

Article

Premature Mortality and Costs Attributable to Imported Primary PM_{2.5} from a Densely Urbanized Metropolis

Adolfo Hernández-Moreno *  and Violeta Mugica-Álvarez 

Basic Sciences Department, Universidad Autónoma Metropolitana-Azcapotzalco, Av. San Pablo No. 420, Col. Nueva el Rosario, Azcapotzalco, Ciudad de México C.P. 02128, Mexico; vma@azc.uam.mx

* Correspondence: aherm@azc.uam.mx; Tel.: +52-5520261218

Abstract

Cross-state air pollution can degrade air quality in regions surrounding urban areas. However, assessing health impacts and economic costs requires quantifying annual pollutant transport. This type of annual assessment poses significant technical challenges, including the need to differentiate between external and local pollution, which have different spatial distributions; the large number of required air quality simulations; and the extensive post-processing of results. The Mexico City Metropolitan Area is located within the most polluted airshed in the country and exports large quantities of atmospheric pollutants to neighboring airsheds; however, until now, the annual magnitude of the impact on the population and its associated costs had not been quantified. This paper presents the estimation of potentially avoidable premature mortality and the annual economic cost associated with importing PM_{2.5} from the Mexico City Metropolitan Area into the metropolitan areas of Toluca and Cuernavaca. These estimates are based on 8640 simulations of air quality using the Hysplit 5.3.0 model, corresponding to each hour of 360 days in one year. Geoprocessing tools specifically designed in ArcGIS 10.4 were used to automate the calculations of PM_{2.5} mass exchange, and the premature mortality and health costs were calculated using the BenMap-CE 1.5.0.4 program. Results indicate that the export of PM_{2.5} from the Mexico City Metropolitan Area in 2018 may have resulted in 19,473 potentially avoidable premature deaths in the two recipient metropolitan areas. This impact could represent an annual economic cost of \$12,197 million for the Toluca Valley Metropolitan Area and \$4140 million for the Cuernavaca Metropolitan Area.

Keywords: premature deaths; PM_{2.5}; Mexico City; air pollution exportation; Toluca; Cuernavaca



Academic Editor: Sylwia K. Dytłow

Received: 25 January 2026

Revised: 4 March 2026

Accepted: 7 March 2026

Published: 1 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Airsheds, or atmospheric basins, are regions characterized by local climatic conditions. Their formation is closely related to orographic features and typically corresponds to valleys surrounded by high mountains [1–3]. Atmospheric pollutants can be temporarily confined within airsheds, and air mass exchange with surrounding regions occurs primarily through orographic channels (mountain passes) [4,5]. Within airsheds, pollutants frequently accumulate due to cyclonic and anticyclonic wind recirculation patterns [6]. Subsequently, airflow can transport pollutant masses to open regions or neighboring airsheds. The half-life of PM_{2.5} (particulate matter with aerodynamic diameter equal to or less than 2.5 µm) is estimated to range from three to fifteen days in the troposphere [7]; consequently, this pollutant can be transported over long distances before being removed by dry or wet deposition [8]. Export events become particularly significant when the

emitting atmospheric basin contains a densely urbanized metropolitan area with high pollutant emission rates, as substantial pollutant loads may be transported to other cities, worsening the air quality in the receiving airshed and increasing exposure among surrounding populations [9–13]. Cross-state air pollution is associated with 43–53% of premature mortality in the United States [14]. On the Tibetan Plateau, external inflows contribute about 20–40% of total pollution [13], and other studies estimate transboundary PM_{2.5} levels in the 20 to 40 µg m^{−3} range [15]. Anthropogenic emissions from the United States are an important contributor to CO concentrations (11%) and summertime O₃ concentrations (17%) in Quebec [16]. The transboundary air pollution significantly contributes to the deterioration of air quality, while local health systems and populations internalize the associated costs, often unconsciously.

The export of air pollutants is especially concerning when the receiving airshed is densely populated, as many inhabitants may be affected. In the Mexico City Metropolitan Area (MCMA), the main sources of PM_{2.5} are open waste burning (2484 tons year^{−1}), on-road mobile sources (6224 tons year^{−1}), and industrial combustion (2169 tons year^{−1}) [17]. PM_{2.5} consists of fine inhalable particles capable of reaching the alveolar region of the lungs, where toxic compounds may enter the bloodstream [18,19]. PM_{2.5} is composed of various harmful substances, such as toxic metals (e.g., cadmium and lead), metalloids (e.g., arsenic), and hydrocarbon aromatic polycyclic (e.g., anthracene and benzo[a]pyrene) [20–26]. Recognized health effects associated with PM_{2.5} exposure include lung cancer, chronic obstructive pulmonary disease, lower respiratory infections, asthma, cerebrovascular disease, cardiovascular disease, and ischemic heart disease [19,27–32].

To attribute the impacts of cross-state air pollution, it is necessary to differentiate air quality modeling [33,34]. However, a more accurate calculation requires data over a full year at 1 h intervals, because a coarser temporal resolution (e.g., daily, weekly) would allow a significant amount of the pollutants entering the basin to leave or be removed before they could be quantified, and fewer modeled days would not provide representative estimations. The large number of pollutant transport simulations and the enormous number of output files required to calculate annual premature deaths are the major challenges in calculating the associated costs. Examples of these situations can be seen in recently published articles. Dedoussi et al. [14] opted to estimate early deaths using the sensitivity of source–receptor matrices since, otherwise, their case study would have required 1300 simulations. Furthermore, they used a coarse spatial resolution of 50 × 50 km per grid cell to keep the computational requirements manageable. In other study cases, only a few days were modeled [35,36], or statistical techniques such as those presented by [37–44] were used to avoid air quality modeling. These approaches use epidemiological data cross-referenced with environmental monitoring data, assuming that monitoring stations represent the air quality of large regions. Table 1 summarizes the findings of the cited studies.

Table 1. Relevant case studies on estimating the impacts of air pollution in terms of mortality and costs.

Reference	Methodology	Findings
Gupta & Mohan, 2013 [35]	Authors used the WRF-Chem model to model air quality over a week to estimate the export of atmospheric pollutants.	58 to 89% of the pollution present in the megacity Delhi comes from outside.
Von Stackelberg et al., 2013 [37]	VSL of \$7.4 million and concentration–response functions were applied to estimate premature mortality.	A total estimate of \$31 billion (2007 \$) was estimated for the United States.
Mink, 2025 [38]	Data from hospital visits and air quality monitoring from 2015 to 2018 were used.	Marginal increases in PM _{2.5} concentration cause significant effects on weekly health costs.

Table 1. Cont.

Reference	Methodology	Findings
Lakner et al., 2024 [39]	Hungary's Global Burden of Disease [GBD] information system was used to estimate the health costs of 14 air pollution-related diseases.	The health costs represent a loss of 4.1 to 9.4% of GDP over the next fifty years.
Kubatko & Kubatko, 2019 [40]	The main air pollution-related diseases in Ukraine and the estimated costs associated with diseases.	Total economic costs attributed to air pollution and selected morbidities range 1.14–2.12 billion.
Becerra-Pérez et al., 2021 [41]	PM _{2.5} concentration relationships with total and cardiovascular mortality and VSL for Mexico were used.	Average health cost for three Mexican cities is between \$600 and \$690 million.
Trejo-González et al., 2019 [42]	Estimation of the benefits of PM _{2.5} emission reduction in Mexican cities using concentration–response functions and an adjusted VSL.	A reduction of 10 µg m ^{−3} can prevent mortality from related causes by 8.1%.
Yin et al., 2024 [43]	Data from 204 countries and concentration–response models were used to estimate the health costs attributable to PM _{2.5} pollution.	Global healthcare costs estimated at \$1.1 trillion globally in 2019.

Researchers and environmental managers use several metrics to quantify the impact of atmospheric pollution on population health. Among the most widely used for comparative purposes are estimates of potentially avoidable premature deaths (PAPDs) and economic costs based on the value per statistical life (VSL). According to the National Cancer Institute, a premature death is defined as “a death that occurs before the average age of death in a certain population” [45,46]. By analogy, potentially avoidable premature deaths are those attributable to preventable causes, like exposure to environmental pollution. In economic terms, the VSL represents the population's willingness to pay for reductions in mortality risk [47,48]. The U.S. Environmental Protection Agency (U.S. EPA) has developed the Environmental Benefits Mapping and Analysis Program (BenMap-CE) to support air pollution health impact assessments [49,50]. The BenMap-CE is used to estimate the PAPD and the annual costs associated with air quality scenarios. The program quantifies premature mortality using exposure–response functions derived from the epidemiological literature and calculates economic impacts using the VSL approach. BenMap-CE has been used in many studies and is widely accepted worldwide for the strategic assessment of air quality policies. As summarized in Table 1, two main methods have been used to estimate the costs of air pollution. One method uses the costs of treating air pollution-related illnesses, and the other frequently uses the concept of the statistical value of life. Recently, a significant number of studies using BenMap-CE have been published; Table 2 summarizes a list of them.

Table 2. Recent studies using the BenMap program.

Reference	Country	Journal
Aldegunde et al., 2023 [51]	Colombia	<i>Environments</i>
Altieri & Keen, 2019 [52]	South Africa	<i>Science of the Total Environment</i>
Bryan & Landrigan, 2023 [53]	United States	<i>Frontiers in Public Health</i>
Chen et al., 2023 [54]	China	<i>Air Quality, Atmosphere & Health</i>
Coffman et al., 2024 [55]	United States	<i>Environmental Health Perspectives</i>
Getachew et al., 2025 [56]	Ethiopia	<i>Environmental Health Insights</i>
He et al., 2025 [57]	United States	<i>Environmental Research Letters</i>
Hu et al., 2024 [58]	China	<i>Sustainability</i>
Kabir & Pal, 2024 [59]	Bangladesh	<i>Lecture Notes in Civil Engineering</i>
Kianizadeh et al., 2022 [60]	Iran	<i>Environmental Monitoring and Assessment</i>
Li & Wilson, 2023 [61]	United States	<i>Applied Sciences</i>
Lindsey et al., 2025 [62]	United States	<i>GeoHealth</i>
Meng et al., 2024 [63]	United States	<i>BMJ Public Health</i>

Table 2. Cont.

Reference		Country	Journal
Ngamsang et al., 2023	[64]	Thailand	<i>Journal of Environmental and Public Health</i>
Safari et al., 2022	[12]	Iran	<i>International Journal of Biometeorology</i>
Salehi et al., 2023	[65]	Iran	<i>PLoS ONE</i>
Sekmoudi et al., 2025	[66]	Morocco	<i>Euro-Mediterranean Journal for Environmental Integration</i>
Wang et al., 2023	[67]	China	<i>Atmosphere</i>
Žero et al., 2022	[68]	Bosnia and Herzegovina	<i>Environmental Science & Technology</i>

BenMap-CE users can prepare scenarios by interpolating measurements from air quality monitoring stations with limited precision or by using dispersion modeling for greater accuracy. The Hybrid Single Particle Lagrangian Integrated Trajectory (Hysplit) can be used to simulate such air quality scenarios [69,70]. Hysplit is widely applied for modeling the transport and dispersion of atmospheric pollutants [13,71–75]. Its application for estimating pollutant mass interchange between atmospheric basins was first demonstrated by this research group [9]. One of the main advantages of using Hysplit in these types of studies is its ability to generate output files in formats suitable for post-processing within geographic information systems. Additionally, by implementing geoprocessing algorithms, multiple output files can be automatically processed to produce more detailed estimates of particulate mass exchange, rather than merely estimating pollutant concentrations. This approach allows for a clearer distinction between transported pollutants from each source.

The health impacts of pollution exported from a highly polluted area become more significant when the receiving area is also located within an atmospheric basin capable of retaining pollutants, such as the cities surrounding Mexico City. Therefore, the following research question arises: How many premature deaths occur, and what are the associated costs as a result of importing primary PM_{2.5} from a highly urbanized atmospheric basin such as the MCMA?

For the purpose of estimating the annual impacts associated with atmospheric pollutant mass received by one population from another densely urbanized airshed, this manuscript displays, for the first time, the results of annual PM_{2.5} mass interchange modeling (8640 simulations), PAPD, and associated cost calculations, using the Hysplit 5.3.0 model and the BenMap-CE 1.5.0.4 software, complemented with geoprocessing tools developed by this group in ArcGis® 10.4. The methodology was applied to two metropolitan areas neighboring a highly urbanized metropolitan area, particularly the Mexico City Metropolitan Area. This approach allows for greater precision in epidemiological estimation.

2. Materials and Methods

2.1. Study Area

The MCMA is the biggest urban zone in the Mexican megalopolis, located in the central region of Mexico. This metropolitan area is within an airshed at 2240 AMSL. In the surrounding area, it borders other airsheds containing metropolitan areas, such as the Toluca Valley Metropolitan Area (TVMA) in the State of Mexico to the east and the Cuernavaca Metropolitan Area (CMA) in the State of Morelos to the south. The MCMA is the most populated (21 million inhabitants), the most motorized (6.24 million vehicles), and has high pollutant emission rates (14,939 tons year^{−1} of PM_{2.5}) [17,76]. High quantities of atmospheric pollutants are exported from the MCMA to surrounding areas and added to local emissions in other airsheds. The TVMA is located inside the Toluca airshed at 2600 AMSL and has 2,353,924 inhabitants, and the CMA is located inside another airshed at 1500 AMSL and has 1,121,122 inhabitants. The population in the MCMA is predominantly urban (97%); in contrast, the populations in the TVMA and CMA are 87% urban.

2.2. Emissions Inventory

In Mexico, emission inventories are calculated by the ministries of environment, and the 2018 inventory was the most recent inventory available to research groups at the time of this study. The 2018 emissions inventory of point and area sources of the Mexico Megalopolis was provided by the Environmental and Natural Resources Ministry (SEMARNAT, by its Spanish acronym). The MCMA inventory includes 77,000 industrial sources, 850,000 commercial sources, and 6.24 million vehicles. The modeled PM_{2.5} total emissions in the MCMA were: point sources = 3174.4 ton-year⁻¹, area sources = 5906.1 ton-year⁻¹, and mobile sources = 7097.5 ton-year⁻¹ [77]. The spatial distribution of point and area emissions was provided by the SEMARNAT. On-road mobile emissions were spatially distributed by street category: 50% to highways, 30% to secondary avenues, and 20% to tertiary streets. Total emissions rates were integrated into a grid with 5 × 5 km cells to protect confidential information. Natural emissions (322 ton-year⁻¹) were not included in the modeling because the objective of this study is to provide recommendations regarding the management of anthropogenic emission impacts. Figure 1 shows the grid with all emission rates integrated in grams per second (units required by Hysplit 5.3.0 modeling). PM_{2.5} emissions data of each cell are available in the repository linked to Dataset #1 (see the Data Availability Statement Section).

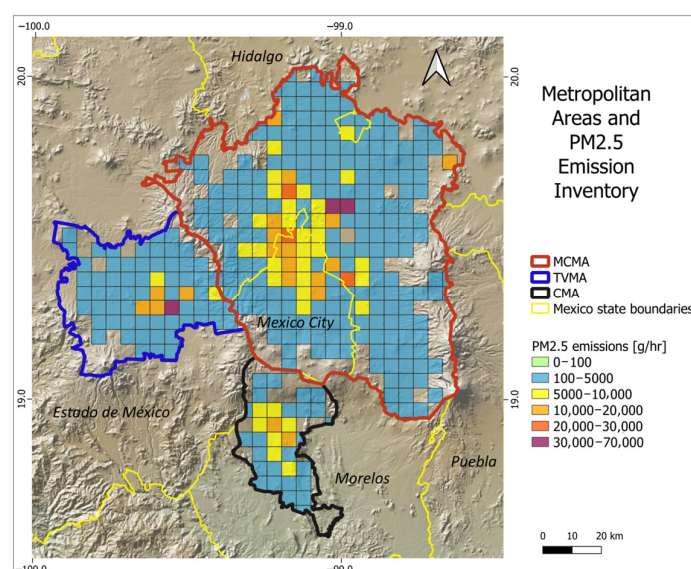


Figure 1. Study area: metropolitan areas and the PM_{2.5} emissions grid.

2.3. PM_{2.5} Dispersion Modeling with Hysplit 5.3.0

The Hysplit 5.3.0 model (user account #182) was used to simulate PM_{2.5} transport across atmospheric basins. Hourly intervals were modeled for each one of the 24 h of the 30 days of the twelve months of 2018. The meteorological files from the NCEP/NCAR Global Reanalysis Data and the Global Data Assimilation System were downloaded from the National Oceanic and Atmospheric Administration repositories [78].

The Hysplit 5.3.0 model was executed using the “Daily run” special mode. This mode executes multiple automated concentration simulations. Hysplit 5.3.0 was configured to run 1 h simulations for 14-day intervals. The concentration setup was configured to model particles with a diameter of 2.5 µm and to model wet and dry deposition. The top of the model was adjusted to 2000 m above ground level. The simulations were computed on a workstation manufactured by Hewlett-Packard in the United States with an Intel Core i9-10900F 10a 2.8 GHz 10 cores processor, memory RAM DDR4 128 Gb and liquid cooling.

2.4. Post-Geoprocessing

Output files were post-processed in the ArcGis 10.4 geographic information system. Custom tools were developed with ModelBuilder[®] to automatically process the large number of output files by Hysplit 5.3.0 and to calculate the importation of PM_{2.5} mass. The particle mass was calculated by applying Equation (1).

$$M = \sum_{i=1}^n C_i \times A_i \times H \quad (1)$$

For each *i*-polygon, *M* represents the mass of PM_{2.5} [g] dispersed within a metropolitan area. *C_i* is the PM_{2.5} concentration [g m⁻³]. *A_i* is the area of the polygon associated with concentration *C_i*, and *H* is the modeling height [m].

The post-geoprocessing procedure includes the following stages: (1) conversion of Hysplit output text files into PM_{2.5} concentration polygons; (2) spatial intersection between concentration polygons and municipal boundary polygons; (3) estimation of PM_{2.5} particulate mass. The geoprocessing results are hourly quantifications of PM_{2.5} mass. Results of this geoprocessing workflow consist of the hourly quantifications of imported PM_{2.5} mass for each urban polygon in 2018. Flow diagrams of the geographic tools designed to automate mass calculation are present in Appendix A.

2.5. The Premature Mortality and Costs Calculation

Potentially avoidable premature deaths and their associated costs were calculated using the BenMap-CE 1.5.0.4 program. Two scenarios were compared: (i) the alternative scenario (without PM_{2.5} imports from MCMA) and (ii) the baseline scenario (with PM_{2.5} imports). The Krewski health impact function is the most used in the state-of-the-art to calculate the premature deaths, assuming a log-linear concentration–response relationship. This function relates the annual average PM_{2.5} concentration to the risk estimator (called the beta coefficient, *β*) according to Equation (2) [79]. The associated costs were calculated using the most recent local VSL reported by Becerra-Pérez et al. [41]: \$0.9 million for the State of Mexico and \$0.7 million for Morelos (base year 2021).

$$\Delta Y = Y_0(1 - e^{-\beta \times \Delta PM_{2.5}}) \times Population \quad (2)$$

where *ΔY* is the change in mortality, *Y₀* is the baseline mortality rate (incidence), *β* is the unit risk coefficient, and *ΔPM_{2.5}* is the difference in PM_{2.5} mass in grams.

In summary, the transport of primary PM_{2.5} emissions from MCMA to CMA and TVMA was modeled with Hysplit 5.3.0 at one-hour intervals in 2018 (8640 simulations) using the 2018 emission inventory. Later, the imported PM_{2.5} mass was calculated using geographic tools. Finally, the potentially avoidable premature deaths and the associated costs were estimated using the BenMap-CE 1.5.0.4 program.

Figure 2 presents a flow diagram summarizing the modeling and calculus processes. Initially, the PM_{2.5} primary emissions inventory is integrated into the geodatabase and spatially distributed in a grid. Next, the transport of PM_{2.5} is modeled with Hysplit, including the meteorological data. Subsequently, the Hysplit output files are rearranged to prepare for post-geoprocessing. Then, all output files are geoprocessed in ArcGis 10.4 to calculate the PM_{2.5} mass exchange. Finally, premature mortality and costs are calculated using the BenMap-CE program.

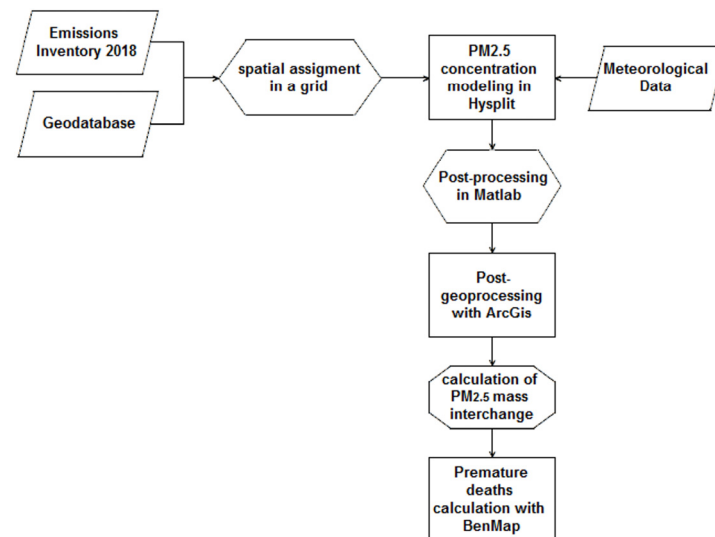


Figure 2. Workflow of premature mortality and cost estimation.

3. Results

The modeling results for mass interchange between the MCMA and the TVMA indicate that, in 2018, the $PM_{2.5}$ mass hourly average in the TVMA, originally emitted in the MCMA, was 565 kg. Figure 3 shows the results of hourly imported $PM_{2.5}$ mass modeled with Hysplit and geoprocessing tools. Imported particle mass frequently reaches approximately 4000 kg in the TVMA and 2000 kg in the CMA. This fact could be related to the airshed area size. The winds blow from the MCMA, and their pollutants can be deposited within the basin or blown out when winds are strong (whole-year modeling considers all meteorological conditions). In this atmospheric dynamic, the airshed area limits the deposited $PM_{2.5}$ mass. Occasionally, mass peaks of 10,564 kg and 8918 kg impact the TVMA.

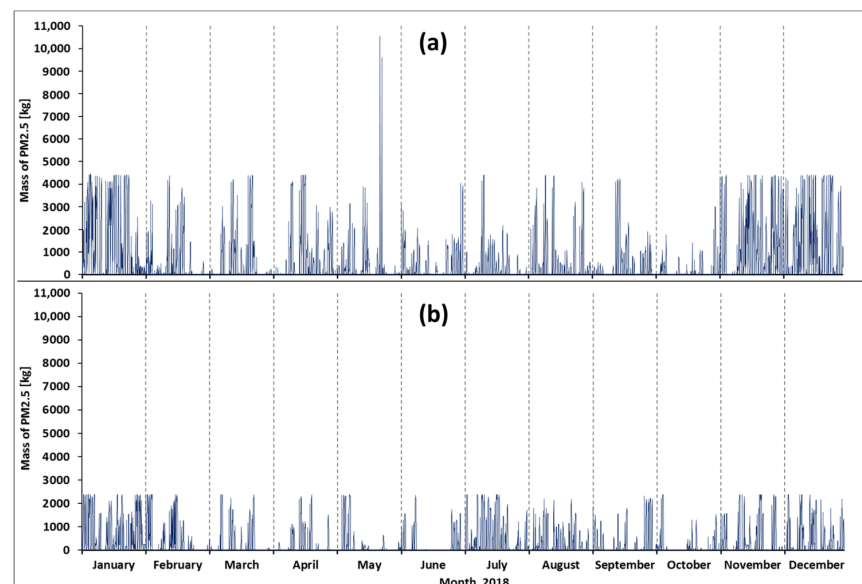


Figure 3. Hourly $PM_{2.5}$ mass exports. (a) $PM_{2.5}$ mass exported from MCMA to TVMA, (b) $PM_{2.5}$ mass exported from MCMA to CMA.

January, November, and December were the months with the greatest particle export from MCMA to neighboring airsheds. The accumulated monthly amounts of imported $PM_{2.5}$ mass are presented in Figure 4. The pattern is associated with the prevailing northerly winds during the winter season. In the CMA case, the average hourly amount of $PM_{2.5}$

from the MCMA was 284 kg. However, an enormous amount of $PM_{2.5}$ was observed in the summer as well. The main differences in impacts between the TVMA and the CMA are related to airflow restrictions imposed by the mountain chain separating the MCMA and the CMA. These topographic barriers become more penetrable during periods of intense summer winds and higher temperatures. Strong winds disrupt anticyclonic recirculation patterns and facilitate the transport of pollutants across mountain passes.

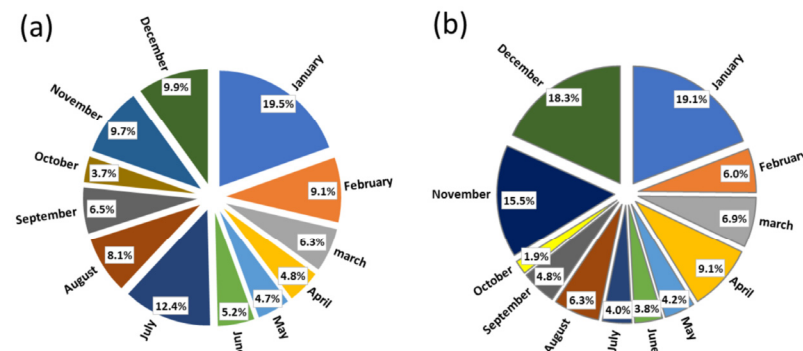


Figure 4. Monthly distribution of imported $PM_{2.5}$ mass: (a) Toluca Valley Metropolitan Area; (b) Cuernavaca Metropolitan Area.

The dispersion of $PM_{2.5}$ causes differentiated increases in the urban municipalities of the receiving metropolitan areas. Figure 5 illustrates the differences in $PM_{2.5}$ mass between the alternative and baseline scenarios. In the TVMA, municipalities closer to the MCMA show the greatest increases, while the municipality of Toluca, farther away, shows moderate increases. These lower increases are relevant because the municipality of Toluca is the capital of the State of Mexico and, therefore, one of the most populated. In contrast, in the CMA, Cuernavaca, the capital municipality of the State of Morelos, is the most populated municipality and also one of the closest to the MCMA, thus showing greater increases in $PM_{2.5}$ mass. Consequently, in the CMA, the import of $PM_{2.5}$ is more significant.

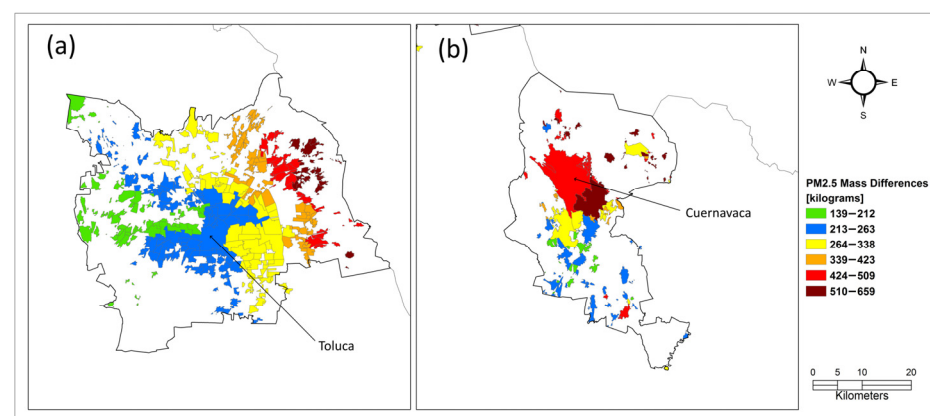


Figure 5. $PM_{2.5}$ mass differences between the alternative and baseline scenarios: (a) TVMA; (b) CMA.

Imported $PM_{2.5}$ mass was spatially integrated into the basic geostatistical areas (AGEB, by the Spanish acronym) for subsequent analysis in BenMap-CE. The corresponding data are available in the repository linked to Dataset #2 (see the Data Availability Statement Section). Figure 6 displays the BenMap-CE results of mortality calculations at the AGEB level. The most densely populated and locally polluted municipalities exhibit the highest PAPD. The impact of incoming $PM_{2.5}$ is greatest in regions with high local emission rates because the relationship between health risks is non-linear [79]. The exponential function implies that even small increases in particulate concentrations can produce significant

health impacts. In total, 13,553 PAPD were estimated for the TVMA and 5915 PAPD for the CMA. Data is available in the repository linked to Dataset #3 (see the Data Availability Statement Section).

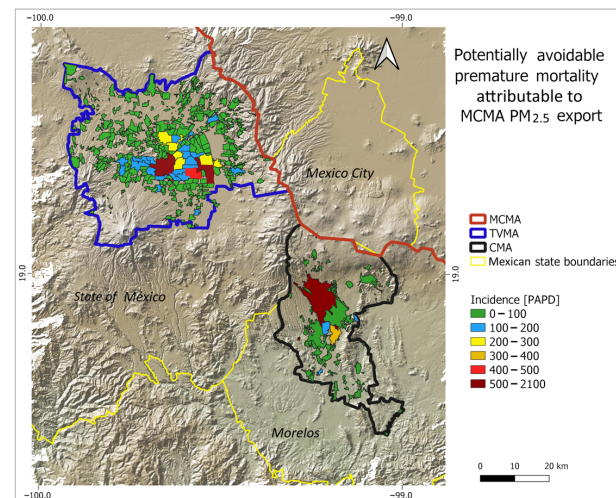


Figure 6. Premature mortality in the TVMA and in the CMA attributable to MCMA $PM_{2.5}$ exports.

The three most impacted municipalities in the TVMA are Toluca de Lerdo (capital of the State of Mexico) with an incidence of 1354 PAPD (population: 223,876 inhabitants), San Mateo Atenco with 540 PAPD (population of 88,734 inhabitants), and San Salvador Tizatlalli with 425 PAPD (population of 70,013 inhabitants). It is worth noting the high incidence in Toluca de Lerdo, despite its considerable distance from the MCMA. In the CMA, the municipalities with the highest incidence are Cuernavaca, Calera Chica, and San Agustín Tetlama with 2062, 1048, and 587 PAPD, respectively. The total PAPD in the Cuernavaca municipality is higher than in Toluca de Lerdo, reflecting a larger difference between the baseline and alternative scenarios.

The results of the impact valuation of $PM_{2.5}$ imports are directly proportional to incidence, as defined in Equation (2), where the population variable has a directly multiplicative effect. Figure 7 shows the BenMap-CE results of attributable costs by AGEb; data are available in Dataset 3 (see the Data Availability Statement Section). The health impacts' calculus was valued at \$12,197 million for the TVMA and \$4140 million for the CMA. It is important to note that VSL values were applied to each metropolitan area.

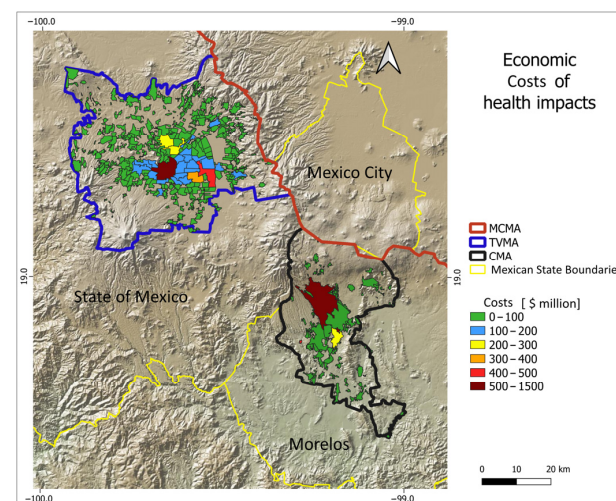


Figure 7. Economic costs of health impacts applying the local VSL.

4. Discussion

November, December, and January were the months with the highest PM_{2.5} exports from the MCMA to the metropolitan areas of Toluca and Cuernavaca. This pattern is consistent with the prevailing wind directions during 2018. The MCMA is partially confined by the mountain system of the Trans-Mexican Volcanic Belt to the southwest and by the Sierra Madre Oriental to the southeast. Consequently, predominant winds enter the MCMA airshed from the north and exit through the orographic channels between the mountains at the south, west, and southwest (Figure 8). In 2018, the winds in January, March, April, June, November, and December predominantly blew toward the Toluca and Cuernavaca airsheds, carrying loads of pollutants emitted in the MCMA.

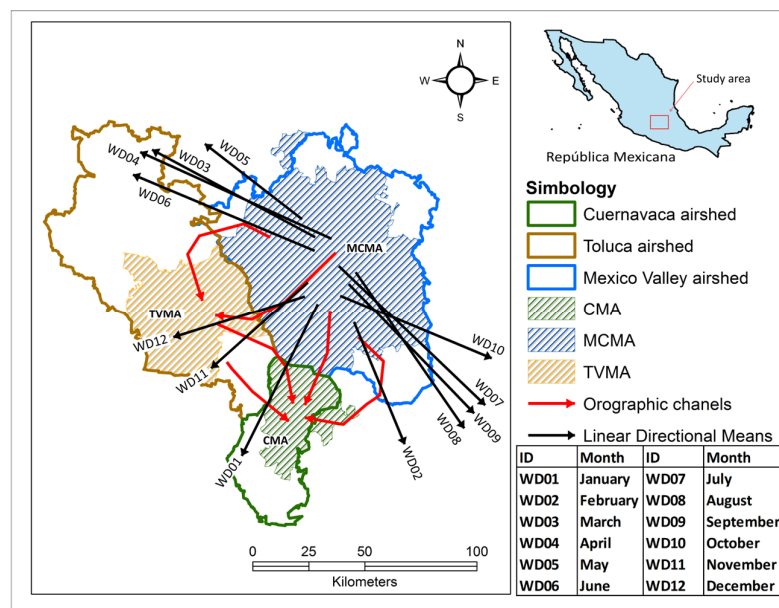


Figure 8. Predominant wind directions blowing out from MCMA.

The high imports during the winter season are a cause for concern because the low ambient temperatures during those months increase the risks for population health. Additionally, low temperatures can lead to thermal inversions, which slow pollutant dispersion, increasing the population's exposure time to high concentrations of air pollutants. It would be expected that during the winter months, greater emphasis would be placed on managing prevention and treatment measures of diseases related to air pollution. Although the modeling results show significant PM_{2.5} imports in July in Toluca and in April in Cuernavaca, these could disperse more quickly due to the higher temperatures of spring and summer.

Compared to other case studies, premature deaths attributable to out-of-state pollution in 2018 were estimated at 1280 PAPD in Alabama, 1430 PAPD in Kentucky, and 2010 PAPD in Richmond, Virginia [14]. The higher estimated values in this study could be associated with three factors. First, the high levels of PM_{2.5} exported by MCMA; second, the fact that MCMA is located within an atmospheric basin, where air pollutants can accumulate before being exported; and third, the impacted populations are themselves located within atmospheric basins, which increases the residence time of imported pollutants.

The costs attributable to PM_{2.5} imports are often substantial and controversial. The VSL variation across different countries makes it difficult to compare. A possible comparison could be per capita. The attributable costs estimated in this study for the TVMA and CMA are \$5181.00 and \$3693.00 per capita, respectively. These results are higher than the global average of \$147.00 per capita calculated by Yin et al. [43].

The exchange of atmospheric pollutants has been a subject of growing concern for two decades. The findings indicate that the export of atmospheric pollutants may be responsible for thousands of premature deaths and millions of dollars in associated costs. However, these costs are largely internalized by the affected populations and states. Each airshed experiences distinct impacts of PM_{2.5} imports, and its orographic characteristics are factors to consider. The TVMA is at 2600 AMSL (400 m above the MCMA). This elevation, combined with the dry–cold season, thermal inversions, and increased importation of PM_{2.5} from the MCMA, may intensify adverse health effects in the Toluca population. In striking contrast, the CMA is 700 m below the MCMA. Therefore, the PM_{2.5} mass imported during the summer and winter seasons is rapidly dispersed southward.

Regarding the limitations, several aspects should be acknowledged: (1) The most recent emissions inventory available was published in 2018. (2) The spatial distribution of on-road emissions based on street hierarchies is also a rough approximation, which was used because these emissions are not spatially distributed in the emission inventories. (3) This study only evaluated the impacts of imported primary PM_{2.5}; secondary particulate matter and other imported pollutants that also pose risks to public health were not included in the analysis.

5. Conclusions

Premature mortality and costs associated with the import of primary PM_{2.5} from a densely urbanized metropolitan area to two surrounding urban areas were calculated for the first time in this study based on 8640 hourly transport simulations of mass throughout 2018. In the MCMA case, the results indicate that 13,553 PAPD in the TVMA and 5915 PAPD in the CMA are attributable to PM_{2.5} imports. In addition, this pollutant exchange process represents annual economic costs of \$12,197 million for the TVMA and \$4140 million for the CMA. Equivalent to per capita economic costs of \$3693 in the CMA and \$5181 in the TVMA. The main contributing factors are the high emission rates of the MCMA and the effects of atmospheric basins on pollutant accumulation.

Neighboring health institutions and the population unconsciously internalize the costs of the pollutants arriving from highly urbanized cities. The interchange of atmospheric compounds between airsheds is natural and inevitable. However, the relevance of impacts critically reveals that air policy management should consider import pollution impacts beyond administrative limits. When a government office makes wrong decisions, neighboring populations are negatively affected. It is therefore necessary to conduct more comprehensive assessments to support decision-making, even for policies applied within a single municipality.

Policy and Management Implications

In the MCMA case, the winter months had the highest frequency of pollutant imports; therefore, it is important to emphasize actions to reduce exposure to air pollution during this period and to consider compensation mechanisms for the receiving cities, primarily through the provision of medical services. Intergovernmental plans could be established to design such compensation mechanisms, recognizing that exported pollution causes economic losses in the form of reduced productivity in neighboring cities.

The significant impacts on the air quality and public health by atmospheric pollutant export make evident the need for regional management of urban public policies. All types of urban policies influence the atmospheric pollutant emissions (road network design, housing developments, growth of vehicle fleets, urban sprawl, services and travel attractors, etc.), especially when they reach metropolitan cover. Considering the effects of these policies

on pollutant emissions and their impacts on neighboring populations would enhance the sustainability of national development.

As an additional recommendation, a policy framework similar to the Cross-State Air Pollution Rule (CSAPR) [80] could be designed to promote emissions control measurements in highly urbanized metropolitan areas when large amounts of pollutant mass are exported to other populated airsheds.

Author Contributions: Formal analysis, methodology, investigation, and writing—original draft preparation, A.H.-M. Project administration, resources, and writing—review and editing, V.M.-Á. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank the National Humanities, Science and Technology Council (Conahcyt) for project 316642 funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in this study are openly available in Dataset #1: URL (accessed on 18 February 2026) https://data.4tu.nl/private_datasets/nvn-CeHfnC7wskx_u_q88ofT3-gYVR0fw0gqE4S2XEY. Dataset #2: URL (accessed on 18 February 2026) https://data.4tu.nl/private_datasets/u66JskHmQqTah-skkgSbNiDWrhU4v6-SrYFZZLANx50. Dataset #3: URL (accessed on 18 February 2026) https://data.4tu.nl/private_datasets/1TqrfeoBgVbTnv2AFM23k0Gbihzwm8CLkpCRvWXclH8.

Acknowledgments: The authors thank the General Management Direction of Air Quality and Pollutant Emissions and Transference Register of the Environment and Natural Resources Ministry (SEMARNAT, by the Spanish acronym) for sharing the 2018 Megalopolis Emission Inventory.

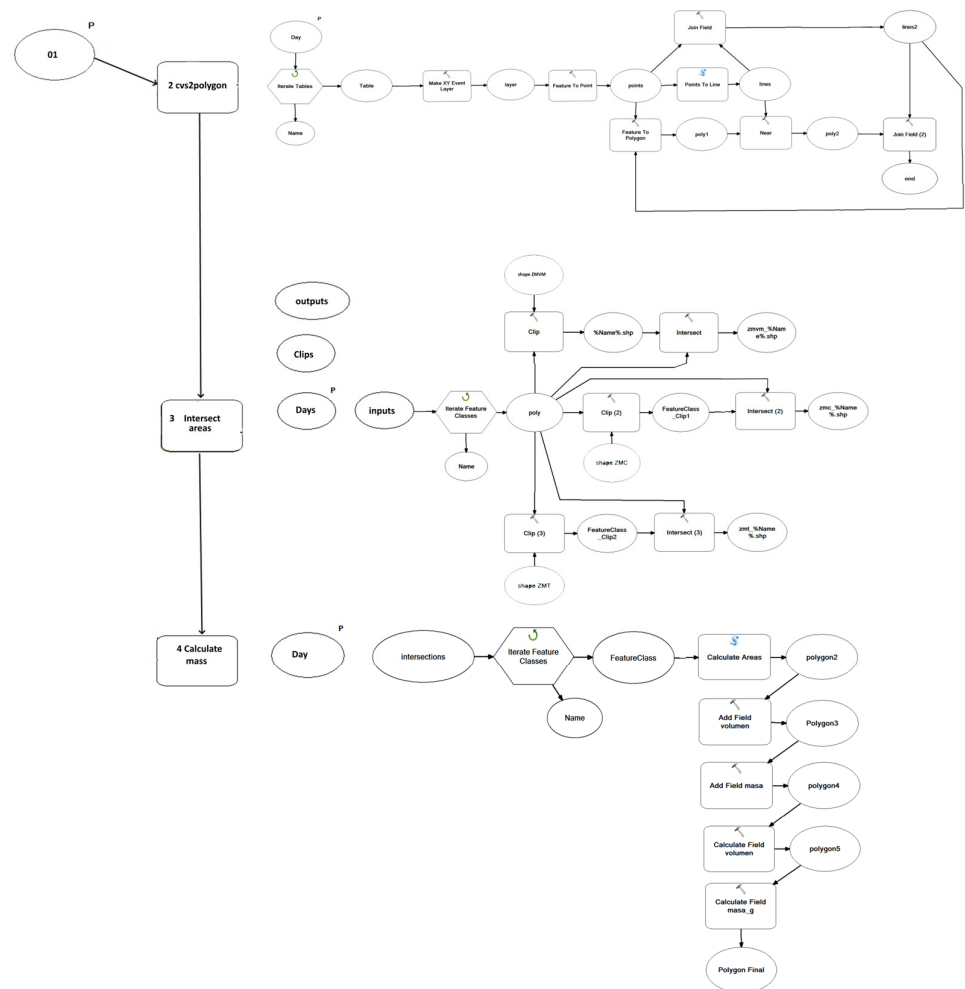
Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AMSL	Above meters sea level
BenMap-CE	Environmental Benefits Mapping and Analysis Program
CMA	Cuernavaca Metropolitan Area
Hysplit	Hybrid Single Particle Lagrangian Integrated Trajectory
MCMA	Mexico City Metropolitan Area
PAPD	Potentially avoidable premature deaths
PM _{2.5}	Particulate matter with aerodynamic diameters equal to 2.5 µm and smaller
TVMA	Toluca Valley Metropolitan Area
VSL	Value of a Statistical Life

Appendix A



References

1. Khan, A.A.; Kumar, P.; Gulia, S.; Khare, M. A Critical Review of Managing Air Pollution through Airshed Approach. *Sustain. Horiz.* **2024**, *9*, 100090. [[CrossRef](#)]
2. Sparling, D.W. Community-Level and Ecosystem-Level Effects of Environmental Chemicals. In *Ecotoxicology Essentials*; Academic Press: Cambridge, MA, USA, 2016; pp. 337–359. [[CrossRef](#)]
3. Jones, L.; Reis, S.; Hutchins, M.; Miller, J.; He, B.; Seifert-Dähnn, I.; Xu, C.Y.; Hagen-Zanker, A.; Yu, J.; Lin, T.; et al. Airsheds, Watersheds and More—The Flows That Drive Intra-Extra-Urban Connections, and Their Implications for Nature-Based Solutions (NBS). *Nat.-Based Solut.* **2022**, *2*, 100040. [[CrossRef](#)]
4. De Foy, B.; Fast, J.D.; Paech, S.J.; Phillips, D.; Walters, J.T.; Coulter, R.L.; Martin, T.J.; Pekour, M.S.; Shaw, W.J.; Kastendeuch, P.P.; et al. Basin-Scale Wind Transport during the MILAGRO Field Campaign and Comparison to Climatology Using Cluster Analysis. *Atmos. Chem. Phys.* **2008**, *8*, 1209–1224. [[CrossRef](#)]
5. Jazcilevich, A.D.; García, A.R.; Ruíz-Suárez, L.G. A Study of Air Flow Patterns Affecting Pollutant Concentrations in the Central Region of Mexico. *Atmos. Environ.* **2003**, *37*, 183–193. [[CrossRef](#)]
6. Díaz-Esteban, Y.; Barrett, B.S.; Raga, G.B. Circulation Patterns Influencing the Concentration of Pollutants in Central Mexico. *Atmos. Environ.* **2022**, *274*, 118976. [[CrossRef](#)]
7. Seinfeld, J.H.; Pandis, S.N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*; John Wiley & Sons: Hoboken, NJ, USA, 2006.
8. Emmons, L.K.; Apel, E.C.; Lamarque, J.-F.; Hess, P.G.; Avery, M.; Blake, D.; Brune, W.; Campos, T.; Crawford, J.; DeCarlo, P.F.; et al. Impact of Mexico City Emissions on Regional Air Quality from MOZART-4 Simulations. *Atmos. Chem. Phys.* **2010**, *10*, 6195–6212. [[CrossRef](#)]
9. Hernández-Moreno, A.; Trujillo-Páez, F.I.; Mugica-Álvarez, V. Quantification of Primary PM_{2.5} Mass Exchange in Three Mexican Megalopolis Metropolitan Areas. *Urban Clim.* **2023**, *51*, 101608. [[CrossRef](#)]
10. CCA-UNAM. *Diagnóstico Sobre la Calidad del Aire en Cuencas Atmosféricas de México*; CCA-UNAM: Mexico City, Mexico, 2016.

11. Xu, R.; Stalter, R.M.; Doubleday, A.; Naismith, K.; Schulte, J.; Kadlec, M.; Ellison, R. Mortality Associated with Long-Term PM_{2.5} Exposure among Overburdened Communities in Washington State. *Air Qual. Atmos. Health* **2025**, *18*, 1021–1033. [\[CrossRef\]](#)
12. Safari, Z.; Fouladi-Fard, R.; Vahedian, M.; Mahmoudian, M.H.; Rahbar, A.; Fiore, M. Health Impact Assessment and Evaluation of Economic Costs Attributed to PM_{2.5} Air Pollution Using BenMAP-CE. *Int. J. Biometeorol.* **2022**, *66*, 1891–1902. [\[CrossRef\]](#)
13. Li, Y.; He, Y.; Wang, Y.; Li, G.; Zhang, X.; Niu, H.; Zhang, Y.; Wang, L. Identification of Local and Transboundary Sources and Mechanisms of PM_{2.5} and O₃ Pollution on the Tibetan Plateau: Implications for Sustainable Air Quality Governance. *Sustainability* **2025**, *17*, 10853. [\[CrossRef\]](#)
14. Dedoussi, I.C.; Eastham, S.D.; Monier, E.; Barrett, S.R.H. Premature Mortality Related to United States Cross-State Air Pollution. *Nature* **2020**, *578*, 261–265. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Diao, B.; Lu, W.; Wang, Y.; Chen, Y. Quantitative Estimation and Influencing Factors of Transboundary Air Pollution from the Perspective of Regional Heterogeneity. *Environ. Monit. Assess.* **2025**, *197*, 682. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Pope, C.A.; Dockery, D.W. Transboundary Transport of Air Pollution in Eastern Canada. *Environ. Sci. Adv.* **2024**, *3*, 448–469. [\[CrossRef\]](#)
17. Secretaría del Medio Ambiente de la Ciudad de México (SEDEMA). *Inventario de Emisiones de la Zona Metropolitana del Valle de México 2020*; Gobierno de la Ciudad de México: Mexico City, Mexico, 2023.
18. USEPA. How Can the Air Quality Index Help? Pollutants. What Is Particle Pollution? Available online: www.epa.gov/air (accessed on 16 November 2025).
19. Sicard, P.; Khaniabadi, Y.O.; Perez, S.; Gualtieri, M.; De Marco, A. Effect of O₃, PM₁₀ and PM_{2.5} on Cardiovascular and Respiratory Diseases in Cities of France, Iran and Italy. *Environ. Sci. Pollut. Res.* **2019**, *26*, 32645–32665. [\[CrossRef\]](#)
20. Bandowe, B.A.M.; Meusel, H. Nitrated Polycyclic Aromatic Hydrocarbons (Nitro-PAHs) in the Environment—A Review. *Sci. Total Environ.* **2017**, *581–582*, 237–257. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Ronderos-Lara, J.G.; Millán-Vázquez, F.; Murillo-Tovar, M.A.; Saldarriaga-Noreña, H.A.; Valle-Hernández, B.L.; López-Velázquez, K.; Mugica-Álvarez, V. Atmospheric Estrogenic Semi-Volatile Compounds and PAH in PM_{2.5} in Mexico City. *Atmosphere* **2025**, *16*, 178. [\[CrossRef\]](#)
22. Valle-Hernández, B.L.; Amador-Muñoz, O.; Jazcilevich-Diamant, A.; Hernández-López, A.E.; Villalobos-Pietrini, R.; González-Oropeza, R. Polycyclic Aromatic Hydrocarbons in Particulate Matter Emitted by the Combustion of Diesel and Biodiesel. *Combust. Sci. Technol.* **2013**, *185*, 420–434. [\[CrossRef\]](#)
23. Vega, E.; Ruiz, H.; Escalona, S.; Cervantes, A.; Lopez-Veneroni, D.; Gonzalez-Avalos, E.; Sanchez-Reyna, G. Chemical Composition of Fine Particles in Mexico City during 2003–2004. *Atmos. Pollut. Res.* **2011**, *2*, 477–483. [\[CrossRef\]](#)
24. Venkatraman, G.; Giribabu, N.; Mohan, P.S.; Muttiah, B.; Govindarajan, V.K.; Alagiri, M.; Abdul Rahman, P.S.; Karsani, S.A. Environmental Impact and Human Health Effects of Polycyclic Aromatic Hydrocarbons and Remedial Strategies: A Detailed Review. *Chemosphere* **2024**, *351*, 141227. [\[CrossRef\]](#)
25. Ventura, L.M.B.; Mateus, V.L.; de Almeida, A.C.S.L.; Wanderley, K.B.; Taira, F.T.; Saint’Pierre, T.D.; Gioda, A. Chemical Composition of Fine Particles (PM_{2.5}): Water-Soluble Organic Fraction and Trace Metals. *Air Qual. Atmos. Health* **2017**, *10*, 845–852. [\[CrossRef\]](#)
26. Park, M.; Wang, Y.; Chong, J.; Lee, H.; Jang, J.; Song, H.; Kwak, N.; Borlaza, L.J.S.; Maeng, H.; Cosep, E.M.R.; et al. Simultaneous Measurements of Chemical Compositions of Fine Particles during Winter Haze Period in Urban Sites in China and Korea. *Atmosphere* **2020**, *11*, 292. [\[CrossRef\]](#)
27. Chen, C.Y.; Huang, K.Y.; Chen, C.C.; Chang, Y.H.; Li, H.J.; Wang, T.H.; Yang, P.C. The Role of PM_{2.5} Exposure in Lung Cancer: Mechanisms, Genetic Factors, and Clinical Implications. *EMBO Mol. Med.* **2025**, *17*, 31–40. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Cohen, A.J.; Brauer, M.; Burnett, R.; Anderson, H.R.; Frostad, J.; Estep, K.; Balakrishnan, K.; Brunekreef, B.; Dandona, L.; Dandona, R.; et al. 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* **2017**, *389*, 1907–1918. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Correia, A.W.; Pope, C.A.; Dockery, D.W.; Wang, Y.; Ezzati, M.; Dominici, F. Effect of Air Pollution Control on Life Expectancy in the United States. *Epidemiology* **2013**, *24*, 23–31. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Pope, C.A.; Ezzati, M.; Dockery, D.W. Fine-Particulate Air Pollution and Life Expectancy in the United States. *N. Engl. J. Med.* **2009**, *360*, 376–386. [\[CrossRef\]](#)
31. Wesley, E.J.; Brunzell, N.A.; Rahn, D.R.; Saint Onge, J.M.; Kane, N.J.; Kennedy, K.F. Neighborhood Effects on Acute Pediatric Asthma: Race, Greenspace, and PM_{2.5}. *Urban Sci.* **2024**, *8*, 176. [\[CrossRef\]](#)
32. Héluain, V.; Molinier, L.; Mazières, J. Air Pollution and Lung Cancer: A Comprehensive Review. *J. Epidemiol. Popul. Health* **2025**, *73*, 203152. [\[CrossRef\]](#)
33. Hou, X.; Liao, K.-J. Impacts of Interstate Transport of Pollutants on Ozone Air Quality Attainment in the Mid-Atlantic Region. In Proceedings of the 11th Annual CMAS Conference, Chapel Hill, NC, USA, 15–17 October 2012.
34. Potts, B.H. The Practical, Legal and Equitable Problems with EPA’s New Cross-State Air Pollution Rule. *Electr. J.* **2011**, *24*, 8–17. [\[CrossRef\]](#)

35. Gupta, M.; Mohan, M. Assessment of Contribution to PM₁₀ Concentrations from Long Range Transport of Pollutants Using WRF/Chem over a Subtropical Urban Airshed. *Atmos. Pollut. Res.* **2013**, *4*, 405–410. [CrossRef]
36. Yang, Q.; Zhao, T.; Tian, Z.; Kumar, K.R.; Chang, J.; Hu, W.; Shu, Z.; Hu, J. The Cross-Border Transport of PM_{2.5} from the Southeast Asian Biomass Burning Emissions and Its Impact on Air Pollution in Yunnan Plateau, Southwest China. *Remote Sens.* **2022**, *14*, 1886. [CrossRef]
37. Von Stackelberg, K.; Buonocore, J.; Bhawe, P.V.; Schwartz, J.A. Public Health Impacts of Secondary Particulate Formation from Aromatic Hydrocarbons in Gasoline. *Environ. Health* **2013**, *12*, 19. [CrossRef] [PubMed]
38. Mink, J. The Healthcare Costs of Air Pollution in France. *J. Environ. Econ. Manag.* **2025**, *134*, 103242. [CrossRef]
39. Lakner, Z.; Popp, J.; Oláh, J.; Zéman, Z.; Molnár, V. Possibilities and Limits of Modelling of Long-Range Economic Consequences of Air Pollution—A Case Study. *Heliyon* **2024**, *10*, e26483. [CrossRef]
40. Kubatko, O.; Kubatko, O. Economic Estimations of Air Pollution Health Nexus. *Environ. Dev. Sustain.* **2019**, *21*, 1507–1517. [CrossRef]
41. Becerra-pérez, L.A.; Ramos-álvarez, R.A.; Delacruz, J.J.; García-páez, B.; Páez-osuna, F.; Guillermo Cedeño-Laurent, J.; Boldo, E. An Economic Analysis of the Environmental Impact of PM_{2.5} Exposure on Health Status in Three Northwestern Mexican Cities. *Sustainability* **2021**, *13*, 10782. [CrossRef]
42. Trejo-González, A.G.; Riojas-Rodriguez, H.; Texcalac-Sangrador, J.L.; Guerrero-López, C.M.; Cervantes-Martínez, K.; Hurtado-Díaz, M.; de la Sierra-de la Vega, L.A.; Zuñiga-Bello, P.E. Quantifying Health Impacts and Economic Costs of PM_{2.5} Exposure in Mexican Cities of the National Urban System. *Int. J. Public Health* **2019**, *64*, 561–572. [CrossRef]
43. Yin, H.; McDuffie, E.E.; Martin, R.V.; Brauer, M. Global Health Costs of Ambient PM_{2.5} from Combustion Sources: A Modelling Study Supporting Air Pollution Control Strategies. *Lancet Planet. Health* **2024**, *8*, e476–e488. [CrossRef]
44. Mukerjee, S.; Shadwick, D.S.; Smith, L.A.; Somerville, M.C.; Dean, K.E.; Bowser, J.J. Techniques to Assess Cross-Border Air Pollution and Application to a US-Mexico Border Region. *Sci. Total Environ.* **2001**, *276*, 205–224. [CrossRef]
45. NCI (National Cancer Institute). NCI Dictionary of Cancer Terms. Available online: <https://www.cancer.gov/publications/dictionaries/cancer-terms/def/premature-death> (accessed on 8 January 2026).
46. Smith, K.R.; Hanson, H.A. Early Life Influences on Health and Mortality in Adulthood. In *International Encyclopedia of the Social & Behavioral Sciences*, 2nd ed.; Wright, J.D., Ed.; Elsevier: Amsterdam, Netherlands, 2015; Volume 25, pp. 752–758. [CrossRef]
47. Becerra-Pérez, L.A.; Ramos-Alvarez, R.A.; DelaCruz, J.J.; García-Páez, B. Value per Statistical Life at the Sub-National Level as a Tool for Assessing Public Health and Environmental Problems. *Inq. J. Health Care Organ. Provis. Financ.* **2024**, *61*, 00469580241246476. [CrossRef]
48. USEPA. Mortality Risk Valuation. Available online: <https://www.epa.gov/environmental-economics/mortality-risk-valuation> (accessed on 11 September 2025).
49. Abt Associates Inc. BenMAP: Environmental Benefits and Mapping Analysis Program. Prepared for the US EPA Office of Air Quality Planning and Standards. Available online: <https://www.epa.gov/benmap> (accessed on 18 December 2025).
50. Sacks, J.D.; Lloyd, J.M.; Zhu, Y.; Anderton, J.; Jang, C.J.; Hubbell, B.; Fann, N. The Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE): A Tool to Estimate the Health and Economic Benefits of Reducing Air Pollution. *Environ. Model. Softw.* **2018**, *104*, 118–129. [CrossRef]
51. Aldegunde, J.A.Á.; Bolaños, E.Q.; Fernández-Sánchez, A.; Saba, M.; Caraballo, L. Environmental and Health Benefits Assessment of Reducing PM_{2.5} Concentrations in Urban Areas in Developing Countries: Case Study Cartagena de Indias. *Environments* **2023**, *10*, 42. [CrossRef]
52. Altieri, K.E.; Keen, S.L. Public Health Benefits of Reducing Exposure to Ambient Fine Particulate Matter in South Africa. *Sci. Total Environ.* **2019**, *684*, 610–620. [CrossRef]
53. Bryan, L.; Landrigan, P. PM_{2.5} Pollution in Texas: A Geospatial Analysis of Health Impact Functions. *Front. Public Health* **2023**, *11*, 1286755. [CrossRef]
54. Chen, Y.; Ran, Z.; Wang, Y.; Liu, X.; Yang, P.; Han, K.; Yin, X.; Zou, C.; Wu, R.; Mao, H.; et al. Health Benefits of Traffic-Related PM_{2.5} and CO Reduction—A Case Study of Tianjin, China, from 2015 to 2019. *Air Qual. Atmos. Health* **2023**, *16*, 2297–2307. [CrossRef]
55. Coffman, E.; Rappold, A.G.; Nethery, R.C.; Anderton, J.; Amend, M.; Jackson, M.A.; Roman, H.; Fann, N.; Baker, K.R.; Sacks, J.D. Quantifying Multipollutant Health Impacts Using the Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE): A Case Study in Atlanta, Georgia. *Environ. Health Perspect.* **2024**, *132*, 037003. [CrossRef]
56. Getachew, M.; Mekonnen, A.; Fitsum, D. Health and Economic Impact Estimation of Ambient Air Particulate Matter (PM_{2.5}) Pollution in Addis Ababa Using BenMAP-CE Model. *Environ. Health Insights* **2025**, *19*, 11786302241312061. [CrossRef] [PubMed]
57. He, H.; Canty, T.P.; Dickerson, R.R.; Dreessen, J.; Sapkota, A.; Boudreaux, M. Assessing PM_{2.5} Pollution in the Northeastern United States from the 2023 Canadian Wildfire Smoke: An Episodic Study Integrating Air Quality and Health Impact Modeling with Emissions and Meteorological Uncertainty Analysis. *Environ. Res. Lett.* **2025**, *20*, 114042. [CrossRef]

58. Hu, Y.; Chao, K.; Zhu, Z.; Yue, J.; Qie, X.; Wang, M. A Study on a Health Impact Assessment and Healthcare Cost Calculation of Beijing–Tianjin–Hebei Residents under PM_{2.5} and O₃ Pollution. *Sustainability* **2024**, *16*, 4030. [\[CrossRef\]](#)
59. Kabir, M.; Pal, S.K. Analyzing the Effects of PM10 Exposure on Health and Economy, a Case Study of Chattogram City Corporation (CCC). In *Proceedings of the 2nd International Conference on Advances in Civil Infrastructure and Construction Materials (CICM 2023)*; Lecture Notes in Civil Engineering; Springer: Cham, Switzerland, 2024; Volume 512, pp. 329–339. [\[CrossRef\]](#)
60. Kianizadeh, F.; Godini, H.; Moghimbeigi, A.; Hassanvand, M.S. Health and Economic Impacts of Ambient Air Particulate Matter (PM_{2.5}) in Karaj City from 2012 to 2019 Using BenMAP-CE. *Environ. Monit. Assess.* **2022**, *194*, 847. [\[CrossRef\]](#)
61. Li, K.; Wilson, J.P. Modeling the Health Benefits of Superblocks across the City of Los Angeles. *Appl. Sci.* **2023**, *13*, 2095. [\[CrossRef\]](#)
62. Lindsey, S.; Garcia-Gonzales, D.A.; Jerrett, M.; Bekker, C.; Marlier, M.E.; Su, J.G.; Gaw, E.; Li, Y. Assessing Air Quality and Health Benefits of Enhanced Management of Forests, Shrublands, and Grasslands Against Wildfires in California. *GeoHealth* **2025**, *9*, e2025GH001475. [\[CrossRef\]](#)
63. Meng, Y.-Y.; Yu, Y.; Garcia-Gonzales, D.; Al-Hamdan, M.Z.; Marlier, M.E.; Wilkins, J.L.; Ponce, N.; Jerrett, M. Health and Economic Cost Estimates of Short-Term Total and Wildfire PM_{2.5} Exposure on Work Loss: Using the Consecutive California Health Interview Survey (CHIS) Data 2015–2018. *BMJ Public Health* **2024**, *2*, e000491. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Ngamsang, P.; Amnuaylojaroen, T.; Parasin, N.; Pimonsree, S. Health Impact Assessment of Short-Term Exposure to Particulate Matter (PM₁₀) in Northern Thailand. *J. Environ. Public Health* **2023**, *2023*, 1237768. [\[CrossRef\]](#)
65. Salehi, M.; Hashiani, A.A.; Karimi, B.; Mirhoseini, S.H. Estimation of Health-Related and Economic Impacts of PM_{2.5} in Arak, Iran, Using BenMAP-CE. *PLoS ONE* **2023**, *18*, e0295676. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Sekmoudi, I.; Khomsi, K.; Idrissi, L.; Tanarhte, M.; El jarmouni, M. Assessing Health and Economic Benefits of Ambient Air Quality Improvement: Covid-19 Lockdown as a Case Study. *Euro-Mediterr. J. Environ. Integr.* **2025**, *11*, 47. [\[CrossRef\]](#)
67. Wang, J.; Ju, T.; Lei, S.; Li, B.; Niu, X. Study on Characteristics, Influencing Factors and Health Benefits of Atmospheric Multi-Pollutants in Southern Xinjiang. *Atmosphere* **2023**, *14*, 1681. [\[CrossRef\]](#)
68. Žero, S.; Žužul, S.; Huremović, J.; Pehnec, G.; Bešlić, I.; Rinkovec, J.; Godec, R.; Kittner, N.; Pavlović, K.; Požar, N.; et al. New Insight into the Measurements of Particle-Bound Metals in the Urban and Remote Atmospheres of the Sarajevo Canton and Modeled Impacts of Particulate Air Pollution in Bosnia and Herzegovina. *Environ. Sci. Technol.* **2022**, *56*, 7052–7062. [\[CrossRef\]](#)
69. Draxler, R.R.; Hess, G.D. *Description of the HYSPLIT_4 Modeling System*. NOAA Tech. Memo. ERL ARL-224; NOAA Air Resources Laboratory: Silver Spring, MD, USA, 1997.
70. Draxler, R.R.; Hess, G.D. An Overview of the HYSPLIT_4 Modelling System for Trajectories, Dispersion, and Deposition. *Aust. Meteorol. Mag.* **1998**, *47*, 295–308. [\[CrossRef\]](#)
71. Chen, Y.; Luo, Y. Analysis of Paths and Sources of Moisture for the South China Rainfall during the Presummer Rainy Season of 1979–2014. *J. Meteorol. Res.* **2018**, *32*, 744–757. [\[CrossRef\]](#)
72. Chen, B.; Stein, A.F.; Maldonado, P.G.; Sanchez de la Campa, A.M.; Gonzalez-Castanedo, Y.; Castell, N.; de la Rosa, J.D. Size Distribution and Concentrations of Heavy Metals in Atmospheric Aerosols Originating from Industrial Emissions as Predicted by the HYSPLIT Model. *Atmos. Environ.* **2013**, *71*, 234–244. [\[CrossRef\]](#)
73. Chatoutsidou, S.E.; Kordonouri, I.; Lazaridis, M. An Air-Quality-Based Analysis of NO, NO₂, and O₃ at a Suburban Mediterranean Site. *Atmosphere* **2025**, *17*, 7. [\[CrossRef\]](#)
74. Liu, X.; Liu, Z.; Pei, W.; Zhang, X.; Jie, X.; Yang, Z.; Liu, L.; Gao, Y.; Hu, R.; Zhang, M. Source-Specific PM_{2.5} Exposure and Associated Health Risks During Beijing Winter. *Toxics* **2025**, *13*, 1081. [\[CrossRef\]](#)
75. Molozhnikova, Y.; Shikhovtsev, M.; Khodzher, T. Results of a Comprehensive Study on Atmospheric Pollution at the Tankhoi Observation Point (Southeastern Coast of Lake Baikal, Russia): Temporal Variability and Identification of Sources. *Environments* **2025**, *12*, 462. [\[CrossRef\]](#)
76. Comisión Ambiental de la Megalópolis [CAME]. *Programa de Gestión Federal Para Mejorar La Calidad Del Aire de La Megalópolis 2017–2030*; Comisión Ambiental de la Megalópolis [CAME]: Ciudad de México, Mexico, 2018.
77. SEDEMA. *Inventario de Emisiones de la Zona Metropolitana del Valle de México Contaminantes Criterio, Tóxicos y Gases y Compuestos de Efecto Invernadero 2018*; Secretaría del Medio Ambiente de la Ciudad de México: Ciudad de México, Mexico, 2020.
78. NOAA PSL Physical Sciences Laboratory. Available online: <https://psl.noaa.gov/> (accessed on 8 December 2025).
79. Krewski, D.; Jerrett, M.; Burnett, R.T.; Renjun, M.; Hughes, E.; Shi, Y.; Turner, M.C.; Pope, C.A.; Thurston, G.; Calle, E.E.; et al. *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality*; Health Effects Institute: Boston, MA, USA, 2009.
80. EPA. *Revised Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS*; EPA: Washington, DC, USA, 2021; Volume 86, pp. 23054–23235.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.