90 days of COVID-19 social distancing and its impacts on air quality and health in Sao Paulo, Brazil

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Abstract

The coronavirus disease (COVID-19) pandemic caused by spreading rapidly a severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has imposed a unique situation for the humanity. Sao Paulo has reported 124,105 confirmed cases of COVID-19 and 5,623 deaths up to June 14th, being considered the epicenter of the pandemic in Brazil and in South America. Due to the measures for social distancing, there was a drop in the air pollution concentration in Sao Paulo. Starting on March 16th, 2020, we broke 90 days of social distancing into 13 weeks and compared to an equivalent period in 2019. We investigated the air quality improvement during the quarantine period and compared the associated avoided deaths to COVID-19 burden deaths. Nitrogen dioxide (NO_2) was the best indicator of air quality in the analyzed weeks, since its reduction reached 58 %. Our study showed that the 5,623 deaths occurred during the analyzed weeks of quarantine represents an economic health loss of US$ 10.5 billion. In opposite, we observed a significant air quality improvement due to pollutants concentrations' reductions during the analyzed weeks. Considering PM_{10}, $PM_{2.5}$ and NO_2, the decrease of concentration levels respectively avoided 78, 337 and 387 premature deaths and prevented up to US$ 1.5 billion on health costs. These results highlight the importance of continuing to enforce existing air pollution regulations and measures to protect human health both during and after COVID-19 pandemic.

Keywords: COVID-19; Air pollution; Air quality; Health effects; Economic burden.

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INTRODUCTION

The coronavirus disease (COVID-19) pandemic caused by spreading rapidly a severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has imposed a unique situation for the humanity since the Spanish flu pandemic, transmitted by the H1N1 influenza A virus, which devastated at least 50 million people in 1918. Considered the deadliest pandemic in modern history, its impacts exceed the limit of the 18's decade due to subsequent outbreaks caused by new strains of H1N1 virus, such as the most recent in 2009, formerly known as swine flu (Brida *et al*., 2020; Tu *et al*., 2020; Martini *et al*., 2019; Dhama *et al*., 2012; WHO, 2010; CDC, 2009; Bradley *et al*., 2011; Chowell *et al*., 2006).

Likewise, in the past two decades, the coronaviruses have also shown a continuing potential threat to public health since the emergence of severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV). SARS-CoV and MERS-CoV can cause severe respiratory distress syndrome in humans and despite the SARS-CoV-2 being highly pathogenic and more deadly to humans, SARS epidemic (2003 - 2004) and MERS outbreak (2012) were responsible for the deaths of thousands of people worldwide, as shown in **Fig. 1** (Brida *et al*., 2020; Tu *et al*., 2020; Martini *et al*., 2019; Dhama *et al*., 2012; WHO, 2010; CDC, 2009; Bradley *et al*., 2011; Chowell *et al*., 2006).

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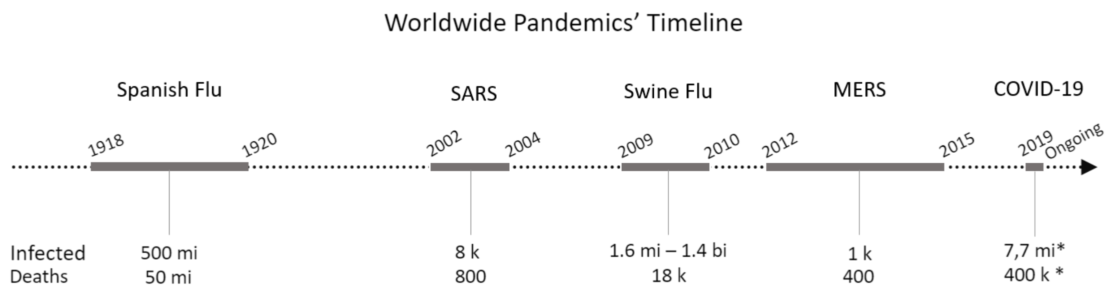

Fig. 1. Worldwide Pandemics' Timeline. Estimated numbers of infected people and deaths to Spanish flu, SARS, swine flu, MERS, and COVID-19, between 1918 and 2020. * Until June 14th, according to WHO Coronavirus Disease (COVID-19) Dashboard (WHO, 2020).

Since its emergence in Wuhan, the capital of Hubei province at the end of 2019, the SARS-CoV-2 has quickly spread worldwide, characterizing a pandemic. On January 30th, 2020, the Emergency Committee of the World Health Organization (WHO) declared a global health emergency based on the increasing rates of case reporting on different continents (Velavan and Meyer, 2020).

The first case in Latin America was confirmed on February 2020, in Sao Paulo city, Brazil. The confirmed patient had travelled to Lombardy, in northern Italy, and the same origin was confirmed for the virus, by genome sequencing (Faria, 2020). Since then, an exponential increase of confirmed cases was observed in the following weeks. No specific drugs or vaccines are available, and health systems are overburdened in every city, especially in Sao Paulo city, which reported 124,105 confirmed cases of COVID-19 and 5,623 deaths up to June 14th, being considered the epicenter of the pandemic in Brazil and in South America.

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In addition to the worrying symptoms of pneumonia, acute respiratory distress syndrome (ARDS) and multiple organ dysfunction, which can lead to death, mainly in people considered to be at risk groups, such as the elderly and people with chronic non-communicable diseases and respiratory diseases, (Singhal, 2020; Ahmed *et al*., 2020; Rothan and Byrareddy, 2020; Lake, 2020), some studies have suggested that is a higher susceptibility of COVID-19 infection of populations exposed to high concentrations of air pollution (Conticini *et al*., 2020; Frontera *et al*., 2020; Tavella *et al*., 2020). Wu *et al*. (2020) conducted a cross-sectional study in order to investigate whether long-term average exposure to fine particulate matter ($PM_{2.5}$) is associated with an increased risk of COVID-19 death in the United States. They found that an increase of only 1 μg / m^3 in $PM_{2.5}$ is associated with an 8 % increase in the COVID-19 death rate (95 % confidence interval: 2 %, 15 %) (Wu *et al*., 2020). Considering that, in heavily populated and polluted places, the care to prevent the COVID-19 progress should be more severe.

Sao Paulo, one of the largest urban centers of the world, stands out not only for its economic and industrial performance but also its high levels of atmospheric pollutants and greenhouse gases emissions mainly from motor vehicles, responsible for air quality degradation and negative impacts on public health (CETESB, 2018; IBGE, 2019; Andrade *et al*., 2017).

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According to measurements carried out by the Sao Paulo's Environmental Agency, vehicles are responsible for 96.7 % of carbon monoxide (CO), 63.9 % of nitrogen oxides (NO_x), and 40 % of particulate matter with less than 10 µm (PM_{10}) emissions (CETESB, 2018).

Considering only the particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$), 5,012 premature deaths occur per year in Sao Paulo city (Abe and Miraglia, 2016). In addition, Leirião *et al*. (2020) recently reported the strong influence of diesel-fueled heavy-duty vehicles in air quality. Merely during the Brazilian truck-driver strike in 2018, the reduction in the PM_{10} concentration resulted in the prevention of between six and eight deaths, which implies between 321 and 442 avoided deaths in a year scenario only in Sao Paulo.

Several factors, mainly of anthropogenic origin, are related to increased risk of disease outbreaks of vector-borne and zoonotic diseases, such as mega-trends in human population growth, ecosystems reduction and fragmentation and land use modification and climate change (Rizzoli *et al*., 2019; Allen *et al*., 2017; Guo *et al*., 2019; Loh *et al*., 2015). Therefore, the relationship between a pandemic, as the current COVID-19, global environmental change and human health is overly complex and deep.

In this context, this pandemic has also been a great opportunity to discuss the effects of anthropogenic activities on air quality and its implications on public health. Therefore, we aimed to investigate the air quality improvement during the quarantine period, as well as to compare the

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associated avoided deaths to COVID-19 burden deaths, considering the relative risk and the economic outcomes in Sao Paulo megacity.

METHODS

The study was performed in Sao Paulo (23°32´50´´S - 46°38´09´´W), the most populous city in Brazil, with a population approximately of 12,252,023 inhabitants in 2019 (IBGE, 2019). As the largest Brazilian economic center, Sao Paulo has high levels of air pollution, with a fleet of approximately 9.1 million vehicles (DETRAN, 2019). Considering the 87.83 million km travelled daily by all vehicles in Sao Paulo, automobiles account for 69.5 % and are responsible for 72,6 % of greenhouse gases emissions per day (DETRAN, 2019; IEMA, 2015).

On March 11st, the World Health Organization has declared the new coronavirus a pandemic. In Brazil, on March 16th, 2020, some activities started to cease, as universities, schools and some companies have imposed home office, and the first death was reported in Sao Paulo city on March 17th. Thus, the Sao Paulo government officially decreed quarantine on March 22nd.

According to these initial events, we chose to investigate the air quality in the city of Sao Paulo, starting on March 16th and breaking the analysis period into 13 weeks, ending at June 14th. As a reference for the comparison, the days in the equivalent period in 2019 (March 16th - June 14th, 2019) were selected. This set of days was designated as the “control period.”

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Daily records of precipitation, wind speed and means of air temperature were obtained from Sao Paulo Environmental State Agency Air Quality Information System - QUALAR (CETESB, 2020) and from Brazilian Agro-meteorological Monitoring System (AGRITEMPO, 2020). These meteorological parameters were used as a criterion to exclude the days of the control period that differed from the range of the meteorological conditions of quarantine period.

The pollutants selected for analysis were nitrogen dioxide (NO_2), particulate matter with less than 10 µm (PM_{10}) and particulate matter with less than 2.5µm ($PM_{2.5}$). Hourly atmospheric concentrations data were obtained from records of Sao Paulo Environmental State Agency Air Quality Information System - QUALAR (CETESB, 2020) for both periods. CETESB has 17 automatic monitoring stations in the municipality of Sao Paulo. Not all stations measure all pollutants. Therefore, PM_{10}, $PM_{2.5}$ and NO_2 concentrations in both periods were collected, according to the availability of data from 15 monitoring stations (**Fig. 2**), and compiled on their respective week, as previously established, to calculate the pollutants' weekly average.

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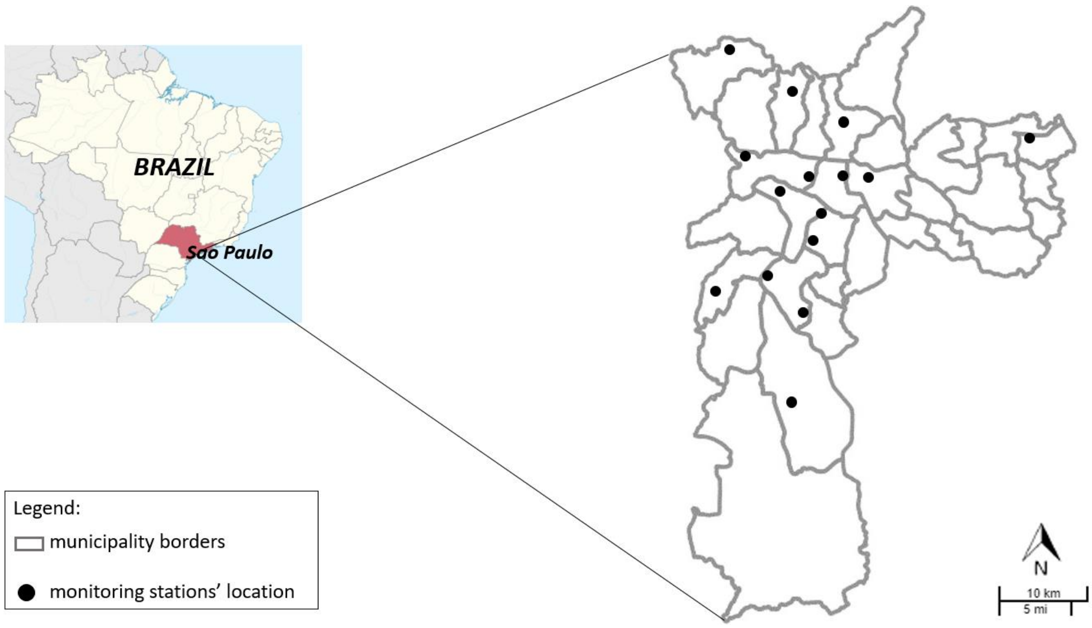

Fig. 2. Location of the analyzed automatic monitoring stations in the municipality of Sao Paulo.

The statistical analyses were performed using GraphPad Prism® 5.0 software for analysis and graphing. The data were analyzed for normality by the D'Agostino-Pearson test. As the pollutants' concentrations behave as nonparametric variables, we used the Mann-Whitney test or Kruskal-Wallis test followed by the Dunn's post hoc test to compare the weekly average of quarantine and control periods.

The images of NO_2 were detected through the Tropospheric Monitoring Instruments (TROPOMI) on-board ESA's Sentinel-5 satellite. The extraction and processing of the images were performed by Sentinel Hub EO Browser, Google Earth Pro and ImageJ. This latter software was used to convert the images from RGB to 8-bit grayscale and to quantify the mean gray value, as an approach to estimate the NO_2 reduction (Lopez *et al.*, 2019; Ciobotaru *et al.*, 2019).

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Based on air pollution reduction results for the quarantine period, the relative risk and avoided deaths attributed to each pollutant were estimated, adopting regression coefficients from epidemiological studies, a well-established method used to estimate the outcomes of air pollution on health (Mudu *et al*., 2016; Abe *et al*., 2018; Bell *et al*., 2009; Hemminki and Pershagen, 1994; Hoek *et al*., 2002; Jerrett *et al*., 2005; Nyhan *et al*., 2019; Ostro *et al*., 2014). The regression coefficients (β) assumed in this study was 0.0008 for PM_{10}, 0.00405 for $PM_{2.5}$, and 0.00135 for NO_2-related deaths, as previously (Mudu *et al*., 2016; Mead and Brajer, 2006; Ostro *et al*., 2004).

The coefficients were used to estimate the probability of mortality associated to the exposure of the pollutants, named as relative risk (RR), obtained by Eq. (1)

$$RR = \exp\left[^{\beta} (\Delta x)\right] \qquad (1)$$

where, RR is the relative risk of all-cause mortality due to air pollution; β exposure–response coefficients related to each pollutant; ΔX is the decrease in the pollutant concentrations ($\mu g / m^3$), the difference of pollutant concentrations between quarantine period and equivalent period in 2018.

The RR values were used to calculate the attributable fraction (AF), the fraction of deaths attributable to the risk factor of PM10, PM2.5 or NO2 variation, defined in Eq. (2), in order to estimate the avoided daily mortality during the quarantine period, based on the mean mortality on control period.

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$$AF = (RR - 1)/RR \quad (2)$$

The daily mean of the all-cause mortality on control period were calculated and multiplied by the attributable factors in order to estimate the all-cause mortality avoided per day during the quarantine.

The latest update of all cause daily mortality between March 2019 and June 2019 was collected on Brazilian Health System Database (DATASUS, 2020). For effects of short-term exposure to $PM_{2.5}$, only all-cause mortality in people older than 30 years old was considered. For PM_{10} and NO_2 all ages were considered. The daily data of COVID-19 deaths were obtained from the State System for Data Analysis Foundation database from March, 16th 2020 to June, 14th 2020 (SEADE, 2020).

The economic valuation of health outcomes was performed by the value of statistical life (VSL) estimation, a well-known approach (Alberini *et al*., 2006; Ding *et al*., 2019; Ran *et al*., 2018; Robinson, 2017; Wolfe *et al*., 2019). Considering the avoided deaths related to air pollutants' emissions reduction, an economic gain is expected. However, due to the deaths caused by COVID-19, a considerable economic loss is expected.

In order to estimate the economic impact of the quarantine and to calculate the trade-off between mortality and economic costs, data of confirmed deaths caused by COVID-19, collected from governmental records (CVE, 2020) was multiplied by VSL established value. The same calculus was done for avoided deaths related to air pollutants' emissions.

VSL can be defined as a measure of willingness to pay for reducing the risk of dying, thus consists of the monetary value of postponed deaths (Alberini *et al*., 2006; Wolfe *et al*., 2019). For each avoided death and deaths caused by COVID-19, the VSL assumed was US$ 1.88 million, previously proposed by OECD (Roy and Braathen, 2017).

RESULTS

Air quality improvement during 90 days of COVID-19 social distancing

As a first-step approach, we verified the daily records of precipitation, wind speed and mean temperature. Comparing both periods, we observed that wind speed and mean temperature presented similar ranges. For precipitation, we detected a discrepancy (**Table 1**).

Table 1. Summary of the daily records of precipitation, wind speed and mean temperature during quarantine and control periods.

	Precipitation (mm)		Wind (m/s)		Temperature (°C)	
	Control period	Quarantine	Control period	Quarantine	Control period	Quarantine
N	91	91	91	91	91	91
Mean (SD)	3.7 (8.1)	1.5 (4.3)	1.8 (0.4)	1.9 (0.4)	26.4 (3.3)	25.3 (3.2)
Median	0.1	0	1.9	2.0	27.5	25.7
Minimum	0	0	1	1	17.8	15.8
Maximum	37.2	25.7	2.8	3.6	32.4	32.2

Number of observations (N); Standard deviation (SD).

Considering that precipitation is an important factor that influences the dilution and dispersion of pollutants (Chou *et al*., 2005; Pellon de Miranda *et al*., 2004; Ramis and Santos, 2013; Yu, 2012), 12 days of control period, with precipitation above 10 mm, were not considered in this

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study. After excluding these outlier days, we can observe that the means and ranges of meteorological variables were similar over the weeks of the quarantine and control period (**Table 2**).

Table 2. Weekly averages of meteorological variables during quarantine and control periods.

	Precipitation (mm)		Wind (m/s)		Temperature (°C)	
Weeks	Control period	Quarantine	Control period	Quarantine	Control period	Quarantine
1	2.6 (1.7)	5.2 (9.6)	2.3 (0.1)	2.2 (0.1)	26.5 (1.7)	28.5 (1.2)
2	0.8 (1.6)	2.6 (6.9)	2.1 (0.2)	2.3 (0.2)	28.6 (0.9)	26.9 (0.6)
3	0.05 (0.1)	1.7 (4.6)	2.0 (0.2)	2.2 (0.2)	29.5 (0.8)	28.6 (0.4)
4	1.9 (3.4)	0.5 (1.2)	1.9 (0.1)	2.1 (0.1)	26.3 (1.9)	24.3 (1.2)
5	0.4 (0.9)	0.8 (1.7)	1.8 (0.1)	2.1 (0.1)	28.5 (0.5)	24.3 (0.7)
6	0.4 (0.7)	0 (0)	1.8 (0.1)	1.7 (0.1)	28.7 (0.3)	26.9 (0.6)
7	0.2 (0.3)	0.03 (0.1)	1.6 (0.1)	1.9 (0.1)	27.9 (0.8)	26.1 (0.8)
8	0.5 (0.7)	0.5 (1.2)	1.8 (0.2)	1.9 (0.1)	26.7 (1.1)	23.4 (1.4)
9	2.4 (1.6)	0.5 (1)	1.9 (0.1)	1.7 (0.2)	26.1 (1.4)	23.7 (1.3)
10	0.9 (1.3)	1.2 (2.6)	1.9 (0.2)	2.3 (0.3)	24.9 (1.2)	23.9 (1.5)
11	1.3 (3.1)	0.03 (0.1)	2.1 (0.2)	2.1 (0.3)	25.2 (1.6)	22.6 (1.0)
12	0 (7.1)	5.5 (7.4)	2.1 (0.2)	1.6 (0.1)	20.4 (1.3)	23 (1.0)
13	0.4 (0.7)	0.7 (1.3)	1.3 (0.1)	1.8 (0.2)	25.2 (0.8)	26.2 (1.3)

Data were expressed as mean ± standard deviation (SD).

Taking into account the months that comprise the analysis period, we observed an upward trend over the months in both years. Despite the significative reductions were only observed for PM10 and PM2.5 for April, we can observe a consistent decrease in 2020 concentrations of all pollutants compared to 2019 values (**Fig. 3**).

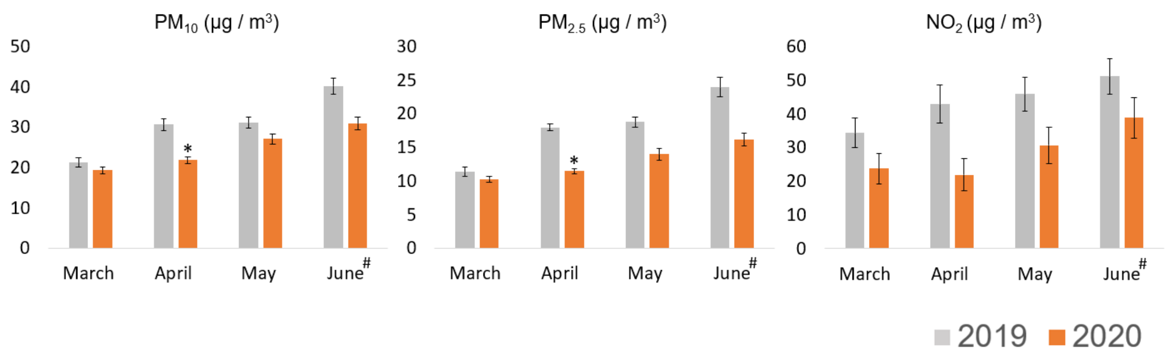

Fig. 3. Monthly comparison of the analyzed pollutants. Bars represent the average ± SEM. The analysis was conducted by Kruskal-Wallis test followed by the Dunn's post hoc test (* $p < 0.05$). # Until June 14th.

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However, from this initial analysis, we can conclude that the division of the analysis period on a weekly scale could provide more detailed information about the variation of pollutants.

During 13 weeks of social distancing, we observed that the pollutants showed a gradual increase in concentrations over the weeks, similarly to the monthly analysis. For PM_{10}, the average concentrations ranged between 16.9 (week 2) and 32.38 μg/m^3 (week 13). $PM_{2.5}$ presented average concentrations varying between 9.05 (week 4) and 17.15 μg/m^3(week 12). And for NO_2, the average concentrations ranged between 17.21 (week 1) and 40.71 μg/m^3 (week 11) (**Fig. 4**).

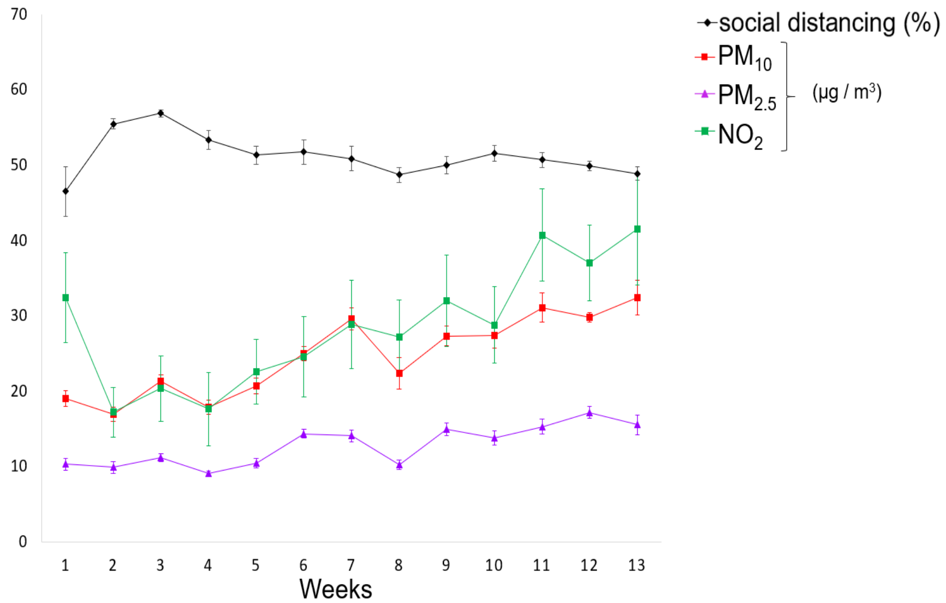

Fig. 4. Averages of social distancing index and PM_{10}, $PM_{2.5}$ and NO_2 concentrations, during 13 weeks of quarantine period in Sao Paulo city. Bars represent the average ± SEM.

The average of social distancing also fluctuated, presenting the lowest index at week 1 (46.5 %) and the highest between week 2 and 4 (55.4; 56.9 and 53.3 %, respectively). In the remaining weeks, the average of social distancing ranged between 51.7 and 48.7 %.

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The best air quality indexes for all pollutants were observed at the weeks 2 and 4 with social distancing above 53.3 %; and the worst concentrations were detected at the weeks 12 and 13, with social distancing less than 50 %.

From week 4 on, we also found a slackening in the social distancing accompanied by an increase in the average of pollutants concentrations, quite evident for PM_{10} and NO_2. The remaining weeks recorded at least 2 days, reaching 6 consecutive days at week 13, with less than 50 % of social distancing. Some factors has contributed for the reduction in social distancing, such as popular manifestations against this measure which occurred in several days, differences in federal and local governments recommendations concerning Covid-19 prevention actions, and mostly important the poor and working class who do not have alternatives in this matter, can also explain the reduction in its index and consequently the fluctuation of pollutants' concentrations.

As shown in **Fig. 5**, the comparison between the PM_{10} concentrations during quarantine and control periods revealed 6 weeks with a reduction of at least 25 %, the highest reaching - 45 % in week 3 ($p < 0.001$). For $PM_{2.5}$, we found 8 weeks with a reduction of at least 29 %, reaching – 46 % in week 13 ($p < 0.001$). The air quality improvement in terms of NO_2, showed 9 weeks with a reduction of at least 33 %, reaching - 58 % in week 3 ($p < 0.01$).

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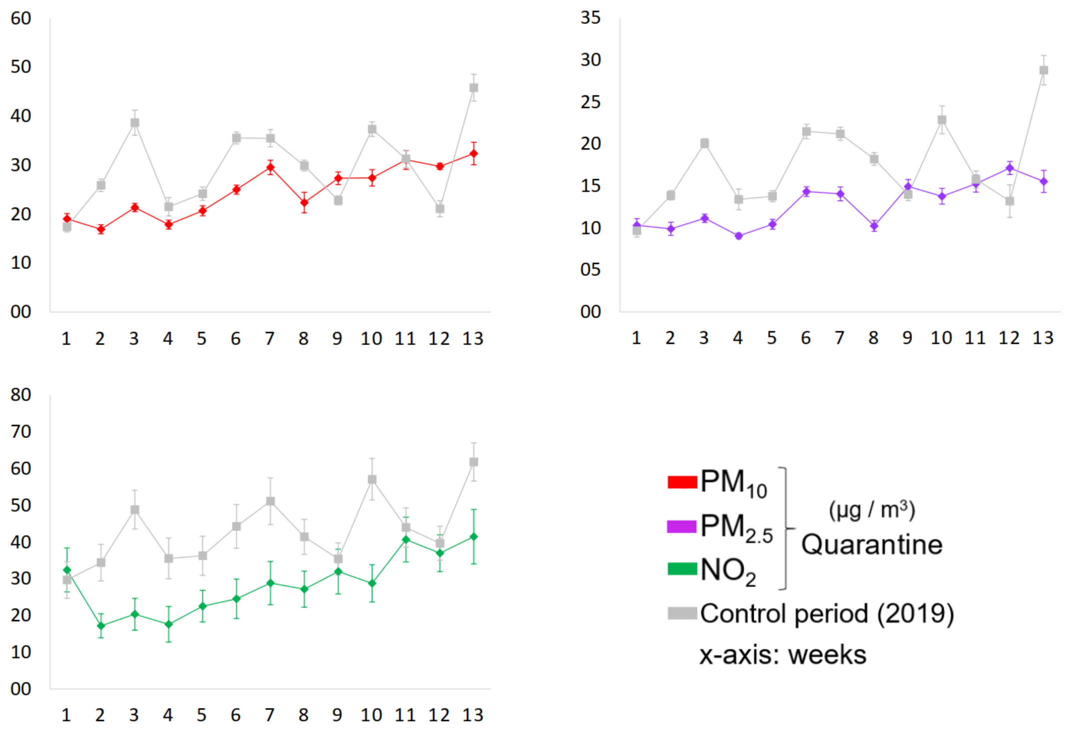

Fig. 5. PM_{10}, $PM_{2.5}$ and NO_2 concentrations, during 13 weeks of quarantine and control periods. Bars represent the average ± SEM.

Followed by $PM_{2.5}$, NO_2 was the best indicator of air quality in the analyzed weeks. This finding could be confirmed from the satellite images, detected on May 21st, 2019 and May 25th, 2020, that showed an abrupt decline of 62.8 % in tropospheric NO_2 concentrations (**Fig. 6**).

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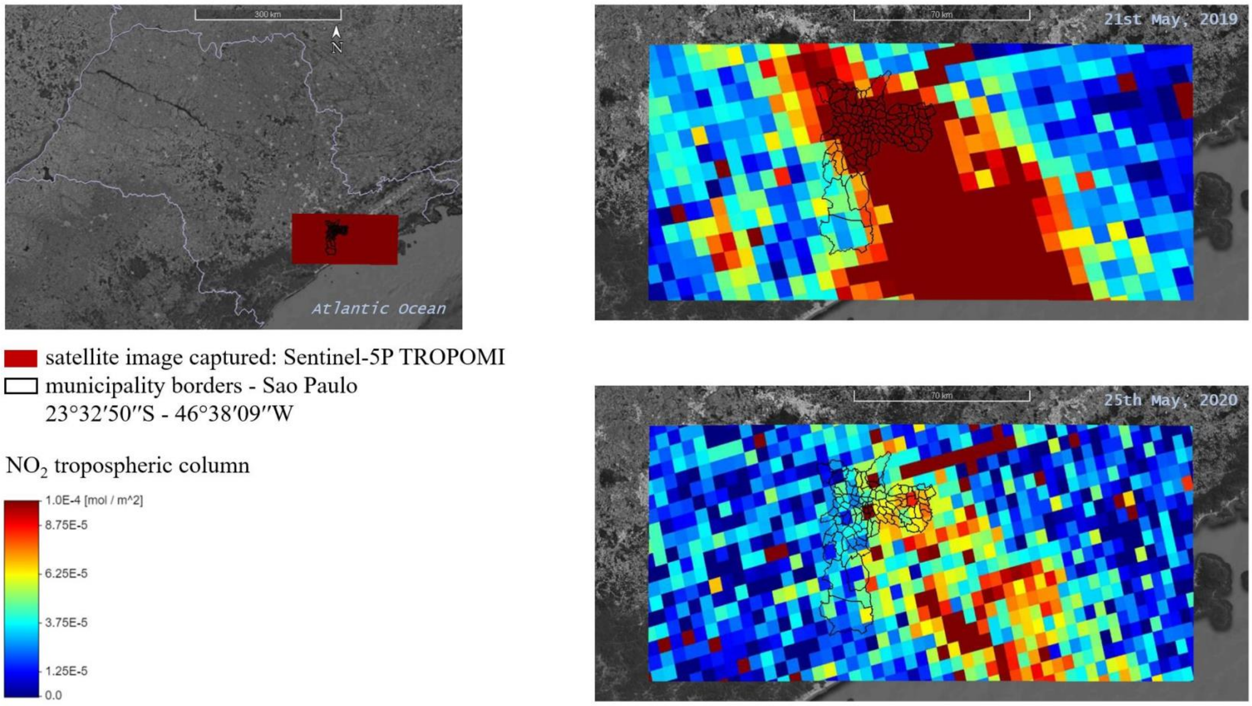

Fig. 6. Tropospheric vertical column of NO_2 detected on May 21st, 2019 and May 25th, 2020.

Associated health economics outcomes

Based on Based on the results presented in **Fig. 5**, we estimated the potential health and economic benefits related to pollutants' reductions achieved during the analyzed weeks of quarantine. As it can be seen from the **Table 3**, Relative Risks (RR) were estimated between 0.993 and 1.013 for PM_{10}, 0.996 and 1.055 for $PM_{2.5}$ and 0.996 and 1.039 for NO_2. Thus, Attributable Factors (AF) ranged were 0.2 % - 0.8 % for PM_{10}, 0.9 % - 3.2 % for $PM_{2.5}$ and 4 % - 6.9 % for NO_2. As to be expected, due to NO_2 has presented the greatest levels of reduction compared to the control period, its weekly RR and AF values was also higher in relation to other analyzed pollutants.

Table 3. Relative Risk (RR) and Attributable Factor (AF), related to PM_{10}, $PM_{2.5}$ and NO_2 exposures.

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Relative Risks and Attributable Fractions						
Weeks	PM_{10}		$PM_{2.5}$		NO_2	
	RR	AF (%)	RR	AF (%)	RR	AF (%)
1	0.998	-0.13	0.997	-0.26	0.996	-0.37
2	1.007	0.72	1.016	1.60	1.023	2.30
3	1.013	1.38	1.036	3.56	1.039	3.77
4	1.002	0.29	1.017	1.74	1.024	2.39
5	1.002	0.28	1.013	1.34	1.018	1.84
6	1.008	0.84	1.029	2.86	1.026	2.63
7	1.004	0.47	1.029	2.86	1.030	2.96
8	1.006	0.60	1.032	3.18	1.019	1.90
9	0.996	-0.36	0.996	-0.38	1.004	0.46
10	1.007	0.79	1.037	3.62	1.039	3.75
11	1.000	0.01	1.002	0.20	1.004	0.44
12	0.993	-0.70	0.984	-1.61	1.003	0.37
13	1.010	1.07	1.055	5.22	1.027	2.71

Therefore, concomitant with the increase in the number of deaths of COVID-19 infection, which reached 5623 on the last day of this analysis, the decrease of PM_{10}, $PM_{2.5}$ and NO_2 concentration levels prevented 78, 337 and 387 premature deaths respectively in Sao Paulo city (**Fig. 7**).

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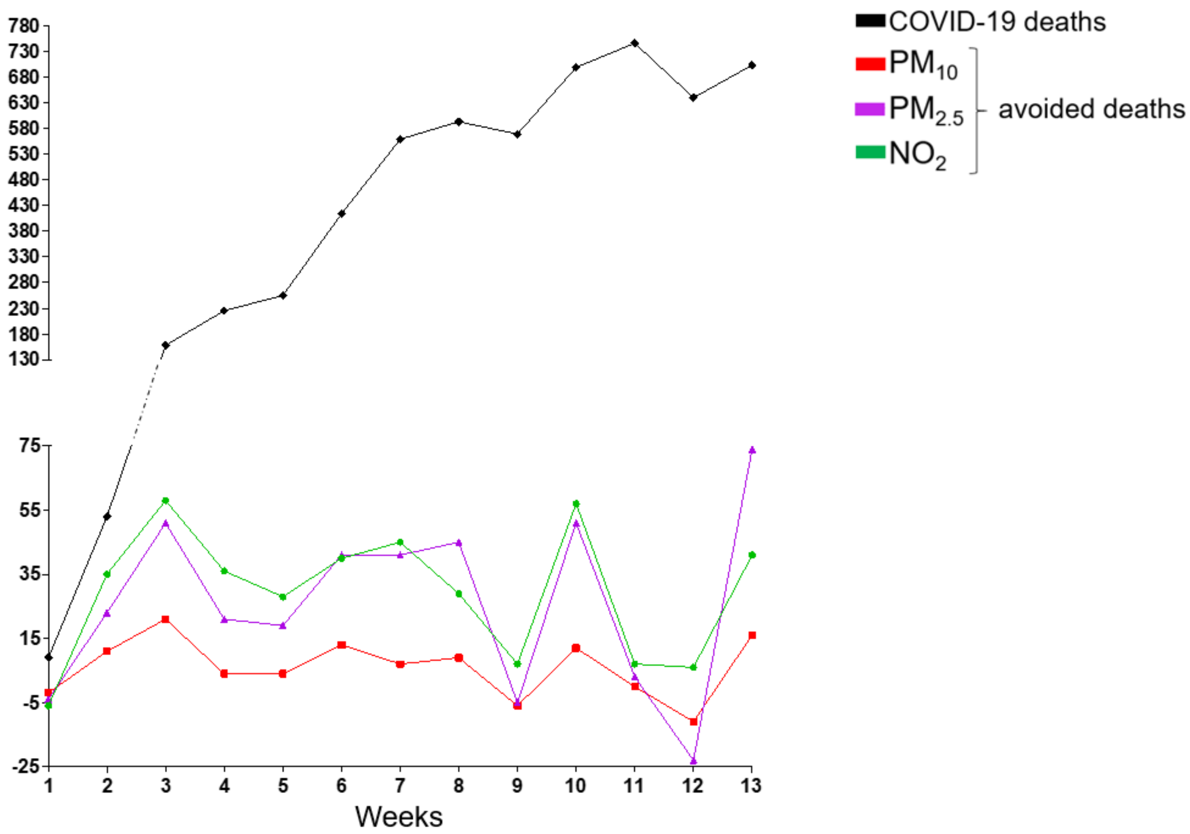

Fig. 7. COVID-19 deaths, PM_{10}, $PM_{2.5}$ and NO_2 avoided deaths, during the weeks of quarantine period in Sao Paulo city.

Given the monetary value for the observed health outcomes from analyzed improvement of pollutants concentrations by VSL approach, a well-known and widely used method (Markandya *et al*., 2018; Roy and Braathen, 2017), we applied the economic valuation of deaths caused by COVID-19 and of the avoided deaths due to the reduction on short-term exposure to PM_{10}, $PM_{2.5}$ and NO_2 (**Table 4**).

Table 4. Economic valuation of deaths caused by COVID-19 and of avoided deaths due to the reductions of PM_{10}, $PM_{2.5}$ and NO_2

	Deaths	Economic Outcome (US$ million)*
COVID-19 deaths	5623	10571.2 (-)
PM_{10} avoided deaths	78	146.6 (+)
$PM_{2.5}$ avoided deaths	337	633.6 (+)
NO_2 avoided deaths	383	720.0 (+)

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* Based on VSL value.

During the analyzed weeks of quarantine period in Sao Paulo city, the deaths caused by COVID-19 accounted for an economic health loss around US$ 10.5 billion. On the other hand, we can consider a potential economic health benefit in terms of the prevented premature deaths related to the observed improvement in air quality. Thus, we estimated that the expressive number of avoided deaths due to PM_{10}, $PM_{2.5}$ and NO_2 reductions can represent an economy of US$ 1.5 billion.

DISCUSSION

In a tightly connected and integrated world, the impacts of emerging infectious diseases can be devastating, causing large-scale mortality and morbidity, as we are observing over the days of this global outbreak. Some changes in the pattern of hospital admissions for other conditions have also been noted during the early days of the COVID-19 outbreak, as for instance the rate of hospital admissions for acute coronary syndrome (ACS). De Filippo *et al*. (2020) argue that in northern Italy some patients have died from ACS without seeking medical attention during the COVID-19 pandemic. The adverse effects go beyond and the size and persistence of the economic impacts of ongoing COVID-19 pandemic are still uncertain and our findings raise intriguing questions.

On the one hand, we estimated the economic health loss associated with deaths related to COVID-19 in Sao Paulo city, which was shown exceedingly raised, even before reaching the

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important goal of flatten the curve of coronavirus infections, that makes us wonder about the efficiency of the applied public policies and the commitment of the strategies of control the pandemic and population's commitment to comply with social distancing. On the other hand, we observed that the epidemic control actions were closely related to the improvement of air quality, due to the major source of air pollution in the region, the emissions from vehicles' exhaust, which were significantly reduced. An impact assessment evaluation can consider the exposure to a multi-pollutant mixture. Adding pollutant-specific effects may be justified when levels of the specific pollutants are clearly not correlated (WHO, 2000). In this research, we estimated the health effects concerning a reduction in PM_{10}, $PM_{2.5}$ and NO_2 concentrations. Our results showed that air quality improvement contributed with a substantial fraction of the avoided deaths associated to a significant monetized health co-benefits, signaling that the governments have the capability to improve air quality through policy measures.

The quarantine and cities in shutting down have also caused a supplementary effect, the improvement of environmental quality, particularly in relation to air quality. Satellite images have captured a dramatic reduction in air pollution over China during February 2020, accounting for over 30 % less in NO_2 levels, compared to early January when power plants were operating at normal levels. In addition, the study also estimated a reduction of CO_2 emissions by 25 % (Isaifan, 2020). Xu *et al*. (2020) showed that, from January to March 2020, the decrease in NO_2

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concentration was of great significance and much higher than other pollutants, such as PM_{10} and $PM_{2.5}$. Moreover, Anjum (2020) also showed from satellite images a remarkable reduction of air pollution in Italy, France and USA. Our results corroborate these findings since we also showed a significant reduction in NO_2 concentration in Sao Paulo city which was greater than the other analyzed pollutants, confirmed by the abrupt decline of 62.8 % in tropospheric NO_2 concentrations also observed by satellite images (**Fig. 6**).

Human activities do not change only the atmosphere with the emission of pollutants, or only the climate system with the emission of greenhouse gases, the consequences are systemic, since they can affect directly human health, socio-economic and political stability. Emissions of air pollutants, related to the exacerbation of prevalence of cardiorespiratory diseases, type 2 diabetes, mental disorders; land use modification associated with deforestation that modifying disease host / vector communities, elevating disease risk and driving wildlife zoonotic diseases emergence; and mega-trends in climate accompanied by extreme weather conditions makes the population becomes increasingly vulnerable. These conditions have resulted in several socioeconomic impacts, such as morbidities, mortality, migration, poverty exacerbation, violent conflict, affecting people of all ages and all nationalities (Rizzoli *et al*., 2019; Grande *et al*., 2020; Watts *et al*., 2018).

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Furthermore, in addition to the reduced number of deaths due to air pollution, we should consider that there are other benefits attributable to the reduction in air pollution itself and could also have positive benefits in reducing preventable non communicable diseases (Chen and Bloom, 2019; Neira *et al.*, 2018). In this sense, a more comprehensive analysis should contemplate other health outcomes.

In this context, the current global crisis we are experiencing, goes beyond showing that environmental degradation is closely related to human resilience. In times of crisis, borders do not matter, showing the importance of cooperation and engagement of governments and all the people to work together for a common purpose and solution.

Foregone income related to laid-off workers or unable to work, disruption of supply chains, restrictions on international travel enforced by governments, unprecedented consequences on stock markets are examples of already observed economic and social impacts. Individualities and structural differences of each country make forecasts difficult, however, there are some published estimates. According to Fernandes (2020), for Brazil, the GDP growth in 2020, assuming shutdown lasts 3 months, can reach -4.0 % [from -5.9 % to -2.1 %]. Moreover, according to OECD, for global GDP growth, is projected to slow from 2.9 % in 2019 to 2.4 % in 2020 (Baldwin and di Mauro, 2020; OECD, 2020; Fernandes, 2020). The COVID-19 pandemic has hit underserved populations and communities of color particularly hard, exacerbating longstanding

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health disparities in Brazil. This fact can be observed in Sao Paulo municipality, which districts of poorer areas has been suffering most of the cases of COVID-19.

Politicians and some businessmen are against the social distancing measures due to the impact in economy, claiming that the virus is less harmful than presented; they do not value life. Life values more than economy – there is no need to have good economic indicators if the population dies. Nevertheless, there will be economic effects of the distance measures and the impacts on the mental health of the populations affected by them. In addition to anxiety due to fear of the disease, there are the effects of a prolonged quarantine for several weeks faced by a huge number of people around the world.

In a strongly linked and integrated world, the impacts of this disease go way beyond mortality. Unemployment and several companies shutting down operations or announcing dismissals, as well as the change in consumption habits are influencing stock markets and contributing to a financial crisis worldwide. Fernandes (2020) analyzed different scenarios of the economic shock posed by the current COVID-19 crisis (and a confidence interval), expressed as a percentage of GDP for each analyzed country. For Brazil, a mild scenario considered a drop of –3.9 % of the GDP.

We found that decrease of PM_{10}, $PM_{2.5}$ and NO_2 concentration levels could respectively prevent 78, 337 and 387 premature deaths, which an economy of US$ 1.5 billion, providing an

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evidence for policy making by the quantification and monetization of air-pollution-related health effects. This is a tool for planning purposes, once the monetized value of avoided premature mortality typically dominates the calculated benefits of air pollution regulations.

In this sense, our analysis presents an estimate of what could be achieved if determined measures would be taken towards air pollution emissions' control in an urban center of a developing country like Sao Paulo, Brazil. The implementation of permanent or partial home-office jobs and the dynamization of the ecommerce are some examples of sustainable procedures which can diminish air pollution emissions in large urban centers.

CONCLUSIONS

Our study showed that during 90 days of COVID-19 social distancing in Sao Paulo city, Brazil, 5,623 deaths occurred due to this new disease estimated in an economic health loss of US$ 10.5 billion. In opposite, we observed a significant air quality improvement. During the analyzed weeks, the decrease of $PM_{2.5}$, PM_{10} and NO_2 levels respectively reached up 45 %, 46 % and 58 % reduced in comparison to control period. The positive impact on air quality in terms of $PM_{2.5}$, PM_{10} and NO_2 respectively provided avoided 78, 337 and 387 premature deaths and prevented up US$ 1.5 billion on health costs. These results highlight the importance of continuing

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to enforce existing air pollution regulations and measures to protect human health both during and after the COVID-19 global health crisis.

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