response associations for the two categories and $\widehat{\text{SE}_1}^2$ and $\widehat{\text{SE}_2}^2$ denote the corresponding standard errors.

Moreover, we performed sensitivity analyses to verify the robustness of our findings from the core model by altering the *df* values for calendar time from 6 to 8 and by including the mean wind speed in the main model using a natural cubic spline with 3*df*. Sensitivity analyses were conducted for district-specific associations between air pollutants and mortality.

Previous studies have reported that the O_3 concentrations were higher in the warm season (Lu et al., 2018; Maji & Namdeo, 2021), which covers 6 months from April to September (Lefohn et al., 2018), and warm season O_3 exposure has been recommended for assessing acute health effects (Maji & Namdeo, 2021). Therefore, this study evaluated the impacts of $PM_{2.5}$ for the whole year and the impacts of O_3 for the warm season. Additionally, we divided the study period into the pre-emission reduction period (2013–2014) and the post-emission reduction period (2015–2016). We then used the GAM to estimate the mortality risks associated with $PM_{2.5}$ and O_3 exposure during both periods.

The above analyses were conducted using the "mgcv" package in the R software (R 4.1.1) (R Core Team, 2020). All statistical tests were two-sided, and statistical significance was set at $P < 0.05$.

3. Results

3.1. Data Description and District-Specific Urban Vulnerability Index

Currently, there are 16 districts in Beijing, of which the Dongcheng, Xicheng, Chaoyang, Fengtai, Shijingshan, and Haidian districts belong to the central urban area (Beijing Municipal Bureau of Statistics, 2021). Therefore, these six districts were counted as urban areas, and the others were counted as suburban areas (Figure 1).

Many of the eight urban vulnerability variables were highly correlated (Table S1 in Supporting Information S1). The principal component analysis yielded two factors with primary loading (Table 1). The first factor combined the proportion of the urban population, illiteracy, people living alone, per capita disposable income, and average years of education. The second factor combined the proportion of people aged ≥65 years, the number of beds per 1,000 people, and the proportion of unemployed. As shown in Figure 1, districts in suburban areas had relatively higher vulnerability levels than those in urban areas.

From 2013 to 2016, the daily average temperature was 13.5°C in urban areas, slightly higher than that in the suburban areas (12.7°C). The annual average $PM_{2.5}$ concentrations in all districts exceeded the Chinese National

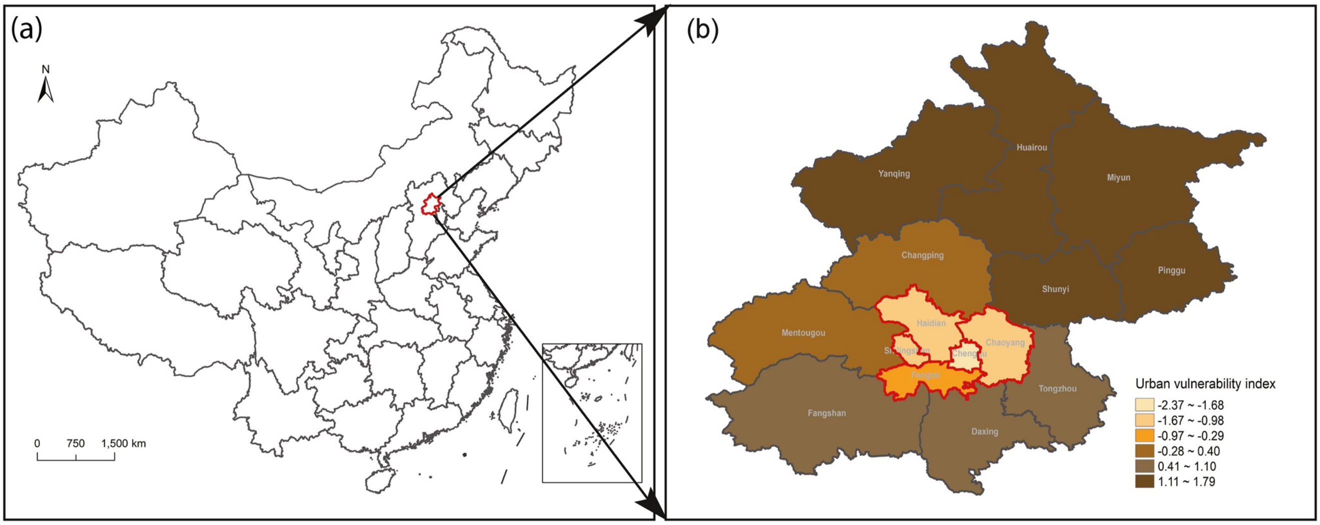

Figure 1. (a) Geographical location and (b) distribution of district-specific urban vulnerability index in Beijing, China. The Xicheng and Dongcheng districts were combined to form the Chengqu district. Districts marked with red boundaries belonged to urban areas, and the others belonged to suburban areas.

Ambient Air Quality Standard Grade II (35 μg/m^3). The daily average concentrations of $PM_{2.5}$ were 87.5 and 80.9 μg/m^3 for urban and suburban areas, respectively. The Fangshan and Tongzhou suburban districts had the most severe $PM_{2.5}$ pollution, with daily average concentrations of 106.1 and 101.2 μg/m^3, respectively (Figure S2 in Supporting Information S1). The O_3 pollution was higher in the suburban area, with DMA8 O_3 concentrations of 137.1 and 130.0 μg/m^3 during the warm season in the suburban area and urban area, respectively. There was an average of 232 days during the warm season when O_3 exceeded the Grade II standard (160 μg/m^3) in all districts, ranging from 176 days in the Haidian District to 283 days in the Daxing District. After implementing the Action Plan, daily average $PM_{2.5}$ concentrations in all districts declined, while the average DMA8 O_3 concentration increased in most districts (Figure S3 in Supporting Information S1).

During the 4 years, a total of 293,227 deaths occurred due to nonaccidental causes in Beijing, ranging from 4,841 (an average of 3.3 deaths per day) in the Huairou District to 48,227 deaths (an average of 33 deaths per day) in the Chaoyang District (Figure S2 in Supporting Information S1). Of those, there was a total of 167,688 deaths due to cardiorespiratory diseases, ranging from 3,034 (an average of 2.1 deaths per day) in Huairou District to 26,201 deaths (an average of 17.9 deaths per day) in Chaoyang District (Figure S2 in Supporting Information S1). Nonaccidental deaths in urban regions accounted for 63% of the total number, and the corresponding proportion of deaths from cardiorespiratory diseases was 60%.

Table 1
Principal Components Analysis of Urban Vulnerability Variables in the 16 Districts of Beijing

	Factor 1	Factor 2
Proportion of the urban population	**0.86**	0.37
Number of beds per 1,000 people	0.37	**0.87**
Per capita disposable income	**0.89**	0.38
Average years of education	**0.99**	0.09
Proportion of population aged ≥65 years	−0.06	**−0.92**
Proportion of the unemployed	0.46	**−0.66**
Proportion of illiteracy	**0.90**	−0.11
Proportion of the population living alone	**−0.85**	0.20

Note: The values denote factor loadings that represent correlations between the variables and factors and also the weights of each variable on the factors. The bold values denote the significant loadings on that factor.

3.2. Air Pollution-Related Mortality in Urban and Suburban Areas

The lag patterns between air pollutants and mortality were similar in urban and suburban areas, with the highest estimates being lag0 for $PM_{2.5}$ and lag1 for O_3 (Figure 2a). However, there were discrepancies in the exposure-response associations of air pollutants and mortality between urban and suburban areas (Figure 3). The effects of both $PM_{2.5}$ and O_3 on mortality were smaller in urban than in suburban areas (Figure 2b). For $PM_{2.5}$, the effect estimates for nonaccidental mortality per 10 μg/m^3 increase in $PM_{2.5}$ concentrations were 0.20% (95% CI: 0.12–0.28) in urban and 0.46% (95% CI: 0.35–0.58) in suburban areas. The corresponding estimates for cardiorespiratory mortality were 0.29% (95% CI: 0.19–0.40) in urban areas and 0.50% (95% CI: 0.36–0.65) in suburban areas. The differences in the estimates between urban and suburban areas for both mortality outcomes were statistically significant. For the impacts of O_3 in the warm season, the estimated risks for nonaccidental mortality per 10 μg/m^3 increase in O_3 concentrations were 0.13% (95%

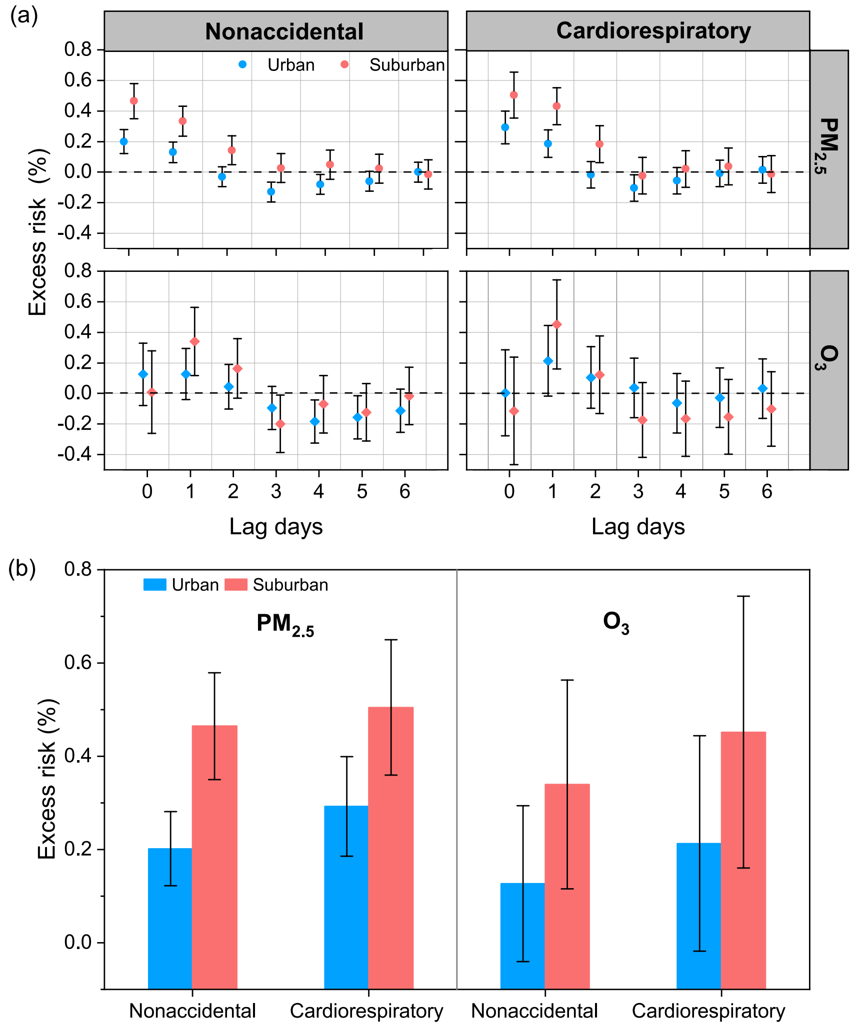

Figure 2. (a) Lag patterns between air pollutants and mortality in urban and suburban areas of Beijing. (b) Estimated excess risks for mortality per 10 μg/m^3 increase in concentrations of air pollutants in urban and suburban areas of Beijing.

CI: −0.04–0.29) in urban areas and 0.34% (95% CI: 0.12–0.56) in suburban areas. Accordingly, the estimates for cardiorespiratory mortality were 0.21% (95% CI: −0.02–0.44) in urban and 0.45% (95% CI: 0.16–0.74) in suburban areas. However, the differences in the estimates between urban and suburban areas for both mortality outcomes were not statistically significant.

3.3. District-Specific Associations Between Air Pollution and Mortality

The estimated impacts of $PM_{2.5}$ and O_3 on mortality exhibited distinct spatial heterogeneity (Figure 4). For the impacts of $PM_{2.5}$, the estimated risks per 10 μg/m^3 increase in $PM_{2.5}$ concentrations ranged from 0.13% (95% CI: −0.08–0.35) in Dongcheng District to 0.60% (95% CI: 0.21–0.99) in Miyun District for nonaccidental mortality, and from 0.08% (95% CI: −0.30–0.45) in Shijingshan District to 0.87% (95% CI: 0.38–1.36) in Miyun District for cardiorespiratory mortality. For the impacts of O_3 in the warm season, the estimated risks per 10 μg/m^3 increase in O_3 concentrations ranged from 0.01% (95% CI: −0.08–0.35) in Fengtai District to 1.08% (95% CI: 0.37–1.79) in Pinggu District for nonaccidental mortality, and from 0.24% (95% CI: −0.23–0.72) in Fengtai District to 1.24% (95% CI: 0.40–2.09) in Pinggu District for cardiorespiratory mortality. Sensitivity analyses indicated that district-specific estimates from the core model were robust (Figure S4–S6 in Supporting Information S1).

The correlation analyses showed different associations between the mortality risk estimates and the urban vulnerability index for $PM_{2.5}$ and O_3. The estimated ERs on mortality for $PM_{2.5}$ significantly increased alongside urban vulnerability levels, whereas the changes in the estimated ERs of O_3 were not significant (Figure 5).

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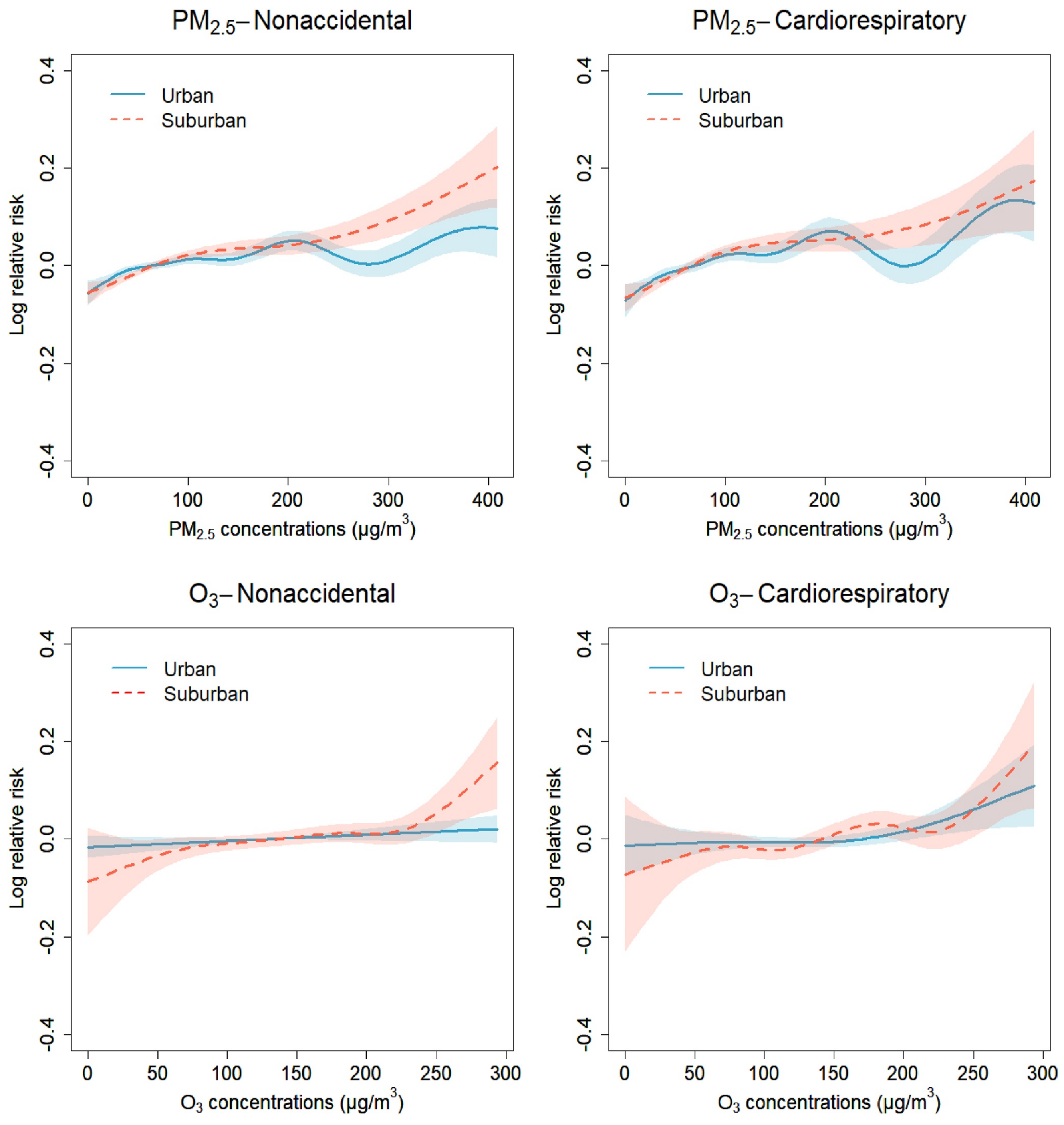

Figure 3. Exposure-response curves of $PM_{2.5}$, O_3 against mortality risks in urban and suburban areas in Beijing, China. Blue solid lines and red dotted lines denote the predicted log-relative risk of urban areas and suburban areas, respectively; shaded areas denote the 95% confidence intervals.

3.4. Air Pollution-Related Mortality Before and After Emission Reduction

After implementing the Action Plan, the estimated effects of $PM_{2.5}$ and O_3 on mortality decreased in both urban and suburban areas (Table S2 in Supporting Information S1). However, the differences in the estimates between the urban and suburban areas were not statistically significant.

For changes in the district-specific estimations (Figure S7 in Supporting Information S1), after emission reduction, the ERs of $PM_{2.5}$ on nonaccidental and cardiorespiratory mortality generally decreased in most districts but

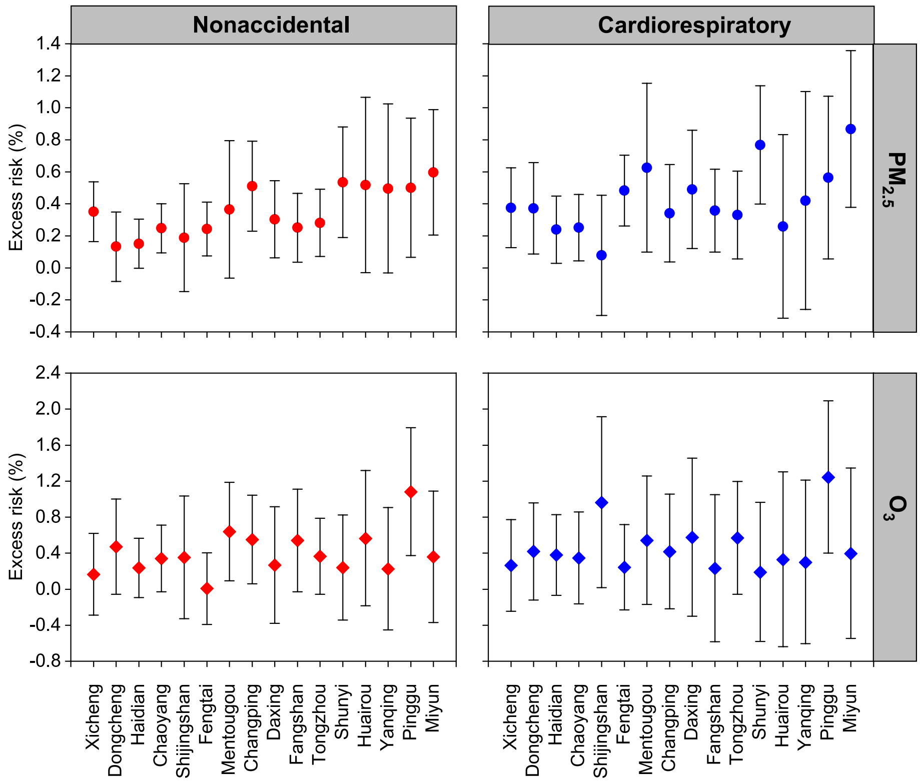

Figure 4. Estimated excess risks of mortality per 10 μg/m^3 increase in air pollutant concentrations in Beijing, China. The districts on the *x*-axis are sorted by urban vulnerability levels, from low vulnerability to high vulnerability.

increased in some districts, such as the Fengtai, Miyun, and Yanqing districts. The differences in the estimates between pre- and post-emission reductions in all districts were not statistically significant. In contrast, the ERs of O_3 on nonaccidental mortality increased in Haidian, Tongzhou, Shunyi, Huairou, and Pinggu districts after emission reduction but decreased or changed slightly in other districts. Only the increase in the Huairou district estimates was statistically significant. Similarly, the ERs of O_3 on cardiorespiratory mortality increased in some districts, especially in districts with lower urbanization levels, after the emission reduction. However, the differences in the estimated risks for all districts were not statistically significant.

4. Discussion

In this study, we explored the intra-city spatial distribution of air pollution-related mortality and analyzed how urbanization modified such distribution in Beijing, China. The results indicated significant spatial variations in

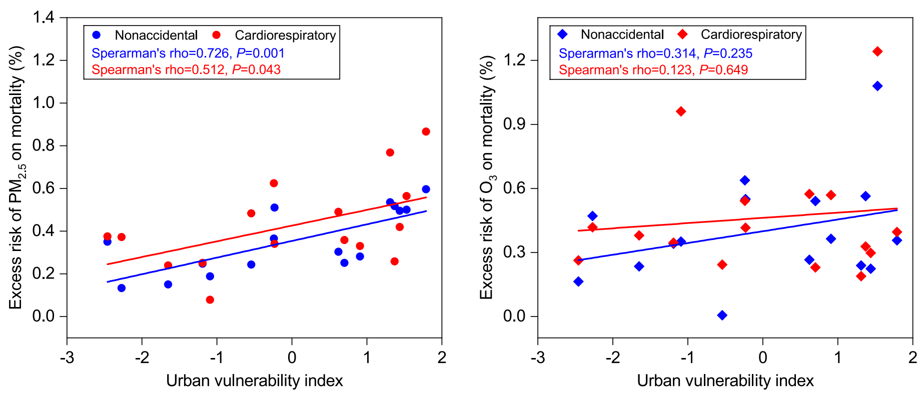

Figure 5. Correlations of the urban vulnerability index with estimated mortality risks of $PM_{2.5}$ and O_3, respectively.

$PM_{2.5}$- and O_3-related mortality risks in Beijing, which were lower in urban than in suburban areas. Furthermore, as the urbanization level decreased, the $PM_{2.5}$-related mortality risks in different districts increased. Our study makes a contribution to the literature because it reveals the need for precise and varied air pollution management policies that take into account the levels of urbanization within the areas of application.

The intra-urban spatial heterogeneity in mortality risks linked to air pollution reflects health inequality associated with urbanization. The majority of low-income and middle-income countries are undergoing rapid and unplanned urbanization. However, the needed social and economic infrastructure rarely are available to support such rapid population expansion. Consequently, health inequality arises due to unbalanced economic development levels and differences in individual demographic and socio-economic characteristics. For instance, the population living in slums faces more significant challenges in improving their health than populations from other parts of the country. In China, rural-to-urban migration dominates the urban population growth. The migrants are more vulnerable to the health risks of urbanization due to the disparity in access to healthcare, housing, sanitation systems, and education between them and registered urban citizens (Yang et al., 2018). The issue of health inequality has attracted the government's attention and has been considered in urban design for sustainable development. The Healthy China 2030 plan has been proposed to address health inequality among different regions and population segments within urban and rural areas to achieve health for all citizens.

Many studies have examined health inequalities associated with air pollution, providing evidence that socio-economic deprivation could exacerbate the adverse health effects of air pollution (Castillo et al., 2021; T. Liu et al., 2021; Martins et al., 2004; Morelli et al., 2016; Wong et al., 2008). Recently, a nationwide study including 2,640 Chinese counties found that people living in counties with lower literacy, college education, GDP per capita, and urbanization levels were more vulnerable to the mortality risks of long-term $PM_{2.5}$ exposure than those living in counties with higher levels of these parameters (L. Han et al., 2021). In addition to the health effects of air pollution, ambient non-optimal temperatures (both hot and cold temperatures) have also been reported to pose higher risks to populations living in suburban and rural areas than those in urban areas (K. Chen et al., 2016; Hu et al., 2019; Xing et al., 2020), challenging the assumption that populations living in urban areas may bear higher risks of temperature due to urban heat island effects. However, it should be noted that the lower estimates of exposure-response associations in urban areas did not mean that the mortality burden attributable to air pollution was lower in urban areas, because the mortality burden caused by air pollution was comprehensively associated with multiple factors, including estimates of exposure-response relationships, number of exposed populations, and levels of air pollutants. Existing studies have indicated that air pollution has led to a significant mortality burden in urban areas (Sun et al., 2022; Xie et al., 2016).

In recent years, ambient O_3 has become another air pollutant that endangers the population's health in China. Nationwide O_3 concentrations across China have been promptly monitored since expanding the number of monitoring sites in 2013, and severe episodes have been frequently reported (Kuerban et al., 2020; Wang et al., 2017). Although implementing the Action Plan has led to nationwide reductions in ambient $PM_{2.5}$, decreased $PM_{2.5}$ may have caused an increase in the level of O_3 due to changes in aerosol photolysis rates and heterogeneous chemistry on aerosol surfaces (J. Li et al., 2018). In this study, we observed decreased levels of $PM_{2.5}$ concentrations in all districts in Beijing and increased levels of DMA8 O_3 concentrations in most districts after the implementation of the Action Plan. Moreover, we assessed changes in $PM_{2.5}$- and O_3-related mortality risks after the Action Plan implementation. The results showed that the mortality risks associated with $PM_{2.5}$ decreased in both urban and suburban areas when utilizing aggregate data, providing further evidence for the health benefits of the emission reduction plan. However, the results changed when we conducted a comparative assessment of each district. After emission reduction, the estimated risks of $PM_{2.5}$ decreased in most districts but increased in districts such as Miyun, which has the lowest urbanization level. Similarly, although O_3-related mortality risks decreased in both urban and suburban areas when aggregate data were used, more detailed information when analyzing changes in district-specific estimates showed that the mortality risk associated with O_3 exposure increased in districts with low urbanization levels. Although the differences in the estimates between the pre- and post-emission reduction periods were overall not statistically significant, these results suggested that the urbanization's advantages may offset air pollution's health risks and that a low urbanization level may amplify the adverse effects of air pollution. These findings also highlight the necessity of adopting disaggregated data or high-resolution data to identify vulnerable populations. However, the change in the effects of $PM_{2.5}$ and O_3 on mortality after the implementation of the Action Plan still requires further investigation.

Our study has valuable implications for accurately evaluating the effect of air pollution on human health and improving air pollution control policy. The results indicated that instead of using unified parameters for the entire city, different exposure–response association coefficients should be used for regions with different urbanization levels when the associations between air pollution and mortality are being evaluated. Moreover, although the health hazards of air pollution have been considered into the policy on air pollution mitigation (Du et al., 2020; Hoffmann et al., 2021; WHO, 2021), the present policy does not consider health inequality within cities. Our study indicated that the urbanization levels should be considered while formulating air pollution control policy, with full consideration and more risk avoidance measures to the residents of less urbanized areas.

However, this study has faced some limitations. First, due to the limited accessibility of mortality data, we could not estimate the spatial heterogeneity of air pollution-related mortality risks or assess the role of urbanization in more recent years. To the best of our knowledge, this is the first study that simultaneously estimated the mortality risks associated with $PM_{2.5}$ and O_3 exposure at the district level within a city and assessed the dynamic changes in those risks after the implementation of the national emission control plan. Second, compared with high spatial resolution data, the district-level air pollutant concentrations might not accurately represent individual exposure, thus leading to exposure measurement errors. We hope to use finer-resolution data to measure the spatial variations in the health risks of air pollution in future studies. Finally, differences in chemical constituents of the air pollutants between urban and suburban areas also contribute to discrepancies in the associated health risks (Bai et al., 2022; B. Li et al., 2021). However, we could not analyze the underlying impacts of the chemical composition owing to the lack of data.

5. Conclusions

In conclusion, distinct spatial variations are found in the association between air pollution and mortality within Beijing. Populations living in less urbanized areas were more adversely exposed to $PM_{2.5}$ and O_3 than those living in highly urbanized areas. The decision-makers need to attach more importance to the problem of intra-city health inequity caused by air pollution and develop targeted interventions for populations in less urbanized areas.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The mortality data at the district level for Beijing, China used in this study are not publicly available due to confidentiality of patient information. The meteorological data used in this study are available at https://www.resdc.cn/data.aspx?DATAID=230. The air pollution data are publicly available at http://zx.bjmemc.com.cn/getAqiList.shtml?timestamp=1668402696544. The demographic and socio-economic variables used for establishment of urban vulnerability index are publicly released at Beijing Municipal Bureau of Statistics. The 2014 Beijing Regional Statistical Yearbooks is publicly available at http://nj.tjj.beijing.gov.cn/nj/qxnj/2014/zk/indexch.htm, and the Beijing Regional Statistical Yearbooks during 2015–2017 are also publicly available at the website.

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