Environmental Pollution 263 (2020) 114388

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Public health benefits of optimizing urban industrial land layout - The case of Changsha, China☆

Wanjun Xu [a, 1], Zhuotong Zeng [b, 1], Zhengyong Xu [c, 1], Xiaodong Li [a, *], Xuwu Chen [a], Xin Li [a], Rong Xiao [b], Jie Liang [a], Gaojie Chen [d], Anqi Lin [a], Jinjin Li [a], Guangming Zeng [a]

[a] College of Environmental Science and Engineering, Hunan University, Changsha, 410082, PR China
[b] Department of Dermatology, Second Xiangya Hospital, Central South University, Changsha, 410011, Hunan, PR China
[c] Science and Technology Service Center of Hunan Province, Changsha, 410013, PR China
[d] College of Mathematics and Econometrics, Hunan University, Changsha, 410082, PR China

ARTICLE INFO

Article history:
Received 25 September 2019
Received in revised form
12 March 2020
Accepted 14 March 2020
Available online 19 March 2020

Keywords:
Health impacts
$PM_{2.5}$
Industrial land layout
Emission locations
Economic burden

ABSTRACT

In China, ambient fine particulate matter ($PM_{2.5}$) causes a large health burden and raises specific concerns for policymakers. However, assessments of the health effects associated with air pollution from industrial land layouts remain inadequate. This study established a comprehensive assessment framework to quantify the health and economic impacts of $PM_{2.5}$ exposure at different industrial geographical locations. This framework aims to optimize the spatial distribution of industrial emissions to achieve the lowest public health costs in Changsha, a representative industrial city in China. Health effects were estimated by applying the integrated exposure-response model and a long-range pollution dispersion model (CALPUFF). The value of statistical life (VSL) was used to monetize health outcomes. It was found that implementing an optimal industrial land layout can yield considerable social and financial benefits. Compared with the current industrial space layout, in 2030, the averted contribution by Changsha's industrial sector to $PM_{2.5}$-related mortality and corresponding economic losses will be 60.8% and 0.69 billion US dollars (USD), respectively. The results of optimization analyses highlighted that population density and emission location are significant factors affecting the health burden. This method can identify the optimal geographical allocation of industrial land with minimal expected health and economic burden. These results will also provide policymakers with a measurable assessment of health risks related to industrial spatial planning and the associated health costs to enhance the effectiveness of efforts to improve air quality.

1. Introduction

With the rapid development of industrialization, China has made remarkable economic achievements over the last four decades. Over the past decade, industrial output accounted for 36.82% of gross domestic product (GDP) in China (http://data.stats.gov.cn). However, industrialization has brought serious air pollution to China, and $PM_{2.5}$ has become the primary source of environmental health (Burnett et al., 2014; Cohen et al., 2017; Lim et al., 2012). $PM_{2.5}$ pollution has caused adverse environmental problems and raised concerns about public health in many industrialized countries, including (primarily Beijing, Tianjin, and Shanghai), America, India, Indonesia, Germany, Turkey, Mexico, and Russia. For instance, Lelieveld et al. (2015) found that 8% of China's premature mortality attributed to air pollution was caused by the industrial sector. Matus et al. (2012) estimated that the economic loss caused by $PM_{2.5}$-related health problems equaled 5.9% of China's GDP in 2005. Etchie et al. (2017) estimated that $PM_{2.5}$ pollution in Nagpur, India, caused 3.3 thousand premature deaths in 2013, resulting in an economic loss of 2.2 billion USD. Therefore, governments are facing the challenge of trying to reduce the public health risks associated with air pollution while simultaneously maintaining industrial economic growth.

Epidemiological and toxicological studies have established evidence of reasonable mechanisms between PM and the adverse health effects from the production of iron, steel, fuel, bricks,

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.

* Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha, 410082, PR China.
E-mail address: lxdfox@hnu.edu.cn (X. Li).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.envpol.2020.114388
0269-7491/

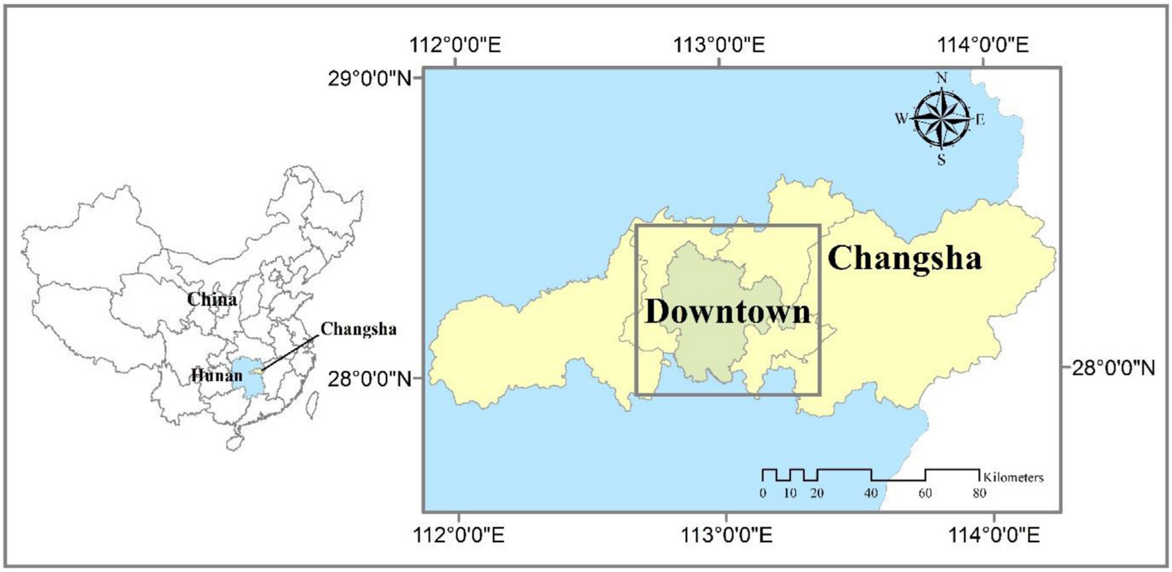

Fig. 1. Location of the Downtown area in Changsha city.

chemicals, and other manufacturing processes (Hennig et al., 2014; Khan et al., 2019; Santibáñez-Andrade et al., 2017; Senthil et al., 2018; Shen et al., 2018). Due to its large surface area, $PM_{2.5}$ can bind with toxic compounds. It can penetrate the respiratory system, reach the lungs, and enter the human alveoli, accounting for about 96% of the particulate matter that remains in the lung parenchyma (Feng et al., 2016; Mardones, 2019). Studies indicate that long-term exposure to $PM_{2.5}$ in individuals can cause adverse health effects, including ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC) (Cohen et al., 2017; Guan et al., 2016; Maji et al., 2018b). Exposure to high concentrations of $PM_{2.5}$ that contain complex toxic chemicals could increase the risk of cause-specific diseases. For instance, Senthil et al. (2018) demonstrated that transitional metals and organic compounds present in the PM from industrial processes can cause oxidative DNA damage and induce carcinogenesis. Pan et al. (1994) found that people living near facilities for the petrochemical industry are prone to various cancers. However, research to quantify the public exposure risks associated with the industrial pollutants has not yet been comprehensively conducted.

In China, recent national air quality policies have extensively focused on industrial air pollution. The Air Pollution Prevention and Control Action Plan (2013–2017) issued by the Ministry of Environmental Protection of China asserted that China's industrialization has increased the necessity for ambient air pollution control and optimize the industrial space layout (Ministry of Environmental Protection of China, 2013). Furthermore, the State Council issued the Three–Year Action Plan for Winning the Blue-Sky War (2018–2020), which calls for accelerated improvement of ambient air quality and the full compliance with industrial pollution emissions standards (Ministry of Environmental Protection of China, 2018). The mitigation of industrial air pollution has become an urgent problem that needs to be solved. In research cohort, studies largely focus on the revision of China's National Ambient Air Quality Standards (NAAQS), the formulation of overall control strategies for ambient air pollutants, the exploration of pollutant mitigation technologies, and the research of sectoral emissions in China (Apte et al., 2015; Aunan et al., 2006; Chen et al., 2017; Dasadhikari et al., 2019; GBD MAPS Working Group, 2016; Gu et al., 2018; Kishimoto et al., 2017; Li et al., 2017; Ma et al., 2017; Peng et al., 2017a; Peng et al., 2017b; Reddington et al., 2019; Shen et al., 2019; Tian et al., 2018; Wu et al., 2019; Zhou et al., 2014). These studies mainly focus on total emissions control, but relatively few investigations consider pollution mitigation from the perspective of spatial allocation. Moreover, there is no basic investigation that systematically assesses industrial sector emissions and the related health impacts at urban spatial levels. Therefore, due to a lack of reference methods in terms of urban industrial planning, local policies are currently insufficient to evaluate the relevant financial burden. In this context, research that quantifies both the health and economic burdens associated with urban pollution from industrial $PM_{2.5}$ is essential to provide useful policy-making approaches.

In this study, a comprehensive risk assessment was developed to optimize urban industrial land allocation by estimating the health effects of $PM_{2.5}$ exposure, using the city of Changsha as a case study. Land-unit characteristics were used to analyze the relationship between industrial locational patterns and $PM_{2.5}$ exposure. While the population of other geographies may be affected by industrial distribution, the domain was limited to the city's downtown area to obtain information directly relevant to urban policy analysis (Fig. 1). By analyzing the health effects attributable to industrial land management, the following two questions are proposed to achieve the optimal scenario:

1. What is the impact of industrial emission location on the $PM_{2.5}$-associated health burden?
2. How can the urban industrial land layout be optimized with the lowest public health cost?

This is the first study to combine industrial land planning with epidemiology at the city level. The results of this research are expected to deepen the understanding of variability in the relationship between industrial emissions and population exposure. These findings will provide valuable references for the development of effective strategies for air pollution-related health damage in China's rapid industrialization process and can provide exposure assessments for similar cities in other developing countries.

2. Methodology

2.1. Study area

Changsha is the economic and cultural center of Hunan province. It is located in the middle-lower reaches of the Xiang River and has a subtropical monsoon climate. Changsha is a typical industrial city, and 47.4% of its local economy was in the industrial sector in 2017. According to the Environmental quality report of Changsha, Hunan Province (2011–2015), in 2014, industry-related $PM_{2.5}$ accounted for 34% of total anthropogenic emissions and 16% of the total annual average concentrations. Therefore, urban industrialization has adversely impacted on air quality in the city of Changsha. According to the local official environmental quality report (2013–2015), particulate matter pollution in Changsha is relatively serious, especially in autumn and winter. In 2014, the annual average $PM_{2.5}$ concentration was 74 $\mu g/m^3$, while the highest daily average $PM_{2.5}$ concentration in winter reached 306 $\mu g/m^3$. This concentration greatly exceeds the daily Class-Istandard limit (35 $\mu g/m^3$) specified by the Chinese NAAQS. As a new first-tier city, Changsha's population has increased, making pollution control a crucial and urgent problem. Moreover, Changsha's $PM_{2.5}$ pollution characteristics are representative of the pollution status in many Chinese cities. Therefore, the selection of Changsha a case study for this research object is both important and pertinent.

2.2. Integrated assessment methodology

The method in this study was built upon a framework. Fig. 2 outlines the connection between the five steps of this integrated assessment. The Land unit planning module provided land units as industrial zones. The air quality model provided 1 km-resolution grid data for the annual average $PM_{2.5}$ concentration in the downtown area in 2030. A health module was used to quantify all-cause premature mortality. The modeling domain was divided into 4 areas: areas A, B, C, and D. The optimization process included four independent optimization simulations, and the optimal industrial land layout was determined on the combination of the four regional optimization results. The industrial emission site with the lowest mortality was considered to be the optimal location for the industrial zone in each area. The economic assessment module then monetized the relevant mortality outcomes. The details of these modules were introduced in the following section.

2.3. Land unit planning

The objective of land unit planning is to ensure the geographic heterogeneity of the target area, so that the outcome can be assessed according to the spatial distribution of industrial zones. A land unit is defined as a regional unit that is spatially divided from an area to facilitate urban land use management (van Niekerk, 2010). These units are represented as geographical frameworks and are assumed to have homogeneous land properties. Urban rapid transit systems and ecological or administrative boundaries are considered to be the ideal demarcations for a land unit. According to the above criteria, this study divided the downtown area into 42 land units using the main roads, district boundaries, rivers, and the ecological control lines of Changsha (Fig. 3(a)). The geographical data were acquired from the latest Atlas of the Overall Planning of Changsha City (2014) and were identified by the geographic information system (GIS) model. The year 2030 was set as a target year because it is the year identified as the long-term objective year in government plans. Furthermore, considering that some land units were planned to be densely populated and as unit 36 was an airport zone, 17 of these 42 units were selected as potential industrial areas. Fig. 3(b) depicts the geographical distribution of the 42 land units and the 17 potential industrial emission sources, all land units were indexed by i.

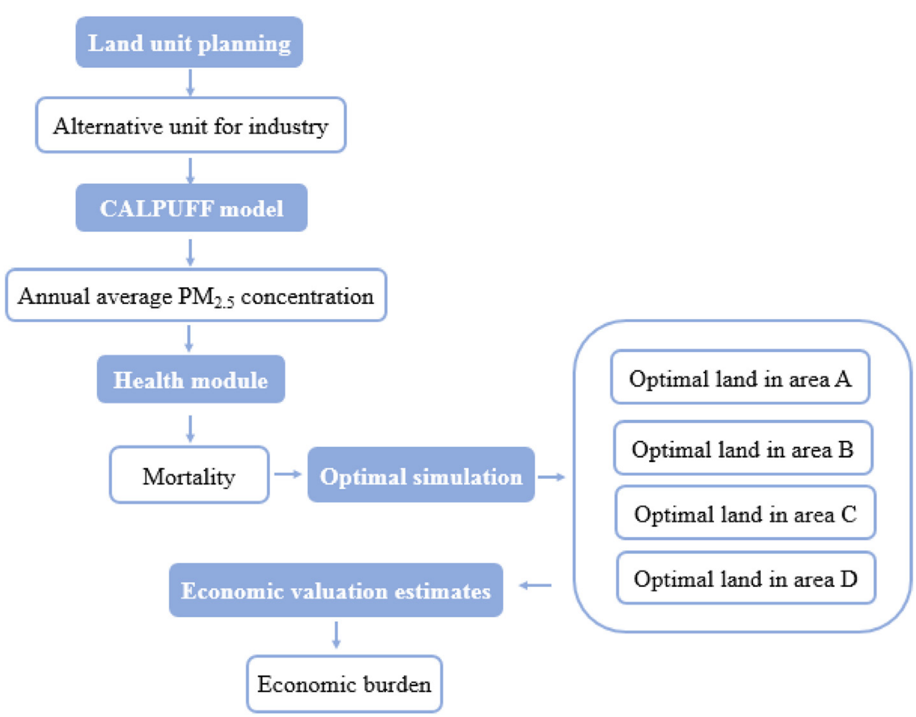

Fig. 2. Flowchart of the optimal industrial land layout.

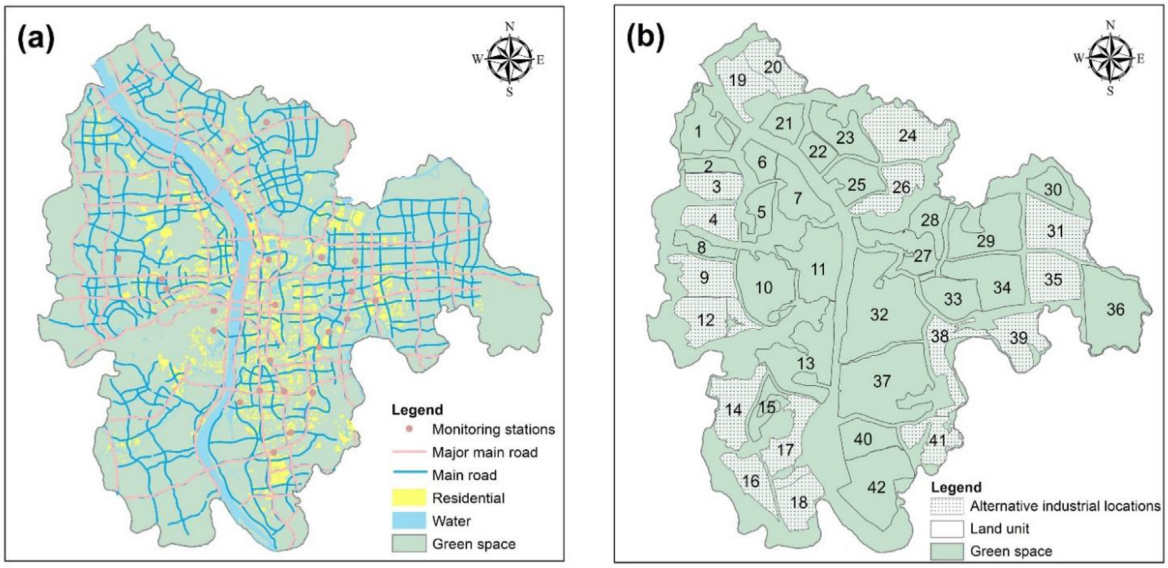

Fig. 3. (a) Study area component map, (b) Land unit planning layout.

2.4. Air quality modeling

The CALPUFF (version 6.0) system was applied to simulate the distribution of $PM_{2.5}$ at a resolution of 1 km. As a smoke dispersion model, CALPUFF is recommended by the U.S. Environmental Protection Agency (EPA) as a regulatory guidance model for long-range transport simulation (US-EPA, 2012). This model has been widely used to assess urban environmental quality and simulate the long-range transport of ambient air pollutants over 50 km (Giaiotti et al., 2018; Henderson et al., 2011; Tartakovsky et al., 2013; Tartakovsky et al., 2016). Moreover, it has performed well in public health studies related to PM exposure (Dai et al., 2014; Howard et al., 2019; Ravina et al., 2018; Ruiz Bautista, 2019; Zhou et al., 2006) and is thus well suited for this research.

In this case study, the size of the entire study area was 61.36 km $\times$ 60.96 km. There were 62 grid cells in the X direction and 61 grid cells in the Y direction, with a grid spacing of 1 km, resulting in 3782 grid cells encompassing the modeling domain. The southwest corner of the domain is located at 27.94 °N, 112.71 °E (Fig. 1). The $PM_{2.5}$ emission inventory used in this work was established by the Changsha Environmental Protection Bureau in 2014. Total contamination includes primary particulate matters and secondary $PM_{2.5}$ precursors containing sulfur dioxide and nitrogen oxides (Guttikunda and Jawahar, 2012; Liu et al., 2016; Yao et al., 2016). After relevant data sets were acquired (Text S1), regional simulations were conducted to obtain the distribution pattern of $PM_{2.5}$.

In this study, the performance of the model was evaluated by comparing the predicted values with the observed values from the same site in 2014. Considering that there are only 8 $PM_{2.5}$ government monitoring stations in downtown Changsha, 17 $PM_{2.5}$ monitoring samples (shown in Fig. 3(a)) were added to verify the CALPUFF model. All of these sampling sites were located in open areas away from potential $PM_{2.5}$ sources and were monitored in 2014 (Liu et al., 2015). For the accuracy of the sampling results, a parallel sampler was established at each site and the average of two measurements was used as the final $PM_{2.5}$ concentration. The 14-day concentrations were monitored each season (Li et al., 2015) and were averaged to estimate the annual average $PM_{2.5}$ concentrations at each sampling point. The Root Mean Square Error (RMSE) and the FAC2 index were employed in this study to evaluate the performance of the CALPUFF model (Ghannam and El-Fadel, 2013; Holnicki et al., 2016; Tian et al., 2013). Subsequently, the predicted and the monitored $PM_{2.5}$ concentrations from these 25 monitoring stations were applied for model validation (Text S1).

To quantify the health benefits of implementing the optimized industrial land distribution, a scenario without industrial emission sources was used as the reference (RT scenario). By comparing the results of the RT scenario, the health impact of the current (2014) and projected future (2030) industrial spatial distribution was assessed. Simulated concentration values were formed as grid data posted by the CALPOST module and identified by the GIS. The annual average $PM_{2.5}$ concentration of each unit was the weighted average of the concentration of all grids in the unit.

2.5. Industrial zone site selection

In accordance with the Overall Planning of Changsha City (2014–2030) derived from the Changsha government agency, this study selected 4 out of 42 land units as industrial zones. The significant difference in area between different units makes it difficult to determine the independent impacts of population and location on mortality outcomes. Therefore, based on current industrial land characteristics, an area of 12.8 km^2 was chosen as the size of the industrial zone in the center of each simulation unit. Considering the policy of coordinated development, the modeling domain was divided into four areas: areas A and B in the West-River district, while areas C and D in the East-River district. A land unit was selected in each area as a zone site, and the relevant $PM_{2.5}$ exposure health risks for the 17 sites were subsequently assessed. The simulation sequence of land units follows the index i.

2.6. Health impact assessment

To determine the health effect of industrial location optimization, mortality was used as a simple parameter to assess the health impacts of different industrial site selection. Life expectancy loss due to exposure to environmental $PM_{2.5}$ air pollution is associated with IHD, stroke, COPD, and LC (Cohen et al., 2017; Guan et al., 2016). Eq. (1) below was used to estimate the mortality caused by

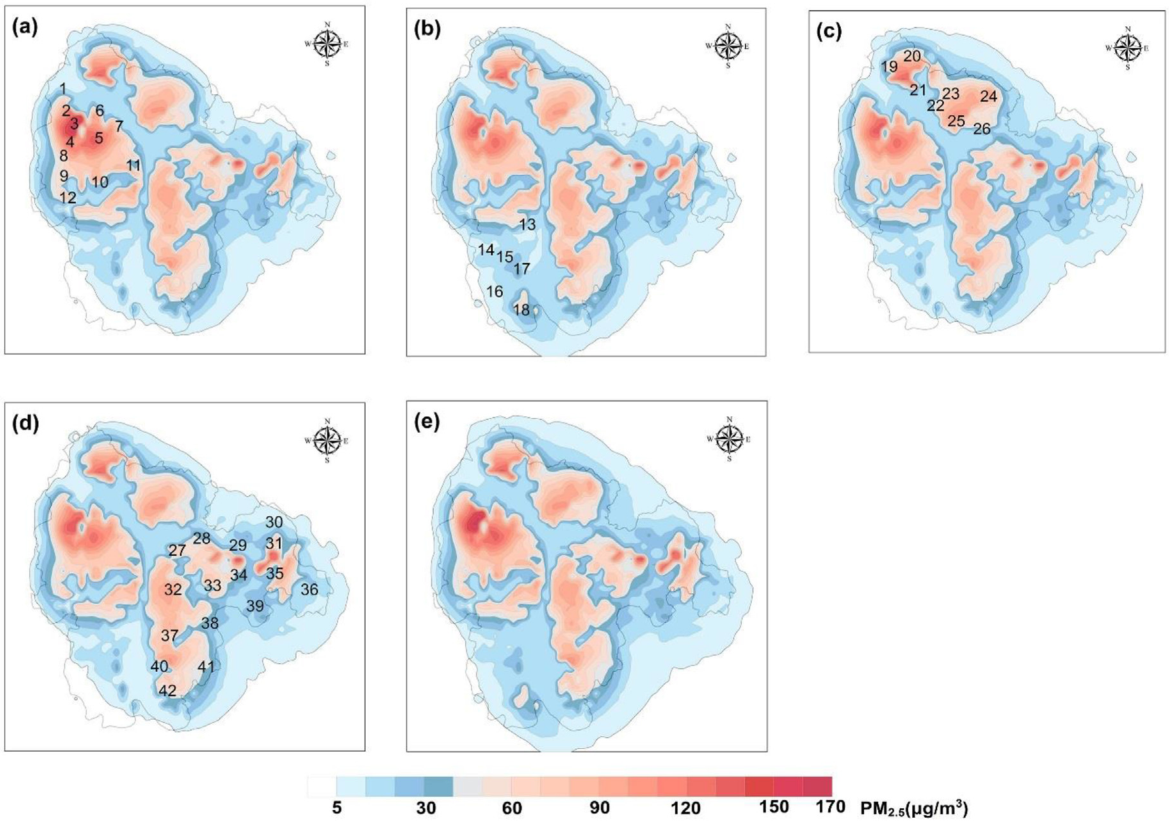

Fig. 4. Attributable $PM_{2.5}$ spatial distribution for industrial land unit selection at 1 km resolution. (a–d) Concentration contribution of the best industrial land selection in area A, area B, area C, and area D. (e) Annual $PM_{2.5}$ concentration under the optimal industrial land layout.

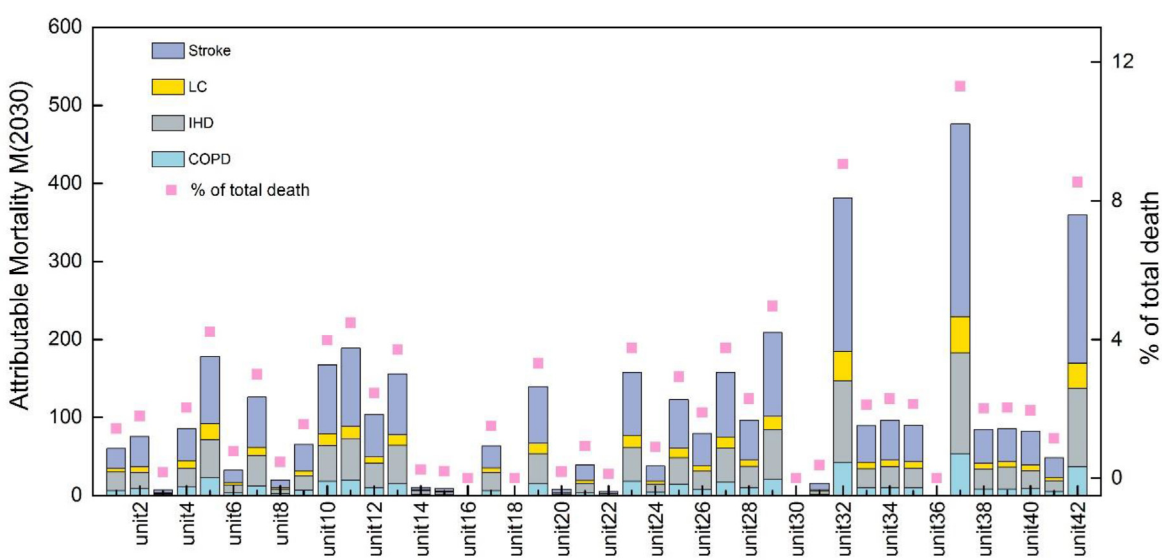

Fig. 5. Premature mortality from COPD, IHD, LC, and Stroke attribute to ambient $PM_{2.5}$ of Downtown in the year 2030.

$PM_{2.5}$ exposure (Lelieveld et al., 2015):

$$\Delta M = \sum_{i=1}^{N} P_i \times [(RR - 1) / RR] \times B \quad (1)$$

where N is the amount of data; P_i represents the population of unit I; RR is the epidemiological relative risk between each healthy endpoint and the $PM_{2.5}$ exposure concentration, determined by the $PM_{2.5}$ exposure-response (E-R) function; B represents the provincial disease-specific baseline incidence; ΔM is the premature mortality of four specific diseases attributable to $PM_{2.5}$. Due to the lack of detailed information on the 2030 population, the current population density per square kilometer and residential land data from the future land expansion map were applied to predict the population distribution of Changsha in 2030. The national disease-specific baseline incidence was obtained from the Global Burden of Disease (GBD) 2017 (https://vizhub.healthdata.org/gbd-compare/). The medium criteria baseline incidence for IHD, stroke, COPD and LC in China were 115.96, 140.60, 64.35, and 44.04 per 10^5 people, respectively, and were assumed to remain unchanged in 2030. In this study, the negative health risks of 2030 were described by employing the Integrated Exposure-Response (IER) function (Apte et al., 2015; Maji et al., 2018a) (Text S2). The IER model has been widely applied in health concentration-response assessment because it integrates the epidemiological relative risk of $PM_{2.5}$ exposure to different emission types (Burnett et al., 2014; Lelieveld et al., 2015). The IER lookup table was acquired from the Institute for Health Metrics and Evaluation (IHME, 2013). Eq. (1) and the IER model was combined to calculate the four cause-specific mortality of the entire domain in each industrial site selection.

2.7. Economic valuation estimates

For economic valuation, the VSL was used in this study. VSL is a standard metric to assess the monetization of human life (Weis et al., 2015). It was first proposed by American scholar Schelling in 1968, and it represents the price people are willing to pay to reduce the risk of death (Giannadaki et al., 2018). The mortality risk of individuals estimated by VSL is commonly associated with income and inflation (Fann et al., 2018). The equation recommended by the BENMAP model was used in this study (Text S3). The resulting VSL for China in 2030 is 2.87 million USD. Consequently, the total economic burden in Changsha from different industrial site selection can be calculated by applying the equation (Table S1).

3. Results

3.1. Regional patterns in mortality and industrial site selection

17 of the 42 land units were identified as potential industrial zone sites. Table S2 summarizes the annual premature mortality at the four healthy endpoints for each industrial zone location. The optimal layout consists of the simulation results of four independent regions. In area A, land unit 3 has the lowest premature mortality among 6 units, making it the best location for an industrial zone. According to the same optimization procedure, units 18, 24, and 31 are calculated to be the best sites for industrial zones in areas B, C, and D, respectively.

The spatial distributions of annual average $PM_{2.5}$ concentrations in each area under the optimal scenario are illustrated in Fig. 4. According to Fig. 4(a–d), the addition of an industrial zone during the optimization process only has a slight impact on the spatial distribution of $PM_{2.5}$ contamination in the entire domain. Under this optimal scenario, the weighted annual average $PM_{2.5}$ concentration of 42 land units ranges from 10 $\mu g/m^3$ to 118 $\mu g/m^3$ (Fig. 4(e)). Table S3 illustrates the annual average $PM_{2.5}$ concentration simulated by the CALPUFF model and the associated health losses of the 42 units. All monitoring points meet the FAC2 criteria (Fig. S1), indicating that the simulated and monitored data are well-matched. The RMSE value of the predicted concentration was estimated to be 9.75 $\mu g/m^3$, indicating that the accuracy of predicted concentrations is acceptable.

These four areas contain four million residents, and the mortality patterns of $PM_{2.5}$ exposure vary substantially among these land units. To visualize the differences in the distribution of four cause-specific mortalities among different land units, the spatial distributions of four individual endpoints (COPD, IHD, LC, and stroke) were plotted (Fig. 5). In this figure, the empty bars indicate the land units with no premature mortality, which is due to this region being unpopulated. According to the IER function, the mortality caused by $PM_{2.5}$-COPD, $PM_{2.5}$-IHD, $PM_{2.5}$-LC, and $PM_{2.5}$-stroke are 0.46, 1.21, 0.40, and 2.16 thousand, respectively, accounting for 10.8%, 28.6%, 9.3%, and 51.3% of the total losses in Changsha in 2030. Overall, stroke is the leading cause of mortality induced by $PM_{2.5}$, followed by IHD, COPD, and LC. The land units with the highest mortality in 2030 are units 32, 37, and 42, with total mortalities of 0.38, 0.48, and 0.36 thousand, respectively. The losses in these three units account for 9.1%, 11.3%, and 8.5% of the total health losses in 2030 respectively.

To investigate the relationship between concentration and mortality risk, three guidelines were used in this study: the $PM_{2.5}$ concentration guidelines derived from the World Health Organization (WHO) (10 $\mu g/m^3$), National ClassIstandard (15 $\mu g/m^3$), and National ClassIIstandard (35 $\mu g/m^3$). According to the above air quality standards, the simulated concentrations were segmented into three groups (L1-L3). Table S4 reveals that the $PM_{2.5}$ concentrations in all units do not meet the WHO standard of 10 $\mu g/m^3$. Among the 8 units with the most negative health impacts, units 32 and 37 have the units with the highest $PM_{2.5}$ concentration in the study area. Therefore, they are expected to suffer the greatest health burden. It is estimated that around two-thirds of residents live in areas with $PM_{2.5}$ concentrations higher than 35 $\mu g/m^3$ (L3), the population in these areas contributed to 76.7% of all cause-

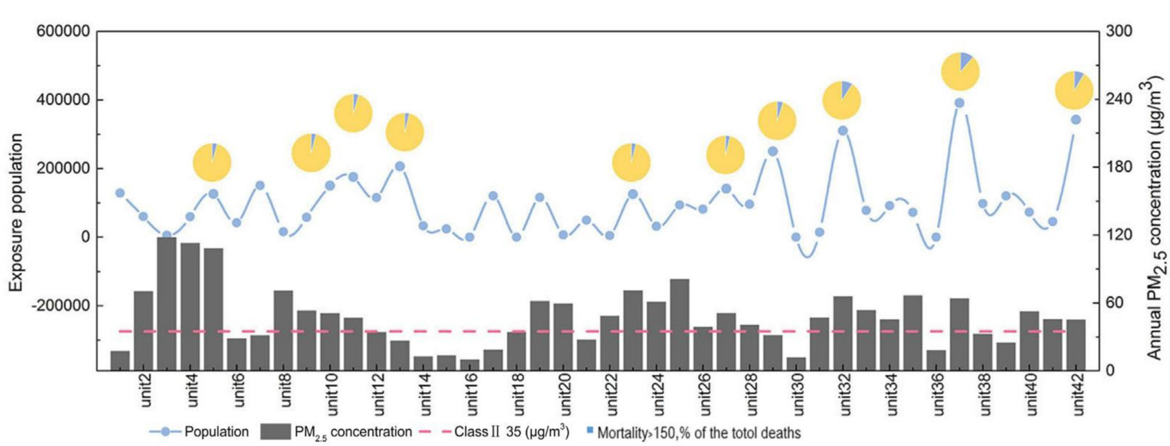

Fig. 6. The spatial pattern of population and annual average $PM_{2.5}$ concentration in 42 land units.

specific mortalities. Another one-third of the population live in low and intermediate concentration (L1 and L2) units and account for only about one-fifth of total mortality. These results confirm that low air pollution conditions are of great benefit in reducing the population's health burden.

3.2. Economic loss

By applying the VSL value to the optimal scenario, the corresponding economic loss of 4.21 thousand deaths in 2030 equates to approximately 12.1 billion USD. It is also found that the industrial land layout with the highest mortalities (units 12, 17, 26, and 38) could cause 4.39 thousand deaths (Table S5) and could lead to an economic loss of 12.6 billion USD. In the current industrial situation, the mortality related to $PM_{2.5}$ pollution is 4.45 thousand. According to Table S6, by optimizing the industrial land layout, the mortality for COPD, IHD, LC, and stroke in 2030 can be reduced by 7.0%, 4.2%, 7.1%, and 5.4%, respectively. Compared with the burden of the RT scenario, the industrial sector accounts for 8.8% of the health burden in the current industrial spatial distribution. After the optimization, $PM_{2.5}$-related mortality in Changsha's industrial sector drops by approximately 60.8%, while the monetary value of the averted mortality is 0.69 billion USD. These results confirm that the optimal land layout has a relatively significant impact on alleviating additional health risks and economic losses.

3.3. The characteristic of high-risk areas

This analysis revealed that populations living in areas of poor urban environmental quality comprise a large proportion of the urban health burden (Table S4). Under this condition, identifying the characteristics of high-risk areas has profound significance. Table S2 demonstrates that premature mortality varies with the change of industrial land location. Table S3 shows the population distribution, which ranges from 4.7 to 391 thousand (Table S3). However, many factors can lead to variation in results. For instance, the industrial sites at units 18, 24, and 31 are remote from the city center and have relatively small populations, so the overall health burdens from $PM_{2.5}$ exposure are low.

To gain a deeper insight into the specific factors that contribute to variations between sites, the relationship between negative health impacts and $PM_{2.5}$ concentrations, population, and geographical characteristics was also explored. Fig. 6 reveals that the $PM_{2.5}$ concentration is positively correlated with the population density in this domain. In this scenario, the areas with the most negative health impacts are unit 5 (178, 4.2%), unit10 (168, 4.0%), unit11 (189, 4.5%), unit13 (156, 3.7%), unit 23 (158, 3.8%), unit 27 (158, 3.8%), unit 29 (209, 5.0%), unit 32 (381, 9.1%), unit 37 (476, 11.3%), and unit 42 (359, 8.5%). Of the 10 units with the most negative health impacts, 6 have larger populations (units 11, 13, 29, 32, 37, and 42). Therefore, it can be concluded that because populous regions tend to have more emission sources, they will incur higher premature mortality by 2030.

It is worth mentioning that premature mortality is not only associated with population density but also with geographical location. Results reveal that emission sources tend to directly influence the mortality of the surrounding areas. For instance, the areas around transportation networks (units 8, 23, 25, and 35), residential areas (units 32 and 37) and industrial zones (units 3, 4, and 5) have relatively high $PM_{2.5}$ concentrations. Moreover, high mortality is also commonly observed in low-lying areas. For instance, the commercial area (units 25, 27, and 32) has a relatively higher pollution level than other densely populated areas, because the lower terrain makes pollutant dispersal difficult outside of the vicinity.

4. Discussion

4.1. Optimization analysis of industrial land layout

Due to land restrictions in many densely populated cities in China, numerous factories are located near to expressways or communities. With an increasing emphasis on environmental health risk management, optimization analysis can identify sites for industrial land relocation. According to this study's simulation results, high mortality tends to occur in areas with potential emission sources, such as dense residential areas, commercial districts, and industrial zones. Therefore, it can be concluded that the mortality associated with $PM_{2.5}$ exposure is highly dependent on geographical location, which is in line with the standpoint of Fantke et al. (2019). The transport situation is another significant factor affecting population-exposure (Li et al., 2015). It is not recommended to relocate industrial areas to transport hubs, as the industrial distribution scenario suggests that high premature mortality is projected to occur in the relatively dense traffic networks (such as units 11 and 29). It is also noteworthy that although $PM_{2.5}$ concentrations in units 13 and 29 are relatively low, their health risks are relatively high. This is because dense populations make more significant contributions to total mortality, despite low levels of individual exposure. This observation agrees well with the previous research of Zhou et al. (2006) and is consistent with the fact that anthropogenic emission sources contribute significantly to $PM_{2.5}$ pollution (Lelieveld et al., 2015). From this perspective, population distribution and geographical location are found to be the major contributors to the public health burden.

From the perspective of urban public health, risks can be reduced by integrating current industries into industrial zones and relocating them from the city to suburban areas. To implement the land replacement strategy, the Changsha government has already relocated factories near schools and residential units to the High-tech Industrial Development Zone to optimize the land use structure. In this circumstance, the planning scheme given in this paper can provide suggestions for the relocation, especially in areas with a high risk of individual exposure. Moreover, to minimize the $PM_{2.5}$ related health burden of new industrial land, this approach can also inform future urban planning. Overall, it is preferable to relocate industrial zones away from densely populated areas for optimal spatial allocation. However, given the need for good transport provision in industrial areas, policymakers should consider these issues accordingly.

4.2. Future situation under the optimal scenario

Although the average annual $PM_{2.5}$ value will drop to 48 $\mu g/m^3$ by 2030, it is still below the primary standard of the Chinese NAAQS (15 $\mu g/m^3$). Therefore, even if the optimal industrial layout is implemented, additional control measures are still required for an urban air mitigation strategy. Lelieveld et al. (2019) have emphasized that fossil fuel-related emissions account for approximately 65% of premature deaths induced by air pollution. Consequently, clean energy technologies need to be gradually applied to industrial combustion to eliminate emissions from fossil fuels.

Furthermore, it was found that under the optimal industrial land layout, road transport is projected to be the main source of $PM_{2.5}$ emissions (Fig. S2). This finding is consistent with previous research that identifies Hunan as having the highest mortality induced by $PM_{2.5}$ exposure from transportation among all the Chinese provinces (Tian et al., 2018). Furthermore, by relocating industrial zones to a transportation hub, the health burden will be greater than the independent emission source. This indicates that there may be interactions among different types of pollution sources, which synergistically enhance the ambient air pollution. Accordingly, policymakers should increase restrictions on building factories around transportation hubs to constrain the impact of pollutant interactions.

The second leading cause of $PM_{2.5}$-related deaths is residential emissions (Fig. S2). Previous studies have revealed that the residential combustion of solid fuels is a prime contributor to the health burden attributable to $PM_{2.5}$ in China (Dasadhikari et al., 2019; Gao et al., 2019; GBD MAPS Working Group, 2016; Gu et al., 2018; Ma et al., 2017; Reddington et al., 2019; Shen et al., 2019). This study found that premature mortality in Changsha was significantly linear with population density (Fig. S3), a strong correlation was indicated by a Pearson correlation coefficient of 0.96. Under this condition, the rural population is continually migrating to the city, which exacerbates the health risks from ambient air pollution during the urbanization process. Xie et al. (2016) have identified that nearly 40% of premature mortality in China occurred in urban areas. Urbanization may also have negative impacts on air pollution associated with the disease burden in populous cities (Shen et al., 2017). Therefore, it is critical for cities in the development stage to gradually incorporate this optimization approach into urban planning. Based on the linear relationship between population and health burden, policymakers can establish a population density threshold for industrial areas to minimize such problems.

In future epidemiological studies, the simulation of high-risk areas may also be potentially useful in predicting long-term exposure. Polluted areas such as units 5, 23, 32, and 37 have higher projected health burdens, which reflect the large air pollution emissions in these regions. To minimize the damage to health, the government should substantially strengthen air quality monitoring and issue public early warnings to avoid outdoor activities when poor air quality is detected. Optimization results can provide a reference for the ratio between the number of monitoring stations and the concentrations of pollutants. Additionally, in the areas with high health risks identified in this research, $PM_{2.5}$ source analyses can be established to effectively control $PM_{2.5}$ air pollution.

4.3. Policy implications

The impact of industrial $PM_{2.5}$ emissions has led to a deterioration in air quality and an upsurge in premature mortality, bringing big challenges for industrial cities like Changsha. Consequently, integrating factories into industrial zones and then relocating them away from urban centers is an inevitable trend of China's sustainable development and environmental protection policies. For instance, in 2018, the Beijing government relocated small and middle-sized enterprises and factories from urban to suburban areas. Similarly, the Changsha government has incorporated industrial land integration into future urban planning. Although the link between urban construction and public health has not yet been considered, it is becoming increasingly valued by government policymakers. Additionally, since CALPUFF is a regulatory guidance model for evaluating urban environmental quality, the optimization methodology in this present study can be well applied to the field of future urban planning. The research results can also provide useful inspiration for the formulation of effective air pollution mitigation policies.

4.4. Uncertainty analysis

The optimal layout was simulated under the same meteorological condition to isolate its impact on the emission location-exposure relationship in this research. However, previous studies have reported that climate and weather can cause changes in $PM_{2.5}$ contamination (Asif et al., 2018; Xu et al., 2020). The uncertainty of meteorological data to the industrial layout in this optimization method is further explored (Text S5). Findings indicate that climate and weather changes present a slight uncertainty for the optimal layout, but this uncertainty is limited to the order interchange of optimal and suboptimal locations, that is, the optimal becomes the suboptimal and the suboptimal becomes the optimal (Tables S2 and S7). Land units with the highest health risks remain unchanged in each area, and there are significant differences in mortality between the optimal and the pessimal selections. Mortality in the pessimal location was 2.27 times (95% confidence interval: 1.80, 2.76) the mortality in the optimal location.

4.5. Research limitations

Despite some meaningful research findings, this study has some limitations. Compared with global estimates, the GBD approach (GBD, 2017 Disease and Injury Incidence and Prevalence Collaborators, 2018) applied in this study has more uncertain estimates for low- and middle-income countries, especially China and India. Inadequate epidemiological studies, higher pollutant concentrations, and demographic changes make it difficult for these emerging economies to extrapolate exposure-response functions (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2019; Li et al., 2018; Ostro et al., 2018). These deficiencies are inevitable, however, they could be remedied by providing adequate surveillance data and conducting further cohort studies on local ambient air pollution. In addition, since the CALPUFF model lacks the chemical transformation of all secondary $PM_{2.5}$, the evaluation is conservative. This factor can be incorporated into further studies to improve the accuracy of the results. Despite these limitations, this optimization approach is still an effective way to combine population exposure with urban industrial planning in epidemiological studies.

5. Conclusions

This study constructed a comprehensive assessment framework to evaluate the health and economic burdens associated with industrial geographical distribution. Based on this framework, an optimal spatial allocation of industrial land was presented. The results are noteworthy because the Changsha government could reap considerable financial and social benefits by implementing the optimal industrial spatial layout, without implementing technological controls. Furthermore, the economic benefits predicted in this research can provide a reference for the cost-effectiveness of relocating industrial land.

In the context of urban planning, the government still lacks adequate assessment and consideration of public exposure risks in industrial constructions. To the best of our knowledge, the optimization approach in this study is the first attempt to incorporate health impacts into urban industrial land planning. The optimization method can provide both a strong reference and guidance for industrial land use management in Changsha and similar Chinese cities. Nevertheless, the estimated results from the optimization analysis merely depict the best consequence from a certain perspective. In urban industrial distribution planning, many factors influence on decision-making, such as the availability of resources, transportation, land prices, policies, labor, and public facilities. Therefore, while implementing this optimization strategy to alleviate industry-related air pollution, the government should consider a wider range of factors according to the specific conditions to balance the cost-effectiveness and the risks to public health.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

CRediT authorship contribution statement

Wanjun Xu: Writing - original draft, Conceptualization, Methodology. **Zhuotong Zeng:** Writing - review & editing. **Zhengyong Xu:** Writing - review & editing. **Xiaodong Li:** Resources, Software. **Xuwu Chen:** Resources, Software. **Xin Li:** Data curation. **Rong Xiao:** Data curation. **Jie Liang:** Data curation. **Gaojie Chen:** Data curation. **Anqi Lin:** Data curation. **Jinjin Li:** Data curation. **Guangming Zeng:** Data curation.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51579094, 51679082 and 51521006), the Hunan Science & Technology Innovation Program (2018RS3037), and the Natural Science Foundation of Hunan Province (2019JJ20002).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2020.114388.

References

Apte, J.S., Marshall, J.D., Cohen, A.J., Brauer, M., 2015. Addressing global mortality from ambient PM2.5. Environ. Sci. Technol. 49, 8057–8066.
Asif, Z., Chen, Z., Guo, J., 2018. A study of meteorological effects on PM2.5 concentration in mining area. Atmos. Pollut. 9, 688–696.
Aunan, K., Fang, J., Hu, T., Seip, H.M., Vennemo, H., 2006. Climate change and air quality—measures with Co-benefits in China. Environ. Sci. Technol. 40, 4822–4829.
Burnett, R.T., Pope 3rd, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Anderson, H.R., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H., Laden, F., Pruss-Ustun, A., Turner, M.C., Gapstur, S.M., Diver, W.R., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122, 397–403.
Chen, L., Shi, M., Li, S., Bai, Z., Wang, Z., 2017. Combined use of land use regression and BenMAP for estimating public health benefits of reducing PM 2.5 in Tianjin, China. Atmos. Environ. Times 152, 16–23.
Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918.
Dai, C., Cai, X.H., Cai, Y.P., Huang, G.H., 2014. A simulation-based fuzzy possibilistic programming model for coal blending management with consideration of human health risk under uncertainty. Appl. Energy 133, 1–13.
Dasadhikari, K., Eastham, S.D., Allroggen, F., Speth, R.L., Barrett, S.R.H., 2019. Evolution of sectoral emissions and contributions to mortality from particulate matter exposure in the Asia-Pacific region between 2010 and 2015. Atmos. Environ. 216, 116916.
Etchie, T.O., Sivanesan, S., Adewuyi, G.O., Krishnamurthi, K., Rao, P.S., Etchie, A.T., Pillarisetti, A., Arora, N.K., Smith, K.R., 2017. The health burden and economic costs averted by ambient PM2.5 pollution reductions in Nagpur, India. Environ. Int. 102, 145–156.
Fann, N., Alman, B., Broome, R.A., Morgan, G.G., Johnston, F.H., Pouliot, G., Rappold, A.G., 2018. The health impacts and economic value of wildland fire episodes in the U.S.: 2008-2012. Sci. Total Environ. 610–611, 802–809.
Fantke, P., McKone, T.E., Tainio, M., Jolliet, O., Apte, J.S., Stylianou, K.S., Illner, N., Marshall, J.D., Choma, E.F., Evans, J.S., 2019. Global effect factors for exposure to fine particulate matter. Environ. Sci. Technol. 53, 6855–6868.
Feng, S., Gao, D., Liao, F., Zhou, F., Wang, X., 2016. The health effects of ambient PM2.5 and potential mechanisms. Ecotoxicol. Environ. Saf. 128, 67–74.
Gao, M., Smith, K.R., Lelieveld, J., Dentener, F., West, J., Hu, J., Kin, K., Yung, L., Kinney, P., Evans, J., Wang, Z., Nielsen, C.P., 2019. Where does ambient PM2.5 come from in China: a comparison and synthesis of recent estimates. Risk Assess. Econ. Eval. Decis.
GBD 2017 Disease and Injury Incidence and Prevalence Collaborators, 2018. Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392, 1789–1858.
GBD MAPS Working Group, 2016. Burden of Disease Attributable to Coal-Burning and Other Air Pollution Sources in China.
Ghannam, K., El-Fadel, M., 2013. Emissions characterization and regulatory compliance at an industrial complex: an integrated MM5/CALPUFF approach. Atmos. Environ. 69, 156–169.
Giaiotti, D., Oshurok, D., Skrynyk, O., 2018. The Chernobyl nuclear accident 137 Cs cumulative depositions simulated by means of the CALMET/CALPUFF modelling system. Atmos. Pollut. Res 9, 502–512.
Giannadaki, D., Giannakis, E., Pozzer, A., Lelieveld, J., 2018. Estimating health and economic benefits of reductions in air pollution from agriculture. Sci. Total Environ. 622–623, 1304–1316.
Gu, Y., Wong, T.W., Law, C.K., Dong, G.H., Ho, K.F., Yang, Y., Yim, S.H.L., 2018. Impacts of sectoral emissions in China and the implications: air quality, public health, crop production, and economic costs. Environ. Res. Lett. 13, 084008.
Guan, W.-J., Zheng, X.-Y., Chung, K.F., Zhong, N.-S., 2016. Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. Lancet 388, 1939–1951.
Guttikunda, S.K., Jawahar, P., 2012. Application of SIM-air modeling tools to assess air quality in Indian cities. Atmos. Environ. 62, 551–561.
Henderson, S.B., Brauer, M., Macnab, Y.C., Kennedy, S.M., 2011. Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. Environ. Health Perspect. 119, 1266–1271.
Hennig, F., Fuks, K., Moebus, S., Weinmayr, G., Memmesheimer, M., Jakobs, H., Brocker-Preuss, M., Fuhrer-Sakel, D., Mohlenkamp, S., Erbel, R., Jockel, K.H., Hoffmann, B., Heinz Nixdorf Recall Study Investigative, G, 2014. Association between source-specific particulate matter air pollution and hs-CRP: local traffic and industrial emissions. Environ. Health Perspect. 122, 703–710.
Holnicki, P., Kałuszko, A., Trapp, W., 2016. An urban scale application and validation of the CALPUFF model. Atmos. Pollut. Res 7, 393–402.
Howard, D.B., The, J., Soria, R., Fann, N., Schaeffer, R., Saphores, J.M., 2019. Health benefits and control costs of tightening particulate matter emissions standards for coal power plants - the case of Northeast Brazil. Environ. Int. 124, 420–430.
IHME, 2013. Global Burden of Disease Study 2010 (GBD 2010) - Ambient Air Pollution Risk Model 1990–2010 (Seattle, United States).
India State-Level Disease Burden Initiative Air Pollution Collaborators, 2019. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. The Lancet Planet. Health 3, e26–e39.
Khan, M.W., Ali, Y., De Felice, F., Salman, A., Petrillo, A., 2019. Impact of brick kilns industry on environment and human health in Pakistan. Sci. Total Environ. 678, 383–389.
Kishimoto, P.N., Karplus, V.J., Zhong, M., Saikawa, E., Zhang, X., Zhang, X., 2017. The impact of coordinated policies on air pollution emissions from road transportation in China. Transport Res D-TR E 54, 30–49.
Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371.
Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R.T., Haines, A., Ramanathan, V., 2019. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. Pnas 116, 7192–7197.
Li, L., Lei, Y., Wu, S., Chen, J., Yan, D., 2017. The health economic loss of fine particulate matter (PM 2.5) in Beijing. J. Clean. Prod. 161, 1153–1161.
Li, T., Zhang, Y., Wang, J., Xu, D., Yin, Z., Chen, H., Lv, Y., Luo, J., Zeng, Y., Liu, Y., Kinney, P.L., Shi, X., 2018. All-cause mortality risk associated with long-term exposure to ambient PM2·5 in China: a cohort study. Lancet Public Health 3, e470–e477.
Li, X., Liu, W., Chen, Z., Zeng, G., Hu, C., León, T., Liang, J., Huang, G., Gao, Z., Li, Z., Yan, W., He, X., Lai, M., He, Y., 2015. The application of semicircular-buffer-based land use regression models incorporating wind direction in predicting quarterly NO 2 and PM 10 concentrations. Atmos. Environ. 103, 18–24.
Lim, S.S., Vos, T., Flaxman, A.D., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380, 2224–2260.
Liu, B.S., Song, N., Dai, Q.L., Mei, R.B., Sui, B.H., Bi, X.H., Feng, Y.C., 2016. Chemical composition and source apportionment of ambient PM2.5 during the non-heating period in Taian, China. Atmos. Res. 170, 23–33.
Liu, W., Li, X., Chen, Z., Zeng, G., León, T., Liang, J., Huang, G., Gao, Z., Jiao, S., He, X., Lai, M., 2015. Land use regression models coupled with meteorology to model spatial and temporal variability of NO2 and PM10 in Changsha, China. Atmos. Environ. 116, 272–280.
Ma, Q., Cai, S., Wang, S., Zhao, B., Martin, R.V., Brauer, M., Cohen, A., Jiang, J., Zhou, W., Hao, J., Frostad, J., Forouzanfar, M.H., Burnett, R.T., 2017. Impacts of coal burning on ambient PM2.5 pollution in China. Atmos. Chem. Phys. 17, 4477–4491.
Maji, K.J., Dikshit, A.K., Arora, M., Deshpande, A., 2018a. Estimating premature

mortality attributable to PM2.5 exposure and benefit of air pollution control policies in China for 2020. Sci. Total Environ. 612, 683–693.
Maji, K.J., Ye, W.F., Arora, M., Shiva Nagendra, S.M., 2018b. PM2.5-related health and economic loss assessment for 338 Chinese cities. Environ. Int. 121, 392–403.
Mardones, C., 2019. Determining the 'optimal' level of pollution (PM2.5) generated by industrial and residential sources. Environ. Impact Assess. Rev. 74, 14–22.
Matus, K., Nam, K.-M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Global Environ. Change 22, 55–66.
Ministry of Environmental Protection of China, 2013. Air Pollution Prevention and Control Action Plan(2013-2017). Gov. China.
Ministry of Environmental Protection of China, 2018. Three–year Action Plan for Winning the Blue Sky War (2018–2020). Gov. China.
Ostro, B., Spadaro, J.V., Gumy, S., Mudu, P., Awe, Y., Forastiere, F., Peters, A., 2018. Assessing the recent estimates of the global burden of disease for ambient air pollution: methodological changes and implications for low- and middle-income countries. Environ. Res. 166, 713–725.
Pan, B.J., Hong, Y.J., Chang, G.C., Wang, M.T., Cinkotai, F.F., Ko, Y.C., 1994. Excess cancer mortality among children and adolescents in residential districts polluted by petrochemical manufacturing plants in Taiwan. J. Toxicol. Environ. Health 43, 117–129.
Peng, W., Yang, J., Wagner, F., Mauzerall, D.L., 2017a. Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China. Sci. Total Environ. 598, 1076–1084.
Peng, W., Yuan, J., Zhao, Y., Lin, M., Zhang, Q., Victor, D.G., Mauzerall, D.L., 2017b. Air quality and climate benefits of long-distance electricity transmission in China. Environ. Res. Lett. 12, 064012.
Ravina, M., Panepinto, D., Zanetti, M.C., 2018. Didem - an integrated model for comparative health damage costs calculation of air pollution. Atmos. Environ. 173, 81–95.
Reddington, C.L., Conibear, L., Knote, C., Silver, B.J., Li, Y.J., Chan, C.K., Arnold, S.R., Spracklen, D.V., 2019. Exploring the impacts of anthropogenic emission sectors on PM2.5 and human health in South and East Asia. Atmos. Chem. Phys. 19, 11887–11910.
Ruiz Bautista, L., 2019. Cardiovascular impact of PM2.5 from the emissions of coal-fired power plants in Spain during 2014. Med. Clínica 153, 100–105.
Santibáñez-Andrade, M., Quezada-Maldonado, E., Osornio-Vargas, Á., Sánchez-Pérez, Y., García-Cuellar, C., 2017. Air pollution and genomic instability: the role of particulate matter in lung carcinogenesis. Environ. Pollut. 229, 412–422.
Senthil, K.S., Muthuselvam, P., Pugalenthi, V., Subramanian, N., Ramkumar, K.M., Suresh, T., Suzuki, T., Rajaguru, P., 2018. Toxicoproteomic analysis of human lung epithelial cells exposed to steel industry ambient particulate matter (PM) reveals possible mechanism of PM related carcinogenesis. Environ. Pollut. 239, 483–492.
Shen, G., Ru, M., Du, W., Zhu, X., Zhong, Q., Chen, Y., Shen, H., Yun, X., Meng, W., Liu, J., Cheng, H., Hu, J., Guan, D., Tao, S., 2019. Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. Nat. Commun. 10, 3405.
Shen, H., Tao, S., Chen, Y., Ciais, P., Güneralp, B., Ru, M., Zhong, Q., Yun, X., Zhu, X., Huang, T., Tao, W., Chen, Y., Li, B., Wang, X., Liu, W., Liu, J., Zhao, S., 2017. Urbanization-induced population migration has reduced ambient PM2.5 concentrations in China. Sci. Adv. 3, e1700300.
Shen, M., Xing, J., Ji, Q., Li, Z., Wang, Y., Zhao, H., Wang, Q., Wang, T., Yu, L., Zhang, X., Sun, Y., Zhang, Z., Niu, Y., Wang, H., Chen, W., Dai, Y., Su, W., Duan, H., 2018. Declining pulmonary function in populations with long-term exposure to polycyclic aromatic hydrocarbons-Enriched PM2.5. Environ. Sci. Technol. 52, 6610–6616.
Tartakovsky, D., Broday, D.M., Stern, E., 2013. Evaluation of AERMOD and CALPUFF for predicting ambient concentrations of total suspended particulate matter (TSP) emissions from a quarry in complex terrain. Environ. Pollut. 179, 138–145.
Tartakovsky, D., Stern, E., Broday, D.M., 2016. Dispersion of TSP and PM(10) emissions from quarries in complex terrain. Sci. Total Environ. 542, 946–954.
Tian, H., Qiu, P., Cheng, K., Gao, J., Lu, L., Liu, K., Liu, X., 2013. Current status and future trends of SO2 and NOx pollution during the 12th FYP period in Guiyang city of China. Atmos. Environ. 69, 273–280.
Tian, X., Dai, H., Geng, Y., Wilson, J., Wu, R., Xie, Y., Hao, H., 2018. Economic impacts from PM2.5 pollution-related health effects in China's road transport sector: a provincial-level analysis. Environ. Int. 115, 220–229.
US-EPA, 2012. Documentation of the Evaluation of CALPUFF and Other Long Range Transport Models Using Tracer Field Experiment Data.
van Niekerk, A., 2010. A comparison of land unit delineation techniques for land evaluation in the Western Cape, South Africa. Land Use Pol. 27, 937–945.
Weis, D., George, F., Roy, R., 2015. Economic Cost of the Health Impact of Air Pollution in Europe.
Wu, R., Liu, F., Tong, D., Zheng, Y., Lei, Y., Hong, C., Li, M., Liu, J., Zheng, B., Bo, Y., Chen, X., Li, X., Zhang, Q., 2019. Air quality and health benefits of China's emission control policies on coal-fired power plants during 2005–2020. Environ. Res. Lett. 14, 094016.
Xie, R., Sabel, C.E., Lu, X., Zhu, W., Kan, H., Nielsen, C.P., Wang, H., 2016. Long-term trend and spatial pattern of PM2.5 induced premature mortality in China. Environ. Int. 97, 180–186.
Xu, G., Ren, X., Xiong, K., Li, L., Bi, X., Wu, Q., 2020. Analysis of the driving factors of PM2.5 concentration in the air: a case study of the Yangtze River Delta, China. Ecol. Indicat. 110, 105889.
Yao, L., Yang, L., Yuan, Q., Yan, C., Dong, C., Meng, C., Sui, X., Yang, F., Lu, Y., Wang, W., 2016. Sources apportionment of PM2.5 in a background site in the North China Plain. Sci. Total Environ. 541, 590–598.
Zhou, Y., Hammitt, J., Fu, J.S., Gao, Y., Liu, Y., Levy, J.I., 2014. Major factors influencing the health impacts from controlling air pollutants with nonlinear chemistry: an application to China. Risk Anal. 34, 683–697.
Zhou, Y., Levy, J.I., Evans, J.S., Hammitt, J.K., 2006. The influence of geographic location on population exposure to emissions from power plants throughout China. Environ. Int. 32, 365–373.