

# Association between long-term exposure to ambient air pollutants and mortality rates because of circulatory and respiratory diseases in South Korea

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## Research article

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# Abstract

**Background :** Associations between long-term exposure to common air pollutants including nitrogen dioxide, carbon monoxide, sulfur dioxide (SO<sub>2</sub>), ozone, and particulate matter (PM<sub>10</sub>) and health consequences have been studied. We investigated spatial effects of exposure to air pollution on mortality by circulatory and respiratory diseases nation-wide and in metropolitan.

**Methods:** Means of daily concentration of the common air pollutants from 2005 to 2016 were calculated by district unit using linear interpolation. Age-standardized mortality rates of people suffering from heart disease (HD); cerebrovascular disease (CVD); ischemic heart disease (IHD); pneumonia (PN) and chronic lower respiratory disease (CLRD) were acquired from population census data. Sub-divided comparisons were performed to adjust spatial heterogeneity. Pearson's correlation coefficients between mortality rates and air pollutant concentrations were investigated. Multivariable linear regressions were performed to investigate associations considering confounding factors.

**Results:** Air pollutant concentration in metropolitan was the highest, except SO<sub>2</sub>; in particular, PM<sub>10</sub> concentration was higher than air quality standard (PM<sub>10</sub>: 55.27 µg/m<sup>3</sup>, air quality standard: 50.00 µg/m<sup>3</sup>, P<0.05). Pearson's correlation coefficient between PM<sub>10</sub> and mortality rates was significant (r = 0.313, 0.596, 0.420, -0.277 and 0.523 for HD, CVD, IHD, PN, and CLRD, all P<0.05) in metropolitan. The powers of regression model for PM<sub>10</sub>, smoking rate, education level, and population density were 0.532 and 0.482 (adjusted R<sup>2</sup>) for mortality rates of CVD and CLRD, respectively.

**Conclusion :** Long-term exposure study with sub-divided analysis showed overall associations between air pollution exposure and circulatory and respiratory disease mortalities. PM<sub>10</sub> exposure was significantly associated with mortality of CVD and CLRD in metropolitan.

## Background

Air pollution includes a complex mixture of gaseous and particulate compounds with common ambient air pollutants such as particulate matters up to 10 µm in size (PM<sub>10</sub>), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), and ozone (O<sub>3</sub>) [1]. The World Health Organization (WHO) announced that an estimated 4.2 million deaths occur per year because of circulatory and respiratory diseases caused by air pollution. Furthermore, the concentration of air pollutants where around 91% of general population lives exceeds the WHO air quality standards [2].

The American Heart Association (AHA) published scientific statements that ambient air pollutant increases the event of cardiovascular diseases such as heart disease (HD), ischemic heart disease (IHD), and cerebrovascular disease (CVD) [3, 4]. Furthermore, ambient air pollution has been consistently reported as one of the biggest risk factors for respiratory diseases including pneumonia (PN) and chronic lower respiratory disease (CLRD) [5–7].

According to the Organization for Economic Cooperation and Development, the air quality level in South Korea is the worst among its member states, so the public interest regarding air pollution control has been rapidly increasing in South Korea [8]. Several cohort studies in South Korea have reported that PM<sub>10</sub> affects health outcomes such as mortality caused by circulatory diseases [9–11], while other studies state that there were non-significant or marginal associations between PM<sub>10</sub> and mortality rates [12, 13]. Although many studies have been conducted to meet public demands, the findings were inconsistent because of the data examined was from different study groups or different types of statistics methods were used. In addition, the short-term studies showed inconsistent results regarding the association between PM<sub>10</sub> and the mortality due to cerebrovascular diseases because of temporal differences [11, 13].

These epidemiologic studies of short-term exposure could have been vulnerable to short-term effects of weather and healthcare and industrial development status. In contrast, long-term exposure studies also could suffer from effects of development of industry and health care system and the changes in premature death counts and deaths caused by chronic diseases [5, 6, 14, 15].

Therefore, to understand the association between exposure to various kinds of air pollutants and disease mortality rates in detail, a long-term nation-wide analysis was needed. In addition, spatial analysis was introduced for covariant analysis of effects of temporal changes for which long-term analysis is vulnerable. Hence, our study aimed to investigate the associations between the disease mortality rates and air pollutant concentrations at the nation-wide level and in sub-divided areas for 12 years.

## Methods

### Study design

Our study design included the spatial association between five common ambient air pollutants (PM<sub>10</sub>, NO<sub>2</sub>, CO, SO<sub>2</sub>, and O<sub>3</sub>) and the mortality rates related to circulatory and respiratory diseases obtained from 2005 to 2016 in South Korea. For spatial analysis, a nation-wide dataset was sub-divided into 252 districts with 332 monitoring stations. These 252 districts were divided into five areas: Metropolitan, Gyeongsang, Jeolla, Chungcheong, and Gangwon areas (Table 1). For example, Area 1, which includes Seoul city, Incheon city, and Gyeonggi-do as the metropolitan region, is composed of 79 districts with 143 monitoring stations. The districts were presented on Korean map using 'leaflet' and 'kormap' R package.

### Ambient air pollutants

This study utilized daily data acquired from Air-Korea (<http://www.airkorea.or.kr>) which is an ambient air quality monitoring system operated by the Korea Environment Corporation (KEC), a quasi-governmental organization under the Ministry of Environment. The KEC operates 323 monitoring stations in 252 districts for measuring daily air pollution. In this study, five common pollutants including NO<sub>2</sub>, CO, SO<sub>2</sub>, O<sub>3</sub> (in ppm), and PM<sub>10</sub> (in µg/m<sup>3</sup>) were considered. Because location of air quality monitoring stations was

not exactly matched with the districts, we linearly interpolated air quality data in the districts by calculating the mean concentration of the surrounding three nearest stations by using the Python package, 'scipy.interpolate.griddata' [16]. In addition, annual data of all air pollutant concentrations were evaluated. In comparison with air quality standards and the annual concentration in each area, criteria of the common pollutants were obtained from National Environmental Policy Act.

## Mortality rates and population

According to the 10th revision of the International Classification of Diseases, the mortality rates of circulatory (I00-99) and respiratory (J00-98) diseases were obtained from death certificates, and population census data were obtained from the National Statistical Office of Korea (NSOK) from 2005 to 2016. In detail, mortality rates of HD (I20-51), IHD (I20-25), and CVD (I60-69) in the circulatory diseases and PN (J12-18) and CLRD (J40-47) in the respiratory diseases were obtained. Based on each district, age-standardized mortality rate per 100,000 persons was calculated as follows [17]:

$$\text{Age standardized mortality rate} = \sum \frac{\text{mortality rate in age group} \times \text{population of age group}}{\text{total population}} \quad (1)$$

For sub-divided analysis, sex of each patient who died was considered. The annual average of confounding covariates including smoking rate, education level, and population density by district were collected from NSOK. The smoking rate was normalized by population of smokers smoking more than five packs of cigarette during their lifetime. Because the survey for smoking rate was started at 2008, the missing values of smoking rates from 2005 to 2007 were extrapolated using data from 2008. The education level, which is the number of people with high educational status, was observed every five years in 2005, 2010, and 2015, so we interpolated missing data from the nearest observed datasets. Because the population density for 2006 and 2007 was not available, we also interpolated missing values using data from 2005 and 2008.

## Statistical analysis

The Shapiro Wilk test was performed to verify the normal distribution of continuous variables [18]. To compare the actual air quality with air quality standards, one sample t-test was used. R package 'Hmisc' was used to evaluate the Pearson's correlation coefficients to investigate the associations between air pollutants and the age-standardized mortality rates [19]. For all analysis, the significance level (alpha) was 0.05. R package 'tidyverse' was used to perform multivariable linear regressions to evaluate the associations between air pollutants and mortality rates by controlling the confounding factors [20]. R package 'ggfortify' was also used for verifying the regression models [21]. Statistical analyses were performed by using R version 3.5.2 (R Foundation for Statistical Computing, Vienna, Austria).

## Results

To analyze air pollution, we evaluated the annual concentration of five common ambient pollutants at the nation-wide level and in five areas. At the national level, the mean concentrations of all ambient air pollutants did not exceed the standard concentration. Furthermore, the concentrations of some pollutants (PM<sub>10</sub>: 55.27 µg/m<sup>3</sup>, NO<sub>2</sub>: 0.0323 ppm, CO: 0.5312 ppm, SO<sub>2</sub>: 0.0049 ppm) in the Area 1 (metropolitan region) were greater than those in the other four areas. However, the concentration of O<sub>3</sub> showed an opposite trend than other pollutants. Air quality standards were reported on an annual basis (PM<sub>10</sub>, 50 µg/m<sup>3</sup>; NO<sub>2</sub>, 0.03 ppm; SO<sub>2</sub>, 0.02 ppm) and every 8 hours (CO, 9 ppm; O<sub>3</sub>, 0.06 ppm). The concentration of PM<sub>10</sub> in Area 1 was statistically higher than the air quality standard in Korea (P < 0.05), whereas the concentration of NO<sub>2</sub> in Area 1 was insignificantly higher than the standard level (P = 0.06) (Table 2).

To compare the differences between the air pollution in Area 1 and that in the others (Area 2, 3, 4, and 5) temporally, the average annual concentrations of PM<sub>10</sub> were evaluated. The concentration of PM<sub>10</sub> in Area 1 was significantly higher than that of Areas 2 to 5 (all P < 0.05), which showed similar trends (Supplementary Fig. 1). Baseline characteristics with spatially visualized distribution of PM<sub>10</sub> concentration and mortality rates because of circulatory and respiratory diseases are presented as per the five sub-divided areas (Supplementary Fig. 2). The mean concentration of PM<sub>10</sub> in Area 1 (55.27 µg/m<sup>3</sup>) was the highest whereas that in Area 3 (45.27 µg/m<sup>3</sup>) was the lowest. The highest annual mortality rate because of circulatory diseases was in Area 2 (105.5 per 100,000), whereas the lowest mortality rate was in Area 1 (83.1 per 100,000). In contrast, mortality rate because of respiratory diseases was the highest in Area 5 (35.85 per 100,000) and the lowest in Area 1 (8.85 per 100,000) (Supplementary Fig. 2, Supplementary Table 1).

To evaluate the spatial associations between mortality rates and air pollutants, Pearson correlation analysis was performed at the national level and in the five clustered areas (Table 3). The Shapiro-Wilk test showed that all variables were normally distributed. Correlation tests were performed using the total mortality rates and sex-based mortality rates separately. However, the correlation coefficients for men and women were not significantly different (Supplementary Table 2). The nation-wide analysis showed that mortality rates of circulatory diseases (IHD, HD, and CVD) were significantly correlated with PM<sub>10</sub> and SO<sub>2</sub> concentrations; however, except HD and PM<sub>10</sub> were not found to be correlated. Only O<sub>3</sub> levels were positively correlated with mortality due to respiratory diseases, whereas the other pollutants presented a negative correlation except with CLRD. In Area 1, PM<sub>10</sub> and SO<sub>2</sub> showed stronger correlations with mortality due to circulatory diseases as well as CLRD compared with their associations at the national level. Pearson's r of PM<sub>10</sub> and mortality rates because of IHD, HD, CVD, and CLRD were 0.420, 0.313, 0.596, and 0.523, respectively. (Table 3)

The mortality rates because of HD, IHD, CVD, and CLRD were significantly positively correlated with PM<sub>10</sub> concentrations at the national level, which led to investigation regarding the associations between PM<sub>10</sub> and mortality rates at the district-level. Figure 1 showed the spatial distribution of Pearson's coefficients

of these associations. Districts are marked in gray did not show statistical significance. Figure 1C shows the most remarkable map with significant correlations between PM<sub>10</sub> concentrations and mortality from CVD in Area 1 (Table 3).

The adjusted R<sup>2</sup> values from the multivariable linear regression models are presented in Table 4. To estimate the effect of PM<sub>10</sub> concentrations on mortality rates in Area 1, several regression models were examined including control variables: smoking rate, education level, and population density. The univariate regression with only PM<sub>10</sub> showed a 35.4% variance in mortality rates for CVD, while each of smoking rate, education, and population density showed rates of 26.8%, 31.1%, and 0.9%, respectively (adjusted R<sup>2</sup>). In Table 4, the multivariable regression model including PM<sub>10</sub>, smoking rate, education level, and population density to predict mortality rate of CVD shows the highest adjusted R<sup>2</sup> of 0.532.

## Discussion

Previous studies have suggested multiple effects of air pollution on circulatory and respiratory diseases [5, 22-24]. Our findings strongly support the relations between PM<sub>10</sub> concentration and the risk of mortality from CVD and CLRD. PM<sub>10</sub> induces infection and inflammation in the circulatory and respiratory systems [5, 25, 26]. Hoek G demonstrated that PM<sub>10</sub> was associated with a significant rise in blood pressure as well as induced infection and inflammation in circulatory and respiratory diseases [24]. Hiraiwa and Eeden suggested that excess cytokines like IL-1, IL-6, and TNF can induce vascular events in patients with chronic obstructive pulmonary disease by systemic oxidative stress and inflammation in the lung to promote endothelial dysfunctions and vulnerability of atherosclerotic plaques to rupture, possibly leading to acute cardiac events or stroke [25]. According to Mukae et al, human alveolar macrophages, when exposed to high concentrations of PM<sub>10</sub>, can phagocytose these particles and produce an array of cytokines like TNF $\alpha$  and IL-1 $\beta$  that are part of the innate immune response [26]. Hence, long-term exposure to PM<sub>10</sub> could aggravate premature mortality by CVD and CLRD. In addition, according to Pearson's correlation test, PM<sub>10</sub> and well-known confounding factors such as smoking rate and education level were not found to be related among the predictor variables ( $r_{PM10-edu}=0.32$ ,  $r_{PM10-smoking}=0.15$ , and  $r_{PM10-pop}=0.19$ ). Findings from the multivariable linear regression models present that PM<sub>10</sub> was significantly correlated with the mortality rates as much as smoking rate, which is well known as one of the major risk factors associated with circulatory and respiratory diseases [27].

Through the long-term exposure study in which the five areas were analyzed, we could investigate the positive associations between air pollutants and mortality rates for circulatory and respiratory diseases. Because short-term exposure studies could be vulnerable to effects of weather and healthcare and industrial development status, outcomes of short-term studies might be inconsistent depending on the study period [11, 13]. Even though long-term studies have been conducted in South Korea, their results could be affected by temporal changes [9, 12, 28]. Therefore, we spatially analyzed mortality rates with long-term exposure to reduce effects of temporal changes. Furthermore, it would be difficult to assess whether these measurements could suitably reflect the concentration of air pollutions in each district

because many stations were not located where most people reside and several districts have no stations. To compensate for these limitations, we linearly interpolated air pollution concentrations per district with the nearest three stations. Finally, the mortality rates in this study were evaluated using a nation-wide dataset.

Moreover, we evaluated mortality data and air pollution datasets based on district units on the national level. The mean concentration of air pollutants at the nation-wide level did not seem to be harmful because the concentration was lower than the air quality standard level (for example,  $PM_{10} < 50 \mu\text{g}/\text{m}^3$ ). However, concentrations of  $PM_{10}$ ,  $NO_2$ ,  $CO$ , and  $SO_2$  in the Area 1 including the most urbanized districts were especially higher than those of the nation-wide levels as well as the air quality standard levels. Therefore, the associations with the mortality rates were more significant in Area 1 than in other areas. Because differences of population densities (especially in areas with more than 25 million people in Area 1) result in the accessibility of healthcare service as well as advanced technologies in public health [29-31], the mortality rates of circulatory and respiratory diseases in the Area 1 could be relatively lower than those in other areas.

There are several limitations in our study. Using only the national database, individual cases could not be followed up. In addition, individual exposure to air pollutants could not be analyzed properly because it is impossible to comprehend individual movement spatially. For future studies, an individualized cohort study is required. In addition, there were differences in density of distributed stations per  $\text{km}^2$  (Area 1, 1  $[\text{n}/\text{km}^2]$ ; Area 2,  $[\text{n}/\text{km}^2]$ ; Area 3,  $[\text{n}/\text{km}^2]$ ; Area 4,  $[\text{n}/\text{km}^2]$ ; and Area 5,  $[\text{n}/\text{km}^2]$ ) which could lead to possible bias of daily measurement of the air pollutants [17]. Because associations between exposure to ambient air pollutants and mortality rates have been still controversial, further studies need to examine the association between air pollutant concentrations and mild outcomes such as morbidity and frequency of hospital visits. Moreover, our findings need to be extended to various spatial scales as well as to investigations in other countries so as to verify the explanatory power of the prediction model.

## Conclusion

We demonstrated that yearly exposure to  $PM_{10}$  is a significantly important risk factor as much as smoking rate for mortality rates from CVD and CLRD through spatial analysis with long-term period data. Although there were spatial variations in the concentration of air pollutants, our study dealt with these spatial heterogeneities using an interpolation method and by performing spatial comparisons. Our study could be used effectively to improve air quality management for public health protection.

## Abbreviations

HD  
heart disease  
CVD  
cerebrovascular disease  
IHD  
ischemic heart disease  
PN  
pneumonia  
CLRD  
chronic lower respiratory disease  
PM<sub>10</sub>  
particulate matters up to 10 µm in size  
NO<sub>2</sub>  
nitrogen dioxide  
CO  
carbon monoxide  
SO<sub>2</sub>  
sulfur dioxide  
O<sub>3</sub>  
ozone  
KEC  
Korea Environment Corporation  
NSOK  
National Statistical Office of Korea  
IQR  
inter quartile range

## **Declarations**

*Ethics approval and consent to participate*

Not applicable

*Consent for publication*

Not applicable

*Availability of data and materials*

All datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

### *Competing interests*

The authors declare that they have no competing interests.

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### *Author's contributions*

JK, JH, and NK conceived the study design. JK, JH, and HJB have made contributions to the acquisition of data. JK, JH, HY, and NK did the statistical analysis and data interpretation. MJ and NK checked the integrity of the manuscript including consistency of the analysis results and data interpretation. JK and NK wrote the first draft. JH, HY, and MJ critically revised the draft. All authors have reviewed and approved the final draft.

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## Tables

**Table 1.** Clustered areas with administrative level of province (-do) and major cities from the 252 sub-divided districts in South Korea.

	Area	N <sub>d</sub> <sup>a</sup>	N <sub>s</sub> <sup>b</sup>	Description
Area 1	Metropolitan area	79	143	Seoul capital city, Incheon city, Gyeonggi-do
Area 2	Gyeongsang area	75	90	Daegu city, Busan city, Ulsan city, Gyeongsang-do
Area 3	Jeolla area	44	47	Gwangju city, Jeolla-do, Jeju-do
Area 4	Chungcheong area	36	41	Daejeon city, Chungcheong-do
Area 5	Gangwon area	18	11	Gangwon-do

Note: <sup>a</sup> Number of districts; <sup>b</sup>Number of air quality monitoring stations.

**Table 2.** Average concentrations of common ambient air pollutants (PM<sub>10</sub>, NO<sub>2</sub>, CO, SO<sub>2</sub>, O<sub>3</sub>) for a period of 12 years at the national level and in the five clustered areas in South Korea (Means and inter quartile ranges).

		Nation-wide	Area 1 <sup>a</sup>	Area 2	Area 3	Area 4	Area 5
Air pollutants	PM <sub>10</sub> (µg/m <sup>3</sup> )	49.18 (45.57-54.16)	55.27 (51.97-58.29)*	47.52 (45.41-49.72)	45.17 (43.50-47.75)	48.24 (46.20-52.44)	45.43 (41.32-46.82)
	NO <sub>2</sub> (ppm)	0.020 (0.014-0.028)	0.032 (0.028-0.036)	0.018 (0.015-0.023)	0.014 (0.013-0.017)	0.018 (0.014-0.022)	0.014 (0.008-0.015)
	CO (ppm)	0.531 (0.462-0.597)	0.597 (0.559-0.650)	0.465 (0.415-0.526)	0.479 (0.445-0.538)	0.548 (0.492-0.585)	0.498 (0.408-0.608)
	SO <sub>2</sub> (ppm)	0.005 (0.004-0.006)	0.006 (0.005-0.006)	0.005 (0.004-0.006)	0.004 (0.004-0.005)	0.004 (0.004-0.005)	0.004 (0.003-0.004)
	O <sub>3</sub> (ppm)	0.025 (0.022-0.029)	0.021 (0.020-0.022)	0.027 (0.025-0.029)	0.026 (0.023-0.027)	0.029 (0.025-0.032)	0.029 (0.027-0.032)
	Confounding factors	Education level <sup>b</sup> (%)	33.94 (23.20-42.48)	41.2 (36.00-49.95)	33.7 (22.55-38.95)	22.3 (16.35-35.95)	30.3 (22.65-40.50)
Smoking rate <sup>c</sup> (%)		24.63 (23.40-26.05)	25.0 (23.35-26.15)	25.2 (24.35-26.25)	22.8 (21.80-24.05)	24.8 (23.70-25.45)	26.4 (25.83-27.10)
Population		4073	8971 (1482-	3288	783	941	152
density <sup>d</sup> (n/km <sup>2</sup> )		(109-6302)	16047)	(90-5660)	(75-491)	(131-878)	(33-209)

Note: \* Significantly higher than air quality standard level (P<0.05); <sup>a</sup> Metropolitan area including Seoul capital city, Incheon city, and Gyeonggi-do;

<sup>b</sup> The ratio of college graduates to the population; <sup>c</sup> Ratio in population of people who smokes more than five packs of cigarettes during their lifetimes; <sup>d</sup> Population density, population measured per km<sup>2</sup>;

Abbreviations: IQR (inter quartile range), PM<sub>10</sub> (particulate matter less than 10 µm in aerodynamic diameter), NO<sub>2</sub> (nitrogen dioxide), CO (carbon monoxide), SO<sub>2</sub> (sulfur dioxide), O<sub>3</sub> (ozone), ppm (parts per million)

**Table 3.** Pearson correlation coefficients (*r*) between ambient air pollutants and mortality because of circulatory and respiratory diseases at the national level and in Area 1.

		PM <sub>10</sub>	NO <sub>2</sub>	CO	SO <sub>2</sub>	O <sub>3</sub>
Nation-wide	<b>Circulatory</b>	0.272 *	-0.098 *	0.058 *	0.235 *	-0.124 *
	HD	0.015	-0.154 *	-0.192 *	0.090 *	0.059 *
	IHD	0.181 *	-0.037	0.003	0.173 *	-0.082 *
	CVD	0.378 *	-0.032	0.236 *	0.251 *	-0.228 *
	<b>Respiratory</b>	-0.204 *	-0.441 *	-0.175 *	-0.202 *	0.320 *
	CLRD	0.089 *	-0.360 *	-0.006	0.003	0.110 *
	PN	-0.280 *	-0.234 *	-0.256 *	-0.244 *	0.296 *
Area 1 <sup>a</sup>	<b>Circulatory</b>	0.572 *	-0.144 *	0.155 *	0.416 *	-0.193 *
	HD	0.313 *	-0.162 *	-0.016	0.271 *	-0.043
	IHD	0.420 *	-0.139 *	0.067	0.347 *	-0.091 *
	CVD	0.596 *	-0.100	0.222 *	0.403 *	-0.238 *
	<b>Respiratory</b>	0.118 *	-0.373 *	-0.201 *	0.043	0.227 *
	CLRD	0.523 *	-0.316 *	0.054	0.180 *	-0.020
	PN	-0.277 *	-0.186 *	-0.274 *	-0.053	0.290 *

Note: \* P < 0.05,

<sup>a</sup> Metropolitan area including Seoul capital city, Incheon city, and Gyeonggi-do.

Abbreviations: PM<sub>10</sub> (particulate matter less than 10 µm in aerodynamic diameter), NO<sub>2</sub> (nitrogen dioxide), CO (carbon monoxide), SO<sub>2</sub> (sulfur dioxide), O<sub>3</sub> (ozone), HD (heart disease), IHD (ischemic heart disease), CVD (cerebrovascular disease), CLRD (chronic lower respiratory disease), PN (pneumonia)

**Table 4.** Comparisons with explanatory powers of multivariable linear regression models with PM<sub>10</sub> controlling confounding factors in Area 1 to predict the mortality rate of each disease.

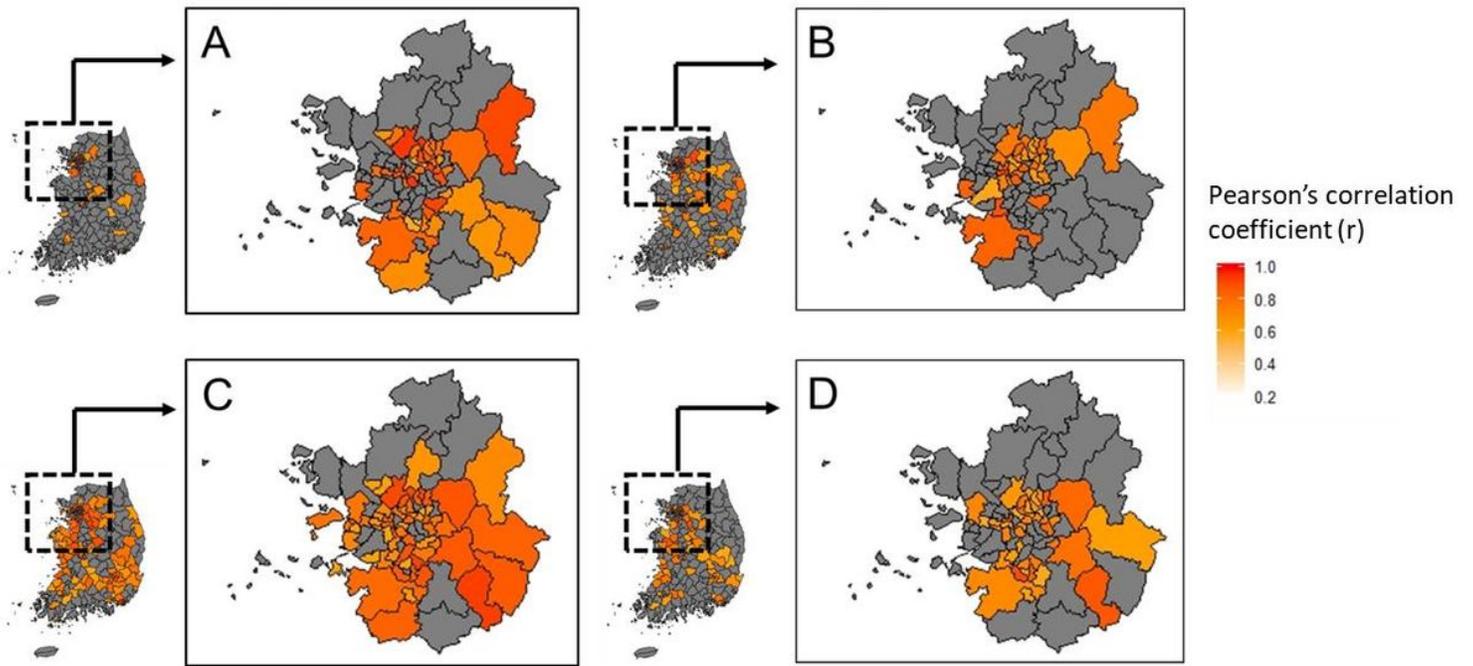
	Adjusted R <sup>2</sup>									
	HD		IHD		CVD		CLRD		PN	
PM <sub>10</sub>	0.097	*	0.175	*	0.354	*	0.273	*	0.076	*
Smoke <sup>a</sup>	0.215	*	0.202	*	0.268	*	0.278	*	0.001	
Edu <sup>b</sup>	0.233	*	0.220	*	0.311	*	0.341	*	0.019	*
Pop <sup>c</sup>	0.017	*	0.010	*	0.009	*	0.114	*	0.001	
PM <sub>10</sub> and Smoke	0.242	*	0.279	*	0.462	*	0.407	*	0.079	*
PM <sub>10</sub> and Edu	0.269	*	0.300	*	0.494	*	0.47	*	0.135	*
PM <sub>10</sub> and Pop	0.122	*	0.197	*	0.361	*	0.311	*	0.085	*
PM <sub>10</sub> , Smoke and Edu	0.285	*	0.311	*	0.503	*	0.475	*	0.156	*
PM <sub>10</sub> , Smoke and Pop	0.241	*	0.284	*	0.475	*	0.425	*	0.085	*
PM <sub>10</sub> , Edu and Pop	0.291	*	0.330	*	0.526	*	0.476	*	0.13	*
PM <sub>10</sub> , Smoke, Edu and Pop	0.298	*	0.333	*	0.532	*	0.482	*	0.153	*

Note: \* P < 0.05;

<sup>a</sup> Ratio in people who smoke more than five packs of cigarettes during their lifetimes; <sup>b</sup> Ratio of college graduate population; <sup>c</sup> Measurement of population per km<sup>2</sup>

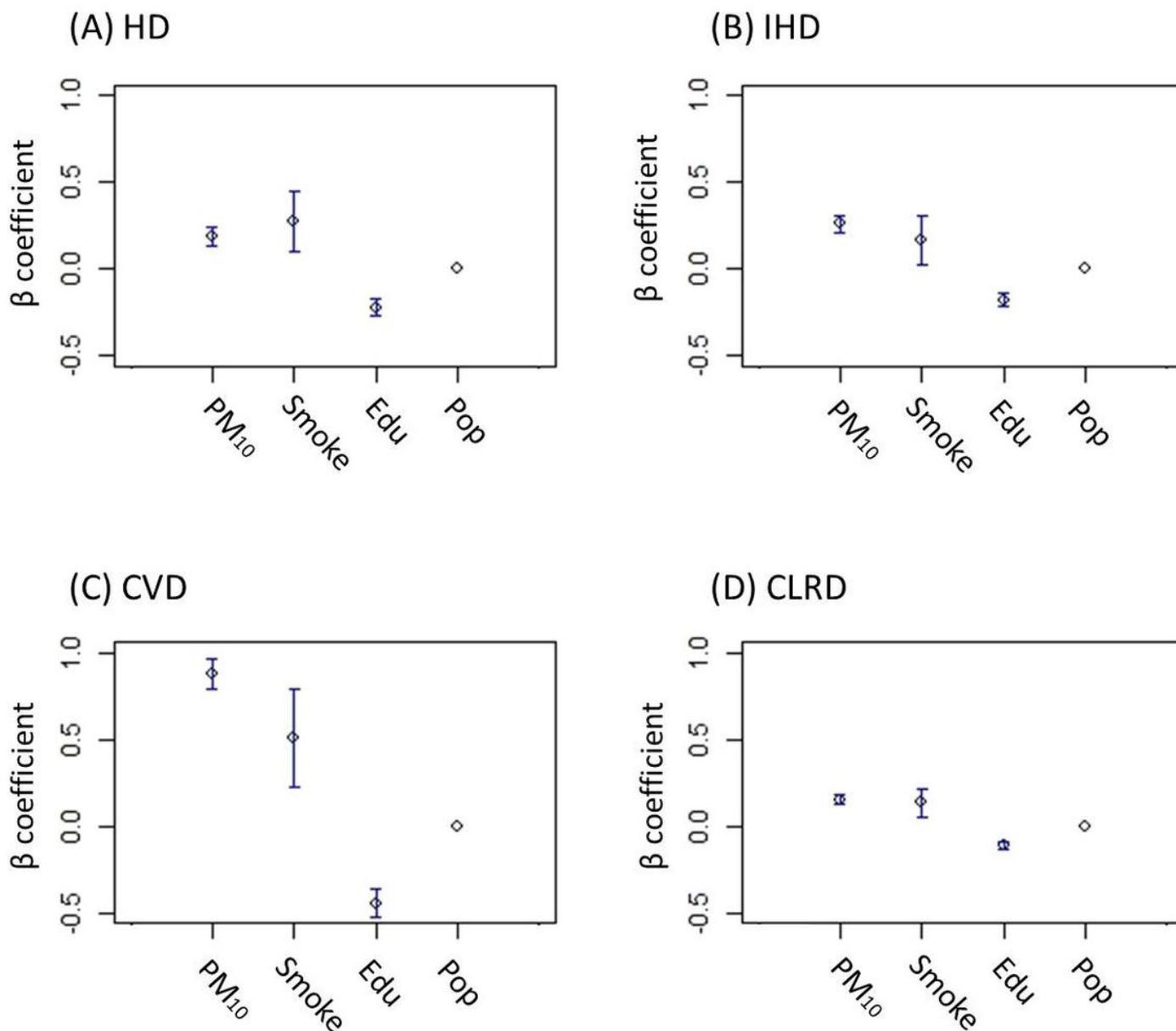
Abbreviations: PM<sub>10</sub> (particulate matter less than 10 µm in aerodynamic diameter), HD (heart disease), IHD (ischemic heart disease), CVD (cerebrovascular disease), CLRD (chronic lower respiratory disease), PN (pneumonia)

## Figures



**Figure 1**

Spatial distributions of Pearson correlation coefficients (r) between mean concentration of PM10 and mortalities caused by circulatory and respiratory diseases: (A) heart disease (HD), (B) ischemic heart disease (IHD), (C) cerebrovascular disease (CVD), and (D) chronic lower respiratory disease (CLRD) in districts in Area 1 (metropolitan area). The colored bar denotes statistical significance (P < 0.05).



**Figure 2**

Beta coefficients and their 95% confidence intervals between predictor variables (PM<sub>10</sub>, smoking rate, education level, and population density) and the mortality rates of (A) heart disease (HD), (B) ischemic heart disease (IHD), (C) cerebrovascular disease (CVD), and (D) chronic lower respiratory disease (CLRD).

## Supplementary Files

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- [SupplementaryFigure2.tif](#)

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