Impacts of Covid-19 interventions on air quality: evidence from Brazilian metropolitan regions

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Abstract
The Covid-19 pandemic has negatively disrupted the way our economy and society functions. Nonetheless, there have also been some positive externalities of the pandemic on the environment. This paper aims to evaluate the concentration of nitrogen dioxide in Brazilian metropolitan regions after the policies adopted to confront Covid-19. In terms of methodological approach, the study employs cross-sectional quantitative analyses to compare the period of 36 days, i.e., 12 March to 16 April—before (in 2019) and after (in 2020) the pandemic declaration. The data were obtained from the Sentinel 5-P low-Earth polar satellite concerning Brazilian metropolitan regions (n = 24). Thorough spatial and statistical analyses were undertaken to identify the pre- and during pandemic nitrogen dioxide concentrations. Complementarily, Spearman’s correlation test was performed with variables that impact air quality. The study results a fall in nitrogen dioxide concentration levels in 21 of the 24 metropolitan regions which was observed. The Spearman’s correlation coefficient between the nitrogen dioxide variation and the vehicle density was 0.485, at a significance level of 0.05. With these findings in mind, the paper advocates that while the pandemic has a significant negative consequence on the health of population globally, a series of measures that result in a new social organization directly interfere in the reduction of air pollution that contributes to the quality of the air we breathe.

Keywords Air quality · Brazil · Climate change · Covid-19 · Nitrogen dioxide · Urban policy

Abbreviations
API Application programming interface
CH₄ Methane

CO Carbon monoxide
CO₂ Carbon dioxide
DENATRAN Brazilian Transportation Department
ESA European Space Agency
FEPAM State Foundation for Environmental Protection
HCHO Formaldehyde
IBGE Brazilian Institute of Geography and Statistics
IPEA Institute of Applied Economic Research
MR Metropolitan region
NIR Near infrared
NO₂ Nitrogen dioxide
NRTI Near real-time high-resolution imagery
O₃ Ozone
PM₁₀ Particulate matter—diameter of 10 microns or less
PM₂.₅ Particulate matter—diameter of 2.5 microns or less
SO₂ Sulfur dioxide
SPSS Statistical Package for the Social Sciences
SWIR Short-wave infrared
TROPOMI Tropospheric Monitoring Instrument

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Introduction

Nitrogen dioxide (NO₂), a gas resulting mainly from activities of fossil fuels burning, such as vehicle transport and industrial production, is polluting in high atmospheric concentration, that is, it leads to environmental pollution (Mahbub et al. 2011). However, a scenario of actions and attitudes aimed at containing Covid-19 pandemic led to new behaviors and political attitudes, which directly interfered with the atmospheric concentration of NO₂ (Araujo-Filho et al. 2020).

The current Covid-19 pandemic is related to an acute respiratory disease caused by a new coronavirus (SARS-CoV-2), which is highly contagious, and its evolution is still little known (Brasil 2020). Due to the size and speed at which the infection spreads worldwide, its recovery or control required to work on a global and national scale that, due to local and regional diversities, led countries to plan and take action in different ways, as observed in the current sanitary situation of Covid-19 pandemic many countries (Yigitcanlar et al. 2022)—including Brazil.

Nonetheless, the recent changes in the diagnostic criteria of the disease have led to an increase in the rate of new cases and, every day, increasing numbers and challenges have been the subject of intense debate in the scientific community (Araujo-Filho et al. 2020; Brasil 2020). Despite the recent availability of vaccines, still transmission of SARS-CoV-2 is possible. Hence, the World Health Organization (WHO) recommends social distancing, respiratory etiquette, and hand hygiene as the most efficient measures to combat the pandemic, also called non-pharmacological. In this sense, on January 22, 2020, the Ministry of Health introduced a series of measures to confront Covid-19 and the Brazilian population, such as guidelines on hand hygiene and social distancing (Ogen 2020). Social distancing actions were widely publicized by local governments and have social network as an ally, which could expand the dissemination of necessary measures; it is also a tool to guide government on its decision making (Yigitcanlar et al. 2020). Therefore, ministerial recommendations allied to state governments attitudes led to a decrease in transit, industrial actions, among other activities that, due to social isolation, decreased the concentration of pollutants in the atmosphere (Kroll et al. 2020).

In a study carried out in 10 countries (Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa, and the USA), people declared they have noticed an improvement in the quality of the breathed air after the adoption of social isolation in their regions (Barbieri et al. 2020). Nevertheless, it is not just a matter of noticing the reduction, but of relevant diagnosed improvements in global air quality, with reduction in NO₂ concentrations, carbon monoxide (CO), thin particulate material (PM₂.₅), and increased ozone (O₃) concentration in different regions of the globe (Venter et al. 2020; Liu et al. 2021).

In China, the country where SARS-CoV-2 had its origin and where the isolation measures were started in January 2020, the reduction of atmospheric pollutants, such as NO₂ (Venter et al. 2020; Wang et al. 2020; Chen et al. 2020; Chen et al. 2021) and PM₂.₅ (Venter et al. 2020; Chen et al. 2020; Giani et al. 2020; Shi et al. 2021), has been verified after the adoption of measures to cope Covid-19. In Southeast Asia, air quality during the pandemic period was also object of study, with improvement in cities like India (Mahato et al. 2020; Thomas et al. 2020; Tyagi et al. 2021). In Pakistan, on the other hand there were no significant changes in PM₂.₅ (Mehmood et al. 2021).

The same phenomenon of reduction in the concentration of atmospheric NO₂ during measures to confront Covid-19 was observed in Europe, in German cities (Ogen 2020; Liu et al. 2021; Burns et al. 2021), Italy (Ogen 2020; Liu et al. 2021; Cameletti 2020), France (Ogen 2020; Liu et al. 2021), Spain (3, Liu et al. 2021), and the UK (Liu et al. 2021; Jephcote et al. 2021; Wyche et al. 2021). The reduction of concentrations of PM₂.₅, in the same period was also found in cities of France (Liu et al. 2021; Giani et al. 2020; Shi et al. 2021; Connerton et al. 2020), the UK (Liu et al. 2021; Giani et al. 2020; Shi et al. 2021; Jephcote et al. 2021), Germany and Spain (Liu et al. 2021; Giani et al. 2020; Shi et al. 2021).

In the American continent, large cities in the USA also registered decreased level of PM₂.₅, CO, and atmospheric NO₂ (Shi et al. 2021; Connerton et al. 2020). In Brazil, the focus of this study, São Paulo (Connerton et al. 2020; Debone et al. 2020; Nakada and Urban 2020) and Rio de Janeiro (25), noticed changes in air quality. In the capital of the state of São Paulo, NO₂ concentration reduced up to 60% if the pandemic period was compared to previous ones (Connerton et al. 2020; Debone et al. 2020; Nakada and Urban 2020).

Against this backdrop, this study aims to evaluate the concentration of NO₂ in Brazilian metropolitan regions after the social distancing and isolation policy adopted to confront the Covid-19 pandemic. NO₂ is a chemical that, depending on its concentration, increases air pollution levels, directly influencing on the health of the population and increasing respiratory comorbidities (3,5). In a complementary way, the study focused on evaluating the association of other variables that can directly impact the concentration of atmospheric NO₂, such as the density of vehicles, especially of combustion engines, in the Brazilian metropolitan regions (Kroll et al. 2020; Derísio 2017; He et al. 2020). The novelty of this paper is being the very first study, in the context...
of Brazil, investigating atmospheric NO₂ concentrations by using satellite data and thorough spatial and statistical analyses.

This study was carried out in Brazil in April 2021, with data referring to the period of March 12, 2020, one day after the WHO pandemic state decree, to April 16, 2020, when actions such as social isolation reduced traffic of people and the consequent decrease in industrial production were intensified in Brazil, to avoid Covid-19 (Brasil 2020).

Materials and methods

This is a quantitative, descriptive, cross-sectional, and documentary study. Descriptive and cross-sectional research combined means that the research object can fully studied at a given historical moment (Sampieri and Collado 2013).

The satellite images used to obtain the tropospheric concentration of NO₂ were obtained by the polar satellite of low-Earth orbit Sentinel 5-P, of the European Space Agency (ESA–European Space Agency), whose purpose is to obtain information and services of air quality, ozone layer, and climate (TROPOMI 2018). The satellite is equipped with the tropospheric monitoring instrument (TROPOMI—Tropospheric Monitoring Instrument), an image spectrometer that covers ranges of ultraviolet (UV—ultraviolet), visible (VIS—visible), near infrared (NIR), and short-wave infrared (SWIR), using passive remote sensing techniques to measure, at the top of the atmosphere, the reflected and irradiated solar radiation of the Earth (Veefkind et al. 2012).

Under this configuration, TROPOMI is capable of measuring concentrations of ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), methane (CH₄), formaldehyde (HCHO), and aerosols (Veefkind et al. 2012). Information of NO₂ tropospheric column is available since April 30, 2018, with a current spatial resolution of 3.5 × 5.5 km (de Vries 2016).

The images were processed in the API (Application Programming Interface) of Google Earth Engine, from where it is possible to obtain the mean and standard deviation of NO₂ concentrations after overlapping the images, after defining the polygons of interest, which in this study are based on the territorial delimitation of metropolitan regions (Gorelick et al. 2017).

The variation in the concentration of O₃ was obtained by using the same method used to define the concentration of NO₂, previously described. To examine the monotonic association between the variables, the SPSS software was used, where Spearman’s correlation test was performed. The test was chosen in order to assess the strength of the correlation between the variables, and the association results generated were plotted in a table and interpreted at a significance level of 0.05 (Schober et al. 2018).
Results and discussion

The results of the atmospheric concentration of NO$_2$ are presented in the form of thematic maps (Figs. 1, 2, 3, 4, 5, 6, and 7), which demonstrate the variation of NO$_2$ in all metropolitan regions studied, and also in Table 1, which synthesizes the results obtained and presents the final result, in terms of percentage variation, of the two periods analyzed.

Atmospheric concentration of NO$_2$

Baixada Santista metropolitan region

Baixada Santista metropolitan region, located on the coast of the state of São Paulo, showed a 48.7% reduction in the concentration of NO$_2$ in the comparison between the period of 2019 (left) and 2020 (right). This was the highest percentage reduction observed in the metropolitan regions that were object of this study.

As shown in Fig. 1, in 2020 the high concentrations of NO$_2$ were limited to the urban and industrial nucleus of the cities of Cubatão and Santos, unlike the period of 2019, where the high concentrations were observed more than 40 km from these cities.

Belém, Belo Horizonte, Campinas, and Curitiba metropolitan regions

Belém metropolitan region, located in northern Brazil, presented a little significant reduction of 2.6% in the concentration of NO$_2$ in the two periods studied. The map in Fig. 2 shows a reduction in concentration on the urban center of Belém, compensated by the increase in other areas.

In Belo Horizonte metropolitan region, located in southeastern Brazil, the reduction observed was 11.3%, even though it was delimited in a polygon of larger scale. Then, we observe a significant reduction of 20% in the region of Campinas, which had high concentrations, in 2019, between Campinas and Americana, not observed in the period of 2020.

Finally, the reduction is also substantial in the metropolitan region of Curitiba, located in the Southern region of Brazil, where there was a decrease of 17.5%.

| Metropolitan Region | Period in 2019 | Period in 2020 | Average reduction NO$_2$ (%) |
|---------------------|---------------|---------------|----------------------------|
|                     | Mean (µmol m$^{-2}$) Standard Deviation (µmol m$^{-2}$) | Mean (µmol m$^{-2}$) Standard Deviation (µmol m$^{-2}$) |                      |
| Baixada Santista    | 41.2 27.7     | 21.1 10.9     | 48.7                       |
| São Paulo           | 57.2 39.8     | 35.6 20.4     | 37.9                       |
| Salvador            | 17.9 5.8      | 12.1 3.7      | 32.5                       |
| Florianópolis       | 13.2 3.9      | 9.2 2.2       | 30.3                       |
| Rio de Janeiro      | 32.2 20.1     | 23.6 10.1     | 26.6                       |
| Vale do Paraíba     | 16.9 6.6      | 12.8 5.3      | 24.1                       |
| Recife              | 16.9 4.5      | 12.8 1.8      | 24.1                       |
| Sorocaba            | 22.6 8.9      | 17.7 5.3      | 21.6                       |
| Campinas            | 30.2 8.5      | 24.2 6.4      | 20.0                       |
| Distrito Federal    | 12.0 2.6      | 9.8 2.0       | 18.8                       |
| Fortaleza           | 12.4 3.7      | 10.2 2.0      | 17.8                       |
| Curitiba            | 16.4 8.0      | 13.5 5.3      | 17.5                       |
| Goiânia             | 13.7 3.7      | 11.4 3.3      | 16.6                       |
| Belo Horizonte      | 16.6 5.8      | 14.7 4.5      | 11.3                       |
| São Luis            | 11.1 2.3      | 9.8 3.0       | 11.2                       |
| Petrolina           | 11.2 1.7      | 10.3 1.8      | 8.6                        |
| Natal               | 9.6 1.6       | 8.9 1.1       | 7.4                        |
| Maceió              | 11.4 1.4      | 10.8 1.5      | 5.3                        |
| Manaus              | 6.2 1.6       | 5.8 1.6       | 5.2                        |
| Teresina            | 10.0 1.4      | 9.7 1.6       | 3.7                        |
| Belém               | 8.2 2.4       | 8.0 3.3       | 2.6                        |
| Vitória             | 19.9 7.4      | 20.2 5.9      | -1.7                       |
| Porto Alegre        | 16.0 4.6      | 16.6 4.4      | -3.9                       |
| Cuiabá              | 9.1 2.1       | 10.6 1.7      | -15.7                      |
Florianópolis, Fortaleza, Goiânia, and Maceió metropolitan regions

In the metropolitan region of Florianópolis, in southern Brazil, there was an expressive reduction of 30.3% in the concentration of NO$_2$. As shown in Table 1, it is possible to notice, in addition to the reduction of the mean concentration, a reduction of the standard deviation of the obtained values, even though the values of concentrations are considered low. The metropolitan regions of Fortaleza and Maceió, both located in northeastern Brazil, had a decrease of 17.8% and 5.3%, respectively. These results can be verified in Fig. 3.

Manaus, Natal, Porto Alegre, and Recife metropolitan regions

The metropolitan region of Manaus, located in the state of Amazonas, northern Brazil, showed a small reduction in atmospheric NO$_2$ concentration; however, this reduction of only 5.2% is overshadowed by the scale of the metropolitan region, which covers a polygon with thousands of square kilometers, as illustrated in Fig. 4. The metropolitan regions of Natal and Recife, both located in northeastern Brazil, had a reduction of 7.4 and 24.1%, respectively. On the other hand, the metropolitan region of Porto Alegre, located in southern Brazil, had an increase of 3.9% in the concentration of NO$_2$, different from results observed so far.

Rio de Janeiro, Salvador, São Luís, and São Paulo metropolitan regions

In the metropolitan region of Rio de Janeiro, located in the state of the same name and southeastern region of Brazil, there was a significant reduction in NO$_2$ concentration, 26.6%. In this case, the substantial reduction was observed in both the mean concentration of NO$_2$ and the standard deviation when comparing the results of 2019 and 2020.

In the metropolitan regions of Salvador and São Luís, both located in the northeast region, there was a reduction of 32.5 and 11.2%, respectively. Figure 5 demonstrates the intense reduction observed in the region known as Recôncavo Bahiano.

Finally, the metropolitan region of São Paulo, the largest in the country, also located in the southeast region, had the second largest percentage (37.9%) reduction among the metropolitan regions studied.

Sorocaba, Teresina, São José dos Campos (Vale do Paraíba), and Vitória metropolitan regions

In the metropolitan region of Sorocaba, located in the state of São Paulo, the reduction of NO$_2$ in the compared periods was 21.6%. Figure 6 shows a reduction in the entire length between the cities of Sorocaba and Itu. Also, in the state of São Paulo, the metropolitan region of Vale do Paraíba recorded a reduction of 24.1%, more significant in the urban nucleus of São José dos Campos. Still in the southeast, there was no significant change in the metropolitan region of Vitória, Espírito Santo state. In this region, there was an increase of 1.7% in the mean atmospheric concentration of NO$_2$, although there was a reduction, according to Fig. 6, on the urban centers of Vitória and, mainly, Vila Velha.

The metropolitan region of Teresina, located in the northeast, also showed low variation in the atmospheric concentration of NO$_2$.

Brasília (Federal District), Cuiabá, and Petrolina metropolitan regions

A percentage reduction of 18.8% was observed in the Distrito Federal (Federal District of Brazil), in the Brazilian
Fig. 2 Thematic maps of the mean concentration of \( \text{NO}_2 \) from March 12 to April 16, 2019 and 2020, in the metropolitan regions of Belém, Belo Horizonte, Campinas, and Curitiba
Fig. 3  Thematic maps of the mean concentration of NO₂ from March 12 to April 16, 2019 and 2020, in the metropolitan region of Florianópolis, Fortaleza, Goiânia, and Maceió
Fig. 4  Thematic maps of the mean concentration of NO$_2$ from March 12 to April 16, 2019 and 2020, in the metropolitan regions of Manaus, Natal, Porto Alegre, Recife
Fig. 5 Thematic maps of the mean concentration of NO$_2$ from March 12 to April 16, 2019 and 2020, in the metropolitan regions of Rio de Janeiro, Salvador, São Luís, and São Paulo.
Fig. 6  Thematic maps of the mean concentration of NO$_2$ from March 12 to April 16, 2019 and 2020, in the metropolitan regions of Sorocaba, Teresina, São José dos Campos (Vale do Paraíba), and Vitória
Midwest region. Although the reduction is significant, the concentration values are considered low in both periods, as shown in Fig. 7. The region of Petrolina, in the northeast, showed a reduction of 8.6%.

Finally, the metropolitan region of Cuiabá, also in the Midwest, registered an increase of 15.7% in 2020 compared to 2019, a movement in the opposite direction to that observed in most metropolitan regions. It is observed, however, that like Manaus MR, the MR scale can distort the results, since the urban center of Cuiabá occupies only a small fraction of the polygon.

Figures 8, 9, and 10 show the variation in NO₂ concentration (only reduction) in all metropolitan regions. The higher the reduction, the higher the intensity of green color.

Table 1 summarizes the results obtained by the model for the evaluation of NO₂ concentration in the Brazilian metropolitan regions evaluated.

It is possible to observe that in 21 (87.5%) of the 24 metropolitan regions there was a reduction in the mean concentration of atmospheric NO₂. Even in regions with no reduction, one can verify the effect of the scale of the metropolitan region on the result, as occurred in Cuiabá. Similarly, in Vitória MR, there was a significant reduction in the urban centers of Vitória and Vila Velha; however, the result was affected by the adjacent regions and not necessarily in inhabited areas, although within the metropolitan region.
Variation of NO\textsubscript{2} correlations

The reduction of NO\textsubscript{2} in the comparison between the two periods was observed in most of the metropolitan regions. However, being a continental country, the Brazilian metropolitan regions have different socioeconomic characteristics, such as territorial extension, population, and number of vehicles circulating in the regions.

Table 2 indicates the results of Spearman's correlation between the variation in NO\textsubscript{2} concentration and the population density (number of inhabitants per square kilometer), the density of vehicles (number of vehicles per square kilometer), and the variation in O\textsubscript{3} concentration (in %, in the comparison between 2020 and 2019) in metropolitan regions.

At a significance level of 0.05, a moderate positive correlation (Spearman’s Rho = 0.485) was found between the NO\textsubscript{2} variation and the vehicle density. This means that in the evaluated metropolitan regions, as the density of vehicles increases, a reduction in the concentration of atmospheric NO\textsubscript{2} is expected. The existence of a positive moderate correlation was also verified for population density (Spearman’s Rho = 0.424). These are indications that point to the relevance of the contribution of combustion engines to air quality in metropolitan regions.

Regarding O\textsubscript{3}, as the p-value is above the 0.05 significance level, the association between variations in the concentration of NO\textsubscript{2} and O\textsubscript{3} was inconclusive, although the correlation coefficient shows a moderate negative correlation.

Discussion

Our analysis disclosed that satellite images showed a reduction in average NO\textsubscript{2} concentrations in 21 Brazilian metropolitan regions between March 12 and April 16, 2020, compared to the same period in 2019. Table 1 indicates a reduction in the average concentrations of NO\textsubscript{2} of 48.7% in the metropolitan region of Baixada Santista, a place with the greatest reduction, followed by the region of São Paulo (37.8%) and Salvador (32.5%). In São Paulo, the reduction observed in this study for the concentration of NO\textsubscript{2} is in line with the results obtained by automatic air quality monitoring stations, which revealed a 25% reduction in concentration in March 2020 when compared to March from 2015 to 2019 (Connerton et al. 2020). Likewise, a reduction of 26.6% found in this study for the metropolitan region of Rio de Janeiro is similar to the obtained in the evaluation by two automatic NO\textsubscript{2} monitoring stations, which between March 12 and 14 April during the years 2019 and 2020 experienced a reduction of 32.9% and 24.1% in the concentration of the pollutant (Dantas et al. 2020).

In the state of Rio Grande do Sul, the State Foundation for Environmental Protection (FEPAM) issued a report concluding that there were no significant changes in the concentration of NO\textsubscript{2} in the month of April 2020 when compared to the years 2017 to 2019, obtained by the automatic monitoring stations of Esteio, Guaiba, and Gravataí, all located in the Metropolitan Region of Porto Alegre (DQA 2020). In this work was verified a small increase of 3.6% in the concentration of NO\textsubscript{2} in the MR, confirming the insignificant variation observed by the environmental agency.

In the state of Minas Gerais, the State Environment Foundation published the report entitled “Impacts on air quality after stoppage of activities due to the COVID-19 pandemic.” The report presents significant reductions in the concentration of PM\textsubscript{2.5} and PM\textsubscript{10} in the periods of 20 March and 20 April in 2019 and 2020. There are two automatic monitoring stations in the metropolitan region of Belo Horizonte. The first showed a reduction of 31% in the concentration of PM\textsubscript{10} and 45% in the concentration of PM\textsubscript{2.5}, while the second station pointed out a reduction of 10% for PM\textsubscript{10} and 26% for PM\textsubscript{2.5} (Belo Horizonte 2020). There is no diagnosis for NO\textsubscript{2}, but the report points to a 74% reduction in traffic circulation in Belo Horizonte (2020), indicating a strong tendency to reduce NO\textsubscript{2}, as was verified in this study.

To date, no other published scholarly studies, to our knowledge, found that portrayed the variation in the concentration of air pollutants in other Brazilian metropolitan regions, using automatic air quality monitoring stations as a source of data. Nonetheless, as demonstrated, the existing ones confirm the results obtained in this study.

This reduction may be associated with the Brazilian government decrees recommending social isolation in addition to quarantine as a non-pharmacological measure for coping with coronavirus, which occurred, in general, from March 14, 2020 (Brasil 2020). In some states, the decrees were issued before that date, as in Alagoas (13 March), Distrito Federal (11 March), São Paulo (13 March), which stands out among the findings, because 5 out of the 21 regions that presented reduction in the emission of NO\textsubscript{2} are in its territory. These results explain the perception of improved air quality reported by Brazilian people, where 934 citizens, 60% of the state of Minas Gerais, 21.6% from the state of São Paulo, 3.7% from Rio de Janeiro, 2.4% from Bahia, and 2.3% from Federal District, which makes up more than 90% of the sample, reported a better quality of breathed air (Bbarieri et al 2020). These five states have nine metropolitan regions portrayed by this study, and in all of them there was a reduction in the concentration of atmospheric NO\textsubscript{2}. 

![Fig.8 Thematic maps of reduction in NO\textsubscript{2} concentrations from March 12 to April 16, 2019 and 2020, in the metropolitan regions of Baixada Santista, Belém, Belo Horizonte, Campinas, Curitiba, Florianópolis, Fortaleza, Goiânia.](image-url)
This evidence is not only pointed out by Brazil. China also showed a reduction in the average concentration of NO$_2$, recording a decrease in some of its cities, especially in February 2020, when the government has imposed interdiction measures to contain the Covid-19 epidemic (Chen et al. 2020, 2021; Dutheil et al. 2020; Venter et al. 2020; Wang et al. 2020). Similar situation was also detected in Europe (Ogen 2020; Liu et al. 2021; Burns et al. 2021; Jephcote et al. 2021; Wyche et al. 2021), Asia (Mahato et al. 2020; Thomas et al. 2020; Tyagi et al. 2021), and the USA (Connornt et al. 2020; Shi et al. 2021).

This drop coincides with the recommendation of quarantine and isolation, which limits road transport, considered the largest unnatural source of NO$_2$, and decreases the production of factories and industries and consequent daily burning of fossil fuels that causes a high concentration of atmospheric NO$_2$ (Derisio 2017; He et al. 2020; Chen et al. 2021). In addition to the smaller number of vehicles in circulation, freer traffic conditions and the absence of traffic jams also contribute to a lower emission of pollutants.

The study at hand also investigated the effects of population and vehicle density on the percentage variation of NO$_2$. Considering that social isolation measures were initiated at approximately the same time (second half of March) in all metropolitan regions, that a reduction in concentration was observed and the population and vehicle fleet remained relatively stable during the period, it was possible to observe the indirect effects of population and vehicle density in the reduction of NO$_2$ concentration. At a significance level of 0.05, the Spearman correlation coefficient found was 0.424 (population density) and 0.485 (vehicle density). The results indicate that there seems to be a dependency, albeit indirect, between the variables. This means that in those metropolitan regions where there are more vehicles per square kilometer there is a tendency for a more accentuated variation in the concentration of NO$_2$. Higher vehicle densities may be related to a greater number of NO$_2$ emitting hot spots, such as high-flow highways or roads and traffic jams.

This measure of concentration of pollutants in the air can be an important public health factor, because as pollution levels decrease, there is a 6% reduction in mortality cases (39). Considering that the interaction of the human being with the environment that is lived produces an important part of emissions that lead to air pollution (Derisio 2017), the evidence of this study shows that attitudes of social isolation directly interfere in the reduction of NO$_2$ emission that, consequently, will interfere in other important health indicators.

This is because data from the WHO show that more than four million people died worldwide from respiratory diseases per year (Cohen et al. 2017), caused by air pollution, not to mention preventable non-transmissible diseases, which may also be associated with this factor (Neira et al. 2018; Chen and Bloom 2019).

The pandemic issue sparks an important debate about the need to rethink city designs, looking at them from the perspective of health, habitability, and sustainability (Guaralda et al. 2020). In Italy, for instance, the highest incidence of cases and deaths related to Covid-19 was found in cities known to be more polluted. In cores characterized by the use of renewable energies, with generation of predominantly wind energy, there was a slowdown in the incidence of Covid-19 (Coccia 2020). The high concentration of air pollutants in urban centers exposes the weaknesses of urban centers and that puts the health of the population at risk. In Dhaka and Brisbane, for instance, the most susceptible areas to the direct impacts of climate change over the time are the affected by the peri-urbanization (Mortoja and Yigitcanlar 2020a, b).

The significant variations in NO$_2$ concentration in the metropolitan regions of Brazil also expose the need to reassess Brazil’s urban centers, since they demonstrate the emission of gases harmful to health and the environment and open wide that, although there have been regulatory instruments and development policies for the same time, there is a need for improvements in its effective implementation (Sotto et al. 2019). Encouraging the use of public transport and changing the energy matrix, with the gradual replacement of combustion vehicles, for example, are initiatives that can and should be encouraged, with instant results in air quality, as observed in the regions metropolitan areas that, forcibly, drastically reduced emissions from motor vehicles (Arbolino et al. 2018; Kamruzzaman et al. 2015).

Thus, in view of the direct relationship between the concentration of atmospheric NO$_2$ and pollution, this study can enhance the sustainable resumption of production linked to the emission of precursor gases of NO$_2$, despite the protection of pollution control measures, which directly reflect on the living and health conditions of the population in general, since contingency measures demonstrated a substantial decrease of NO$_2$ concentration levels.

It is, hence, critical to develop sound strategies for not to reverse the air quality improvements achieved during the pandemic years. In other words, stringent government policies are needed to keep the emissions low and even further lower them (Rivers and Jaccard 2005; Pane 2020; Dang and Trinh 2021). To this end, we advocate the following actions for government authorities to adopt:
Putting a cost on pollution by pricing the carbon externality for both producers and users of the polluting goods or services (Sterner 2012; Hagmann et al. 2019); Providing incentives for the development and use of sustainable energy and mobility solutions (Butler et al. 2020, 2021); Revisiting climate and energy-related legislations and adopting the New Green Deal for speeding up a green transition (Hafner and Raimondi 2020; Barry and Hoyne 2021); Investing on the state-of-the-art air quality monitoring and analysis systems (Liu et al. 2018; Gonzalez-Martin et al. 2021); Planning for sustainable urban form and transport integration to reduce emissions (Yigitcanlar and Kamruzzaman 2014; Dur and Yigitcanlar 2015); Offering government-financed stimuli for not rolling back environmental regulations and halting spending on a green transition (Elliott et al. 2020; D’Orazio 2021); Initiating the adoption of degrowth model all across the globe for reduced emissions (Perkins 2019; Kallis 2021); Depoliticizing the climate change and making climate action inclusive of all sides of politics and all members of the public through education and awareness raising campaigns (Díaz-Pont 2021; Mortoja and Yigitcanlar 2022).

**Conclusion**

The measures adopted to contain the Covid-19 virus (SARS-CoV-2) pandemic showed a reduction in the emission of NO$_2$ in most metropolitan regions of Brazil, especially after the state of pandemic, determined by WHO, which in turn decreased fuels burning due to the reduction of circulation of vehicles and industrial activities, to the detriment of social isolation and quarantine measures encouraged to reduce the transmission of SARS-CoV-2.

This study raises the government’s need to encourage public policies that enable a rational organization about economic activities and the preservation of the environment in the post-pandemic period, since such actions impact on the reduction of mortality rates from other diseases respiratory, since the increase in NO$_2$ causes toxicity when there is long-term exposure, in the maintenance of air quality and the planet’s biodiversity, because the high level of this compound in the air leads to damage to nature due to its corrosive characteristic, causing acid rain which, when falling to the surface, alters the chemical composition of the soil and water, reaching food chains, destroying forests and crops. Therefore, this research leads to reflection on new strategies that are alternatives to the reduction of NO$_2$ emission, such as accessible public transport, use of alternative energy sources, such as electricity, solar, biofuel, to maintain the health of the population.

In this regard, we conclude the paper by advocating Quéré et al. (2021) following assertion, “five years after the adoption of the Paris Climate Agreement, growth in global CO$_2$ emissions has begun to falter. The pervasive disruptions from the Covid-19 pandemic have radically altered the trajectory of global CO$_2$ emissions. Contradictory effects of the post-Covid-19 investments in fossil fuel-based infrastructure and the recent strengthening of climate targets must be addressed with new policy choices to

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**Table 2** Spearman’s correlations for NO$_2$ variation, O$_3$ variation, population density, and vehicle density

| Spearman’s Rho | NO$_2$ var (%) | O$_3$ var (%) | Population density | Vehicle density |
|----------------|---------------|---------------|-------------------|----------------|
| NO$_2$ var (%) | Correlation Coefficient | 1.000 | -0.388 | 0.424$^*$ | 0.485$^*$ |
| Sig. (2-tailed) | 0.061 | 0.039 | 0.016 |
| N | 24 | 24 | 24 |

| O$_3$ var (%) | Correlation Coefficient | -0.388 | 1.000 | -0.034 | -0.271 |
| Sig. (2-tailed) | 0.061 | 0.875 | 0.200 |
| N | 24 | 24 | 24 |

| Population density | Correlation Coefficient | 0.424$^*$ | -0.034 | 1.000 | 0.922$^{**}$ |
| Sig. (2-tailed) | 0.039 | 0.875 | 0.000 |
| N | 24 | 24 | 24 |

| Vehicle density | Correlation Coefficient | 0.485$^*$ | -0.271 | 0.922$^{**}$ | 1.000 |
| Sig. (2-tailed) | 0.016 | 0.200 | 0.000 |
| N | 24 | 24 | 24 |

$^*$Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed)
sustain a decline in global emissions in the post-Covid-19 era.” As emphasized by Sarimin and Yigitcanlar (2012) one of the promising policy choices to achieve climate and sustainable development targets is the knowledge-based development of our cities and societies.

Besides the NO$_2$ findings, our study has also underlined the importance of continuous, i.e., time series, analysis on the air quality. Moreover, in interpretation of the results, we note the following limitations of the study. The limitations of this case report are tied to the period researched (the period of 36 days, 12 March to 16 April both in 2019 and 2020), since we considered the WHO declaration of pandemic as the start date for the execution of the research in all regions. Nonetheless, there is a delay between that declaration and the restriction measures adopted by governments and regional agencies. Furthermore, investigation of a single air pollutant is a limitation, despite we also liked at the O$_3$. Another limitation of this study is not to focus on the policy issues and prescribe public policy and actions to address the air pollution and climate change issues in Brazil. Nevertheless, our prospective research will focus on these limitations by considering NO$_2$ and also other pollutants and investigating larger timeframes and conduct time series analyses and prescribe relevant policy actions.

**Appendix**

**Appendix A: GEE code used for São Paulo MR**

```javascript
var regiao = "SaoPaulo";
// Inicia as datas do periodo;
var dataAntes = new Date('2019-04-24');
var dataDepois = new Date('2020-04-24');
var dataDepois = new Date('2020-04-24');
var antes = ee.ImageCollection('COPERNICUS/S5P/NRT/L3_NO2')
  .filterDate(dataAntes, dataAntes);
var depois = ee.ImageCollection('COPERNICUS/S5P/NRT/L3_NO2')
  .filterDate(dataDepois, dataDepois);
// Limite entre paredes, um dos valores: saoPaulo, Vitoria, etc.
var mediaAntes = antes.mean();
var mediaDepois = depois.mean();
var infoAntes = antes.select().filterBounds(regiao)
    .filterDate(dataAntes, dataAntes);
var infoDepois = depois.select().filterBounds(regiao)
    .filterDate(dataDepois, dataDepois);
print('Número de imagens utilizadas para "ANTES"', infoAntes);
print('Número de imagens utilizadas para "DEPOIS"', infoDepois);
// Define a boxcar ou low-pass kernel.
var boxcar = ee.Kernel.square(radius: 3, units: 'pixels', normalize: true);
// Smooth the image by convolving with the boxcar kernel.
var smoothAntes = mediaAntes.convolve(boxcar);
var smoothDepois = mediaDepois.convolve(boxcar);
var band_viz = [
  min: 0,
  max: 0.00004,
  palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']
];
var band_viz2 = [
  min: 0.00004,
  max: 0.00006,
  palette: ['green', 'yellow', 'red']
];
Map.addLayer(boxcar);
Map.addLayer(smoothAntes.clip(regiao), band_viz, 'NO2 Antes', 0);
Map.addLayer(smoothDepois.clip(regiao), band_viz, 'NO2 Depois', 0);
Map.addLayer(smoothAntes.clip(regiao), band_viz, 'NO2 Antes Saws', 0);
Map.addLayer(smoothDepois.clip(regiao), band_viz, 'NO2 Depois Saws', 0);
Map.addLayer(smoothAntes, band_viz, 'NO2 antes global', 0);
Map.addLayer(smoothDepois, band_viz, 'NO2 depois global', 0);
Map.centerObject(regiao);
// Parâmetros.
var redutores = ee.Reducer.sum().combine({
  redutores: ee.Reducer.stdDev(),
  redutores: ee.Reducer.min(),
  redutores: ee.Reducer.max(),
  redutores: ee.Reducer.histogram(),
  redutores: ee.Reducer.first(),
  sharedSpots: true
});
var estatAntes = mediaAntes.reduceRegion(
  redutores: redutores,
  geometry: regiao, projection(),
  scale: 5000,
  maxPixels: 1e9,
  bestEffort: true
);
var estatDepois = mediaDepois.reduceRegion(
  redutores: redutores,
  geometry: regiao, projection(),
  scale: 5000,
  maxPixels: 1e9,
  bestEffort: true
);
print('SD Antes: ', estatAntes);
print('SD Depois: ', estatDepois);
var opcionesAntes = {
  title: 'Quantidade de Pixels X Concentração de NO2 (mol/m^3) - Antes',
  format: 'html',
  xAxis: {title: 'NO2 (mol/m^3)'}
};
```
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Availability of data and material All data are available in its sources.

Code availability (software application or custom code). All softwares are open source. The created code is attached.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Consent to participate Not applicable.

Consent for publication Not applicable.

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