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Article

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

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Abstract

Previous studies have shown that the mass exchange of atmospheric pollutants between airsheds significantly alters the air quality of regions surrounding large urban metropolises. This study presents estimates of potentially avoidable premature mortality and the annual cost that pollutant exchange may impose on receiving areas. The Hysplit model was used to model the exchange of pollutants for the year 2018 among three Mexican metropolitan areas: the México City metropolitan area, as the main exporter of pollutants, and the metropolitan areas of Toluca and Cuernavaca, as recipient areas. The modeling results were processed in ArcGIS®, and the estimated avoidable premature deaths and costs associated with imported PM_{2.5} were calculated using BenMap. The main results indicate that the export of PM_{2.5} from the Mexico City Metropolitan Area in 2018 could have resulted in 19,473 potentially avoidable premature deaths in the two recipient metropolitan areas. The impact could represent an annual cost of \$12,1977 million for the Toluca Valley metropolitan area and \$4,140 million for the Cuernavaca metropolitan area.

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

1. Introduction

Airsheds or atmospheric basins are regions with local climatic characteristics. Their formation is related to the orographic features, usually whole valleys among high mountains [1–4]. Air pollutants are temporally confined in airsheds where air masses exchange between one airshed and the surroundings mainly occurs through orographic channels (mountain passes) [5,6]. Within airsheds there frequently occur the accumulation of atmospheric pollutants due to cyclonic and anticyclonic wind recirculation [7], and subsequently, air flows carry air pollutant masses to open regions or other airsheds. The half-life of particles PM_{2.5} is estimated between three to fifteen days in the troposphere [8]; consequently, this pollutant can be transported over long distances before being removed by dry or wet deposition [9]. Thus, such export events are more relevant when the emitter atmospheric basin contains a densely urbanized metropolitan area with high pollutant emission rates, because high pollutant loads are carried to other cities, polluting the receiving airshed and worsening the air quality for other populations [10,11]. This impact increases premature mortality in the recipient cities [12], and their health institutions and inhabitants internalize the associated costs.

The export of air pollutants is more relevant when the receiving airshed is densely populated, therefore, the health of many inhabitants could be affected. In the Mexico City Metropolitan Area (MCMA), the main sources of PM_{2.5} are open burning of waste (2,484 tons year⁻¹), automotive activity (6,224 tons year⁻¹), and industrial combustion (2,169 tons year⁻¹) [13]. PM_{2.5} is a fine inhalable fraction of suspended particles that can reach the alveolar zone of the lungs, and its toxic compounds can enter the bloodstream [14,15]. The PM_{2.5} are composed by several harmful substances, such as toxic

metals (cadmium, lead), metalloids (arsenic), and hydrocarbon aromatic polycyclic (anthracene, benzo[a]pyrene) [16–22]. Among the recognized health effects of the PM_{2.5} are lung cancer, chronic obstructive pulmonary disease, lower respiratory infections, asthma, cerebrovascular and cardiovascular diseases, ischemic heart disease [15,23–28].

Researchers and environmental managers use a few metrics to quantify the impact of atmospheric pollution on population health. One of the most useful for comparative purposes are estimates of potentially avoidable premature deaths (PAPDs), and costs based on the value per statistical life (VSL). In agreement with the National Institute Cancer, one premature death is “a death that occurs before the average age of death in a certain population” [29,30]. Analogously, the potentially avoidable premature deaths occur due to avoidable causes, like exposure to environmental pollution. In economic terms, the concept of value per statistical life (VSL) reflects the willingness of a given population to pay for reducing a risk [31,32]. The U.S. Environmental Protection Agency (U.S. EPA) has developed the Environmental Benefits Mapping and Analysis Program (BenMap) [33] for health impact assessment purposes. The BenMap program is indeed used to estimate the PAPDs and the yearly cost associated with air pollution scenarios. BenMap estimates premature mortality using exposure-response functions from the literature. Moreover, the program calculates the costs using the VSL. This program has been used in many studies and is widely accepted worldwide for strategic assessment of air quality policies [34–38].

Users BenMap could prepare scenarios for calculations by applying interpolations of averaged concentrations, or, for greater accuracy, by using dispersion modelling scenarios. The Hybrid Single Particle Lagrangian Integrated Trajectory (Hysplit) can model the dispersion scenarios [39,40]. Hysplit is a widely used model for simulating the transport of atmospheric pollutants [41–46]. The Hysplit application for estimation of pollutant interchange between atmospheric basins was demonstrated in a first study authored by this group [10]. The advantage of Hysplit use in these types of studies is its ability to generate output files in formats suitable for post-processing in geographic information systems and, with some geoprocessing algorithms, to automatically process multiple files to produce more detailed estimates of particulate mass exchange.

For the purpose of estimating the yearly impacts associated with atmospheric pollutant mass that receive one population from another densely urbanized airshed, this manuscript displays the results of PM_{2.5} mass interchange modelling, and potentially avoidable premature deaths and associated costs calculations, using the Hysplit model and the BenMap software, complemented with geoprocessing in ArcMap®, for two metropolitan areas neighboring highly urbanized metropolitan area, particularly neighboring Mexico City Metropolitan Area.

2. Materials and Methods

The Mexico City Metropolitan Area (MCMA) is the biggest urban zone in the Mexico megalopolis, located in the central region of Mexico. This metropolitan area is within an airshed. In the surrounding area, it borders other airsheds containing metropolitan areas, such as the Toluca Valley Metropolitan Area (TVMA) in the Estado de México to the east, and the Cuernavaca Metropolitan Area (CMA) in the Morelos state to the south. The MCMA is the most populated (21 million inhabitants), the most motorized (6.24 million vehicles), and one of the most polluted (14,939 tons year⁻¹ of PM_{2.5}) [13,47]. High levels of atmospheric pollutants are exported from the MCMA to surrounding areas and added to local emissions in other airsheds. For this study, the annual exchange of PM_{2.5} mass between the MCMA, the TVMA, and the CMA was quantified along with their impacts in terms of PAPD and associated costs.

This study considered point, mobile, and area sources; though natural sources were not so. The hourly emissions rate calculated by Hernández-Moreno et. al. (2023): 860.6 kg hr⁻¹ for the MCMA, 203.8 Kg hr⁻¹ for the TVMA, and 114.2 Kg hr⁻¹ for the CMA. The 2008 PM_{2.5} emissions inventory was integrated in cells (5x5 km) of a mesh (Figure 1). The reader can consult the PM_{2.5} emissions values for each cell in the data repository linked to Dataset #1 (see Data Availability Statement section).

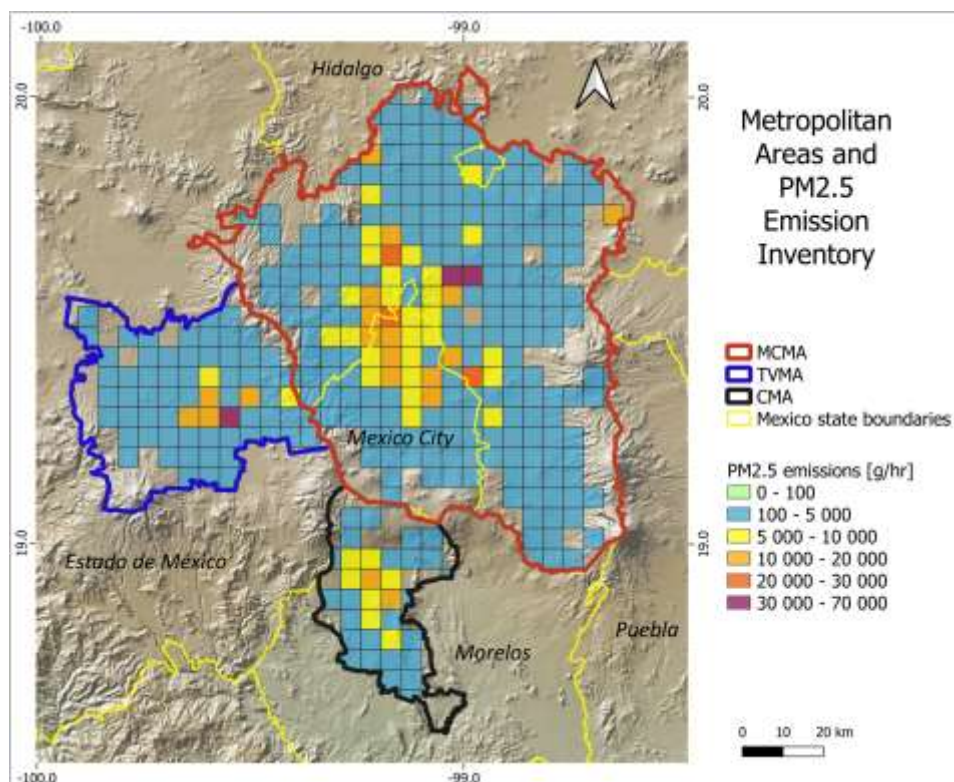


Figure 1. Metropolitan areas and the mesh of PM_{2.5} emissions inventory associated with square cells.

The Hysplit 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 hours 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 [48]. The output files were post-processed in ArcMap® geographic information system, using our own tools to automatically process large number of output files from Hysplit. The particle mass was calculated applying Eq. 1.

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

Where, by every i -polygon, M is the mass of PM_{2.5} in grams [g] dispersed inside one metropolitan area. C_i is the PM_{2.5} concentration in grams per cubic meter [g m⁻³]. A_i is the area of the polygon with the C_i concentration, and H is the modeling height in meters [m].

The potentially avoidable premature deaths and their associated costs were calculated using the BenMap program. The scenarios compared were: Alternative (scenery without imports of PM_{2.5} from MCMA), and Baseline (scenery with PM_{2.5} imports). This study applied the Krewski health impact function to calculate the premature deaths, assuming that the concentration-response function is log-linear for health impact assessment. This function relates the annual average PM_{2.5} concentration and the risk estimator (called the beta coefficient, β) according to the following the equation (1) [49]. The associated costs were calculated using the most recent local VSL published by Becerra-Pérez et al. (2024): \$0.9 million for the Estado de México, and \$0.7 million for Morelos.

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

Where ΔY is the change in mortality, Y_0 is the baseline mortality rate (incidence), and β is the unit risk coefficient. Figure 2 is a flow diagram that summarizes the processes of modelling and calculus.

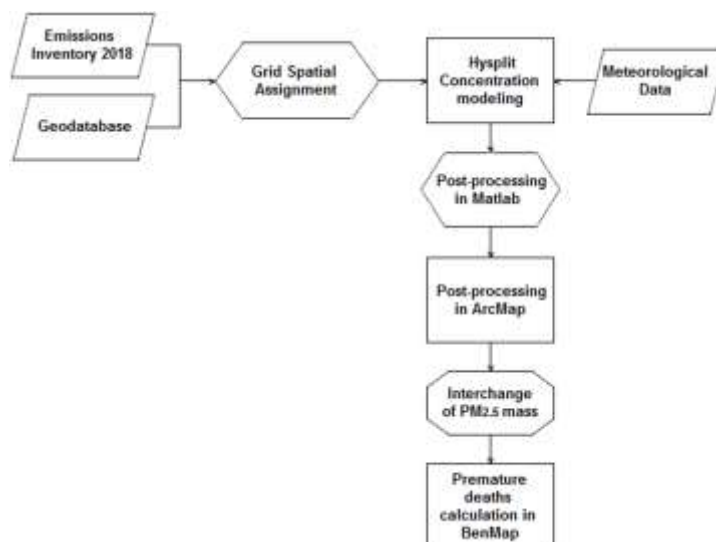


Figure 2. Flow diagram for impacts modeling process.

3. Results

The modelling 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 equivalent to 565 kg. Figure 3 shows that the particle mass frequently reaches approximately 4,000 kg in the TVMA and 2,000 kg in the CMA. This fact could be related to the airshed area size. The winds blow the neighboring airshed, and their pollutants could be either deposited within the basin or could be blown out. In this atmospheric dynamic, the area of the airshed limits amount of PM_{2.5} mass present. Moreover, was observed that high quantities occasionally impact the receiving airshed, as the peaks of 10,564 kg and 8,918 kg in the TVMA in May. These exportation peaks could lead to peaks of PM_{2.5} concentrations in the receiver airshed [10].

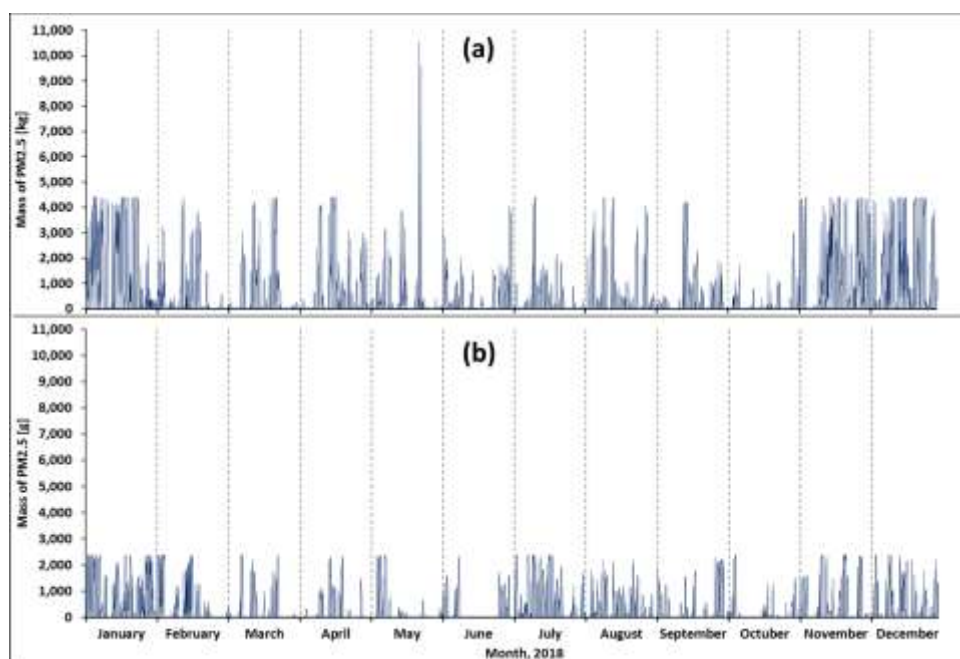


Figure 3. Hourly PM_{2.5} mass exports. (a) Particles PM_{2.5} exported from MCMA to TVMA. Particles PM_{2.5} exported from MCMA to CMA.

January, November, and December were the months when the greatest exportation of particles from MCMA to neighboring airsheds (Figure 4). The characteristic north winds' in the winter season cause this trend. In the CMA case, the hourly average presence of $PM_{2.5}$ emitted originally in the MCMA was 284 k. However, an enormous mass of $PM_{2.5}$ was observed in the summer too. The main difference between impacts between impacts in the TVMA and CMA are related to flow restrictions imposed by the mountain chain between the MCMA and the CMA. These restrictions are more penetrable during the intense summer winds and high temperatures. Strong winds broke the anticyclonic recirculation and crossed the mountain passes.

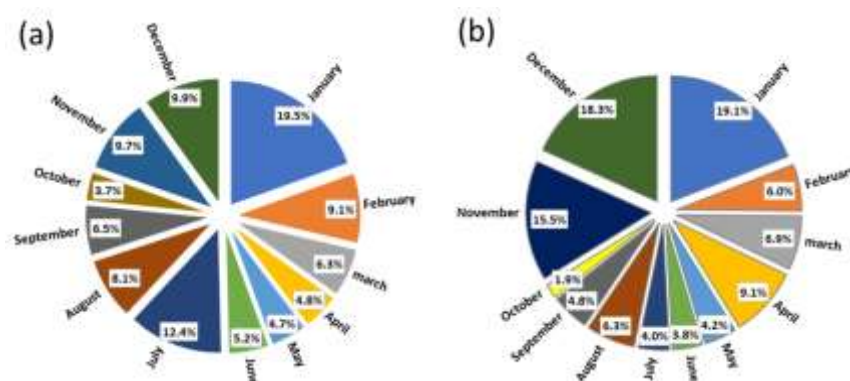


Figure 4. Monthly distribution of imported $PM_{2.5}$ mass. (a) Toluca Valley metropolitan area. (b) Cuernavaca metropolitan area.

$PM_{2.5}$ particulate imports were integrated in grids for modeling in BenMap. Data is available in the repository linked to Dataset #2 (see Data Availability Statement section). Figure 5 displays the results of mortality calculations for PAPD attributable to the increase in $PM_{2.5}$ mass from the MCMA. The most populated and polluted municipalities are those with the highest incidence of PAPD. The impact of arriving foreign $PM_{2.5}$ is greatest in regions with high local emission rates of because the health risks do not have a linear behavior (Krewski et al., 2009). The exponential function implies that small increases can have significant impacts. In total, the TVMA and the CMA were estimated at 13,553 PAPD and 5,915 PAPD, respectively. Data is available in the repository linked to Dataset #3 (see Data Availability Statement section).

The three more impacted municipalities of the TVMA are: Toluca de Lerdo (the capital of the Estado de México) with an incidence of 1,354 PAPD (total population of 223,876 inhabitants), San Mateo Atenco with an incidence of 540 PAPD (total population of 88,734 inhabitants), and San Salvador Tizatlalli with an incidence of 425 PAPD (total population of 70,013 inhabitants). It is worth highlighting the level of incidence in Toluca de Lerdo, despite the long distance from the border with MCMA and the considerable distance between these two metropolitan areas.

In the CMA, the municipalities with the highest incidence are Cuernavaca, Calera Chica, and San Agustín Tetlama (2,062, 1,048, and 587 PAPD, respectively). In contrast to the TVMA, the CMA is a predominantly rural region. The total PAPD in the Cuernavaca municipality is higher than in Toluca de Lerdo due to a larger Baseline-Alternative difference.

The results of the impact valuation are directly proportional to incidence. Figure 6 shows the georeferenced costs by municipality. The detailed data are available in the Annex 3. The health impacts calculus valued at \$12,197.75 million for the TVMA and \$4,140.71 million for the CMA. It is important to remember that there the VSL applied to each metropolitan area is different.

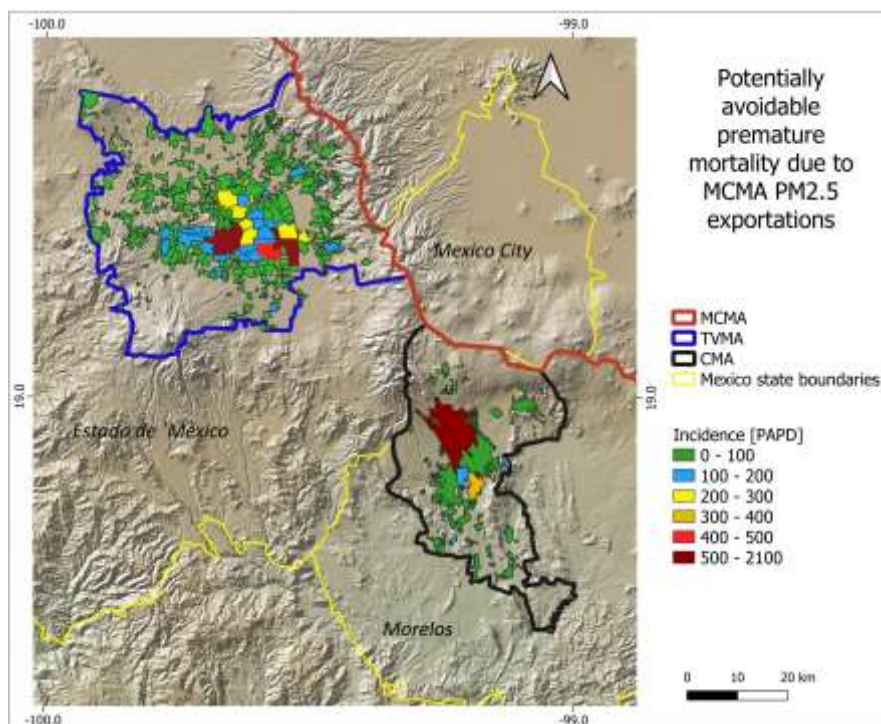


Figure 5. Estimate of the incidence of PAPD in the TVMA and in the CMA due to MCMA PM_{2.5} exports.

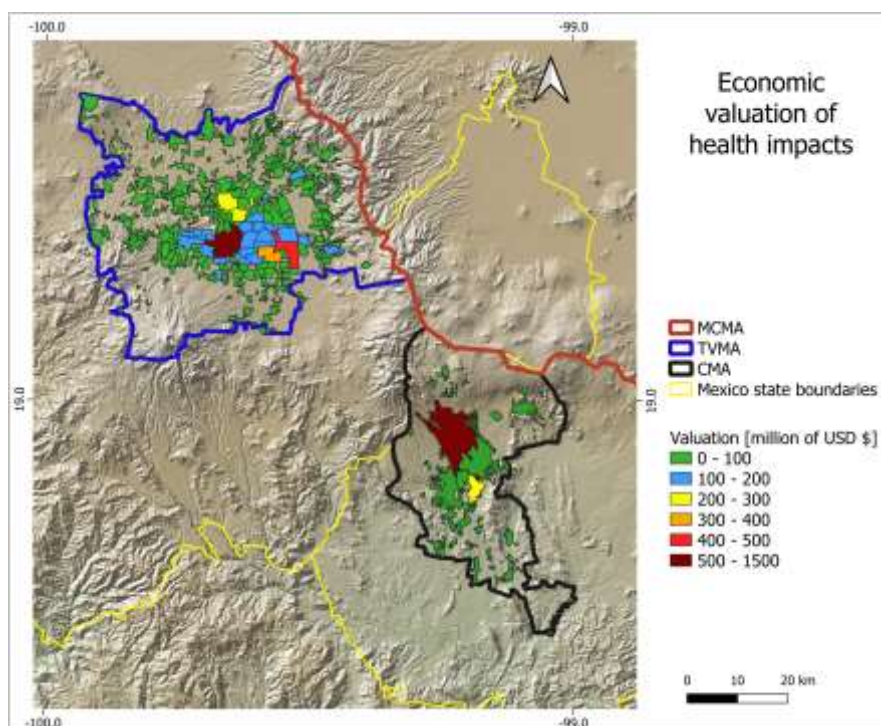


Figure 6. Economic valuation of health impacts applying the current specific VSL.

4. Discussion

The exchange of atmospheric pollutants has been a subject of growing concern for two decades, and this study demonstrates the relevance of these impacts on mortality and costs. The results of this study indicate that the export of atmospheric pollutants is responsible for thousands of premature deaths and millions of dollars in costs. But the costs are being internalized by the affected populations and states. Each receiver airshed suffers particular impacts, and its orographic characteristics are factors to consider. The TVMA is at 2600 m AMSL (400 meters above the MCMA). This geographic

aspect, combined with the dry-cold season, thermal inversions, and increased importation of PM_{2.5} from the MCMA, could have severe impacts on the health of the population of Toluca. In striking contrast, the CMA is at 1500 m AMSL (700 m below the MCMA). The CMA receives high quantities of PM_{2.5} mass in the summer and winter seasons. The foreign pollutants are rapidly dispersed southward. However, because the emissions rates are lower, the differences are more significant. Consequently, the impacts are more important.

5. Conclusions

The interchange of atmospheric compounds between airsheds is natural and inevitable. However, the relevance of impacts reveals critically that air policy management should take into account impacts beyond administrative limits. When a government office makes wrong decisions, neighboring populations are negatively affected. It is therefore necessary the conduction of more comprehensive assessments to support decision-making, even for policies applied within a single municipality. Even the policies applied inside just one municipality.

Neighbor populations usually benefit from the economic activity in big cities. However, neighboring health institutions and the population internalize the costs of the pollutants arriving from highly urbanized cities.

The differences in air quality caused by unfavorable policies in neighboring metropolitan areas have a significant impact on surrounding areas. Especially when the receiver area is an airshed, and its pollutant emissions rate is high. How do the neighboring populations internalize the costs of health impacts caused by the pollution coming from one metropolis? What management mechanisms could be implemented to ensure that air quality management policies do not have adverse impacts on the neighboring populations? These are two questions that can be raised from this study for future research.

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Data Availability Statement: The original data presented in the study are openly available in. Dataset #1: https://data.4tu.nl/private_datasets/bbqqKnTkLLq7I4E5YHt4YxJDeHg2Vv2Qwx6wT2SD57U Dataset #2: https://data.4tu.nl/private_datasets/3NTtvoIKJXn__qnetLFgh1vYyh97BlfSkv-rfjYdi20 Dataset #3: https://data.4tu.nl/private_datasets/idH7p_sc1FJ-uEE0abGR5nZPEpjsqeS_2Zuc5wIIMK

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Use of Artificial Intelligence: “AI or AI-assisted tools were not used in drafting any aspect of this manuscript”.

Abbreviations

The following abbreviations are used in this manuscript:

AMSL	Above meters sea level
BenMap	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 micrometers and smaller
TVMA	Toluca Valley Metropolitan Area

VSL Value of a Statistical Life

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