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ORIGINAL ARTICLE

Quantifying health impacts and economic costs of $PM_{2.5}$ exposure in Mexican cities of the National Urban System

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Abstract

Objectives To estimate avoidable mortality, potential years of life lost and economic costs associated with particulate matter $PM_{2.5}$ exposure for 2 years (2013 and 2015) in Mexico using two scenarios of reduced concentrations (i.e., mean annual $PM_{2.5}$ concentration < 12 μg/m^3 and mean annual $PM_{2.5}$ concentration < 10 μg/m^3).

Methods The health impact assessment method was followed. This method consists of: identification of health effects, selection of concentration–response functions, estimation of exposure, quantification of impacts quantification and economic assessment using the willingness to pay and human capital approaches.

Results For 2013, we included data from 62 monitoring sites in ten cities, (113 municipalities) where 36,486,201 live. In 2015, we included 71 monitoring sites from fifteen cities (121 municipalities) and 40,479,629 inhabitants. It was observed that reduction in the annual $PM_{2.5}$ average to 10 μg/would have prevented 14,666 deaths and 150,771 potential years of life lost in 2015, with estimated costs of 64,164 and 5434 million dollars, respectively.

Conclusions Reducing $PM_{2.5}$ concentration in the Mexican cities studied would reduce mortality by all causes by 8.1%, representing important public health benefits.

Keywords Mexico · Health impact assessment · Years of life lost · Value of a statistical life · Air pollution

Abbreviations

APD	Annual premature deaths
BGA	Basic geostatistical area
CRF	Concentration–response functions
GDP	Gross domestic product
GIS	Geographic information system
HC	Human capital
HIA	Health impact assessment
IARC	International Agency for Research on Cancer
IDW	Inverse distance weighted
INEGI	National Institute of Statistics and Geography
μg/m^3	Microgram per cubic meter
NOM	Mexican Official Standard
O_3	Ozone
PM	Particulate matter
PM_{10}	Particulate matter with an aerodynamic diameter smaller than 10 μm

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$PM_{2.5}$	Particulate matter with an aerodynamic diameter smaller than 2.5 µm
PPP	Purchasing power parity
RR	Relative risk
VSL	Value of a statistical life
WHO	World Health Organization
WTP	Willingness to pay
YLL	Years of life lost
ZMGDL	Metropolitan Area of Guadalajara
ZMM	Metropolitan Area of Monterrey
ZMVM	Metropolitan Area of México Valley
ZMVT	Metropolitan Area of Toluca

Introduction

Recent assessments suggest that atmospheric pollution is the main ambient risk for global health (Global Burden of Diseases 2015). Epidemiological evidence has demonstrated an association between exposure to air pollutants and respiratory symptoms, asthma exacerbations, decline in lung function decline (Brunekreef and Holgate 2002) and an increase in total, cardiovascular and respiratory mortality risk. Particulate matter has been related to premature death; specifically, particles below 2.5 microns ($PM_{2.5}$) were related to 4.3 million premature deaths in 2015. This figure represented 7.6% of total deaths placing ambient $PM_{2.5}$ as the fifth mortality risk factor. In 2015, only one of the 12 Mexican cities with $PM_{2.5}$ monitoring stations met the national standard (12 µg/m^3), (Instituto Nacional de Ecología y Cambio Climático 2014).

Health impact assessment (HIA) is a method recommended by WHO to understand the health benefits of public and private non-sanitary interventions addressed to reduce air pollution (Boldo et al. 2011; Organización Mundial de la Salud 2017; Scott-Samuel 1996; World Health Organization 2015). A study at national level in cities with available data for year 2010 found that approximately 20,500 deaths are caused by high concentrations of particulate matter (Global Burden of Diseases 2015).

Previous studies carried out in Mexico have focused mainly in Mexico City and its metropolitan area, exposure to PM_{10} and do not include a quantitative measure of potential years of life lost and associated costs (Bell et al. 2006; McKinley et al. 2005; Riojas-Rodríguez et al. 2014; Mckinley et al. 2003). The objective of this work is to present an updated calculation of the effects of $PM_{2.5}$ exposure, with data from the years 2013 and 2015, on avoidable mortality, potential years of life lost and its associated costs. It also includes more Mexican cities and metropolitan areas zones.

Fig. 1 Geographic location of Mexico's monitoring stations which recorded $PM_{2.5}$ during 2013 and 2015

Methods

Study design

We performed a health impact assessment study based on information from 2013 to 2015 in Mexican cities, large urban areas usually extend over several municipalities with local atmospheric monitoring networks. In addition to the cities and municipalities, metropolitan areas (ZM for its abbreviation in Spanish of Zona Metropolitana) are also included, which include not only the largest cities but their surrounding municipalities.

The cities and ZM included in the analysis are Metropolitan Area of México Valley (ZMVM), Metropolitan Area of Toluca (ZMVT), Metropolitan Area of Guadalajara (ZMGDL), Guanajuato, Metropolitan Area of Monterrey (ZMM), Queretaro, Metropolitan Area of Puebla-Tlaxcala (ZM Pue-Tlax), Tepic and Mérida. However, the monitoring sites with valid data for 2013 and 2015 are different. Figure 1 shows the geographic location of Mexico's monitoring stations which recorded $PM_{2.5}$ during 2013 and 2015.

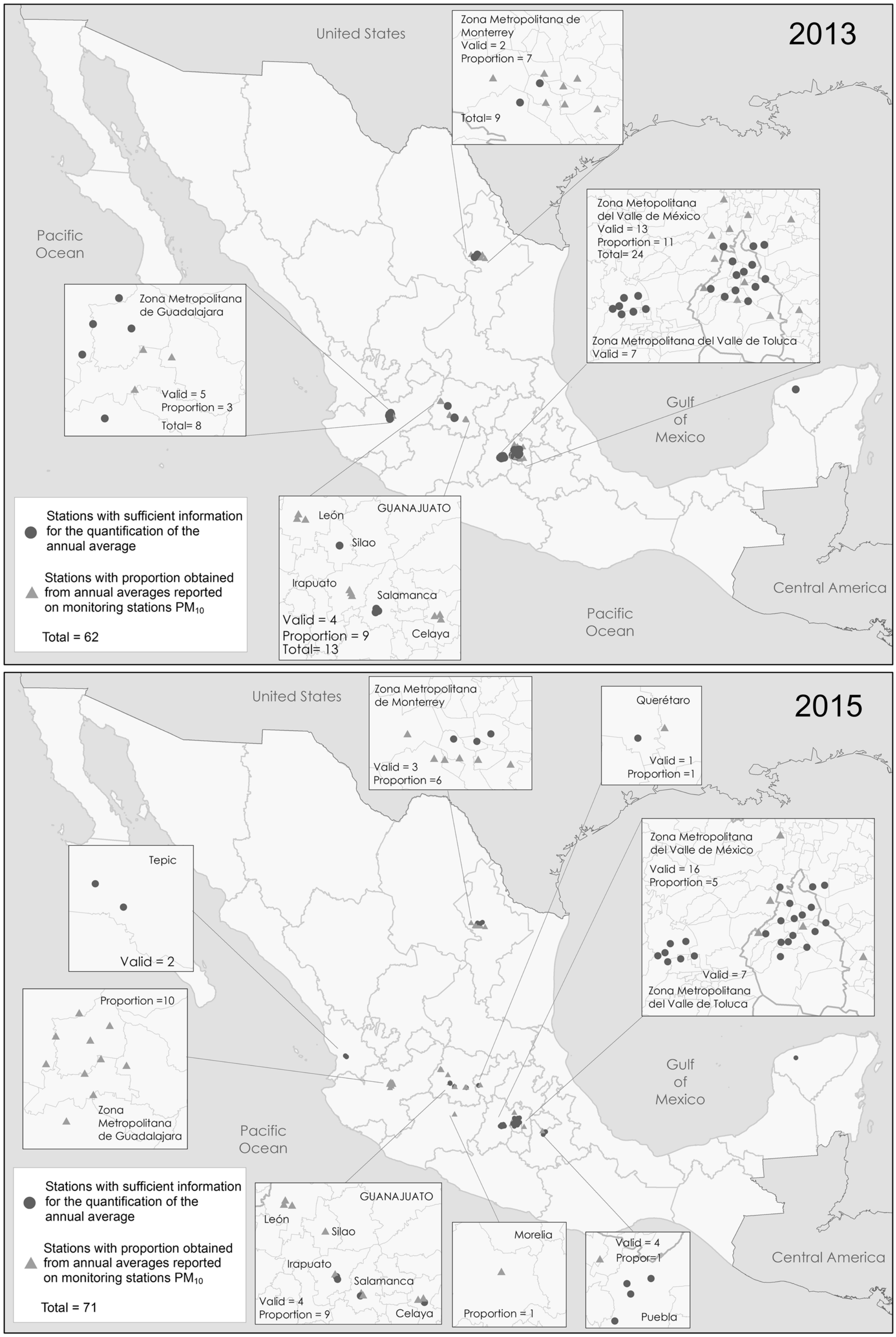
Area and population of study

Delimitation of the area and population of study used the criterion of sufficient annual information on $PM_{2.5}$ measurements through the following procedure:

(a) Air pollution data

Data by hour from the automatic monitoring stations were obtained from the National System of Air Quality Information (SINAICA), accessed through the National Institute of Ecology and Climate Change (INECC) web site (https://sinaica.inecc.gob.mx/). We considered daily and annual averages valid, if at least 75% of the hourly and daily averages were available (Secretaría de Salud 2014). However, in Mexico the number of stations that measure $PM_{2.5}$ is limited and many sites do not fulfill the sufficiency criterion to estimate the annual mean (Instituto Nacional de Ecología-Secretaria de Medio Ambiente y Recursos Naturales 2011). To increase the number of sites for the analysis, we decided to: (a) estimate the concentrations of $PM_{2.5}$, based on hourly $PM_{2.5}/PM_{10}$ ratios (WHO 2006) in those stations that measured both fractions and considering the 75% sufficiency criterion to estimate the annual mean and (b) consider daily and annual mean values valid, if at least 60% of the hourly and daily averages were available.

$PM_{2.5}$ monitoring stations in Mexico, 2013 and 2015



This criterion was not considered if the missing data were concentrated in a trimester.

When we compare the data with the two sufficiency criteria, we observed a difference no greater than 2 μg/m³. In addition, these differences were not statistically significant.

(b) Delimitation of the area and population of study

Population data at levels of state, metropolitan area, municipality and basic geostatistical area (BGA) and by age groups were used. Information for year 2013 was provided by the Consejo Nacional de Población (National Council on Population, CONAPO), and data for 2015 were obtained from the Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography, INEGI 2015; Instituto Nacional de Ecología-Secretaria de Medio Ambiente y Recursos Naturales 2017; Consejo Nacional de Población 2016). Data were paired in a geographic information system (GIS) together with the location and annual means of the monitoring stations.

The area of intersection between the overlap of the layers of the urban/rural BGAs centroids with the layer of buffers of 10 km from the monitoring stations was assessed. Municipalities where the intersection of the urban BGAs was—in proportion—larger than the rural BGAs were selected. Finally, the population by BGA was aggregated by municipality and by city, according to the National Urban System.

The area of study included 15 cities, 121 municipalities and nearly 40 million inhabitants.

(c) Exposure estimates

To estimate the concentration at a BGAs scale, 5- and 10-km buffers were generated around the monitoring stations and the geo-localization of each BGA centroid was spatially analyzed to classify them in an ordinal way in four categories: (a) BGAs in 5-km buffers intersection areas; (b) BGAs in 10-km buffers intersection areas; (c) BGAs within the 5-km buffer and out of the area of intersection of 5-km buffers; and (d) BGAs out of the 5-km buffers and the intersection areas. The concentration of each BGA group was calculated separately, following the classification order described above.

BGAs located in the 5- and 10-km areas of intersection were estimated using the inverse distance weighted (IDW) method, which was defined under the following formula:

$$\hat{z}(X_0) = \frac{\sum_{i=1}^{n} z(X_i) \cdot d_{i0}^{-r}}{\sum_{i=1}^{n} d_{i0}^{-r}}$$

where the prediction in the position $\boldsymbol{X_0}$ is the function of the $\boldsymbol{n}$ neighboring observations, $z(\boldsymbol{X_i})$, $i = 1, 2,\ldots, n$, $\boldsymbol{r}$ is the exponent that determines the weight assigned to each of the observations, and $\boldsymbol{d}$ is the distance by which the place of prediction $\boldsymbol{X_0}$ and the place of observation $\boldsymbol{X_i}$ are separated (Lloyd 2011).

BGAs localized within a 5-km buffer of a monitoring station and out of the intersection areas were assigned the value of the monitoring station. The last group of BGAs was assigned the value of the nearest monitoring station. Finally, the mean by municipality was calculated based on BGAs values.

(d) Estimation of avoidable deaths

Selection of concentration–response functions (CRFs)

We include CRF for events associated to long-term exposures. We used the pool estimate method proposed by Hoek et al. (2013) which combines 11 cohorts rather than a single estimate. This meta-analysis has geographic representation and provides good estimate of the uncertainty. This helped us to consider the variability that exists between different populations in terms of the susceptibility of the individuals and other characteristics of the population, the $PM_{2.5}$ composition, the minimum and maximum concentrations of the pollutant, the frequency of the exposure, etc. (Lepeule et al. 2012; Hoek et al. 2013; Pope et al. 2002, 2004) (Table 1).

To find baseline mortality by cause of interest in the area and the population of the study, INEGI national mortality databases were obtained (Fann et al. 2011) for the years of interest and were aggregated by cause and age group according to the CRFs selected by municipality in Table 1.

Hypothetical scenarios of exposure change

To calculate avoidable deaths, two reference scenarios (or hypothetical scenarios) of change in exposure of the population of the study were selected. The first scenario used the Mexican official standard NOM-025-SSA1-2014 as reference, 12 μg/m³, and the second reference was the air quality guidelines set by the World Health Organization (WHO), 10 μg/m³, both expressed as annual mean.

Calculation of avoidable deaths

Based on the following equation, the number of deaths that could have been avoided in 2013 and 2015 in each municipality of the study was calculated.

$$\text{Avoidable deaths} = \text{Number of cases} - \frac{\text{Number of cases}}{e([\text{CRF corrected}] * \Delta\text{conc})}$$

where Δconc is a change in the exposure to $PM_{2.5}$ concentration under each of the proposed scenarios; *corrected*

Table 1 Concentration–response functions (CRFs)[a] of $PM_{2.5}$ associated with health outcomes

Cause of mortality (ICD-10)[b]	Age group (years)	CRF (CI 95%)	References
All, non-external (A00–R99)	≥ 15	1.06 (1.04–1.08)	Hoek et al. (2013)
Cardiovascular (I00–I99)	≥ 15	1.15 (1.04–1.27)	Hoek et al. (2013)
Ischemic heart disease (IHD) (I20–I25)	≥ 30	1.18 (1.14–1.23)	Pope et al. (2004)
Lung cancer (C33–C34)	25–74	1.37 (1.07–1.75)	Lepeule et al. (2012)
Cardiopulmonary (I10–I70; J00–J98)	≥ 30	1.09 (1.03–1.16)	Pope et al. (2002)

[a]Mortality associated with 10 μg/m³ increase of $PM_{2.5}$

[b]International Classification of Diseases

CRF is *the CRF* expressed as relative risk, corrected for unit of change in $PM_{2.5}$ concentration; and *Number of cases* is total deaths occurring in the year and cause of interest (Riojas-Rodríguez et al. 2014).

Economic assessments of avoidable deaths

We used the willingness to pay (WTP) and the human capital (HC) approaches to assess avoidable deaths in economic terms. We followed the methodology proposed by the Organization for Economic Cooperation and Development (OECD) to estimate the economic value of a statistical life (VSL) (OECD 2016) applying this equation:

$$\mathrm{VSL}^{t}_{\mathrm{Mexico}} = \mathrm{VSL}^{t}_{\mathrm{OECD}} * \frac{Y^{t}_{\mathrm{Mexico}}}{Y^{t}_{\mathrm{OECD}}}^{\beta}$$

where t is the year, $\mathrm{VSL}_{\mathrm{OECD}}$ is 3 million USD in 2005, Y is the gross domestic product (GDP) per capita, and β is income elasticity of 0.9. GDP per capita was adjusted for purchasing power parity (PPP) (World Bank 2017).

The HC approach entails estimating the flow of annual productivities lost because of premature death. Annual productivity was based on the National Survey on Occupation and Employment (ENOE) (Instituto Nacional de Estadística y Geografía 2017). Lost productivity was estimated for each age of death following this equation.

$$\mathrm{Yd} = \sum_{t=i}^{\mathrm{LE}} \frac{Y_{\mathrm{age}}}{(1-r)^{t-i}}$$

where LE = life expectancy = 75 years, Y_{age} = annual productivity in each age, t = Age at death, i = initial age in the age group, r = 0.03. We calculated lost productivity for age groups 15 and more, 30 and more, and 25 to 74 years.

Exchange rate used was 12.76 MXN and 15.87 MXN per USD for 2013 and 2015, respectively.

(e) Estimation of potential years of life lost (YLLs)

To obtain potential YLLs for a health cause or event at specific ages, the following formula was used:

$$\mathrm{AVPP} = N * L$$

where N is the number of deaths and L standard life expectancy at the age of death in years (Scott-Samuel 1996).

The following variables were incorporated by age group: (a) general mortality, (b) mortality by specific causes, (c) mean age of death and (d) mean life expectancy (75 years for Mexico in 2013 and 2015) (Instituto Nacional de Estadística y Geografía 2014). In addition, we calculated the attributable risk fraction associated with $PM_{2.5}$ through the following formula:

$$\text{Attributable Fraction} = (\mathrm{RR} - 1/\mathrm{RR}) * \Delta\mathrm{Conc}$$

where RR is the relative risk for each cause, based on the corresponding CRF. (34) Δconc is the change in $PM_{2.5}$ concentration with respect to WHO scenario.

Potential YLLs were calculated for the total cases, and the result was multiplied by the attributable fraction; hence, the calculated value of potential YLLs was attributable only to $PM_{2.5}$ exposure.

(f) Potential YLLs economic assessment

For the HC approach (Zweifel et al. 2009), we used data for 2013 and 2015 from the ENOE. The expected income from employment was modeled adjusting by age, age-squared, sex, region, quarter of the year and educational level. Expected hourly income by age was multiplied by 8 h and then multiplied by 240 working days (Goetzel et al. 2004) to obtain the annual mean productivity. Under the WTP perspective, we assumed that the value of potential YLL is equal to one GDP (World Bank 2013).

Results

Results of the scenarios for the municipalities and estimation population

Table 2 shows the total of the population and municipalities covered by the monitoring networks for each of the 2 years selected, according to the 75% and 60% of data completeness criteria described in the methods section. The

Table 2 Population covered by the monitoring networks according to the percentage of $PM_{2.5}$ acceptable data

Sufficiency of data	City/metropolitan area	2013				2015			
		Municipalities	Population	No. sites	Mean $PM_{2.5}$ exposure (μg/m^3)	Municipalities	Population	No. sites	Mean $PM_{2.5}$ exposure (μg/m^3)
75%	ZMVMéxico	34	17,353,323	13	25.6	32	17,325,192	13	23.8
	ZMVToluca	16	2,028,161	6	34.2	16	2,213,407	7	32.3
	ZMGuadalajara	6	3,908,389	3	29.7				
	Guanajuato	4	987,012	1	23.4	8	1,714,514	3	19
	ZMMonterrey					7	3,158,874	1	26.1
	Querétaro					4	1,174,224	1	18.1
	ZMPue-Tlax					11	2,238,131	3	20
	Tepic					2	466,499	2	9.5
	Mérida	2	969,107	1	10.9	4	1,026,608	1	15.4
	Total	62	25,245,992	24		84	29,317,449	31	
60%	ZMVMéxico	34	17,353,323	13	25.6	33	17,868,507	16	23.7
	ZMVToluca	16	2,028,161	7	33.8	16	2,213,407	7	32.3
	ZMGuadalajara	8	4,463,241	5	28.5				
	Guanajuato	8	2,824,880	4	25.2	8	1,714,514	4	19.6
	ZMMonterrey	7	2,488,134	2	24.5	10	3,944,834	3	28.3
	Querétaro					4	1,174,224	1	18.1
	ZMPue-Tlax					13	2,254,837	4	20.4
	Tepic					2	466,499	2	9.5
	Mérida	2	969,107	1	11.1	4	1,026,608	1	14.4
	Total	75	30,126,846	32		90	30,663,430	38	
60% + proportion PM_{10}	ZMV de México	61	20,474,830	24	24.8	50	19,697,319	21	23.7
	ZMV de Toluca	16	2,213,407	7	33.8	15	2,112,053	7	32.4
	ZM Guadalajara	8	4,700,209	8	34.3	6	4,725,603	10	36.4
	Guanajuato	13	3,718,441	13	27.5	11	3,512,319	13	21.1
	ZM Monterrey	15	4,410,207	9	21.9	11	4,428,212	9	25.2
	Querétaro					3	1,216,890	2	23
	ZM Pue-Tlax					18	2,382,090	5	19.9
	Tepic					2	471,026	2	9.5
	Morelia					2	890,176	1	17.55
	Mérida	2	969,107	1	11.1	3	1,043,941	1	14.4
	Total	115	36,486,201	62		121	40,479,629	71	

$PM_{2.5}/PM_{10}$ ratios to estimate $PM_{2.5}$ ranged from 0.25 to 0.8 (Table 2).

Estimations for year 2013 included data from 62 stations in ten cities: with a total of 113 municipalities and 36,486,201 inhabitants. The resulting average $PM_{2.5}$ estimates at municipal level for year 2013 were within the ranges of 11.1 and 49 μg/m^3.

The number of available stations increased in 2015, and exposure was estimated in fifteen cities: Monterrey, Guadalajara, Toluca, Mexico City, Leon, Silao, Irapuato, Salamanca, Celaya, Queretaro, Puebla, Tlaxcala, Tepic, Morelia and Merida, including 121 municipalities and 40,479,629 inhabitants. Data from year 2015 showed average municipal estimates between 9.4 and 67.6 μg/m^3, with the highest concentrations in Guadalajara and Toluca which exceeded 30 μg/m^3. In general, $PM_{2.5}$ concentrations did no vary significantly between 2013 and 2015 with the exception of Monterrey, with an increase of 5 μg/m^3 and Guanajuato with a decrease of 6 μg/m^3.

Impact evaluation on general mortality by specific causes

Avoidable deaths (ADs) estimates are shown in Fig. 2 and Table 3, displaying total avoidable deaths for each cause and both scenarios of $PM_{2.5}$ concentrations reduction. In 2013, the calculation indicates that a decrease in $PM_{2.5}$ concentrations to 12 µg/m^3 would avoid around 12,229 deaths, while reducing levels to 10 µg/m^3 would prevent a total of 13,893 deaths.

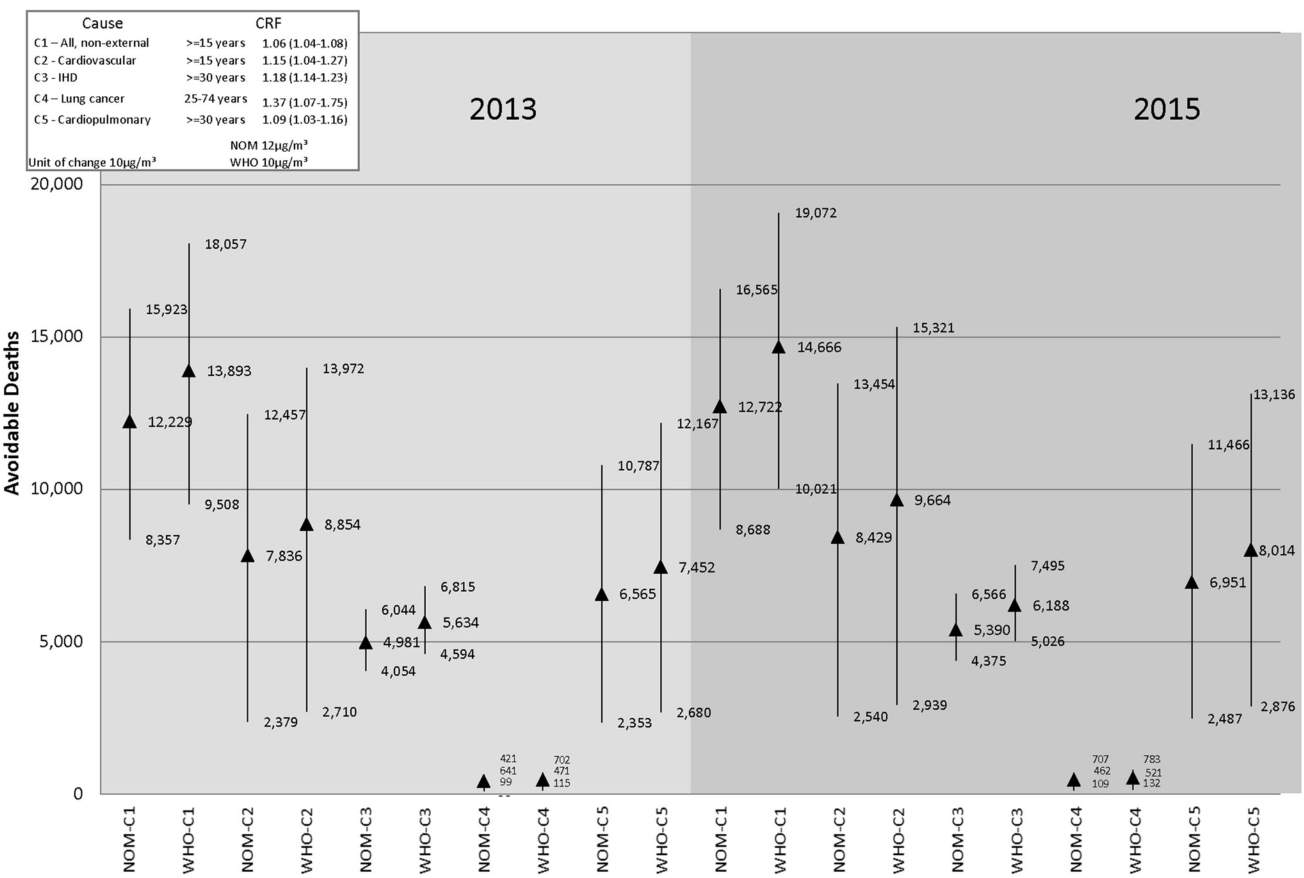
For cardiovascular events, there would be 7836 and 8854 ADs in 2013. Deaths by ischemic heart disease would be reduced in 4981 and 5634 and deaths by lung cancer could be reduced in 421 and 471 deaths, respectively. Also in 2013, the deaths by cardiopulmonary causes could be reduced by 6565 and 7452 deaths in 2013.

In contrast, for the year 2015, 12,722 and 14,666 ADs for general mortality would be avoided if $PM_{2.5}$ concentrations decrease to 12 µg/m^3 and 10 µg/m^3, respectively. For cardiovascular events, 8429 and 9664 ADs would be avoided. Deaths by ischemic heart disease would be reduced in 5390 and 9664 deaths during 2015, and deaths by lung cancer could be reduced in deaths 462 and 521, respectively. Finally, deaths by cardiopulmonary causes could be reduced by 6951 and 8014 deaths in 2015.

Calculation of total potential YLLs by specific causes

The calculation of potential YLLs used the mean CRF for each cause and the WHO scenario of 10 µg/m^3. Figure 2 shows total potential YLLs attributed for each cause and year.

By general causes, 144,289 and 150,771 potential YLLs in years 2013 and 2015, respectively, were attributed to $PM_{2.5}$, while 65,676 and 71,363 potential YLLs were attributed to cardiovascular causes, respectively. Potential YLLs estimates for ischemic heart disease were 36,248 and 39,807; 7403 and 7912 potential YLLs were attributed to



YLLs 2013					YLLs 2015				
WHO-C1	WHO-C2	WHO-C3	WHO-C4	WHO-C5	WHO-C1	WHO-C2	WHO-C3	WHO-C4	WHO-C5
144,289	65,676	36,248	7,403	46,170	150,771	71,363	39,807	7,912	49,993

Fig. 2 Calculated avoidable deaths and potential years of life lost attributed to exposure to $PM_{2.5}$ in Mexico in 2013 and 2015 shown as concentration–response functions

Table 3 Economic costs of avoidable deaths and potential years of life lost attributable to $PM_{2.5}$ in Mexico during 2013 and 2015

Cause/age	Mean CRF	Number of cases	Avoidable deaths		Avoidable deaths VSL (millions USD)		Avoidable deaths Lost productivity due to premature death (millions USD)		YLLs	YLLs WTP (millions USD)	Lost productivity (millions USD)
			NOM 12 μg/m^3	WHO 10 μg/m^3	NOM 12 μg/m^3	WHO 10 μg/m^3	NOM 12 μg/m^3	WHO 10 μg/m^3			
2013											
All, non-external ≥15 years	1.06	157,798	12,229	13,893	19,916	22,626	1,101	1251	144,289	2385	661
Cardiovascular ≥15 years	1.15	45,572	7836	8854	12,761	14,419	706	797	65,676	1085	301
IHD ≥30 years	1.18	25,317	4981	5634	8112	9175	404	457	36,248	599	184
Lung cancer 25–74 years	1.37	1241	421	471	686	767	37	41	7403	122	37
Cardiopulmonary ≥30 years	1.09	59,126	6565	7452	10,692	12,136	533	605	46,170	763	235
2015											
All, non-external ≥15 years	1.06	182,020	12,722	14,666	20,902	24,096	942	1086	150,771	2561	576
Cardiovascular ≥15 years	1.15	53,941	8429	9664	13,849	15,878	624	715	71,363	1212	272
IHD ≥30 years	1.18	29,891	5390	6188	8856	10,167	359	412	39,807	676	166
Lung cancer 25–74 years	1.37	1471	462	521	759	856	33	37	7912	134	33
Cardiopulmonary ≥30 years	1.09	69,157	6951	8014	11,420	13,167	463	534	49,993	849	209

CRF concentration–response functions, *VSL* value of a statistical life, *YLL* years of life lost, *WTP* willingness to pay

lung cancer; and 46,170 and 49,993 PYLLs correspond to cardiopulmonary causes.

Economic costs of mortality and potential YLLs

VSL was estimated in $1.629 million dollars (MD) in 2013 and 1.643 MD in 2015, adjusted by PPP. Lost productivity due to premature death for the age group of 15 years and more was estimated in 0.09 MD in 2013 and 0.07 MD in 2015. For the groups of 30 years and more, estimates were 0.08 and 0.07; and for the group of 25 to 74 years, 0.09 and 0.07 MD, respectively.

The estimate of one YLL was 0.016 MD in 2013 and 0.017 MD in 2015, using one GDP per capita. For the age group of 15 years and more under the HC approach, estimates were of 0.0046 MD in 2013 and 0.0038 MD in 2015. For the group of 30 or more years, lost productivity was estimated in 0.0051 MD and 0.0042 MD for years 2013 and 2015, respectively. For the age group of 25 to 74 years, the estimate was of 0.0051 MD and 0.0042 MD, respectively.

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and 2015, respectively. For the age group of 25 to 74 years, the estimate was of 0.0051 MD and 0.0042 MD, respectively.

Discussion

Our estimates show that if the levels of $PM_{2.5}$ met the current limits established by the Mexican standard, general mortality of people 15 years of age and more within the area of study could be reduced by 8% (12,229 of 157,798) and 7% (12,722 of 182,020) for years 2013 and 2015, respectively. With WHO's more stringent standards, benefits would increase, decreasing mortality by 9% (13,893 out of 157,798) and 8.1% (14,666 out of 182,020).

The calculation of potential YLLs for general mortality represents a total of 144,289 and 150,771 for the years of the study.

Using the 10 $\mu g/m^3$ scenario, when we compared AD between 2013 and 2015 we found a difference of almost 800 total deaths compared with 2013. Although the total number of ADs is larger in 2015, the percentage of avoidable deaths is greater in 2013. These differences are due to population included in the analysis being larger in 2015. The difference in total avoidable deaths could be higher; however, the mean $PM_{2.5}$ concentration is less in 2015 in some the cities. This difference is distributed between the causes.

When we observed the estimations by specific cause of death, it is worth to mention that despite the fact that the CRF for lung cancer is higher compared to the other causes included in the study, the number of avoidable deaths is lower because there is a low number of deaths due to this cause.

As mentioned, in this study we used two counterfactual scenarios. Other studies have used more strictic counterfactual scenarios. Künzli et al. (2000) used alternative scenarios. One of the alternatives is 7.5 $\mu g/m^3$ mean annual exposure. If we applied this counterfactual scenario, the avoidable death would increase in 2095 and 2412 deaths for 2013 and 2015, respectively, compared with the 10 $\mu g/m^3$ scenario (Table S6). We think that this calculation would need to be taken into account for national policies, specially because the WHO guideline is under review (WHO 2017).

Estimations performed by the Global Burden of Disease Study attributed 30 365 deaths to $PM_{2.5}$ in the year 2013 and 30 830 in 2015 in Mexico (Global Burden of Diseases 2018). In our study, these figures are lower, ranged from 13,893 to 14,666 during 2013 and 2015, respectively. The difference is mainly explained by the exposure assessment methods used by the GBD study and because they included type 2 diabetes as a new outcome resulting from long-term exposure to ambient particulate matter pollution. The GBD Study coverage was broader because exposure calculations were carried out through satellite images and were estimated at national level, but in both cases, the most populated cities and those with greater concentrations were included.

Using data from year 2010, the INECC reported that Valle de Mexico, Monterrey and Guadalajara presented $PM_{2.5}$ concentrations above the limits established by the Mexican and international standards, calculating 1317 and 2170 ADs for these three cities. (Instituto Nacional de Ecología y Cambio Climático 2014). Our results exhibit higher numbers of ADs in these three cities caused by cardiovascular diseases and lung cancer: 6847 and 7756 in 2013 and 7254 and 8228 in 2015, respectively. These differences result from the less stringent limits of the norms used in the INECC study, the age groups evaluated and the CRFs used. Their comparison scenarios used an earlier national standard.

A later study estimated ADs for the central region of Mexico for year 2014 (Instituto Nacional de Ecología y Cambio Climático (INECC)-Instituto Nacional de Salud Pública (INSP) 2016), reported figures of 4038 and 4709 ADs, respectively, for Mexico City. The 3541 and 4087 ADs estimated in the study for 2013 are comparable to the results of our study (3421 and 3998 ADs in 2015). Data differences are associated with the number of stations included in the studies, variation in annual means, and the mortality data used for the different years. If overall ADs of the metropolitan zones of Toluca and Valle de Mexico are compared, the figures are: 7744 and 8826 in 2013; 7016 and 8128 ADs in 2014; and 7548 and 8671 in 2015. In this case, both studies used the CRF and similar populations, which strengthens the results.

The CRF is one of the key components of the HIA, but INECC paper used foreign CRFs from cohort or meta-analysis studies. Nonetheless, epidemiological and statistical methods have improved in the last years, allowing extrapolation of results and the use of indicators in other populations. Hence, using different CRFs in this study is valid. However, it is necessary to produce local information in our country for comparative use to strengthen the validity of HIA in this region.

A study in the USA with a population of almost 300 million inhabitants, estimated 130,000 avoidable deaths related with $PM_{2.5}$ and almost 1.1 millions of years of life lost in it is proportionally comparable with their results. Another HIA carried out in the city of Tallinn (Estonia) estimated 296 premature deaths and 3859 potential YLLs caused by $PM_{2.5}$ in 2006 (Orru et al. 2009). These figures are proportionally smaller than those of our study (14,666 ADs and 150,771 potential YLLs in 2015).

However, the main difference is lower $PM_{2.5}$ concentrations in Tallinn than in the Mexican cities.

One estimate of VSL in Mexico was between 0.081 and 2.6 MD (McKinley et al. 2005). However, their estimate was based on an unpublished study in Mexico using hedonistic wages. Another estimate of VSL was between 0.235 and 0.325 MD in 2002 (Instituto Nacional de Ecología y Cambio Climático. 2014). The disadvantage of these studies is their susceptibility to distortions of labor markets. However, the range of estimation of the McKinley et al. study includes our estimates. A more recent study (Instituto Nacional de Ecología y Cambio Climático 2014) found that the VSL in Mexico was 1.65 MD in 2010, based on a systematic review of VSL estimates in the USA. The difference with our study is that we used the VSL for the OECD countries and the suggested income elasticity for middle income countries. Our VSL estimates have the advantages of being calculated with more recent information and using a broader systematic review as reference.

The costs of general mortality with the VSL approach and with WHO scenario represent 1.8% of the GDP, equivalent to 28% of health expenditure in Mexico during 2013. The potential YLLs using the WTP approach represent 0.8% and 3%, respectively. Based on an OECD study on well-being costs derived from mortality caused by outdoors air pollution in 2015 (Pope et al. 2002), the costs represent 2.6% of the GDP in Mexico. The percentage of calculated costs based on OECD's study is greater, but includes total pollution of exterior air, not only pollution by $PM_{2.5}$.

The results of this study can be used to strengthen pollution control policies raising awareness of its social and economic costs. Making health costs visible contextualizes the cost of interventions of the other sectors as compared with the expected benefits. Examples are the air quality national strategy (Secretaria de Medio Ambiente y Recursos Naturales 2017a), and the air quality improvement program for the metropolitan zone of the Valle de Mexico 2011–2020 (Secretaria de Medio Ambiente y Recursos Naturales 2017b).

Limitations of the study

This study is limited by the number of cities and stations measuring $PM_{2.5}$; a number of annual means estimates in some monitors were based on stations that measured PM_{10}, because monitoring in Mexico is still insufficient. This study covered one-third of the country's population; it is necessary to have a greater coverage of correctly functioning stations; efficiency of required data was not fulfilled by several stations. Ideally, at least the 33 cities with more than 500,000 inhabitants (Consejo Nacional de Población 2018) should have a functional monitoring network. Further, we focused our assessment on $PM_{2.5}$ rather than a set of pollutants, for the acknowledged to be the greatest public health problem. This might lead to underestimation of the avoidable deaths.

Conclusions

The results of this HIA in Mexico reveal (a) the need of interventions to decrease $PM_{2.5}$ concentrations; (b) lack of monitoring in many cities. A reduction in the levels of current pollution would avoid thousands of premature deaths and potential YLLs, and its associated economics costs.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors. For this type of study, formal consent is not required.

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