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Breathing the same air? Socioeconomic disparities in $PM_{2.5}$ exposure and the potential benefits from air filtration

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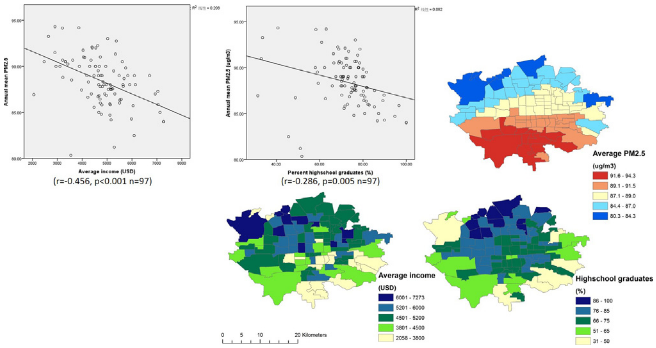
HIGHLIGHTS

- $PM_{2.5}$ level is spatially heterogeneous in Beijing with a substantial difference.
- Poor/less educated residents carry an unproportionally high share of the pollution.
- Air filtration may reduce or enlarge socioeconomic disparities in $PM_{2.5}$ exposure.
- Proper policy can convey the benefit of air filtration to disadvantaged groups.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution caused by particulate matter <2.5 μm in diameter ($PM_{2.5}$) imposes a severe health burden to people worldwide. Across the globe, and even within cities, the health burden of air pollution is not equally shared by citizens. Despite being the region suffering from the most severe air pollution, studies examining the inequity of the burdens of air pollution in Asia are limited. We aim to fill in this gap by analyzing the relationship between $PM_{2.5}$ pollution and residents' socioeconomic characteristics in Beijing, the icon city for $PM_{2.5}$ pollution. Our results show that household income and education were negatively correlated with ambient air quality ($r = -0.62$; $p < 0.05$ and $r = -0.73$; $p < 0.01$ respectively) in 2014. We found in Beijing air quality is worse where residents have less income and lower education rates and are less capable to protect themselves from the potential health risk. To counter the effects of air pollution in Beijing, air filtration has been shown to be an effective means to reduce, at least, indoor $PM_{2.5}$ levels. We illustrate through a simple scenario analysis that air filtration can reduce exposure (26–79%) to a similar extent as the structural mitigation programs (e.g. closing coal factories) achieved in recent years (53%). We argue government intervention is needed to convey the benefit of air filtration to the socioeconomically disadvantaged groups.

1. Introduction

Air pollution caused over 7 million premature deaths worldwide in 2012 (WHO, 2014). Studies consistently show that particulate matter

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exposure increases incidences of lung cancer (Raaschou-Nielsen et al., 2013), cardiovascular morbidity and mortality (Dockery et al., 1993; Langrish et al., 2012; M. Liu et al. 2017). Among the 67 health risk factors, ambient particulate matter pollution ranked ninth globally (Lim et al., 2012) and fourth in China (Yang et al., 2013). In China alone, air pollution caused 25 million disability adjusted life years (Yang et al., 2013) and an estimated economic cost of 1.4 trillion USD in 2010 (OECD, 2014).

Such a heavy toll on the health of the citizens and the economy of China received unprecedented attention (Huang, 2015). The government revised air quality standards, expanded air quality monitoring networks and commissioned a series of efforts to mitigate pollution sources including closing polluting factories, replacing coal with natural gas for household heating and cooking, installing filters for restaurants, and encouraging electric vehicles (Zhang et al., 2015; Zhang et al., 2016; Feng and Liao, 2016). As a result, the $PM_{2.5}$ level decreased considerably in some areas. For example, the average annual $PM_{2.5}$ level in Beijing reduced about 53% from 89 $\mu g/m^3$ in 2013 to 58 $\mu g/m^3$ in 2017. However, with 239 days of $PM_{2.5}$ concentration exceeding the WHO recommended standard in 2017 (WHO, 2006; Beijing MEPB, 2017), air quality in Beijing is still a major health risk. In fact, a recent study found that even if the particulate air pollution level decline substantially by the year 2030, the health impacts from air pollution will continue to increase due to the demographic trends of a growing and aging Chinese population (GBD MAPS Working Group, 2016).

An additional challenge is that the health impacts of air pollution are not shared equally across all the citizens. Globally, the health risks associated with air pollution are higher in low- and middle-income countries, where 88% of the premature deaths due to air pollution occur (WHO, 2014). Similar patterns were found at the local scale. Air pollution levels are usually higher in the most deprived areas within a city (e.g. Fecht et al., 2015; Ngo et al., 2018). The association between air pollutants and health risks was found higher for people from ethnic groups and with lower education level (Hao et al., 2016). Air quality improvement was found to be greatest in the least deprived areas while the most deprived areas bear a disproportionate share of declining air quality (Mitchell et al., 2015). A review of 37 studies found that poorer communities often experience higher levels of air pollution in North America, Europe, Asia, Africa and Oceania (with mixed results in Europe) (Hajat et al., 2015). This review also shows that research examining the association between air pollution, health risk and socioeconomic status is very limited where most, if not all, cities with the worst air pollution are located such as China and India (Y. Liu et al., 2017; Han et al., 2018). Among the 37 studies reviewed, only one case study was conducted in Asia - Hong Kong (Hajat et al., 2015). As such, it is unclear whether the level of outdoor air pollution is homogenous or varies spatially posing unequal health burdens to residents across the urban areas in heavily polluted Asian cities. This is a clear environmental justice issue and understanding such inequalities is crucially important to address the air pollution challenge and its social and health burdens, and thereby to promote the sustainability of urban ecosystems (Sampson, 2017).

In addition to outdoor air pollution, indoor air quality also contributes to the overall health impact of urban air pollution. Air pollution in the outdoor and indoor settings are often treated as two separate research fields involving different major pollutants, mechanisms of dispersal, control management and health consequences. However, when considering human health impacts of air pollution it is important to look at the level and kinds of exposure an individual experiences throughout their day, whether indoors or out of doors. Many cities commission contingency plans to advise residents reduce outdoor activities when air pollution gets severe (Huang, 2015), and use air filtration to reduce people's indoor pollutant exposure (Oh et al., 2014). For example, in order to reduce exposure to high levels of $PM_{2.5}$, the United States Environmental Protection Agency (US EPA) recommends to stay indoors in an area with filtered air (US EPA, 2017). Central air cleaners using high efficiency, or high efficiency particulate air, (HEPA) filters are recommended by California Air Resources Board (2014) for home use, which ventilate a house and provide continuous filtered fresh air. Studies have shown that using air filtration can decrease the indoor $PM_{2.5}$ concentration (Zhang et al., 2011), improve indoor air quality (Oh et al., 2014; van der Zee et al., 2017) and reduce the related health risks significantly (Allen et al., 2011). Considering the great amount of time urban residents stay indoor on average, air filtration technology can effectively reduce people's exposure to $PM_{2.5}$ when the outdoor pollution level remains high.

Given the severe air pollution and limited research on its impacts in China, it is imperative to understand how air quality may vary with people's capacity to cope with its associated health challenges. Using Beijing as a case study, our research had three core questions: (1) How do $PM_{2.5}$ levels vary spatially across Beijing, and how does this variation correlate with household's socioeconomic characteristics? (2) How much exposure to $PM_{2.5}$ can be reduced by using air filtration systems? And (3) Can air filtration be used to address the inequitable burden of air pollution in Beijing?

2. Data and methods

In order to answer the research questions, we conducted three analyses. First, we used spatial analysis to examine the spatial heterogeneity of the $PM_{2.5}$ levels in Beijing based on both monitoring data and remote sensing data. Secondly, we conducted a correlation analysis between average $PM_{2.5}$ levels and socioeconomic characteristics at the Jiedao scale in the urban area of Beijing. Finally, we developed a simple scenario analysis to illustrate the magnitude of exposure reduction through improving indoor air quality by air filtration in the context of Beijing's current pollution level.

2.1. Study area

Our study focused on the city of Beijing, the capital of China. Beijing is the nation's political, educational, financial and cultural center. It is the second largest city in China after Shanghai, with a population of 21.5 million people in 2016 (Beijing Statistical Bureau, 2017). Beijing has 16 districts, with an area of 16,800 km^2. It is located in the northwestern part of the North China Plain (39°28′ – 41°25′N′, 115°25′ – 117°30′E), with mountains to the north, northwest, and west of the city.

In 2016, the average level $PM_{2.5}$ was 73 $\mu g/m^3$ (Beijing MEPB, 2017) with 298 days where the $PM_{2.5}$ levels exceeding 35 $\mu g/m^3$ – the WHO's clean air level for interim target-1 (2006). As a city known for air pollution, growing urban population and rapid economic development, Beijing provides an excellent case to understand the spatial heterogeneity of $PM_{2.5}$ and how air filtration can reduce both indoor $PM_{2.5}$ level as well as the air quality gap across the city.

2.2. Data

We used three air quality datasets in this study. The first was a daily $PM_{2.5}$ concentration dataset for year 2015, derived from the 23 monitoring sites. The second dataset included $PM_{2.5}$ concentration estimated by remote sensing data from the global annual $PM_{2.5}$ concentration dataset provided by the Atmospheric Composition Analysis Group at the Dalhous University, Canada (http://fizz.phys.dal.ca/~atmos/martin/). The $PM_{2.5}$ concentrations in this dataset were estimated based on aerosol optical depth (AOD) derived from MODIS, MISR, and SeaWIFS imagery, using the GEO-chem chemical transport model, and were calibrated to the global ground-based observation of $PM_{2.5}$ using geographically weighted regression (van Donkelaar et al. 2010, 2015 and 2016). Details on calculation and limitation of dataset were discussed in Peng et al. (2016). This dataset has a spatial resolution of 1 km, and was derived from data collected in 2015. We used these two datasets to analyze the spatial pattern of $PM_{2.5}$ level in Beijing.

The third dataset is an hourly $PM_{2.5}$ concentration dataset. Due to data availability, we used a dataset from September 1, 2013 to August 31, 2014, derived from the 11 of the 23 monitoring sites (Fig. 1). We used it to simulate how air filtration would reduce exposure levels in the scenario analysis.

Income and education are the two commonly used variables to describe residents' social vulnerability to environmental hazards (Cutter et al., 2003; Lin et al., 2014). We used these two variables to represent people's capacity to protect themselves from the adverse health impact caused by air pollution. We obtained data on proportion of adults with a high school degree from annual statistic book (Beijing Statistical Bureau, 2015) by Jiedao, which is the smallest census unit. It is worth noting that average income is only available at the district scale, which is one level upper than Jiedao. Here we estimated average income for each Jiedao by combining the average income of the district where the Jiedao is located and the average housing rent of each neighborhood within the Jiedao. Detailed information on income estimation can be found in Tu et al. (2018).

2.3. Air quality standards

Adverse health effects of the airborne particulate matters have been documented at both low and relatively high concentration levels (WHO, 2006). Instead of indicating a complete safe level, air quality standards serve as a tool to facilitate countries to achieve "the lowest concentrations possible in the context of local constraints, capabilities and public health priorities" (WHO, 2006).

We listed the air quality standards recommended by the WHO and China in Table 1. The WHO recommended an annual mean level for $PM_{2.5}$ below 10 μg/m^3 and the 24-h mean level below 25 μg/m^3 (2006). It also provided a set of interim target values (Table 1) to encourage countries to adopt increasing stringent set of standards (WHO, 2006). According to WHO's guidelines and the current pollution situation, China adopted the 1st interim target and developed a 6-level standards to describe the $PM_{2.5}$ pollution from "clean" to "seriously polluted" (Table 1).

2.4. Data analyses and scenarios

Based on the daily $PM_{2.5}$ concentration dataset, we calculated the number of clean air days as well as heavily polluted days defined as having a daily average $PM_{2.5}$ level below 35 μg/m^3 and above 150 μg/m^3 respectively (MEP China, 2012) for each monitoring site.

Here we define the area within the fifth ring road as the urban area in Beijing (Fig. 2). This area contains 97 Jiedao. Based on the 1 km resolution $PM_{2.5}$ dataset, we calculated the annual mean $PM_{2.5}$ level for each Jiedao. We then checked for the linearity between the annual mean $PM_{2.5}$ level and average income as well as the proportion of adults with a high school degree, and calculated the Pearson correlation coefficients (denoted by r) to measure the strength of the association between the annual mean $PM_{2.5}$ level and the two variables. The *t*-test was used to examine the significance of the correlation coefficients. The spatial analysis was conducted in ArcGIS™ and the statistical analysis was conducted in SPSS™.

We developed three scenarios to examine how much $PM_{2.5}$ exposure could be reduced by improving indoor air quality through air filtration. The three scenarios are about where air filtration is installed: using air filtration at work, using air filtration at home and using air filtration at both places. We hypothesized people are at work 9 am–6 pm and at home 8 pm–7 am. As a result, each scenario generated a different time period during which people are exposed to the filtered air. Then we incorporated the three scenarios with the 12-month hourly $PM_{2.5}$ dataset. Previous studies showed that without filtration indoor $PM_{2.5}$ level is close to the outdoor environment because of frequent ventilation (Massey et al., 2009; Oeder et al., 2012). Therefore, we used the reported outdoor $PM_{2.5}$ level to denote the $PM_{2.5}$ level in an indoor environment without filtration in the scenarios. In the three scenarios, we

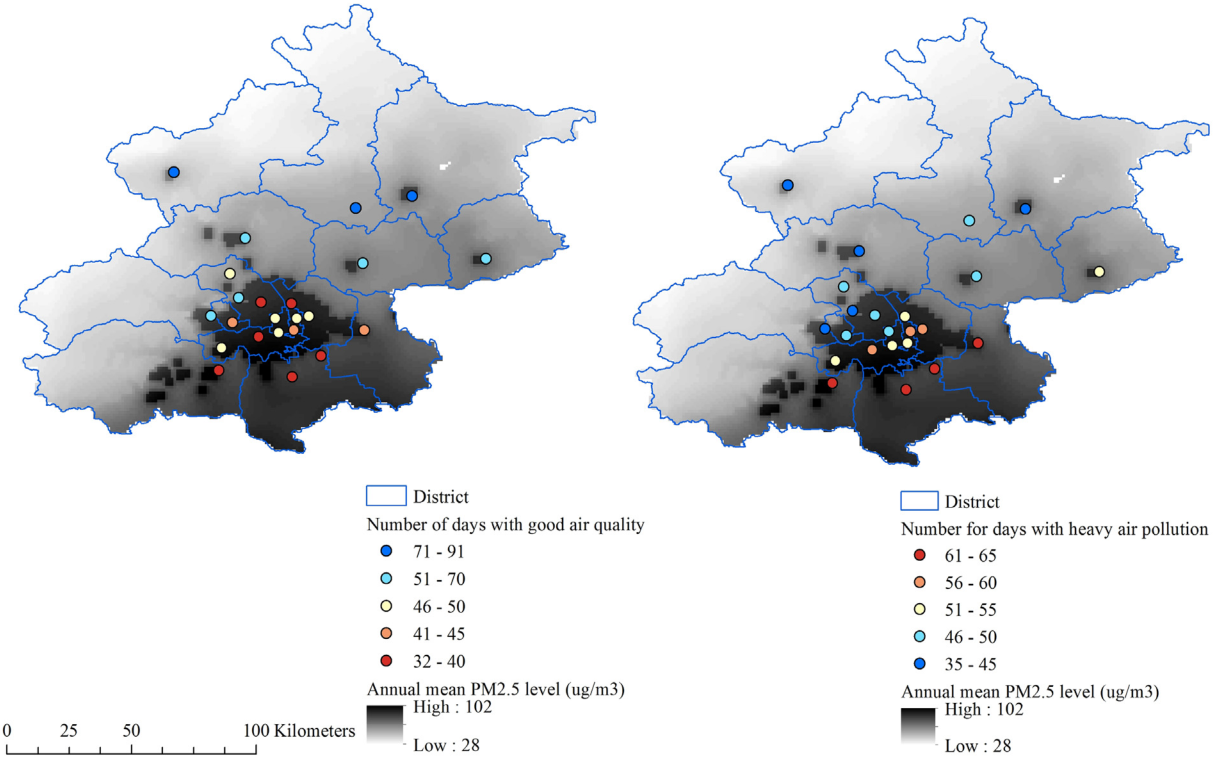


Fig. 1. Spatial patterns of $PM_{2.5}$ concentration in Beijing, 2015. This figure present the spatial pattern of $PM_{2.5}$ levels in Beijing in 2015. The white-black gradient indicates the estimated annual $PM_{2.5}$ concentration based on aerosol optical depth derived from MODIS, MISR, and SeaWIFS imagery. The points are where air quality monitoring stations are located. The color of the points shows the number of days with good air quality lower than 35 μg/m3 (on the left) and with heavy air pollution higher than 150 μg/m3 (on the right).

Table 1
Air quality standards by WHO and China.

		Annual mean			24-h mean					
WHO	Recommended standard	10			25					
	Interim targets	Target-3	Target-2	Target-1						
		15	25	35						
China	Ambient air quality standard	Level 1		Level 2	Clean	Fairly clean	Slightly polluted	Moderate polluted	Highly polluted	Seriously polluted
		15	–	35	0–35	35–75	75–115	115–150	150–250	>250

Unit: μg/m^3.

considered the indoor PM$_{2.5}$ level would meet with the WHO 24-h mean standard of 25 μg/m^3 with proper filtration (WHO, 2006). When the reported real PM$_{2.5}$ level is higher than 25 μg/m^3, we replaced it with 25 μg/m^3 for the time period using air filtration for the three scenarios respectively. This assumption was based on previous studies examining air filtration's efficiency, which found that air filtration is effective to keep indoor PM$_{2.5}$ at a level lower than 25 μg/m^3 (Allen et al., 2011; Butz et al., 2011). The removal rate was around 70–80% (Oh et al., 2014), which tended to be higher with a high outdoor PM$_{2.5}$ concentration. Finally, we calculated the average exposure levels and the percent days with an average concentration below 75 μg/m^3, which is the 24-h mean value issued by China to denote an acceptable level of exposure (MEP China, 2012, Table 1).

3. Results

3.1. The spatial variation of air pollution

In Beijing even the monitoring site reporting the "cleanest air" has an annual mean of 61 μg/m^3 for PM$_{2.5}$ concentration (Beijing MEPB, 2016). This concentration is over 6 times the WHO's air quality guideline for annual mean value (10 μg/m^3), and almost twice the Interim target-I annual mean value (35 μg/m^3) (2006). The geographical differences in air quality, however, delineate areas suffering the most from air pollution in the overall severe situation. Our results show that the air pollutants are spatially heterogeneous in Beijing (Fig. 1). The annual mean level estimated from remotely sensed data is consistent with the air quality monitoring data from the 23 sites (Fig. 1). The spatial pattern has two characteristics. First, the more urbanized areas in the middle tend to have higher pollution level (Figs. 1 and 2a-1). Second, the PM$_{2.5}$ concentration is lower in the northwest and increases toward southeast. Fig. 2b-1 presents the heterogeneity of PM$_{2.5}$ levels within the urban area, which follows a similar pattern – low in the northern area and increase toward the south. An intuitive way to consider the air quality difference is to compare the numbers of days with clean air or heavy pollution (Fig. 3). Yanqing site had the most clean air days (61 days, <35 μg/m^3) and the least heavily polluted days (45 days, >150 μg/m^3) in 2015. In contrast, Huangcun site only had 18 clean air days. Tongzhouxincheng site had the most heavily polluted days, 82 in total (Fig. 3). In another words, within the same city, residents may

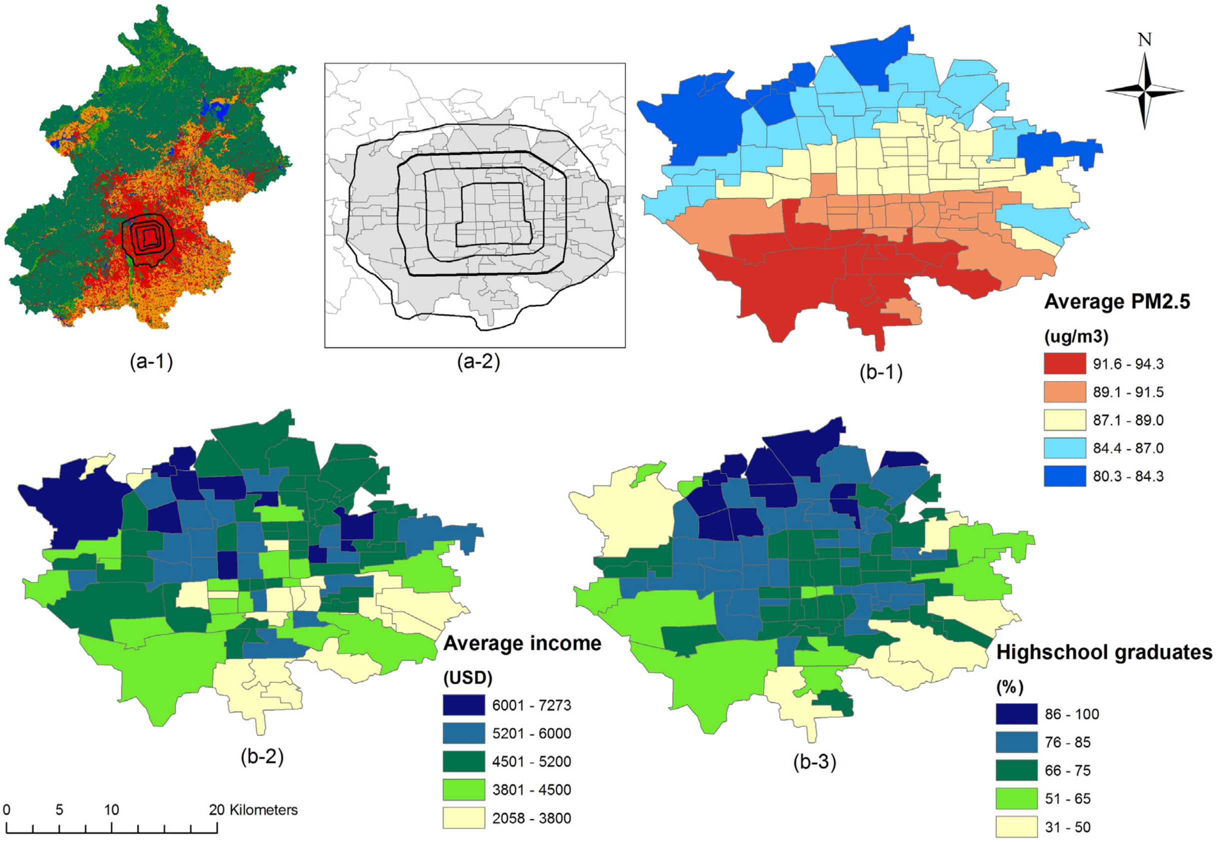


Fig. 2. Air quality, income and education conditions in urban Beijing. This figure shows the spatial heterogeneity of average PM2.5 level, average income and education. Fig. a-1 presents the land cover types in 2015 where red indicates impervious surfaces (dark green: forest; light green: grass; blue: water and wetland; brown: farm field). We selected the most urbanized area, 97 Jiedao within the fifth ring road (as shown in a-2), to analyze the spatial patterns of and relationship between the PM2.5 level (b-1) and average income (b-1) as well as percent of high school graduates (b-3).

have about 40 days under the blue skies or of heavily smog depending on which part of the city they live.

3.2. The association between air pollution and socioeconomic characteristics

We present the spatial patterns of average income and percent high school graduates in each Jiedao within the fifth ring road in Fig. 2 along with the annual mean $PM_{2.5}$ level. Our analysis showed that the annual mean $PM_{2.5}$ concentration had a significantly negative correlation with the average income ($r = -0.456$, $p < 0.001$), and the percent high school graduates ($r = -0.286$, $p = 0.005$) (Fig. 4). The results are statistically significant at 99.9% and 99.5% confident level respectively. Jiedao with higher average income and/or percent high school graduates tend to have lower annual mean $PM_{2.5}$. Both average income and percent high school graduates tend to be higher in northern Beijing and to decrease from north to south (Fig. 2b-2; b-3). This pattern is similar to the $PM_{2.5}$ distribution and results in the significant correlation between air pollution and residents' socioeconomic characteristics. The underlying mechanisms of this patterns are complex and beyond the scope of this study. Nonetheless, the association between air pollution and residents' socioeconomic characteristics itself has important implications on health burdens posed by air pollution.

3.3. Exposure reduction by using air filtration

Our estimation suggested that using filtration substantially reduces the average $PM_{2.5}$ exposure levels across the 11 sites (Table 2). The "using air filtration at work" scenario reduced exposure to $PM_{2.5}$ by 19–24 μg/m^3. The "using air filtration at home" scenario reduced exposure to $PM_{2.5}$ by 25–36 μg/m^3 across the 11 sites whereas the "using air filtration at both places" scenario reduced exposure to $PM_{2.5}$ by 45–60 μg/m^3.

As defined by the scenario assumptions the higher the original pollution level for a Jiadao was, the more the exposure was reduced (Table 2). The maximum reduction happened at Wanliu site, which had an annual mean of 94 μg/m^3. Exposure to $PM_{2.5}$ was reduced at this site by 24, 36 and 60 μg/m^3 in the scenarios of using air filtration at "work", "home", and "work + home" respectively. The sites where the filtration interventions conferred the least benefit were at Huairou and Changping sites. These sites had the annual means of 75 and 76 μg/m^3 respectively and filtration reduced exposure by 19, 25, and 45 μg/m^3 in the scenarios of using air filtration at "work", "home", and "work + home" respectively. The results indicate air filtration can reduce the exposure gap when applied to all the locations. The original pollution levels ranged between 75 and 94 μg/m^3 across sites with a difference of 19 μg/m^3. Using air filtration reduced the differences across locations to 14 μg/m^3, 9 μg/m^3, and 4 μg/m^3 in the "work", "home", and "work + home" scenarios respectively (a reduction of 26%, 53% and 79%) (Fig. 5).

The percentage of days that meet the1st interim standard set by the WHO also substantially increased. They increased on average from 56% to 71%, from 56% to 78% and from 56% to 99% in the "using air filtration at work", "using air filtration at home", and "using air filtration at both places" scenarios respectively. Fig. 5 shows with the increase hours spent in the filtered environment, the average exposure level to $PM_{2.5}$ decreases, the percentage of days that meet with the target increases. More importantly, the variation among the sites decreases indicating a reduced inequity of air pollution burden.

4. Discussion

4.1. Socioeconomic disparities in $PM_{2.5}$ exposure

The spatial variations of $PM_{2.5}$ are mainly caused by two reasons. First, emissions varied spatially due to urban planning and land use practices. The spatial heterogeneity of pollution sources contribute to the uneven distribution of air pollutants (Lin et al., 2014; Zhou et al., 2014). Secondly, local weather and geographic conditions affect how air pollutants diffuse. In the case of Beijing with northwest as the dominant wind direction and the northwest-high-southeast-low terrain, air pollutants tend to accumulate in the southeast part of the city (Li et al., 2015).

People with higher income and education tend to be more aware of the potential health impacts caused by air pollutants (Hammitt and Robinson, 2011). Moreover, people with higher income and education are often better equipped to protect themselves. For example, private car owners are less exposed to outdoor air pollution than those waiting for public transportation (Moore et al., 2012; Godoi et al., 2013; Ramos et al., 2015). Some office and commercial buildings (e.g. the SOHO commercial buildings) in Beijing installed air filtration system to remove $PM_{2.5}$, which benefits the white-collar employees and high-end consumers. The wealthier households are often better-insulated and more likely to have air filtration to improve indoor air quality (Long et al., 2001). In Beijing, recent upper-class apartments have air filtration installed as a selling point to be a "healthy" neighborhood.

Therefore, the fact that the $PM_{2.5}$ level is higher where residents have less income and are less educated means people who are less capable to protect themselves are exposed to higher air pollution. Such "double jeopardy" (Huang and London, 2012) usually results in higher health burden for the entire society, which is not only morally injustice but also inefficient considering the associated economic costs (Li et al., 2017).

4.2. Air filtration: alleviate or exacerbate the inequity?

Results from the scenario analysis indicated that air filtration could be an effective tool to reduce $PM_{2.5}$ exposure. Having filtered fresh air

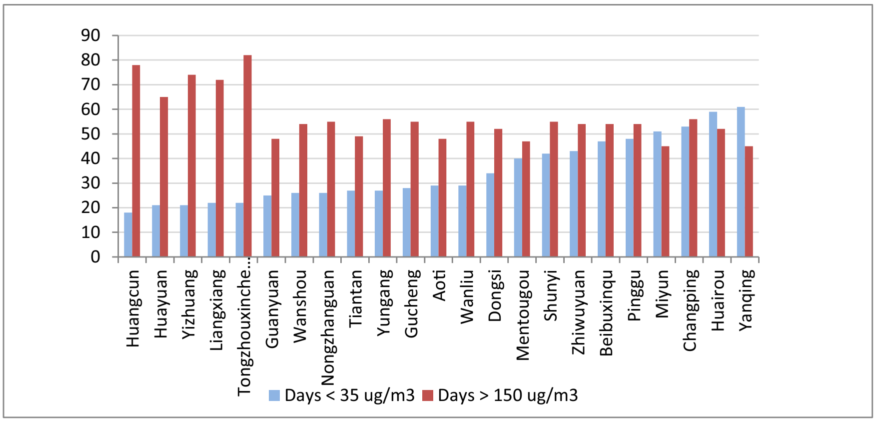
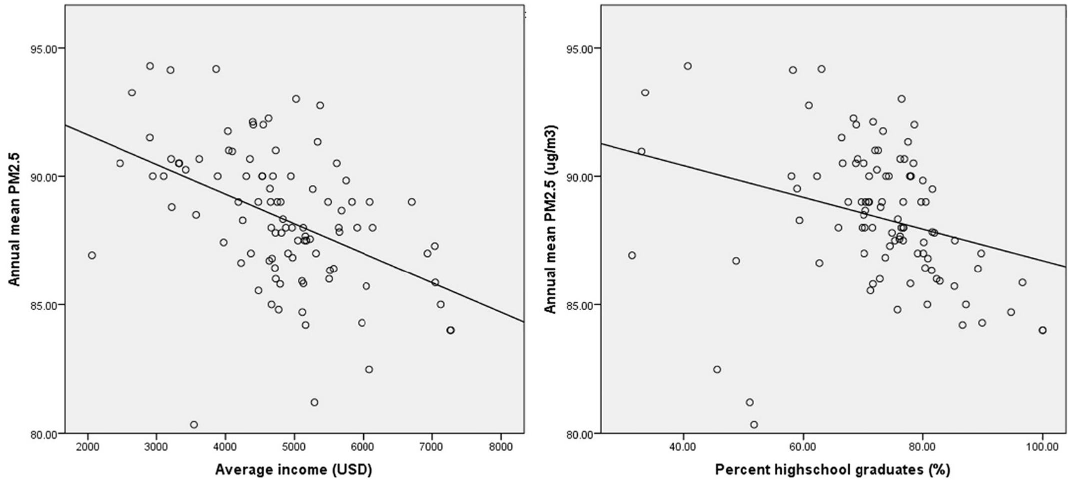


Fig. 3. Numbers of days with average $PM_{2.5}$ concentration below 35 or above 150 μg/m^3 in the 23 monitoring sites in Beijing.



(r=-0.456, p<0.001 n=97)

(r=-0.286, p=0.005 n=97)

Fig. 4. Correlations between air quality, income and education conditions in urban Beijing. This figure indicates that average income and percent high school graduates are negatively correlated with the annual mean $PM_{2.5}$ concentration. Jiedao with higher average income and/or have more high school graduates tend to have lower annual mean $PM_{2.5}$ in 2015.

at work alone can roughly equal to a 26% reduction in exposure to $PM_{2.5}$. For reference, Beijing reduced the average annual $PM_{2.5}$ level by 54% (89.5 μg/m^3 in 2013 to 58 μg/m^3 in 2017), which was achieved through closing >1300 factories and reducing over 13 million tons coal burned in the city (Beijing MEPB, 2014, 2017).

Air filtration program would reduce exposure more in places with higher pollution levels. Therefore, when applied to the entire city, it can help to diminish the gap in exposure rates across the city as shown in our scenario analysis. In reality, however, whether air filtration will alleviate or exacerbate the "double jeopardy" situation largely depends on the planning and decision-making process. We argue when the decisions are left to private sectors and individuals, people with higher income and education are more likely to have filtered fresh air. Although they are more likely to live in areas with relatively less $PM_{2.5}$ pollution, they are often more aware of the health risk, more willing to invest in protection measurements and more likely to afford the cost for filtered air. This represents a classic example of environmental injustice.

Table 2
Comparing average $PM_{2.5}$ concentration and percent days meet with Level 1 interim target in reality and three scenarios.

Monitoring station	Usual avg. $PM_{2.5}$ level; % days meet standard	Scenarios: using air filtration		
		Work avg. $PM_{2.5}$ level; % days meet standard	Home avg. $PM_{2.5}$ level; % days meet standard	Work + home avg. $PM_{2.5}$ level; % days meet standard
Shunyi	82	62	51	31
	58%	71%	79%	99%
Wanshou	87	66	54	32
	55%	68%	78%	99%
Aoti	87	65	55	33
	53%	67%	77%	99%
Huairou	75	56	49	30
	62%	76%	82%	100%
Changping	76	56	51	31
	60%	76%	78%	98%
Dongsi	89	66	55	32
	53%	68%	76%	100%
Wanliu	94	70	58	34
	50%	64%	74%	98%
Nongzhanguan	88	65	55	32
	54%	70%	76%	99%
Gucheng	88	66	56	34
	52%	67%	77%	99%
Tiantan	86	64	54	32
	54%	70%	78%	99%
Guanyuan	87	65	54	33
	53%	69%	77%	99%
Average	84	63	53	32
	56%	71%	78%	99%

One clear example of where this injustice manifests itself is in the Beijing school system. The City of Beijing required primary and middle schools switch to "flexible teaching" during severe air pollution events, which means students can choose to learn from home and each school can design its own way to continue teaching based on the attendance. There were 30 schools in Beijing installed air filtration to improve classroom air quality by January 2017. Among these 30 schools, 11 are private schools and the rest 19 public schools are all key schools where housing values are high in the corresponding school districts (Sohu education, 2017). Daxing district is located in the downwind direction of Beijing and has the highest $PM_{2.5}$ level among the 16 districts of the city. It has 1.54 million residents. The only school that has installed air filtration in Daxing District is a private school called Zhongxin School. During a severe air pollution event in 2016 when students can choose to learn from home, 750 students went to school in Daxing District, among which 700 students were from Zhongxin School (Tan et al., 2017). This example conveys two important messages. First, most schools that took the lead to install air filtration are not located in the worst air pollution areas. Furthermore, the students who have filtered fresh air are more likely from better-off families that are capable or willing to invest in their private school tuition or purchasing estate in good school districts. Second, whether a school can provide filtered fresh air to classroom will not only impact students' health but also make a difference on their attendance and learning during the severe pollution events.

We suggest that the government needs to allocate resources and efforts to the socioeconomic disadvantaged people who bear the biggest costs of poor air quality. This will not only address the environment injustices but also maximize the health benefits returned on money invested. The use of air filtration can be targeted toward the socioeconomically disadvantaged groups as an important intervention measurement to reduce associated health risk. Government can directly invest to install air filtrations in preschools, schools, nursing homes, and hospitals to target the most vulnerable population to air pollution (Dockery and Pope III, 1994; Bateson and Schwartz, 2004). Investments can be designed to target socioeconomically disadvantaged people. Prioritizing people with less income/education with subsidies for installing air filtration at home and/or neighborhood schools can effectively convey

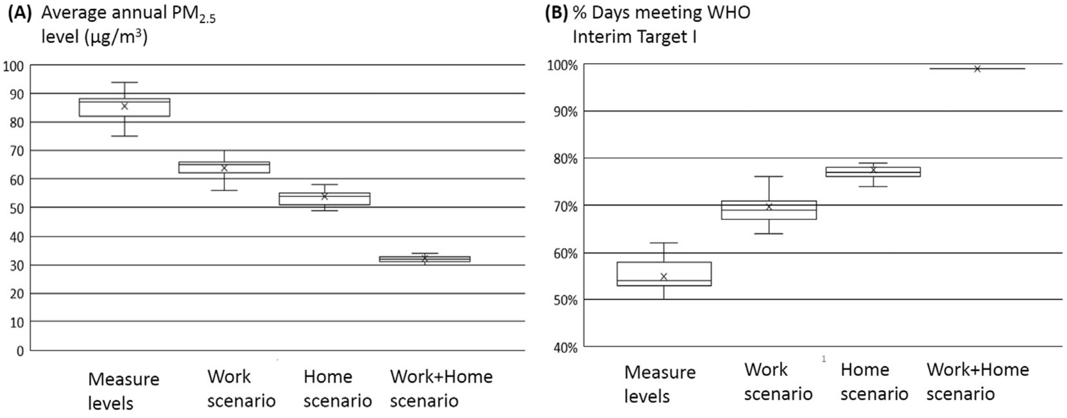


Fig. 5. Differences across 11 sites of average $PM_{2.5}$ levels and percent days that meet the 35 μg/m^3 WHO Interim I target. Comparing real data in 2015 and the three scenarios. The bar denotes the medium value and the "x" denotes the mean value for each plot, boxes show the 25th and 75th percentile, and the whiskers show 1.5 standard deviation.

the potential health benefits. Finally, maintaining good indoor air quality in public places (such as libraries and museums) makes them as shelters during severe pollution events. Similar to the way cooling shelters work for people who cannot afford air conditioners during a heat wave, these filtered air shelters will work for people who cannot afford air filtration and reduce the unequal health burdens levied on the more marginalized in society.

4.3. Limitations

Our study is limited, and therefore indicative, by a few aspects typical of what would be called "ecological studies" in epidemiology. First, our exposure measures are that of the ambient air at the monitoring stations but not direct measurements of air quality actually breathed in by Beijing residents. As such, it is not possible to link $PM_{2.5}$ exposure directly to negative health outcomes in our study, nor get an accurate idea of the variation in exposure levels within the regions represented by a monitoring station. Second, we do not have data on a suite of confounding factors that might also dictate the levels of exposure for individuals across Beijing. These confounders might include time spent outdoors, physical structures (e.g. building, engines, trees) that might exacerbate or mitigate exposure, or even the type of face mask an individual can afford. Despite these limitations the wider hypothesis generation here, we suggest, is quite valid – that poor air quality is unequally distributed exposing the more marginalized to the worst ambient air quality and that air filtration could largely reduce $PM_{2.5}$ exposure.

5. Conclusions

While China is home to some of the world's worst air pollution, studies on association between air pollution and residents' socioeconomic characteristics are rare. Our study of Beijing fills in this gap providing insights on the spatial pattern of $PM_{2.5}$ pollution in Beijing and its association with Jiedao's income and education levels. Our finding is consistent with case studies in North American cities where low-socioeconomic-communities usually experience higher level of air pollution (Hajat et al., 2015).

Air filtration can effectively improve indoor air quality. We illustrated the potential exposure reduction that can be achieved by air filtration through a simple scenario analysis. In the context of Beijing's severe pollution, indoor air filtration can reduce exposure at a significant level, similar to the economics and structural mitigation efforts in recent years. The availability of filtration technology brings hope to reduce the negative health impacts posed by air pollution. However, whether air filtration will alleviate the current socioeconomic disparities in pollution exposure or exacerbate the existing inequity largely depends on how it is used in the society. When left to individual decision-making, the use of air filtration, while reduce exposure to some people, will exacerbate the pollution exposure gap between socio-economic advantaged and disadvantaged groups. We argue government should allocate resources to the disadvantaged people and reduce their pollution exposure through such policy intervention. Such efforts, if taken, can benefit the 1.3 billion people suffering severe air pollution in 280 cities of China (H. Liu et al. 2017). Since 24 of the 31 megacities (cities with >10 million inhabitants) are located in the less developed countries and experience negative health impacts of poor air quality (UN, 2016), our approach here may likely be worth examining in many of these contexts and across the world's poor urban megacities currently battling poor air quality.

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