Excess deaths associated with fine particulate matter in Brazilian cities

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Abstract: Fine particulate matter (PM_{2.5}; $\leq 2.5\mu\text{m}$ in aerodynamic diameter) stands out among all pollutants as more directly responsible for long-term health problems. This work aims to evaluate the public health benefits of improved air quality in Brazil, based on the estimated reduction in mortality from PM_{2.5}, a pollutant commonly related to all causes mortality including non-accidental, cardiovascular, ischemic heart diseases and lung cancer. Annual PM_{2.5} concentrations were obtained from 50 monitoring stations spread across 24 Brazilian cities between the years 2000 and 2017, which constituted the baseline scenario. The control scenario was represented by the annual PM_{2.5} guideline values ($10\mu\text{g m}^{-3}$) of the World Health Organization (WHO). The relationship between the change in baseline and control scenarios with health effects was estimated using the BenMAP-CE program and the application of exposure-response functions. São Paulo city showed the highest number of avoidable deaths, with values ranging from $28,874\pm 9,769$ and $82,720\pm 24,549$ for all causes from 2000 to 2017. In 2009, just three Brazilian cities were monitoring PM_{2.5}. Between 877 ± 295 and $2,497\pm 719$ all causes avoidable deaths related to PM_{2.5} were estimated under the scenario when the WHO guideline was applied. In 2017, the 15 cities with representative annual PM_{2.5} data account for between $2,378\pm 801$ and $6,282\pm 1,818$ avoidable deaths due to all-cause PM_{2.5} mortality, between $2,974\pm 376$ and $10,397\pm 516$ avoidable deaths due non-accidental causes, between $1,373\pm 230$ and $3,428\pm 265$ avoidable deaths due cardiovascular disease, between 927 ± 162 and $2,514\pm 156$ avoidable deaths due ischemic heart diseases and the lowest between 101 ± 45 and 264 ± 88 avoidable deaths due to lung cancer.

Keywords: Fine particles; Health benefits; Avoidable deaths; Monitoring data; Brazil; Urban centers

Research highlights

- Brazilian air quality monitoring data from 24 cities were used to estimate avoidable deaths
- Almost 90% of the annual PM_{2.5} concentrations in Brazilian cities were higher than WHO guideline
- Large urban centers such as Sao Paulo city obtained higher values of avoidable deaths
- National PM_{2.5} standard in Brazil based on WHO guideline could bring health-related benefits

1 Introduction

Urban populations around the world have increased from 46.5% in the year 2000 to 54.3% in 2016, while in Brazil, the urban population reached 85.9% in 2016 (UN, 2015; The World Bank, 2018). It is associated with the intensification of urbanization processes resulting in the consumption of fossil fuel, deforestation, burning, generation of waste and the degradation of air quality (McMichael, 2000). Consequently, air pollution has become a public health concern, even when its levels fall short of current legislation (Curtis et al., 2006).

When determining the concentration of a pollutant in the atmosphere, the degree of exposure of the receptors (humans, animals, plants, materials) is measured as the result of the release of this pollutant into the atmosphere from its emission sources and their physical (dispersion) and chemical (chemical reactions) interactions (Seinfeld and Pandis, 2006). Thus, air quality is the product of the interaction between factors such as emissions, topography and weather conditions.

The World Health Organization (WHO) reported air pollution as the biggest health risk, causing approximately 6.5 million excess deaths globally in 2012, which is 11.6% of all deaths (WHO, 2016a). Among the main causes are the cardiovascular diseases, stroke, chronic obstructive pulmonary disease and lung cancer, in addition to the increased risks of acute respiratory infections (WHO, 2016a). Cohen et al. (2017) reported that fine particulate matter less than 2.5 μm ($\text{PM}_{2.5}$) was the fifth largest risk factor for mortality in 2015, averaging 4.2 million deaths globally (7.6% of all deaths), an increase of 20% in relation to the total deaths in 1990.

In Brazil, Miranda et al. (2012) estimated the number of deaths associated with the excess exposure to $\text{PM}_{2.5}$ for June 2007 to August 2008, based on experimental campaigns in six Brazilian state capitals for adults over 45 years old. São Paulo presented the worst results with 9,700 premature deaths due to long-term exposure. Rio de Janeiro, Belo Horizonte, Porto Alegre and Curitiba added other 3,900 deaths that could be avoidable if the annual $\text{PM}_{2.5}$ concentrations were reduced to the WHO guideline ($10 \mu\text{g m}^{-3}$).

An extensive body of epidemiological research has established a strong association between chronic exposures to $\text{PM}_{2.5}$ and ischemic heart disease (IHD), cardiovascular, lung cancer, all causes and all non-accidental causes mortality (Pope et al., 2002; Pope et

al., 2004; Laden et al., 2006; Krewski et al., 2009; Crouse et al., 2012; Cesaroni et al., 2013; Bentayeb et al., 2015). The interaction between the sources of pollution and the atmosphere defines the level of air quality, which in turn determines the occurrence of adverse effects of air pollution on its receptors. In the Metropolitan Area of São Paulo, for example, Martins et al. (2017) showed that the probability of higher concentrations for CO, NO, NO₂, PM₁₀ and PM_{2.5} were more frequent during the winter, while O₃ episodes occur most frequently during summer. Air quality monitoring aims to provide data to trigger emergency actions during periods of atmospheric stagnation, assess air quality in the light of established limits to protect the health and well-being of people, enable a correct planning of the territory, and monitor trends and changes in air quality due to changes in pollutant emissions.

Exposure to air pollutants is a risk factor for humans and many existing studies that attempt to assess the relationship between air pollution and mortality use pollutant concentration data from air quality monitoring stations (Pope III et al, 2002; Pope et al, 2004; Laden, et al, 2006; Wong et al., 2008; Katanoda et al, 2011; Lepeule et al., 2012; Huang et al., 2012; Thurston et al., 2016). In Brazil, air quality monitoring is still restricted and unsatisfactory in terms of sample history, territorial coverage, number of monitored parameters and representatively in measurements, due to management difficulties and the low number of technicians involved, as well as lack of resources for the purchase and maintenance of equipment and monitoring networks (Brazil, 2014). In addition, the fine particulate matter is not yet nationally legislated.

Until 2017, there were 24 Brazilian cities with PM_{2.5} monitoring. All these cities were in the southeastern region of Brazil. With measurements beginning in the year 2000 in São Paulo city, the concern with this pollutant is increasing, and an annual increase in the number of PM_{2.5} monitoring stations is noticed. For the first time, this study performs an assessment of the number of total avoidable deaths attributable to a reduction in PM_{2.5} concentrations, considering the annual guideline established by the WHO (10 µg m⁻³) for all 24 Brazilian cities during 2000-2017 years with the available monitoring data. These results may be valuable to consider effective strategies to expanding air quality monitoring in Brazil, to improve air quality and for the adoption of a national standard for PM_{2.5}, allowing policymakers to project the population health improvements.

2 Materials and methods

2.1 Health Effects

The US EPA's Environmental Benefits Mapping and Analysis Program (Community Edition; BenMAP-CE; v.1.3) (Sacks et al., 2018) is used to facilitate the analyses of health effects. The inputs included a shapefile, the incident rates of the cause evaluated, population data, a health impact function, baseline and control scenarios of the pollutant evaluated. After acquiring the required data, the health effects were estimated using the Equation (1):

$$\Delta Y = Y_0 * Pop * (1 - e^{-\beta * \Delta PM}) \quad (1)$$

where ΔY is the change in health effects incidence (deaths cases); Y_0 is the baseline incidence (in this case, it is an estimate of the average number of people dying in a given population over a given period); Pop is the exposed population; β , calculated by Equation (2), is the effect estimated, derived from the relative risk (RR) associated with a change in exposure as expressed in concentration-response function, and obtained from epidemiological studies; and ΔPM is the $PM_{2.5}$ concentration change from baseline to control scenario.

$$\beta = \ln(RR) / \Delta Q \quad (2)$$

where ΔQ refers to the change in air quality that the epidemiological study used for RR estimation and which is commonly equal to $10 \mu g m^{-3}$ for fine particles.

As discussed in Section 4, there is no cohort study in Brazil relating to $PM_{2.5}$ mortality. Therefore, the number of deaths was estimated using concentration-response functions based on most cited/used studies of long-term exposure to $PM_{2.5}$ conducted on large cohorts in Europe (Cesaroni et al., 2013) and North America (Pope et al., 2002; Pope et al., 2004; Laden et al., 2006; Krewski et al., 2009; Crouse et al., 2012), as summarised in Table 1. The concentration-response functions that were not already included in BenMAP-CE were added based on β values and their standard errors. Fann and Risley (2013) reported that there are differences between American Cancer Society study (Pope et al., 2002, Pope et al., 2004; Krewski et al., 2009) and the Harvard Six-Cities Study (Laden et al., 2006) such as population size, geographic area covered, education level and $PM_{2.5}$

composition. The same may be applied for the studies conducted by Crouse et al. (2012) and Cesaroni et al. (2013). In order to generate a more comprehensive mortality estimate, it was used different exposure-response functions for each cause assessed, but the results must be interpreted by each function individually due to the differences among the methodology used in each cohort study.

Table 1. Summary of the main features of selected concentration-response functions.

Health outcome	Reference	Age Range	Hazard ratio (95% CI)	β values (STD)
All Causes	Pope et al. (2002)	30-99	1.06 (1.02-1.11)	0.005827 (0.002157)
	Krewski et al. (2009)	30-99	1.03 (1.01-1.05)	0.002956 (0.000991)
	Laden et al. (2006)	25-74	1.16 (1.07-1.26)	0.014842 (0.004170)
Non-Accidental	Cesaroni et al. (2013)	>30	1.04 (1.03-1.05)	0.003922 (0.000491)
	Crouse et al. (2012)	>25	1.15 (1.13-1.16)	0.013976 (0.000668)
Cardiovascular	Cesaroni et al. (2013)	>30	1.06 (1.04-1.08)	0.005827 (0.000963)
	Crouse et al. (2012)	>25	1.16 (1.13-1.18)	0.014843 (0.001104)
	Laden et al. (2006)	25-74	1.28 (1.13-1.44)	0.024686 (0.006184)
Ischemic Heart Disease	Pope et al. (2004)	30 -99	1.18 (1.14-1.23)	0.016551 (0.001938)
	Krewski et al. (2009)	30-99	1.15 (1.11-1.20)	0.013976 (0.001989)
	Crouse et al. (2012)	>25	1.31 (1.27-1.35)	0.027003 (0.001558)
	Cesaroni et al. (2013)	>30	1.10 (1.06-1.13)	0.009531 (0.001631)
Lung Cancer	Pope et al. (2002)	30-99	1.14 (1.04-1.23)	0.013103 (0.004280)
	Krewski et al. (2009)	30-99	1.11 (1.04-1.18)	0.010436 (0.003222)
	Cesaroni et al. (2013)	>30	1.05 (1.01-1.10)	0.004879 (0.002177)

2.2. PM_{2.5} data

To estimate the health-related benefits, baseline scenarios were defined considering the annual PM_{2.5} concentrations for all Brazilian cities with representative monitoring data. Figure 1 shows the locations of the monitoring sites of PM_{2.5} in 2017 (manual and automatic).

São Paulo was the first city that started monitoring PM_{2.5} in Brazil in 2000 with manual measurements (Kumar et al., 2016; Pacheco et al., 2017; Andrade et al., 2017). After 2001, a single measurement site was expanded to nine sites in São Paulo by 2017, with automatic stations operating since 2005. *Rio de Janeiro* city started the PM_{2.5} monitoring in the middle of 2010 at eight monitoring sites, therefore, a representative annual concentration was available just in 2011. *Belo Horizonte*, capital of Minas Gerais, started monitoring PM_{2.5} in 2013 at a single site in the north of the city. Since this monitoring site is located far from the urban center, the values obtained may be underestimated to represent the entire city. Therefore, the avoidable death values may be higher than those

that will be presented. *Vitória* was the fourth capital of a state in Brazil to monitor PM_{2.5}. The measurements started in 2015 at a single site. All cities and years with PM_{2.5} concentration values are available in Supplementary Information, SI, Table S1. For the cities with more than one monitoring station, an average was performed to obtain a single value to represent the city.

In São Paulo state, the automatic stations use Beta radiation method to measure PM_{2.5}, while manual stations use gravimetric methods (virtual impaction – dichotomous; or impaction and cyclone), performed for 24 hours every six days (CETESB, 2017). In Rio de Janeiro state, the PM_{2.5} measurements occur with a frequency of six days with a sample of 24 hours. The samples of particulate material are collected in Large Volume Samplers and then analyzed in laboratories by the State Environmental Institute of Rio de Janeiro (INEA, 2016). In the state of Espírito Santo, the Tapered Element Oscillating Microbalance measurement methodology is used for the continuous measurement of the mass concentration of fine particulate material contained in ambient air (IEMA, 2017). In Minas Gerais, an automatic station monitors the PM_{2.5} concentration in Belo Horizonte using a monitor with Beta radiation method (FEAM, 2016). For criteria of the temporal representativeness of data for the manual stations, half of the daily averages valid for the four-month periods January-April, May-August and September-December were considered, which are the criteria used by São Paulo State Environmental Protection Agency (CETESB).

The control scenario was evaluated considering the maximum annual concentration for PM_{2.5} of 10 µg m⁻³. This is the lowest level at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM_{2.5} (WHO, 2006). Therefore, the benefits will only be evaluated if the baseline scenario concentrations are higher than the control scenario.

Figure 1 - Locations of the monitoring sites of PM_{2.5} in Brazil (2017).

2.3 Population and mortality data

Annually population data were obtained from Departamento de Informática do Sistema Único de Saúde (DATASUS) for each city by age group from 2000 to 2015. Population data from 2000 to 2013 are preliminary estimates made in a study sponsored by Rede Interagencial de Informações para a Saúde (Ripsa), while this data from 2013 to 2015 are preliminary estimates prepared by Coordenação-Geral de Informações e Análises Epidemiológicas (CGIAE) of the Secretariat of Health Surveillance (Secretaria de Vigilância em Saúde - SVS), Ministry of Health (Ministério da Saúde - MS). To estimate the health effects for 2016 and 2017, population data of 2015 was used.

Annually mortality data by age group due all causes (ICD-10: A00-Y98), all non-accidental causes (ICD-10: A00-R99), ischemic heart disease (ICD-10: I20-I25), cardiovascular (ICD-10: I20-I28, I30-I52, I60-I79) and lung cancer (ICD-10: C33-C34) was obtained from DATASUS, which regulates mortality data in the Sistema de Informação sobre Mortalidade (SIM). To estimate the health effects for 2017, the incident rate of 2016 was used.

3 Results

3.1 Overview of annual PM_{2.5} concentrations

About 89% of the total annual PM_{2.5} concentration analyzed were higher than WHO guideline (10 $\mu\text{g m}^{-3}$). As for individual cities, Figure 2 shows the annual average concentrations of PM_{2.5} in São Paulo city over the period of between 2000 and 2017,

showing the annual concentration always above the WHO guideline. There were some periods with a decrease in concentration to $14.6 \mu\text{g m}^{-3}$ in 2009, followed by periods with increased concentrations to $20.2 \mu\text{g m}^{-3}$ in 2011. In 2011, there was a decrease in rainfall, with periods of drought and low humidity, probably as a consequence of the planetary scale phenomenon known as La Niña. The winter in 2011, like the previous year, was among the most unfavorable to the dispersion of the pollutants (CETESB, 2012). Plainly, there is no clear trend in $\text{PM}_{2.5}$ concentrations over the years, but there has been a steady reduction in concentration values over the most recent years from $19.1 \mu\text{g m}^{-3}$ in 2014 to $16.1 \mu\text{g m}^{-3}$ in 2017, mainly because of the reduction in the number of days unfavorable to the dispersion of pollutants during the winter period (CETESB, 2017). Other cities of the São Paulo state, such as São Caetano do Sul and Guarulhos, obtaining annual concentrations higher than São Paulo ($18 \mu\text{g m}^{-3}$ in both cities in 2017). All the concentration values for the 11 cities of São Paulo state are available in SI Table S1 for the years with monitoring data (2000 to 2017).

Figure 2 – Annual $\text{PM}_{2.5}$ concentration for São Paulo, Rio de Janeiro, Belo Horizonte and Vitória over the years.

Figure 2 also shows average annual $\text{PM}_{2.5}$ concentrations for Rio de Janeiro. In the seven evaluated years, $\text{PM}_{2.5}$ levels decreased and increased, with no single tendency, with all concentration values being higher than that recommended by the WHO. For 2016 and 2017, the annual concentration was $13 \mu\text{g m}^{-3}$. According to Godoy et al. (2018), in Rio de Janeiro, the vehicular contribution to $\text{PM}_{2.5}$ ranged from 48 to 70%, with a mean value of $59 \pm 9\%$, during the period from June 2012 to June 2013. Another study carried out from

2003 to 2005 showed that sources related to anthropogenic sources as vehicle traffic and oil combustion, represented about 65% of the PM_{2.5} fraction in Rio de Janeiro (Godoy et al., 2009). The other cities of Rio de Janeiro state obtained annual PM_{2.5} concentration values between 8 and 22 $\mu\text{g m}^{-3}$ (SI Table S1).

In 2013, the annual PM_{2.5} concentration in Belo Horizonte was 12.2 $\mu\text{g m}^{-3}$ as opposed to 13.7 $\mu\text{g m}^{-3}$ in 2014. These are values below than those reported by Miranda et al. (2012) for June 2007 to August 2008 (14.7 $\mu\text{g m}^{-3}$). Recent monitoring data was not available.

The annual PM_{2.5} concentration in Vitória over 2015-2016 was 12 $\mu\text{g m}^{-3}$, slightly above the WHO guidelines. In 2017, the annual concentration dropped down a bit more to 10.4 $\mu\text{g m}^{-3}$. Vila Velha is the other city in Espírito Santo state with a monitoring station. The annual levels for these two first years were 11.4 and 11 $\mu\text{g m}^{-3}$, while in 2017 the concentration dropped to 9.7 $\mu\text{g m}^{-3}$, lower than the WHO guidelines.

In 2014, 92% of the world population was living in places where WHO air quality guideline standards were not met (WHO, 2017). Figure 3 shows a comparison of annual PM_{2.5} concentration in 2014 among São Paulo, Rio de Janeiro, Belo Horizonte and other cities around the world. In South America, Bogotá (Colombia) and Santiago (Chile) presented annual concentrations higher than those observed in Brazilian cities, exceeding 20 $\mu\text{g m}^{-3}$. In the Central Valley of Chile, during most of the year, there is a thermal inversion layer, which favors the accumulation of pollution (Valdés et al., 2012). On the other hand, Montevideo (Uruguay), a coastal city, present a concentration lower than WHO guideline, as Sydney in Australia. In Shanghai and Beijing (China), the average annual concentration of PM_{2.5} was 52 $\mu\text{g m}^{-3}$ and 85 $\mu\text{g m}^{-3}$, respectively, mainly due to motor vehicles emissions (Chan and Yao, 2008; Liu et al., 2014). Paris (France) and Singapore presented values similar to São Paulo, with an annual PM_{2.5} concentration of 18 $\mu\text{g m}^{-3}$ (WHO, 2016b).

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249 Figure 3 - Annual PM_{2.5} concentration in 2014 from different cities around the world (WHO,
 250 2016b). The cities covered in our assessment are presented in grey color.

251 3.2 Population and mortality overview

252 São Paulo is the city with the largest population in Brazil (7.7 million of inhabitants over
 253 25 years in 2015). From 2000, it was observed an increase in the first ten years for all age
 254 groups. After 2010, just the age group 25 to 29 years old presented a decline, while the
 255 other groups still growing up in population. In total numbers, the population increases
 256 30% from 2000 to 2015, reaching 7.7 million of inhabitants in 2015. When the total
 257 number of deaths is observed, the age groups until 49 years presented a decrease of 34.4%
 258 from 2000 to 2016, while the deaths for the group formed with people with more than 80
 259 years went up 90.5%. However, the population of this group more than duplicated in this
 260 period and, therefore, the incident rate (deaths/population) presented a decrease of 19%.
 261 Figure 4 shows the incident rate for all causes over the years. For the younger groups
 262 (<44 years), the incidence rate is lower than 0.005.

Figure 4 – Incident rate for São Paulo city (over 25 years) by age group over the years.

Figure 5 shows the number of deaths for the population (over 25 years) of São Paulo city by all causes, all non-accidental causes, IHD, cardiovascular and lung cancer. In absolute number, there was an increase of deaths for all five causes (22% for all causes, 29% for non-accidental, 12% for cardiovascular, 5% for IHD and 34% for lung cancer, between 2000 and 2016). However, when the incident rate is evaluated, it was observed that just for lung cancer this increase remains the same (i.e., 2.9% of increase from 2000 to 2016). The other causes obtained reductions in incident rate: 6.3% for all causes; 0.8% for non-accidental; 14.2% for cardiovascular and 19.6% for IHD, for the same period.

Figure 5 - Total number of deaths for the population (over 25 years) of São Paulo.

Rio de Janeiro city presented an increase of 3.9% in the number of inhabitants (over 25 years) from 2011 to 2015, reaching approximately 4.2 million. Although some age groups

such as 25 to 29 years and 45 to 49 years showed a decrease of 7.5% and 5%, respectively, over the years. Concerning mortality, the age group with more than 80 years old presented the highest number of deaths, for all causes evaluated. The incident rate increases when the populations get older. There is, for the most of age groups, a decline in incident rate for all five causes over the years evaluated. An exception is, for example, an increase of 8% in the incidence rate for groups up to 44 years for cardiovascular disease. Other increases also found were for the groups of 25 to 29 and 35 to 39 years for non-accidental causes, 24% and 4%, respectively. Compared to São Paulo, Rio de Janeiro had an incident rate higher for all causes and non-accidental causes in all age groups. For cardiovascular diseases, lower values were found. For the other causes, there were higher and lower values depending on the age group.

Belo Horizonte presented a population with more than 25 years of approximately 1.7 million inhabitants in 2015. The incident rates evaluated were lower than those for São Paulo and Rio de Janeiro for all five causes and age groups.

The population over 25 years of Vitória was more than 233 thousand inhabitants in 2015. Compared to Rio de Janeiro, Vitória presented lower values of the incident rate in 2015 for all causes and non-accident causes, for all age groups. Some higher values were found for IHD and lung cancer, especially for the smallest age groups, as for example, for the age group 30 to 34 years, which presented values 40% and 80% higher than Rio de Janeiro for IHD and lung cancer, respectively. Compared to Belo Horizonte, the values for IHD, which are higher, are highlighted. Compared to São Paulo, lower values of incident rate were found for all causes, non-accidental causes, cardiovascular diseases and IHD, for the majority of age groups. On the other hand, the incident rate for lung cancer was higher for most of the age groups.

In São Paulo state, other cities presented incident rate values higher than those found in São Paulo city. For example, in 2015, Guarulhos presented higher values for almost all age group in all the five causes evaluated. Campinas obtained higher values for all causes, non-accidental causes, and lung cancer. Similar situation for Taubaté, which also presented higher values for IHD. In Rio de Janeiro state, compared to the capital, practically all cities presented an incidence rate greater in 2015, with a highlight for Duque de Caxias that presented values superior to the other cities for most causes and age

groups. In Espírito Santo, Vila Velha presented incident rates greater than Vitória for the most causes and age groups.

3.3 Avoided premature mortality against WHO guideline for annual mean concentrations of PM_{2.5}

Table 2 summarizes the avoided mortalities for all causes, non-accidental causes, cardiovascular, IHD and lung cancer for the city of São Paulo for some years. A detailed list of annual mortality estimates between 2000 and 2017 can be found in SI Tables S16 to S18. As expected, São Paulo presented the highest values of avoidable deaths among all cities studied. When considering the concentration-response function of Pope et al. (2002), the analysis indicated a number of avoidable deaths for all causes ranging from 1,657±619 (in 2009) to 4,284±1,625 (in 2000). Depending on the selected relative risk, the maximum value can reach 7,097±2,137 avoidable deaths. This number represents 18% of the total deaths in 2000 (25 to 74 years old). The results obtained with Krewski et al. (2009) relative risk were the lower among all cause category. Adding the avoidable deaths from 2000 to 2017, between 28,874±9,769 and 82,720±24,549 people would not have prematurely died due to PM_{2.5} in São Paulo, depending on the cohort study.

Table 2 - Estimate of avoidable deaths for the city of São Paulo, with the standard deviation in parentheses.

Health outcome	Exposure-response functions	2000	2009	2015	2017
All Causes	Pope et al. (2002)	4,284 (1,625)	1,657 (619)	3,120 (1,172)	2,509 (939)
	Krewski et al. (2009)	2,215 (752)	846 (285)	1,601 (541)	1,284 (433)
	Laden et al. (2006)	7,097 (2,137)	2,423 (698)	4,176 (1,223)	3,379 (980)
Non-Accidental	Cesaroni et al. (2013)	2,676 (342)	1,049 (132)	1,995 (253)	1,615 (204)
	Crouse et al. (2012)	9,056 (472)	3,693 (182)	6,893 (347)	5,634 (281)
Cardiovascular	Cesaroni et al. (2013)	1,481 (253)	524 (88)	950 (160)	775 (130)
	Crouse et al. (2012)	3,578 (291)	1,314 (101)	2,352 (185)	1,932 (150)
	Laden et al. (2006)	3,294 (929)	1,102 (288)	1,930 (519)	1,609 (426)
Ischemic Heart Disease	Pope et al. (2004)	1,783 (230)	617 (75)	1,118 (139)	904 (111)
	Krewski et al. (2009)	1,531 (236)	524 (77)	954 (142)	769 (113)
	Crouse et al. (2012)	2,730 (186)	986 (6)	1,764 (112)	1,438 (90)
	Cesaroni et al. (2013)	1,074 (194)	361 (63)	662 (117)	531 (93)
Lung Cancer	Pope et al. (2002)	224 (78)	98 (33)	189 (64)	144 (48)
	Krewski et al. (2009)	182 (59)	78 (25)	152 (48)	116 (37)
	Cesaroni et al. (2013)	88 (40)	37 (17)	73 (33)	55 (25)

The avoidable deaths for non-accidental cause with the relative risk of Crouse et al. (2012) in 2017 were 67% to 339% higher than those found for all-cause, while the relative risk of Cesaroni et al. (2013) presented lower values, except when compared with Krewski et al. (2009) results. For cardiovascular and IHD, the results obtained with Crouse et al. (2012) were very high compared to others (reaching 173% higher), while the relative risk pointed out by Cesaroni et al. (2013) results in the lower values.

Considering the relative risk of Pope et al. (2002) for lung cancer, the avoidable deaths were more representative in relation to the total number of deaths by lung cancer for the first eight years (2000 to 2007). Until 2007, the average of representativeness was 13.3%, while from 2008 to 2017 it was 8.9%. Considering the entire period, this average reached 10.9%.

The year 2017 presented the highest number of monitoring sites for PM_{2.5} in São Paulo state (20 stations in 11 cities). Table 3 shows the values of avoidable deaths in four of these cities for this year. The complete series of avoidable deaths are presented in SI Tables S9 to S15. Guarulhos city, which is at the border of São Paulo city, showed the highest values of avoidable deaths among the other cities of São Paulo state (524 ± 153 , considering the concentration-response function of Laden et al. (2006) for all causes). Campinas, further north of São Paulo city, also presented high values (more than double of the average in these cities). It is worth pointing out that these two cities presented annual PM_{2.5} concentration higher than São Paulo (Table S1), what contributed to the higher number of avoidable deaths estimated. São Bernardo do Campo and Santos also presented significant values of avoidable deaths.

Table 3 - Estimate of avoidable deaths for four cities of São Paulo state in 2017, with the standard deviation in parentheses.

Health outcome	Exposure-response functions	Campinas	Guarulhos	São Bernardo do Campo	Santos
All Causes	Pope et al. (2002)	266 (100)	320 (18)	148 (55)	129 (48)
	Krewski et al. (2009)	136 (46)	164 (55)	76 (26)	66 (22)
	Laden et al. (2006)	345 (101)	524 (153)	223 (65)	139 (40)
Non-Accidental	Cesaroni et al. (2013)	168 (21)	202 (26)	94 (12)	84 (11)
	Crouse et al. (2012)	583 (29)	700 (35)	327 (16)	291 (14)
Cardiovascular	Cesaroni et al. (2013)	76 (13)	105 (18)	48 (8)	39 (7)
	Crouse et al. (2012)	188 (15)	260 (20)	119 (9)	97 (7)
	Laden et al. (2006)	150 (40)	274 (74)	110 (29)	64 (17)
Ischemic Heart Disease	Pope et al. (2004)	98 (12)	126 (16)	49 (6)	48 (6)
	Krewski et al. (2009)	83 (12)	107 (16)	42 (6)	41 (6)
	Crouse et al. (2012)	154 (10)	198 (13)	78 (5)	76 (5)
	Cesaroni et al. (2013)	58 (10)	74 (13)	29 (5)	28 (5)
Lung Cancer	Pope et al. (2002)	14 (5)	17 (6)	10 (3)	7 (2)
	Krewski et al. (2009)	11 (4)	14 (4)	8 (3)	6 (2)
	Cesaroni et al. (2013)	5 (2)	6 (3)	4 (2)	3 (1)

Table 4 presents the avoidable deaths for the city of Rio de Janeiro for some years. The complete series of avoidable deaths are presented in SI Table S6. The values followed the increase or reduction of the PM_{2.5} concentration over the years (Figure 2). Considering Pope et al. (2002) relative risks, the all-cause avoidable deaths represent 3.5% of all deaths in 2011 and lung cancer 7.7% of deaths by this cause. When the results with Krewski et al. (2009) relative risks is observed, it is noticed that IHD represents 45.5% of all causes avoidable deaths. The results of 2016 and 2017 were equal due to the same incident rate used and because the annual PM_{2.5} concentration was equal in this two years. The other cities of Rio de Janeiro state with representative PM_{2.5} monitoring presented a number of avoidable deaths of about ten times lower. All the values are in presented in SI Tables S3 to S8.

Table 4 - Estimate of avoidable deaths for the city of Rio de Janeiro, with the standard deviation in parentheses.

Health outcome	Exposure-response functions	2011	2013	2015	2017
All Causes	Pope et al. (2002)	1,725 (646)	1,144 (427)	595 (221)	889 (331)
	Krewski et al. (2009)	883 (298)	584 (196)	302 (102)	453 (152)
	Laden et al. (2006)	2,339 (678)	1,517 (435)	780 (222)	1,162 (332)
Non-Accidental	Cesaroni et al. (2013)	1,095 (138)	726 (91)	376 (47)	563 (71)
	Crouse et al. (2012)	3,819 (190)	2,557 (126)	1,339 (65)	1,995 (97)
Cardiovascular	Cesaroni et al. (2013)	438 (73)	296 (49)	156 (26)	233 (39)
	Crouse et al. (2012)	1,090 (84)	742 (57)	395 (30)	589 (45)
	Laden et al. (2006)	925 (245)	614 (160)	333 (85)	494 (127)
Ischemic Heart Disease	Pope et al. (2004)	473 (58)	315 (38)	164 (19)	243 (29)
	Krewski et al. (2009)	402 (59)	267 (39)	138 (20)	206 (30)
	Crouse et al. (2012)	749 (47)	504 (31)	265 (16)	392 (23)
	Cesaroni et al. (2013)	278 (49)	184 (32)	95 (16)	142 (25)
Lung Cancer	Pope et al. (2002)	93 (31)	65 (21)	33 (11)	50 (16)
	Krewski et al. (2009)	75 (24)	52 (16)	27 (8)	40 (12)
	Cesaroni et al. (2013)	36 (16)	24 (11)	13 (6)	19 (8)

Belo Horizonte presented all causes avoidable deaths between 87 ± 29 and 246 ± 70 in 2013 and between 149 ± 50 and 410 ± 117 in 2014, depending on the cohort study, an increase of 68% on average. Considering the relative risks of Cesaroni et al. (2013), the avoidable deaths for cardiovascular, IHD and lung cancer in 2014 represented 37%, 15% and 3% of the non-accidental deaths.

Vitória presented lower values of avoidable deaths. With an improvement of $2 \mu\text{g m}^{-3}$ on the $\text{PM}_{2.5}$ annual average in 2015 and 2016, the values for all five causes investigated were similar in both years. In 2017, due to the lower value of annual $\text{PM}_{2.5}$ concentration ($10.4 \mu\text{g m}^{-3}$), the benefits observed were lower than 10 avoidable deaths. Figure 6 shows the avoidable deaths per 100 thousand inhabitants for São Paulo, Rio de Janeiro, Belo Horizonte and Vitória, over the years, for all causes and lung cancer, according to the relative risk of Pope et al. (2002). São Paulo obtained the higher values for all causes, followed by Rio de Janeiro and Belo Horizonte. Vitória presented low values for the three years with monitoring data, with the values for all causes reaching levels of those for lung cancer for the other cities in 2017, due to lower annual $\text{PM}_{2.5}$ concentration and lower population.

Figure 6 - Avoidable deaths per 100 thousand inhabitants for São Paulo, Rio de Janeiro, Belo Horizonte and Vitória, over the years, for all causes and lung cancer.

Figure 7 shows the avoidable deaths from 2014 to 2017 by non-accidental causes according to Cesaroni et al. (2013). It is noticed that the large urban centers obtained the higher values, mainly due the population size. In some cities, the estimative was not possible because the annual $PM_{2.5}$ concentration was not available, or it was not representative. For the cities with zero avoidable deaths, the $PM_{2.5}$ concentration was below the WHO recommendation.

Figure 7 - Avoidable deaths for non-accidental causes using Cesaroni et al. (2013) relative risk.

4 Discussion

The accuracy of the estimated air pollution impact on health in a specific city, region or country depends on air pollution concentrations and exposure, population groups exposed, background incidence of mortality or morbidity, and concentration-response functions. The choice of which health outcomes to include in the assessment may be determined by the strength of available studies, the accessibility of health information, and the importance of the impact from a health and economic perspective (WHO, 2006). However, the decision on which epidemiological studies to use and how to apply them to evaluate the health impact assessment is left to the analyst.

Epidemiological studies allow estimating the effects of a pollutant on human health. The relationship between changes in short-term air pollution levels and changes in various indicators of population health or the health of individuals is studied in time series, panels, and case timeline studies (Eftim and Dominici, 2005; WHO, 2006). These studies provide the basis to examine the short-term benefits of an improvement on air quality (Lin et al., 2016a; 2016b; Chen et al., 2017; Gopalakrishnan et al., 2018). The estimation of chronic health effects associated with air pollution is carried out through cohort studies, which

examine the risk of a health outcome (e.g. death) in relation to long-term environmental exposure to pollution, generally comparing people living in different geographical locations (Eftim and Dominici, 2005; WHO, 2006).

Cohort studies generally provide higher estimates of pollution effects than time-series studies, indicating that long-term exposures have a greater effect than short-term exposures (Eftim and Dominici, 2005). The disadvantages in carrying out this type of study are logistical difficulties, high implementation costs, monitoring of study populations over long periods of time with great potential for losses, and a large number of individuals generally required to carry out the study. In addition, since exposure is generally considered as a city-wide average, different sites need to be assessed to ensure adequate variability of exposure (WHO, 2006).

Most of the cohort studies in the air pollution literature focused primarily on mortality and provided the most comprehensive estimates of the number of deaths attributable to exposure to pollution and the extent of the average reduction in life expectancy. Therefore, they were considered adequate for health impact assessment (Künzli et al., 2001; Cohen et al., 2004; Chen et al., 2008).

There are some time series studies in Brazil, mainly in São Paulo, relating air pollution and mortality (Saldiva et al., 1994; Saldiva et al., 1995; Gouveia and Fletcher, 2000; Conceição et al., 2001; Gouveia et al., 2003; Freitas et al., 2004; Martins et al., 2004; Dumas et al., 2004; Bravo et al., 2016; Gouveia and Junger, 2018), but none of them evaluated the relationship between fine particulate matter and mortality. Therefore, we have estimated the number of avoidable deaths using cohort studies from the USA, Canada and Italy.

The choice of the cohort study that serves as the basis for estimate the health benefits may generate considerable differences. As reported by Boldo et al. (2014), the disparities among the cohort studies could be due to chemical composition of PM_{2.5} and its heterogeneous mix of particle sizes, thus encompassing the environmental characteristics of each area of study (geographic location, emission sources and pollutants mixtures), the variability among different populations, social-economic conditions and the exposure assessment methodology. Although they are not studies that represent the local fine particulate matter and the Brazilian population, the cohort studies used in this work were

also applied for other countries than those from which they were proposed (Ballester et al., 2008; He et al., 2010; Boldo et al., 2011; Chae and Park, 2011; Nawahda, 2013; Pascal et al., 2013; Boldo et al., 2014; Abe and Miraglia, 2016). Voorhees et al. (2014) reported that it is a common practice to apply concentration-response functions that are not specific to a particular city or region, but which are recognized as being of high quality and produced from well-conducted epidemiological studies. In the extended follow-up of the Harvard Six Cities study (Laden et al., 2006), the historical annual mean PM_{2.5} concentration was 16.4 $\mu\text{g m}^{-3}$ (range, 11.0-29.6 $\mu\text{g m}^{-3}$); for the ACS study (Pope et al., 2002; Pope et al., 2004) was 20 $\mu\text{g m}^{-3}$ (9.0-33.5 $\mu\text{g m}^{-3}$); for the Rome study (Cesaroni et al., 2013) was 43.6 $\mu\text{g m}^{-3}$ (13.0-75.2 $\mu\text{g m}^{-3}$); and for the Canadian study was 8.7 $\mu\text{g m}^{-3}$ (1.9-19.2 $\mu\text{g m}^{-3}$). The annual concentrations observed in the present study attend the range of these cohort studies. Furthermore, the 10th revision of the International Statistical Classification of Diseases and Related Health Problems were used according to the health outcome described by the cohort studies, as the population age interval. Therefore, the results presented provide a good picture for environmental authorities develop air quality policies.

The comparison between the results of avoidable deaths obtained in this work with other similar ones in the world should be done carefully, considering the differences related to the concentration-response function used, age groups and the PM_{2.5} concentration difference between the baseline and control scenarios. Boldo et al., (2014) showed that an improvement of 4.7 $\mu\text{g m}^{-3}$ in Madrid (Spain) between the years 2007 and 2014 resulted in a total of 30, 8 and 4 annual avoidable deaths per 100,000 inhabitants due to all causes, ischemic heart disease, and lung cancer, respectively. In New York City, 65 premature deaths due all causes per 100,000 inhabitants were estimated, based on the difference relative to nonanthropogenic, policy-relevant background concentrations, which represented approximately 5% of average PM_{2.5} concentrations in New York City (Kheirbek et al., 2013). The improvements of air quality in Japan by reducing the emissions of PM_{2.5} from 2006 to 2009 could save 28,400 lives (> 65 years) based on a reduction target of 10 $\mu\text{g m}^{-3}$ annual mean concentration (Nawahda, 2013). In Shanghai, the estimated impact on all causes mortality of a year exposure to an annual mean PM_{2.5} concentration was 1,100 deaths from October 2010 to September 2011 and 180 deaths from October 2011 to September 2012 (Voorhees et al., 2014).

In Brazil, the Resolution CONAMA 03/1990 defines the primary and secondary air quality standards. It is nationally legislated the total suspended particles, smoke, inhalable particles (PM₁₀), sulfur dioxide (SO₂), carbon monoxide (CO), ozone (O₃) and nitrogen dioxide (NO₂). As may be noted, they are standards dating back to 1990 and today, because of the whole body of scientific studies related to air pollution and health, they can be considered outdated standards. Moreover, fine particles are not legislated. Therefore, the states of São Paulo and Espírito Santo created they own air quality legislation, with more restrictive standards over time. They also included standards for fine particles, considering the WHO guideline of PM_{2.5} as the final standard.

In São Paulo, although there was an increase in the number of vehicles and in the consumption of fuels, pollutant concentrations have decreased in the last ten years, except for ozone and PM_{2.5} (Carvalho et al., 2015; Andrade et al., 2017). Vehicular traffic, especially diesel-powered, is a major source of black carbon in urban areas (Sánchez-Ccoyllo et al., 2009; Wang et al., 2011; Alves et al., 2015). These emissions may come from the exhaust, physical wear of tires, brakes, and roads (Pant and Harrison, 2013; Andrade et al., 2017). In São Paulo, Rio de Janeiro and Belo Horizonte, black carbon explained approximately 30% of the PM_{2.5} mass (Andrade et al., 2012; Andrade et al., 2014). Black carbon is an important indicator to evaluate the adverse health effects for being one of the main components of the primary combustion particles (Janssen et al., 2011; WHO, 2012; Li et al., 2016). Some cohort studies have identified a positive relationship between mortality (all causes, natural causes, cardiopulmonary, respiratory, lung cancer) and long-term exposure to black carbon (Filleul et al. 2005; Lipfert et al. 2006; Beelen et al. 2008; Smith et al. 2009). This shows the importance of adoption of control programs which aim to reduce PM_{2.5} emission and concentration in the atmosphere in urban centers.

In this work, we investigated 24 Brazilian municipalities that monitor PM_{2.5}. These cities represent 16.7% of the total inhabitants above 25 years old (in 2015) in the country. In relation to the total number of mortalities across Brazil, these municipalities account for 17.5% of all-causes, 18.0% of non-accidental, 18.9% of cardiovascular, 20.0% of IHD, and 19.6% of lung cancer deaths, according DATASUS/SIM system. WHO (2018) estimated 613 deaths per 100,000 inhabitants in Brazil in 2016 attributable to ambient air pollution. Our work showed that 16 Brazilian cities faced annual PM_{2.5} concentration

above WHO guidelines in 2016 and there were about 28 avoidable deaths per 100,000 inhabitants in these cities.

Although the main centers normally obtain the highest PM concentrations (Boldo et al., 2014; Chen et al., 2017), in this study it was verified that cities around capitals presented higher annual $PM_{2.5}$ concentration, as for example, São Caetano do Sul and Guarulhos in São Paulo and Belfort Roxo and Duque de Caxias in Rio de Janeiro. This shows the importance of a monitoring that covers several areas, and, in terms of emission control strategies, the entire metropolitan region should be considered.

The increase in the elderly population observed has also consequences and implications for society and public health. The vulnerable population have higher incidence rate and therefore are the ones benefitting the most from an improved air quality. It is also important to have an air quality database available and up-to-date so that the population can have access to current and past levels of pollutants, both for the conduct of research and to serve as a public policy instrument.

5 Conclusions

Adopting the WHO's $PM_{2.5}$ annual air quality guidelines, between $2,378 \pm 801$ and $6,282 \pm 1,818$ deaths due to all causes could be avoidable in 2017 in just 15 evaluated cities in Brazil. These numbers show the importance of adoption of a $PM_{2.5}$ guideline in Brazil and improving the monitoring of air quality, expanding throughout the national territory. As $PM_{2.5}$ is also produced via secondary formation in the atmosphere (Seinfeld and Pandis, 2006), reducing the concentration of other pollutants may result in a decrease of the $PM_{2.5}$ formation. Policies and investments supporting cleaner transport, power generation, industry emissions control and better municipal waste management would reduce key sources of fine particles and reduce the exposure.

The accuracy of results depends on air quality data, exposed population, concentration-response functions and mortality incidence rates. The population and mortality data were obtained from a national database. Therefore, the results are expected to be affected by the air quality data and concentration-response functions. It was used a single annual $PM_{2.5}$ concentration to represent each city. But it is known that there are large variations in concentration across different geographic and meteorological areas, even within a city. For some cities, there was more than one monitoring station, which makes the value

obtained more representative, including the local traffic emissions and long-range transport contributions. However, in other, as Belo Horizonte, just one monitoring site was available, sometimes far from the urban center. Therefore, the concentration value obtained may not represent the real mean concentration for the city but is still an indicator of local pollution and may represent a minimum value that would be found in the urban center for that city. As an alternative for monitoring data is the use of photochemical models, as CMAQ and WRF-Chem, for example. However, an emission inventory with high spatial resolution is required, as a well-described meteorological field. In addition, the modeled results must be validated with monitoring concentrations and the effect of spatial resolution must be evaluated (Punger and West, 2013; Jiang and Yoo, 2018).

The actual impact of air pollution on health presented here shows the importance of adopting more restrictive air quality standards. Such information is essential to implementing, monitoring and evaluating policies that help to tackle air pollution while also protecting health. Therefore, a review of the national Brazilian air quality standards is necessary, as the inclusion of pollutants not yet legislated, as PM_{2.5}. The importance of using local cohort studies to estimate health benefits is also recorded. Unfortunately, in Brazil, long-term cohort studies for PM_{2.5} are non-existent.

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