



Air pollution associated respiratory mortality risk alleviated by residential greenness in the Chinese Elderly Health Service Cohort



Shengzhi Sun^{a,b}, Chinmoy Sarkar^{a,c,*}, Sarika Kumari^c, Peter James^d, Wangnan Cao^e, Ruby Siu-yin Lee^f, Linwei Tian^a, Chris Webster^c

^a School of Public Health, The University of Hong Kong, Hong Kong Special Administrative Region

^b Department of Environmental Health, School of Public Health, Boston University, Boston, MA, USA

^c Healthy High Density Cities Lab, HKUrbanLab, University of Hong Kong, Hong Kong Special Administrative Region

^d Department of Population Medicine, Harvard Medical School and Harvard Pilgrim Health Care Institute, Boston, MA, USA

^e Center for Evidence Synthesis in Health, Brown University School of Public Health, Providence, RI, 02906, USA

^f Elderly Health Service, Department of Health, Hong Kong Special Administrative Region

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ABSTRACT

Background: Although residing in lower surrounding greenness and transient exposure to air pollution are independently associated with higher risk of adverse health outcomes, little is known about their interactions.

Objectives: We examine whether residential neighborhood greenness modifies the short-term association between air pollution and respiratory mortality among the participants of Chinese Elderly Health Service Cohort in Hong Kong.

Methods: We estimated residential surrounding greenness by measuring satellite-derived normalized difference vegetation index (NDVI) from Landsat within catchments of residential addresses of participants who died of respiratory diseases between 1998 and 2011. We first dichotomized NDVI into low and high greenness and used a time-stratified case-crossover approach to estimate the percent excess risk of respiratory mortality associated with fine particulate matter (PM_{2.5}), respirable particulate matter (PM₁₀), nitrogen dioxide (NO₂), and ozone (O₃). We further classified NDVI into greenness quartiles and introduced an interaction term between air pollution and the assigned median values of the NDVI quartiles into the models to assess the trend of greenness modification on the air pollution and respiratory mortality associations.

Results: Among 3159 respiratory deaths during the follow-up, 2058 were from pneumonia and 947 from chronic obstructive pulmonary disease. Elders living in the low greenness areas were associated with a higher risk of pneumonia mortality attributed to NO₂ ($p = 0.049$) and O₃ ($p = 0.025$). The mortality risk of pneumonia showed a decreasing trend for NO₂ (p for trend = 0.041), O₃ (p for trend = 0.006), and PM_{2.5} (p for trend = 0.034) with greenness quartiles increasing from Quartile 1 (lowest) to Quartile 4 (highest).

Conclusions: Our findings suggest that elders living in higher greenness areas are less susceptible to pneumonia mortality associated with air pollution, which provides evidence for optimizing allocation, siting, and quality of urban green space to minimize detrimental health effects of air pollution.

1. Introduction

Respiratory disease is a leading cause of disability, morbidity, and mortality, imposing an immense health burden worldwide (Dicker et al., 2018). More than 1 billion people suffer from either acute or chronic respiratory conditions, and 4 million people die prematurely from the chronic respiratory diseases annually (WHO, 2014). Respiratory diseases make up five of the thirty most common causes of

death and account for more than 10% of all disability-adjusted life-years (DALYs) (Dicker et al., 2018; Kyu et al., 2018).

Air pollution is an important contributor to respiratory diseases (Li et al., 2016; Pirozzi et al., 2018; Tian and Sun, 2017). Although continuous efforts have been made to improve air quality, yet 90% of the world's population reside in areas with air quality levels exceeding the World Health Organization (WHO) limits (WHO, 2018). Thus, it is of significant public health interest to identify potential modifying factors

* Corresponding author. Healthy High Density Cities Lab, HKUrbanLab, The University of Hong Kong, Knowles Building, Pokfulam Road, Hong Kong Special Administrative Region.

E-mail address: csarkar@hku.hk (C. Sarkar).

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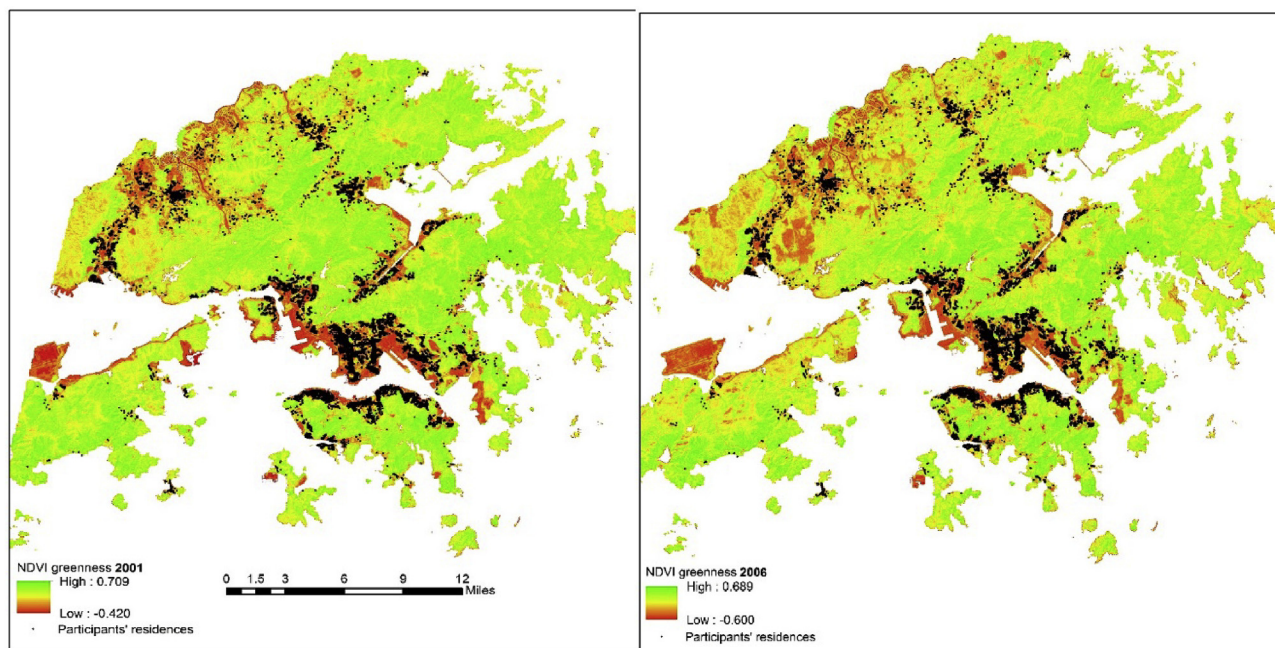


Fig. 1. Normalized Difference Vegetation Index (NDVI) greenness of Hong Kong measured from 30 m resolution Landsat TM data in 2001 and 2006 and geocoded residential locations of Elderly Health Service Cohort participants ($n = 66,820$).

that could be targeted at for interventions and thereby alleviate the health burden of respiratory diseases associated with air pollution.

Numerous studies have explored how nature, specifically green vegetation, is beneficial to an array of health outcomes (Banay et al., 2017; Fong et al., 2018; James et al., 2015; Sarkar et al., 2019; Twohig-Bennett and Jones, 2018; WHO, 2017). Greenness may reduce health risks by reducing personal exposure to air pollution (Dadvand et al., 2012; Givoni, 1991) and/or providing opportunities for physical activity, which might make individuals less susceptible to air pollution (James et al., 2015; Van den Berg et al., 2010). Very few studies have investigated the modification effect of greenness on the adverse health impacts of air pollution (Table S1), and findings have been mixed (de Keijzer et al., 2017; Dimitrova and Dzhambov 2016, 2017; Heo and Bell, 2019; Kioumourtzoglou et al., 2016; Vivanco-Hidalgo et al., 2018; Yitshak-Sade et al., 2019). A study conducted in 364 US counties found that risks of cardiovascular hospitalizations associated with particulate matter were reduced in higher greenness areas (Heo and Bell, 2019). A small-area study in Spain found that the effect modification of the association between air pollution and all-natural mortality by neighborhood greenness varied by urban and rural areas (de Keijzer et al., 2017). On the other hand, higher mortality risks of air pollution were found in greater neighborhood greenness in an analysis of over 35 million Medicare enrollees from 207 US cities (Kioumourtzoglou et al., 2016), or no evidence of greenness effect modification was reported in a study of Spain (Vivanco-Hidalgo et al., 2018).

In the present study, we aimed to examine the effect modification of greenness on the association between air pollution and respiratory mortality. We hypothesize that higher level of greenness alleviates the respiratory mortality risk associated with air pollution. To test this hypothesis, we conducted a case-crossover study in Hong Kong, leveraging a large prospective elderly cohort, where greenness around the geocoded residential address of each deceased participant was quantified by Normalized Difference Vegetation Index (NDVI) measured from satellite imagery.

2. Methods

2.1. Study population

The study population is the participants of the Chinese Elderly Health Service Cohort, which is a prospective cohort initiated by the Hong Kong Department of Health. From 1998 to 2001, 66,820 elders aged 65 years or above in Hong Kong, about 9% of Hong Kong older adults were enrolled into the cohort and were followed up until December 31st, 2011. Demographics and lifestyle information were collected by registered doctors and nurses through face-to-face interviews using a standardized and structured questionnaire (Lam et al., 2007; Schooling et al., 2014). Detailed information on cohort profile and data collection have been described elsewhere (Schooling et al., 2014; Sun et al., 2019a). To ascertain death, we linked the cohort with the death registration database from Department of Health by the unique Hong Kong identity card number and coded deaths according to the International Classification of Diseases, Tenth Revision (ICD-10): total respiratory diseases (J00-J47, J80-J99), pneumonia (J12-J18), and chronic obstructive pulmonary diseases (COPD, J40-J44, J47). Most deaths in Hong Kong occur in hospital and cause of deaths are accurately ascertained (Hospital Authority, 2014). For participants whose cause of death cannot be ascertained, telephone interviews have been conducted to obtain this information (Schooling et al., 2014).

2.2. Residential greenness assessment

We quantified vegetation greenness by measuring the Normalized Difference Vegetation Index (NDVI), a satellite-image-based vegetation index modelled from the differential absorbance and reflectance wavelengths by chlorophyll in green vegetation. NDVI has been widely used as an indicator of green intensity and is measured as the ratio of the difference between the spectral reflectance measurements in the near-infrared region and red (visible) regions of the electromagnetic spectrum and the sum of these two measures. It ranges from -1 to 1 , with higher values indicating higher levels of vegetative density (Earth Observatory, 2000; Tucker, 1979). We obtained NDVI at two time points of 2001 and 2006 from the 30 m resolution Landsat 5, Thematic

Mapper satellite data (Fig. 1). Image chunks of the area covering Hong Kong were mosaicked, and mean NDVI within a buffer of 250 m (NDVI_{250m}) and 500 m (NDVI_{500m}) radius around each study participant's geocoded residential address was measured. The 250 m radius is a measure of greenness immediately surrounding the residence (James et al., 2016), and the 500 m radius is a measure of greenness within a walking distance neighborhood of their homes, which was supported by a prior pilot study of this cohort (Cerin et al., 2013).

As the overall temporal vegetation coverage in Hong Kong was generally stable between 2000 and 2011 and the spatial changes were also limited (Hu and Xia, 2019), we used the mean of NDVI at the year of 2001 and 2006 as the greenness exposure. We first dichotomized participants into those living in areas with low and high residential greenness based on the NDVI median of the participants who died of respiratory diseases (cases). To investigate whether there was a trend in the air pollution and respiratory mortality association by greenness, we further categorized NDVI into greenness quartiles.

2.3. Air pollution assessment

Hourly concentrations of fine particulate matter (PM_{2.5}), respirable particulate matter (PM₁₀), nitrogen dioxide (NO₂), and ozone (O₃) between 1998 and 2011 were obtained from ten general air monitoring stations that met the quality assurance and quality control procedure of Hong Kong Government (Sun et al., 2019b). We created a territory-wide daily time-series of air pollutants by averaging daily air pollutants that have $\geq 75\%$ of the 1 h values on that particular day across the ten air monitoring stations (Wong et al., 2008). We would exclude the entire station if $> 25\%$ of the daily values for a particular pollutant were missing for the whole study period.

The daily mean concentrations of air pollution were 37.3 $\mu\text{g}/\text{m}^3$ for PM_{2.5}, 52.3 $\mu\text{g}/\text{m}^3$ for PM₁₀, 57.7 $\mu\text{g}/\text{m}^3$ for NO₂, and 35.2 $\mu\text{g}/\text{m}^3$ for O₃ (Table 1). We found the Pearson correlation between air pollutants were generally high ($r > 0.5$), except for the correlation between O₃ and NO₂ ($r = 0.27$). Daily ambient temperature ($^{\circ}\text{C}$) and relative humidity (%) were obtained from the Hong Kong Observatory.

2.4. Statistical analysis

We used a time-stratified case-crossover approach to estimate the short-term association between air pollutants and respiratory deaths. The case-crossover approach is a case-only design in which case serves as his/her own control (Maclure, 1991). To control for long-term trend and seasonality, we selected control periods as the same year, month, and day of the week as the case (the event days) (Carracedo-Martínez et al., 2010). We adjusted for variables that fluctuate on a daily basis including ambient temperature at the same day and moving average of the prior 1–3 days (lag₁₋₃) with natural cubic splines (NS) with three degrees of freedom (*df*) each simultaneously in the model (Orazzo et al., 2009; Sun et al., 2020), relative humidity (NS with 3*df*), influenza epidemics, and public holidays.

Table 1

Air pollution concentration on the day of respiratory mortality and Pearson correlation coefficients between air pollutants.

Air pollutants ($\mu\text{g}/\text{m}^3$)	Mean \pm SD	Pearson correlation			
		PM _{2.5}	PM ₁₀	NO ₂	O ₃
PM _{2.5}	37.3 \pm 21.2	1.00	0.91	0.76	0.46
PM ₁₀	52.3 \pm 28.2		1.00	0.68	0.51
NO ₂	57.7 \pm 20.1			1.00	0.27
O ₃	35.2 \pm 20.2				1.00

Abbreviations: SD = standard deviation; PM_{2.5} = particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$; PM₁₀ = particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$; NO₂ = nitrogen dioxide; O₃ = ozone.

As the incubation period of infectious diseases may be 1–4 days (Lessler et al., 2009), we estimated the effects of air pollution at the 4-day moving average (lag₀₋₃). We calculated odds ratios (OR) per 10 $\mu\text{g}/\text{m}^3$ increase in each air pollutant from the conditional logistic regression and expressed results as percent excess risk (ER%; ER% = [OR - 1] \times 100%).

To estimate the differences between risk estimates of air pollution in the low and high greenness, we introduced an interaction term in the models, which was the product of air pollutants and the residential greenness (low and high). *p*-value of the interaction term < 0.05 indicates a statistically significant difference between the risk estimates of air pollution in the low and high greenness areas.

To assess the trend of greenness modification, we further classified NDVI into greenness quartiles: Quartile 1 (lowest), Quartile 2, Quartile 3, and Quartile 4 (highest). We estimated the additional percent excess risk associated with air pollutants in greenness Quartile 2, Quartile 3, and Quartile 4 relative to Quartile 1 by adding an interaction term of the air pollution and greenness quartiles into the models with Quartile 1 as the reference group (Fig. S1) (Sun et al. 2019b, 2020). We tested for a trend in relation to the additional percent excess risks by assigning median values of the NDVI quartiles as a continuous variable in the models (Bhaskaran et al., 2011).

To exclude the possibility of area-level confounding, we conducted a nested case-control study after adjusted for individual- (e.g., age, sex) and area- (e.g., long-term PM_{2.5} air pollution exposure) level confounders, in addition to the variables that fluctuate on a daily basis (i.e., day of the week, ambient temperature, relative humidity, and influenza epidemics) (Sun et al. 2016, 2019b) (Supplementary Material). We conducted all analyses in R software version 3.5.1 with the "Survival" package version 2.42–6 for the conditional logistic regression.

3. Results

Table 2 shows the baseline characteristics of respiratory cases by residential greenness. We identified 3159 respiratory deaths (cases), of which 2058 were pneumonia and 947 were COPD. About half (52.5%) of the respiratory cases were males, and less than one-third were married, overweight or obese, ever-drinker, ever-smokers, or had received secondary or post-secondary education. The characteristics of participants lived in the low and high greenness areas were generally similar.

The risks of total and pneumonia mortality associated with air pollution were stronger in the low residential greenness areas than that in the high greenness areas (Table 3 & Table S2). For example, when using NDVI_{250m} to define residential greenness, the ER% per 10 $\mu\text{g}/\text{m}^3$ increase in NO₂ at 4-day moving average for total respiratory was 3.39% (95% CI: -1.26%, 8.05%) in the low greenness areas and -1.21% (95% CI: -5.92%, 3.51%) in the high greenness areas, and for pneumonia was 4.58% (95% CI: -1.23%, 10.41%) in the low greenness areas and -3.22% (95% CI: -9.15%, 2.75%) in the high residential greenness areas, respectively. The difference between the ERs% of pneumonia in the low and high residential greenness was statistically significant for NO₂ ($p = 0.049$) and O₃ ($p = 0.025$), and was marginally significant ($p = 0.075$) for PM_{2.5}.

After categorized NDVI into greenness quartiles, we found higher greenness quartiles were generally associated with lower air pollution risk estimates (Table 4 & Table S3). For example, when compared to greenness Quartile 1 (lowest) defined by NDVI_{250m}, the additional percent excess risk of pneumonia per 10 $\mu\text{g}/\text{m}^3$ in air pollutants in greenness Quartile 2, Quartile 3, and Quartile 4 was -3.23% (95% CI: -13.90%, 7.54%), -8.19% (95% CI: -19.00%, 2.74%), and -10.50% (95% CI: -21.30%, 0.36%) for NO₂, and -10.60% (95% CI: -20.70%, -0.46%), -12.00% (95% CI: -22.00%, -1.88%), and -15.00% (95% CI: -25.10%, -4.72%) for O₃, respectively. We observed a decreasing trend in risk estimates of pneumonia for PM_{2.5} (p for trend = 0.034), NO₂ (p for trend = 0.041), and O₃ (p for

Table 2
Descriptive characteristic for participants by residential greenness in the Chinese Elderly Health Service Cohort^a.

Population characteristics	Total	Low greenness	High greenness
Participants, n	3159	1579	1580
Age, years, mean (SD)	84.3 (6.6)	84.4 (6.6)	84.3 (6.5)
Sex, n (%)			
Male	1658 (52.5)	846 (53.6)	812 (51.4)
Female	1501 (47.5)	733 (46.4)	768 (48.6)
Marital status, n (%)			
Married	753 (23.8)	371 (23.5)	382 (24.2)
Unmarried	2406 (76.2)	1208 (76.5)	1198 (75.8)
BMI quartile, n (%)			
Underweight [< 19.0 kg/m ²]	684 (21.7)	349 (22.1)	335 (21.2)
Normal [19.0–25.0 kg/m ²]	1663 (52.6)	846 (53.6)	817 (51.7)
Overweight [25.0–30.0 kg/m ²]	719 (22.8)	336 (21.3)	383 (24.2)
Obese [≥30.0 kg/m ²]	93 (2.9)	48 (3.0)	45 (2.8)
Exercise			
Times per week, mean (SD)	5.4 (2.8)	5.4 (2.8)	5.4 (2.8)
Education, n (%)			
Uneducated	1392 (44.1)	623 (39.5)	769 (48.7)
Primary	1238 (39.2)	628 (39.8)	610 (38.6)
Secondary	426 (13.5)	255 (16.1)	171 (10.8)
Post-secondary	103 (3.3)	73 (4.6)	30 (1.9)
Alcohol consumption, n (%)			
Never drink	2088 (66.1)	1064 (67.4)	1024 (64.8)
Former drink	566 (17.9)	256 (16.2)	310 (19.6)
Social/seasonal drinker	370 (11.7)	193 (12.2)	177 (11.2)
Regular drinker	135 (4.3)	66 (4.2)	69 (4.4)
Smoking status, n (%)			
Never	2022 (64.0)	1033 (65.4)	989 (62.6)
Quit	889 (28.1)	432 (27.4)	457 (28.9)
Current	248 (7.9)	114 (7.2)	134 (8.5)

Abbreviations: BMI = body mass index; SD = standard deviation.

^a Low and high greenness were defined by the median (0.065) of normalized difference vegetation index within 250 m.

trend = 0.006) with greenness quartiles increasing from Quartile 1 (lowest) to Quartile 4 (highest). However, we found no obvious trend for total respiratory and COPD. Our findings were not materially different when using NDVI_{500m} to define residential greenness or using the nested case-control study to rule out the possibility of area-level confounders (Table S2 to Table S4).

4. Discussion

Among respiratory deaths in this large prospective cohort of elders in Hong Kong, we found that higher level of residential greenness

Table 3

Percent excess risk and 95% confidence interval of respiratory mortality per 10 µg/m³ increase in air pollutants at 4-day moving average in the low and high residential greenness areas measured by normalized difference vegetation index with 250 m^a.

Mortality	Air pollutant	Low greenness ^a	High greenness ^a	p-Value
Total respiratory	PM _{2.5}	1.61 (−2.77, 6.01)	−1.49 (−5.92, 2.95)	0.311
	PM ₁₀	0.79 (−2.31, 3.90)	−0.66 (−3.80, 2.49)	0.505
	NO ₂	3.39 (−1.26, 8.05)	−1.21 (−5.92, 3.51)	0.146
	O ₃	2.08 (−2.33, 6.50)	−2.10 (−6.58, 2.39)	0.167
Pneumonia	PM _{2.5}	3.25 (−2.25, 8.79)	−3.57 (−9.06, 1.95)	0.075
	PM ₁₀	1.62 (−2.16, 5.42)	−1.87 (−5.66, 1.94)	0.186
	NO ₂	4.58 (−1.23, 10.41)	−3.22 (−9.15, 2.75)	0.049
	O ₃	3.12 (−2.31, 8.59)	−5.20 (−10.68, 0.31)	0.025
COPD	PM _{2.5}	0.11 (−7.76, 8.05)	6.03 (−2.18, 14.30)	0.292
	PM ₁₀	0.81 (−4.85, 6.51)	4.47 (−1.92, 10.90)	0.382
	NO ₂	1.39 (−7.04, 9.88)	7.99 (−0.33, 16.38)	0.248
	O ₃	0.52 (−7.56, 8.67)	6.16 (−2.24, 14.62)	0.315

Abbreviations: PM_{2.5} = particulate matter ≤2.5 µm in aerodynamic diameter; PM₁₀ = particulate matter ≤10 µm in aerodynamic diameter; NO₂ = nitrogen dioxide; O₃ = ozone; COPD = chronic obstructive pulmonary disease.

^a Low and high greenness were defined by the median (0.065) of normalized difference vegetation index within 250 m.

alleviated the short-term association between air pollution and respiratory mortality. The reduced risks in relation to residential greenness were more pronounced for the mortality risk of pneumonia associated with PM_{2.5}, NO₂, and O₃.

Few studies have been conducted to examine the interaction between residential greenness and air pollution on health (de Keijzer et al., 2017; Dimitrova and Dzhambov, 2017; Heo and Bell, 2019; Kioumourtoglou et al., 2016; Vivanco-Hidalgo et al., 2018; Yitshak-Sade et al., 2019). Our study is the first to examine the modification effects of residential greenness on the association between transient exposure to air pollution and respiratory mortality. Although no study was directly comparable, our findings were consistent with the United States study conducted by Yitshak-Sade et al. (2019), who found the association between acute air pollution exposure and cardiovascular mortality was alleviated by greater greenness in areas with lower socioeconomic status (Yitshak-Sade et al., 2019). Our findings were also in line with a US study using data of Medicare enrollees from 364 US counties (Heo and Bell, 2019). A Canada study examined whether the long-term health effects of air pollution differed by residential greenness (de Keijzer et al., 2017). Interestingly, this study found that residential greenness modified the adverse effects of air pollutants with stronger long-term effects of PM₁₀, PM_{2.5}, and O₃ in rural areas with lower NDVI-measured greenness, but the effects were stronger in urban areas with higher greenness (de Keijzer et al., 2017). The study also found that the effects of NO₂ were consistently stronger in areas with higher greenness in both urban and rural areas (de Keijzer et al., 2017). On the other hand, higher mortality risks of air pollution were found in greater neighborhood greenness in an analysis of over 35 million Medicare enrollees from 207 US cities (Kioumourtoglou et al., 2016), or no evidence of greenness effect modification was reported in a study of Spain (Vivanco-Hidalgo et al., 2018). The mixed results in prior studies may be plausibly due to differences in population characteristics, sources of air pollution, greenness quality, as well as differences in perceived and usage of greenness space (Feng and Astell-Burt, 2019).

Although the exact biological mechanisms remain largely unclear, several potential pathways have been proposed to explain the observed interactions. Air pollution may lead to impairing epithelial cells, increasing epithelial permeability and reducing mucociliary clearance, which may confer susceptibility to bacterial pathogens (Chauhan and Johnston, 2003; Olivieri and Scoditti, 2005; Zhou and Kobzik, 2007). The observed interaction might also relate to the reduction in personal exposure to air pollution through direct filtering of air pollutants by vegetation or through improving ventilation in greener areas resulting in increased dispersal of air pollutants (Dadvand et al., 2012; James et al., 2016; Shen and Lung, 2017). Another possible pathway is that greenness might influence urban microclimate, potentially decreasing

Table 4

Additional percent excess risk in respiratory mortality associated with 10 $\mu\text{g}/\text{m}^3$ increase in air pollutants at the 4-day moving average by greenness quartiles within 250 m.

Mortality	Air pollutant	Quartile 1 (lowest)	Quartile 2	Quartile 3	Quartile 4 (highest)	p for trend
Total respiratory	PM _{2.5}	Reference	-6.52 (-14.90, 1.91)	-7.86 (-16.30, 0.67)	-5.13 (-13.70, 3.49)	0.281
	PM ₁₀	Reference	-1.81 (-7.74, 4.16)	-2.49 (-8.42, 3.48)	-2.24 (-8.32, 3.88)	0.471
	NO ₂	Reference	-3.88 (-12.50, 4.80)	-9.12 (-17.80, -0.32)	-4.06 (-12.70, 4.61)	0.287
	O ₃	Reference	-9.79 (-18.00, -1.54)	-9.49 (-17.70, -1.18)	-8.48 (-16.70, -0.20)	0.070
Pneumonia	PM _{2.5}	Reference	-7.33 (-17.80, 3.25)	-9.57 (-20.20, 1.13)	-11.90 (-22.60, -1.10)	0.034
	PM ₁₀	Reference	-1.00 (-8.25, 6.30)	-2.31 (-9.45, 4.88)	-6.01 (-13.60, 1.58)	0.105
	NO ₂	Reference	-3.23 (-13.90, 7.54)	-8.19 (-19.00, 2.74)	-10.50 (-21.30, 0.36)	0.041
	O ₃	Reference	-10.60 (-20.70, -0.46)	-12.00 (-22.00, -1.88)	-15.00 (-25.10, -4.72)	0.006
COPD	PM _{2.5}	Reference	-6.74 (-21.80, 8.58)	-4.69 (-19.90, 10.80)	10.30 (-5.40, 26.30)	0.175
	PM ₁₀	Reference	-3.06 (-13.90, 7.89)	-3.09 (-14.60, 8.58)	7.02 (-4.36, 18.50)	0.237
	NO ₂	Reference	-6.39 (-22.20, 9.63)	-6.43 (-22.30, 9.74)	12.00 (-3.47, 27.70)	0.098
	O ₃	Reference	-7.90 (-22.90, 7.34)	-1.99 (-17.70, 14.00)	4.66 (-10.40, 19.90)	0.385

Abbreviations: PM_{2.5} = particulate matter $\leq 2.5 \mu\text{m}$ in aerodynamic diameter; PM₁₀ = particulate matter $\leq 10 \mu\text{m}$ in aerodynamic diameter; NO₂ = nitrogen dioxide; O₃ = ozone; COPD = chronic obstructive pulmonary disease.

the total intake of airborne pollutants (Dadvand et al., 2012; Givoni, 1991; Gordon, 2003). Greenness is also likely to boost immune functions by promoting physical activity and social engagement, and by improving mental health, rendering people less susceptible to air pollution (James et al., 2015; Van den Berg et al., 2010).

Our study has several potential limitations. First, some degrees of measurement errors may be introduced due to using the territory-wide average air pollution or the residential greenness to represent participants' exposure. However, our study population is elders and their daily activities mostly occur within a 500 m buffer around the participant's home (Cerin et al., 2013). Also, the correlation of air pollutants among the ten air monitoring stations in Hong Kong was generally high (Fig. S2 to Fig. S5). Thus, potential exposure misclassification should be negligible. Second, our analysis was conducted among Chinese older adults; whether our findings are generalizable to younger people or Western countries remains unknown. Further studies in diverse geographical contexts and population sub-groups are recommended. Last but not least, we measured greenness using NDVI which only measured the quantity instead of the quality of greenness space. Nevertheless, as far as the authors are aware, our study is the first to examine the interaction between short-term exposure to air pollution and residential greenness leveraging a large prospective cohort. Findings of this study may provide evidence in support of greening policy formulation, urban planning and public health promotion.

5. Conclusions

Among Hong Kong older adults, we found elders living in neighborhoods with greater greenness were associated with lower mortality risks of air pollution on respiratory diseases, which may be useful when arguing for urban greening strategies. These results exemplify the importance of optimizing allocation and designing green spaces as a public health intervention aimed at minimizing/offsetting personal risks posed by exposures to air pollutants in high density urban environments like Hong Kong. From an urban perspective, there is a need for smarter design and configuration of good quality urban greenspaces, given their evidenced potential to reduce pollution loads through multiple mechanisms of adsorption, deposition, dispersion as well as facilitating ventilation corridors for outward pollutant flows. This will also entail a tighter coupling between existing air pollution control, green design, urban transport and public health policies. From a population perspective, with the increasing demographic shifts towards an elderly population, the role of urban green ameliorating and segregating the risks of air pollution in residential neighbourhoods is likely to be more important among the elderly population who are generally prone to co-morbidities and a higher risk of mortality. Future studies from diverse contexts and population sub-groups are required for an

integrated green allocation-oriented pollution prevention as a population level intervention.

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Declaration of competing interest

The authors declare they have no actual or potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2020.109139>.

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