applied sciences

MDPI

Article

Emissions Reduction of Greenhouse Gases, Ozone Precursors, Aerosols and Acidifying Gases from Road Transportation during the COVID-19 Lockdown in Colombia

Yiniva Camargo-Caicedo [1,*], Laura C. Mantilla-Romo [1] and Tomás R. Bolaño-Ortiz [2,3,4,*]

[1] Environmental Systems Modeling Research Group (GIMSA), Universidad del Magdalena, Santa Marta 470001, Colombia; lauramantillacr@unimagdalena.edu.co
[2] Mendoza Regional Faculty-National Technological University (FRM-UTN), Mendoza M5500, Argentina
[3] National Scientific and Technical Research Council (CONICET), Mendoza M5500, Argentina
[4] Centre for Environmental Technologies (CETAM), Universidad Técnica Federico Santa María, Valparaíso 46383, Chile
* Correspondence: ycamargo@unimagdalena.edu.co (Y.C.-C.); tomas.bolano@frm.utn.edu.ar (T.R.B.-O.)

Abstract: The aim of this work was to analyze the changes in the emissions from the transport sector during the COVID-19 lockdown in Colombia. We compared estimated emissions from road transportation of four groups of pollutants, namely, greenhouse gases (CO_2, CH_4, N_2O), ozone precursor gases (CO, NMVOC, NOx), aerosols (BC, $PM_{2.5}$, PM_{10}), and acidifying gases (NH_3, SO_2), during the first half of 2020 with values obtained in the same period of 2018. The estimate of emissions from road transportation was determined using a standardized methodology consistent with the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories and the European Environment Agency/European Monitoring and Evaluation Program. We found a substantial reduction in GHG emissions for CH_4, N_2O, and CO_2 by 17%, 21%, and 28%, respectively. The ozone precursors CO and NMVOC presented a decrease of 21% and 22%, respectively, while NOx emissions were reduced up to 15% for the study period. In addition, BC decreased 15%, and there was a reduction of 17% for both PM_{10} and $PM_{2.5}$ emissions. Finally, acidifying gases presented negative variations of 19% for SO_2 and 23% for NH_3 emissions. Furthermore, these results were consistent with the Ozone Monitoring Instrument (OMI) satellite observations and measurements at air quality stations. Our results suggest that the largest decreases were due to the reduction in the burning of gasoline and diesel oil from the transport sector during the COVID-19 lockdown. These results can serve decision makers in adopting strategies to improve air quality related to the analyzed sector.

Keywords: COVID-19; lockdown; acidifying gases; aerosols; greenhouse gases; ozone precursors; road transportation; Colombia

check for updates

Citation: Camargo-Caicedo, Y.; Mantilla-Romo, L.C.; Bolaño-Ortiz, T.R. Emissions reduction of Greenhouse Gases, Ozone Precursors, Aerosols and Acidifying Gases from Road Transportation during the COVID-19 lockdown in Colombia. *Appl. Sci.* **2021**, *11*, 1458. https://doi.org/10.3390/app11041458

Academic Editor: Thomas Maggos
Received: 27 December 2020
Accepted: 26 January 2021
Published: 5 February 2021

1. Introduction

COVID-19 emerged on 30 December 2019 [1] and was declared a global pandemic by the World Health Organization on 11 March 2020 [2]. The outbreak of the virus started in Wuhan, the capital of Hubei Province, China, and in a few weeks, it had spread to dozens of other countries in Asia [3]. Since then, the SARS-CoV-2 virus has spread in Africa, America, Asia, Europe and Oceania [4]. It led to most countries adopting isolation measures to stop its spread and avoid the collapse of health systems [5]. The first case in Colombia was confirmed by the National Health Institute on 6 March 2020. The Ministry of Health and Social Protection declared a public health emergency in the country on 12 March 2020, and a few weeks later, the Ministry of Interior ordered preventive lockdown and containment measures starting on 25 March 2020, whereby many human activities in the educational, cultural, transportation, and industrial manufacturing sectors were constrained. Consequently, educational institutes and non-essential factories remained closed, public events were cancelled, and work at home was implemented, to prevent the further spread of the COVID-19 pandemic.

The anthropogenic changes caused by the lockdown led to a decline in industrial production and energy consumption, up to 30% in some countries [6,7]. Energy demand has been altered drastically worldwide, and due to forced confinement, many international borders were closed and populations were isolated in their homes [8]. This led to a change in some consumption patterns for energy, e.g., those related to the transport sector, because of a reduction in mobility. These restrictions on economic activity during the pandemic have reduced NO_2 emissions in China, Europe and the United States during COVID-19 [9].

Mobility has also been one of the things most affected by the COVID-19 restrictions. The changes in patterns of mobility indicate a reduction in vehicular traffic; as a consequence, a decrease in emissions associated with this sector is to be expected, given that the greenhouse gas (GHG) emissions from road and aviation transportation make up 72% and 11% of all GHG emissions, respectively [10]. Consequently, containment measures implemented in various countries have shown changes in the air quality [11–14]. The use of fossil fuels by road vehicles is the main source of four groups of pollutants, including GHG [10], including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); ozone precursor gases, such as carbon monoxide (CO) [15], non-methane volatile organic compounds (NMVOC) [16], and nitrogen oxides (NOx) [17,18]; aerosols, including black carbon (BC) [10] and particulate matter ($PM_{2.5,}$ PM_{10}) [15]; acidifying gases, such as ammonia (NH_3) [19] and sulfur dioxide (SO_2) [20]. GHG emissions, such as CO_2, are mainly produced by power generation and road transport. Other GHG emissions, such as CH_4, are generated by fermentation processes, fossil fuel extraction and use, landfills and waste. In addition, N_2O is produced from soil emissions [21]. Ozone precursor gases, such as CO, are emitted by incomplete fuel combustion of road transport as well as industrial processes [22]. NMVOCs are important air pollutants because of their contributions of secondary compounds (aerosols and ozone), generated from gasoline combustion [16,23,24]. The emissions of NOx (NOx = NO + NO_2) mainly include biomass burning and fuel combustion (e.g., power plant combustion, industrial emissions and transportation emissions) [25]. Aerosol emissions are contributed mostly as by-products of combustion from thermal power stations, vehicle engines and factories [26], with on-road vehicles being the source of fine particulate matter ($PM_{2.5}$) [27]. In addition, one of the main anthropogenic emissions sources of BC is the incomplete combustion of fossil fuels (especially diesel) in vehicles [10]. Acidifying gases are emitted by the combustion of biomass and fossil fuels as well as by industrial activity [19,20]. NH_3 emissions related to road traffic are due to use of catalytic NOx reduction systems on light and heavy-duty vehicles [19], whose devices use an injection of urea or ammonia [28]. Recent studies showed that the containment measures to minimize the spread of SARS-CoV-2 have resulted in reductions of 15% to 40% in industrial sectors and temporarily reduced China's CO_2 emissions by 25%. The European Public Health Alliance (EPHA) states that, in Italy, the urban NO_2 pollution comes mainly from traffic, especially diesel vehicles, which are also a major source of particulate matter; the COVID-19 pandemic has resulted in a remarkable drop in these pollutants. France also showed a drop in NOx emissions as a result of the reduction in economic activities and transportation. During the spread of the COVID-19 pandemic in New York, traffic levels were estimated to be down 35% compared with the previous year; significant decreases in the emissions of CO and CO_2 were registered, with a 5–10% reduction in CO_2 [26].

Some studies have examined the effects of the COVID-19 lockdown on urban mobility [18,29–31]. The data show that mobility has dropped around the world as the spread of the virus has increased; public transportation systems were the most affected due to users refusing to use them in order to avoid social contact, and therefore the risk of contagion [32]. Other studies have shown an improvement in air quality in some Colombian cities due to mobility restrictions during the COVID-19 lockdown [33,34]. However, these studies did not look at the changes in atmospheric emissions associated with the observed air quality changes. Google, in its COVID-19 Community Mobility Reports for Colombia (https://www.google.com/covid19/mobility/), reports that, in April 2020, the country saw the biggest reduction in visits to retail and recreation places (77%), transport stations (77%), parks (67%), grocery stores and pharmacies (59%), and workplaces (58%), while the trend of mobility in residential areas increased by 28%. At the beginning of May, the opening of some economic sectors caused an increase in mobility in relation to the previous month, especially in workplaces (17%), grocery stores and pharmacies (13%), retail and recreation places (10%), and transport stations (9%).

Therefore, the aim of this study is to analyze the changes in the emissions associated with road transportation during the COVID-19 lockdown in Colombia, comparing these emissions with values obtained in the same period of 2018 for four groups of pollutants, namely, GHGs (CH_4, CO_2, N_2O), ozone precursor gases (CO, NMVOC, NOx), aerosols (BC, PM_{10}, $PM_{2.5}$), and acidifying gases (NH_3, SO_2). The results can serve decision makers in the development of strategies to improve air quality related to the road transport sector in Colombia. This article is ordered as follows. Section 2 describes the methodology applied to estimate emissions in Colombia and details the changes in air quality observed by Bogotá's air quality network and from the OMI satellite. Section 4 details the results of the emissions changes and improvements in air quality in Colombia due to its COVID-19 pandemic lockdown, while Section 5 discusses the results and provides further analysis in light of updated literature. Finally, Section 5 reports the main conclusions and perspectives.

2. Materials and Methods

2.1. Study Area

Colombia occupies a total surface of 1,140,000 km^2 in the northern part of South America (Figure 1). It has a population of approximately 49.5 million inhabitants, distributed into 32 departments and one capital district, Bogotá D.C., with a population of 7.8 million [35]. The gross domestic product (GDP) was 323.80 billion USD (at current prices), with a per capita income of 7842 USD (GDP/capita) in 2019, according to the World Bank data and its trading economics projections [36]. The country's vehicle fleet reached 15.6 million units in 2020 [37], with a fuel consumption during the first half of the year equivalent to 2.5 million m^3 diesel oil, 2.6 million m^3 gasoline and 600,000 m^3 compressed natural gas (CNG). According to the last Colombia GHG national inventory presented to the Intergovernmental Panel on Climate Change (IPCC) [38], from a sectorial point of view, annual Carbon Dioxide Equivalent (CO_2 eq.) emissions (for the year 2012) correspond to 158.6 Tg to agriculture, 78.0 Tg to energy, 13.3 Tg to waste, and 8.9 Tg to industry. While the transport sub-sector emitted 28.2 Tg, contributing 36% of energy sector emissions and 11% of the total emissions of the country.

2.2. Emission Estimation

We studied emissions from road transportation in four groups of pollutants that affect climate change, air quality and health, namely, GHGs (CH_4, CO_2 and N_2O), ozone precursor gases (CO, NMVOC and NOx), aerosols (BC, PM_{10} and $PM_{2.5}$), and acidifying gases (NH_3 and SO_2).

Several studies have been conducted to estimate the emissions from road transportation based on fuel consumption [17,39,40]. To estimate these emissions, we selected a standardized methodology consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [41] and the method from the EEA/EMEP Emission Inventory Guidebook 2019. [42]. Thus, we used tier 1 methods that use activity data derived from available statistical information (energy statistics, production statistics, traffic counts, population size, etc.). In addition, tier 1 emission factors were chosen to represent "typical" or "averaged" process conditions; they tended to be independent of technology. Furthermore, we used an additional level of detail (tier 2) for the calculation of SO_2 emissions, since Colombian fuel emission factors were used [43]. This is consistent with previous studies that showed that this methodology was adequate to estimate inventories at the national level, when detailed information by city was not available [20,44–47]. Overall, the method was based on estimating emissions through a linear relationship between activity data and emission factors (Table A1). The calculation was made using Equation (1), as follows:

$$E(p) = \sum_{p,f,v} \left(Fuel_{f,v} * Ef_{p,f,v} \right) \tag{1}$$

where *E (p)* is the total emission for species or pollutant p, *Fuel (f,v)* is the fuel sold (diesel, gasoline and CNG) for type of vehicle v, *Ef (p,f,v)* is the emission factor for pollutant species p, for type of fuel f and vehicle v.

Figure 1. Location of Colombia in South America. Study area covers the entire territory of Colombia.

Therefore, the emission estimate for each polluting species was calculated using Equation (1) with the following data:

Fuel: We used the Statistical Bulletin by Ministry of Mines and Energy [48], which includes activities such as monthly sales of fuels for the first half of 2018. We used the Liquid Fuel Information System (SICOM) [49], which includes monthly sales to fuel retail distributors for the first half of 2020. In addition, we used the Mercantile Exchange

Colombia [50] (as shown in Table A2), for data on the consumption of CNG (Figure A1). Furthermore, considering that consumption was only focused on the transport sector, fuel distribution data was obtained from automotive service stations, assuming 96% of the distribution of the total of this category (retail distributors) was the total of the fuel supply, according to SICOM data [49]. For fuel consumption by vehicle type, the consumption distribution percentages (Table 1) of the indicative action plan for energy efficiency [51] were selected, calculating consumption by vehicle category.

Table 1. Fuel consumption by vehicle category [51].

Fuel	**Consumption (%)**				
	Cars	**Cargo**	**Public Transport**	**Motorcycles**	**Others**
Gasoline	77	-	-	22	1
Diesel oil	18	53	26	-	3
CNG	91	7	2	-	-

Number of vehicles: Census of number of vehicles by type (vehicle category) from the Single National Traffic Registry of Colombia [37].

Emission factors: The emission factors considered were those established by the EMEP/EEE Joint Inventory Guide to Air Pollutant Emissions database [42], for vehicle type and pollutant (GHGs, ozone precursors, aerosols and acidifying gases). The SO_2 emission factor and the power calorific value by type of fuel was obtained from the 2016 UPME FECOC calculator (Colombian fuel emission factors) in energy units (Kg Tj^{-1}) [43], except the CNG power calorific value was taken from the PROMIGAS technical notes [52]. These values were assumed for all types of vehicle under study. Additionally, CO_{2eq} from the main GHGs (CH_4 and N_2O) was estimated. CO_{2eq} emissions with a 100-year horizon global warming potential (GWP100: $CH_4 = 28$ and $N_2O = 298$) have been considered through the IPCC's suggestion in the 5th Assessment Report (AR5) [53]. We analyzed the monthly variations in emissions from January to June 2018 and 2020. The emissions reduction during the COVID-19 pandemic lockdown in Colombia was calculated based on the year 2018.

2.3. Emissions Reduction vs. Air Quality Improvement

We analyzed the improvements in air quality to relate them to the emission reductions analyzed during the quarantine period. We used data from five air quality traffic stations in Bogotá (Carvajal-Sevillana, Estación Móvil, Fontibón, Las Ferias, Minambiente) available in the Bogotá Air Quality Monitoring Database (BAQMD) [54]. These data were used to assess the air quality concentration of CO, SO_2, NO_2 and O_3; the equipment used by BAQMD is specified in Table A3. For each station, data from April, May and June of 2018 were used to calculate the mean concentrations of each pollutant for each month. Similarly, data from April, May and June of 2020 were used to calculate mean levels of each pollutant during the lockdown. It is worth clarifying that BAQMD reports pollutant concentrations under standard conditions (1 atm and 25 °C). Thus, this allowed us to perform a comparison with concentrations during the same period of a base year (2018). This base-year comparison was also performed to control for meteorological conditions. We used tropospheric NO_2 data for April to June 2018 and 2020, retrieved from the ozone monitoring instrument (OMI), a visual and ultraviolet spectrometer aboard the NASA Aura spacecraft [55]. This information enabled the emissions analysis and estimation associated with road transportation in the four groups of pollutants previously cited. In addition, the average NO_2 retrieved from OMI data was estimated for the period of April to June 2018 and 2020 to evaluate the NO_2 level variation during the pandemic lockdown in Colombia [56].

3. Results

Figure 2 shows the monthly emissions of analyzed pollutants for the compared periods. In the first half of 2020, the emissions of the four groups of pollutants associated with road transportation decreased starting in March compared with those estimated for the base year 2018. In late March 2020, the national government adopted vehicle restrictions, so April showed a higher reduction of GHG emissions for CO_2, CH_4 and N_2O in percentages equivalent to 58%, 40% and 71%, respectively. CO_2 reduction was the most representative due its contribution of 97.62% of the total emissions from the transport sector, specifically the burning of fossil fuels by road transportation (lightweight and cargo vehicles) [38]. Later, GHG emissions increased in May by 24%, 16% and 27% for CO_2, CH_4 and N_2O, respectively, owing the reactivation of some economic sectors. Restrictions began to be relaxed, allowing the opening of some activities that were restricted during the confinement. As a result, GHG emissions in June continued to increase, though they remained lower than those of 2018.

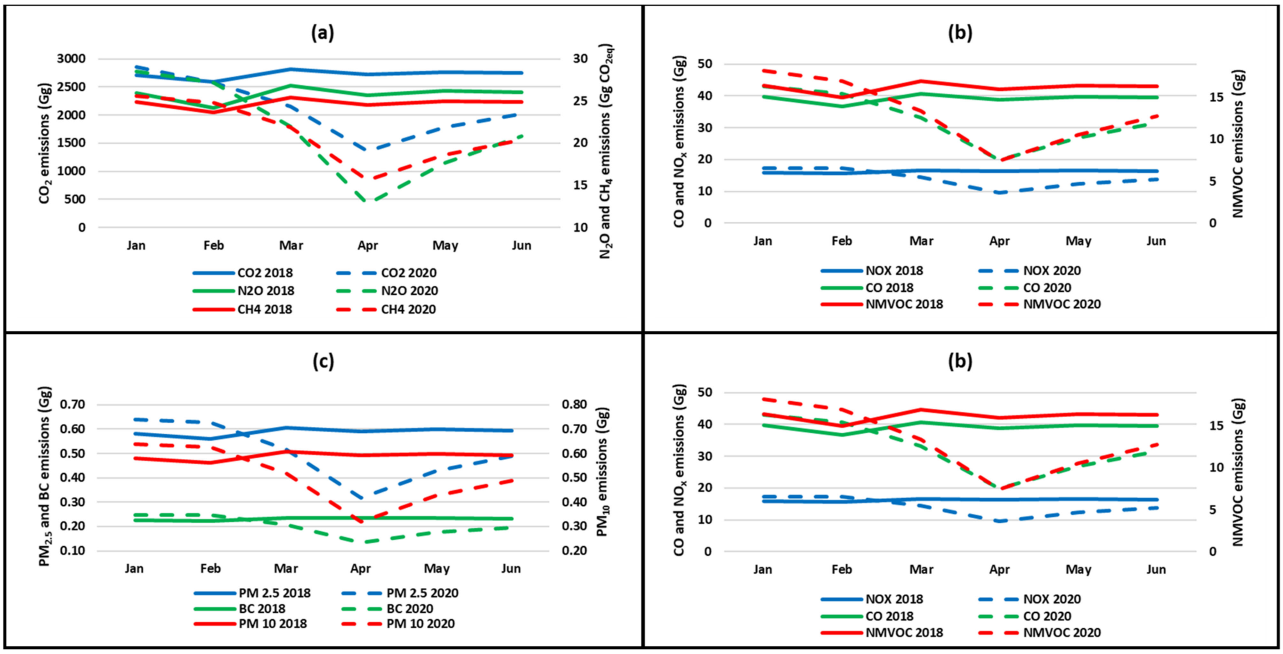

Figure 2. Estimated total emissions (Gg) of the four groups of pollutants that affect climate change, air quality and health: (**a**) GHGs (CH_4, CO_2 and N_2O); (**b**) ozone precursors (CO, NMCOV and NOx); (**c**) aerosols (BC, PM_{10} and $PM_{2.5}$); (**d**) acidifying gases (NH_3 and SO_2) for January to June of 2018 and 2020.

As shown in Figure 3, all estimated pollutants showed reductions between January and June 2020 due to the pandemic lockdown in Colombia. Negative variations in GHG emissions were 28%, 17% and 20% for CO_2, N_2O and CH_4, respectively. While the ozone precursor group showed a reduction of up to 21% and 22% for CO and NMVOC, respectively. The emissions of these pollutants were mostly the result of burning gasoline and diesel oil, which represent 90% of the total emissions. In addition, the NOx emissions variation was −15% for the study period, with 50% of the total emissions by this pollutant attributed to the burning of diesel oil.

Aerosol emissions of PM_{10} and $PM_{2.5}$ each showed a negative emissions variation of 17%, which was associated mostly with the fuel consumption by cargo vehicles and public transport [57]. BC emissions showed a decrease of 15%, and acidifying gases also displayed reductions. SO_2 emissions showed a negative variation of 19%, while NH_3 emissions were reduced by 23% of its. These emissions reductions were mainly produced by the reduction in consumption of gasoline and diesel oil. In general, pollutant groups that registered the most reduction in emissions variations were GHGs (−22%) and acidifying gases (−21%), while CO_2 presented the greatest reduction among all pollutants analyzed.

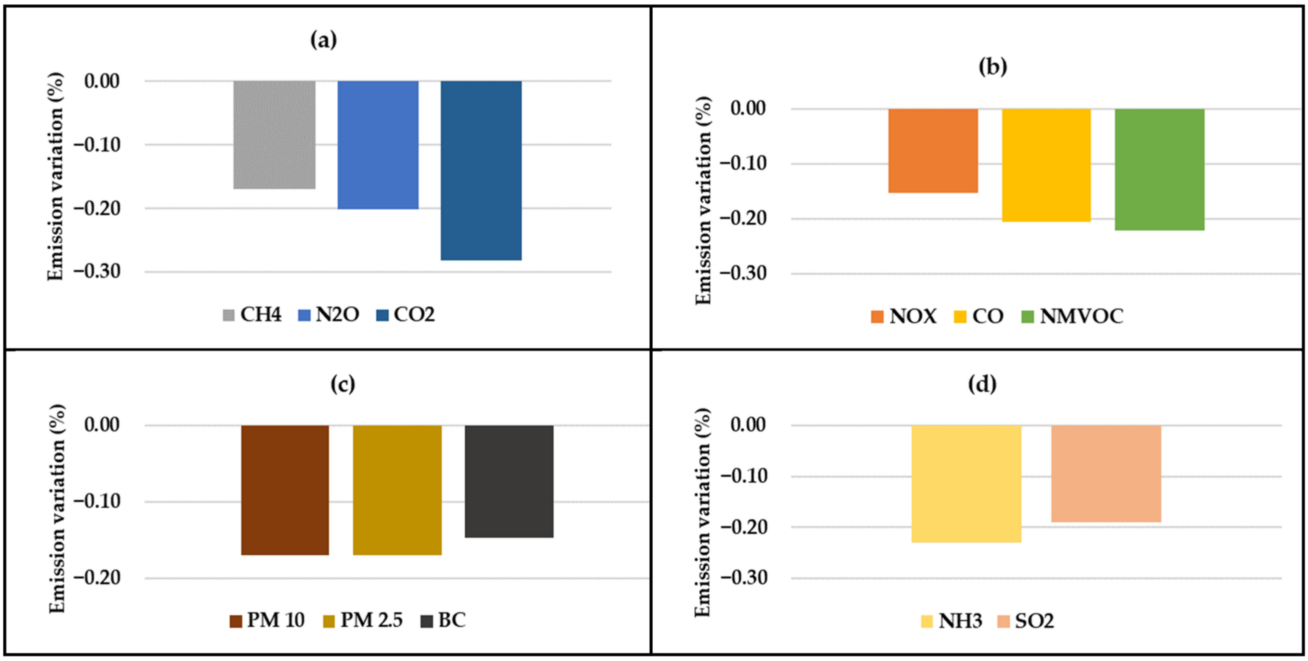

Figure 3. Emissions variations of the four groups of pollutants in the study: (**a**) GHGs; (**b**) ozone precursors; (**c**) aerosols; (**d**) acidifying gases, during the January to June 2020 in relation to the same period of 2018.

Figure 4 shows the variations in CO_2 emissions in Colombia. Territorial divisions that showed the greatest reduction in CO_2 emissions were Bogotá D.C. (−4168 Gg CO_2), Magdalena (−1381 Gg CO_2), Bolívar (−308 Gg CO_2), Atlántico (−118 Gg CO_2), and Caquetá (−30 Gg CO_2). These contrast with positive emission variations in departments such as Valle del Cauca (295 Gg CO_2), Cundinamarca (278 Gg CO_2), Norte de Santander (248 Gg CO_2), Antioquia (232 Gg CO_2), and Cesar (209 Gg CO_2), during the study period.

Colombian administrative divisions that showed the greatest reduction in CO_2 (Bogota, Magdalena, Bolivar, Atlántico and Caquetá) make up 44.5% of the national population. The circulation of people was reduced to avoid contagion by COVID-19. Thus, these territories registered (between March and June 2020) a decrease of 6005 Gg of CO_2 compared to the same period in 2018. While Valle del Cauca, Cundinamarca, Norte de Santander, Antioquia, and Cesar departments reported a total increase of 1262 Gg CO_2. Overall, the net reduction in Colombia was approximately of 4743 Gg CO_2 (Table A4).

Considering the significant emission reduction of CO_2 in Bogotá D.C., associated with road transportation and its population density, we also analyzed data from five air quality traffic stations in Bogotá. In addition, we evaluated the concentrations of CO, SO_2, NO_2 and O_3 during the lockdown period ranging from April to June 2020 and compared these to the same period in 2018. We observed significant air quality improvements through a decrease in CO, SO_2 and NO_2 in areas influenced by vehicular traffic. Drastic reductions in CO (up to −60.85%), SO_2 (up to −73.23%), and NO_2 (up to −60.60%) concentrations were observed in the urban area during the lockdown, as shown in Table 2. By contrast, an increase of up to 106.32% (in May) in ozone concentrations was observed in urban areas of Bogotá.

Figure 5 shows NO_2 concentration reductions visualized by satellite measurement of background tropospheric data available from OMI. The levels of NO_2 over Colombia decreased substantially in the Central Region during the lockdown (April to June 2020) compared to the same period in 2018. Nevertheless, the north region showed an increase in the levels of NO_2 over Atlántico, Bolívar, Cesar, La Guajira and Magdalena departments.

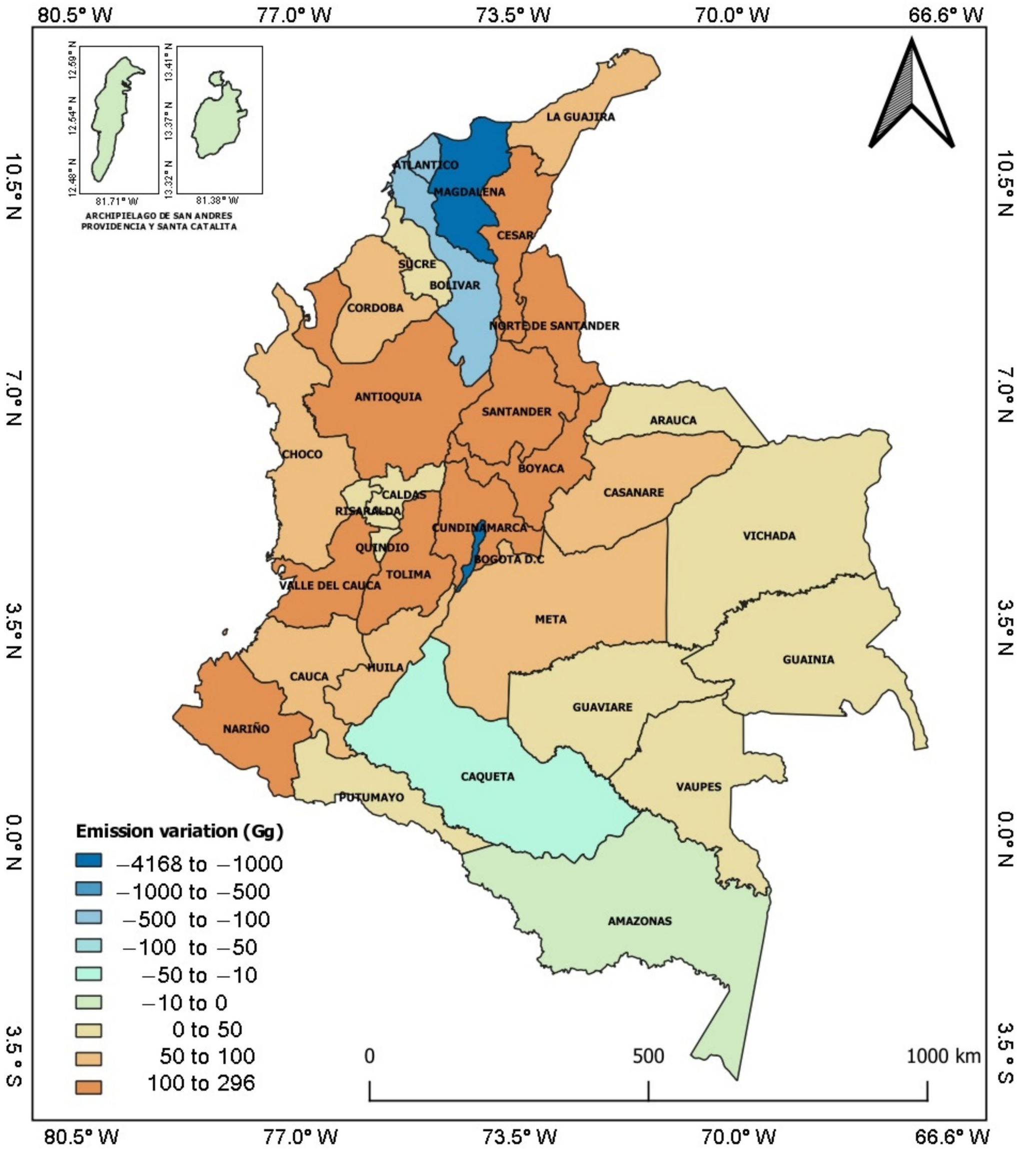

Figure 4. Spatial distribution of CO_2 emissions variation through internal political and territorial divisions (departments). Warm and cold colors indicate an increase and decrease, respectively, in emissions between the March and June 2018 and 2020.

Table 2. Mean concentration and standard deviation of CO, SO_2, NO_2 and O_3 in Bogotá during the lockdown (April to June 2020) compared to the same period in 2018 [54].

Air Pollutant	Mean Concentration 2018 (μg.m^{-3})			Mean Concentration 2020 (μg.m^{-3})			Variation of Mean Concentrations (%) from 2018 to 2020		
	Apr	May	Jun	Apr	May	Jun	Apr	May	Jun
CO	1408.75 ± 363.64	1269.63 ± 304.62	1074.67 ± 396.98	551.55 ± 276.74	787.13 ± 301.38	920.46 ± 422.75	−60.85	−38.18	−13.8
SO_2	3.90 ± 2.00	3.41 ± 1.26	4.50 ± 1.50	2.83 ± 1.19	3.30 ± 2.06	4.13 ± 2.15	−27.39	−16.57	−8.22
NO_2	56.10 ± 12.20	44.70 ± 7.82	46.60 ± 7.46	22.10 ± 9.75	27.80 ± 14.46	29.30 ± 12.59	−60.6	−37.81	−37.12
O_3	14.66 ± 6.88	10.28 ± 3.95	13.06 ± 6.75	37.53 ± 13.61	21.21 ± 7.07	18.16 ± 7.43	60.92	106.32	27.66

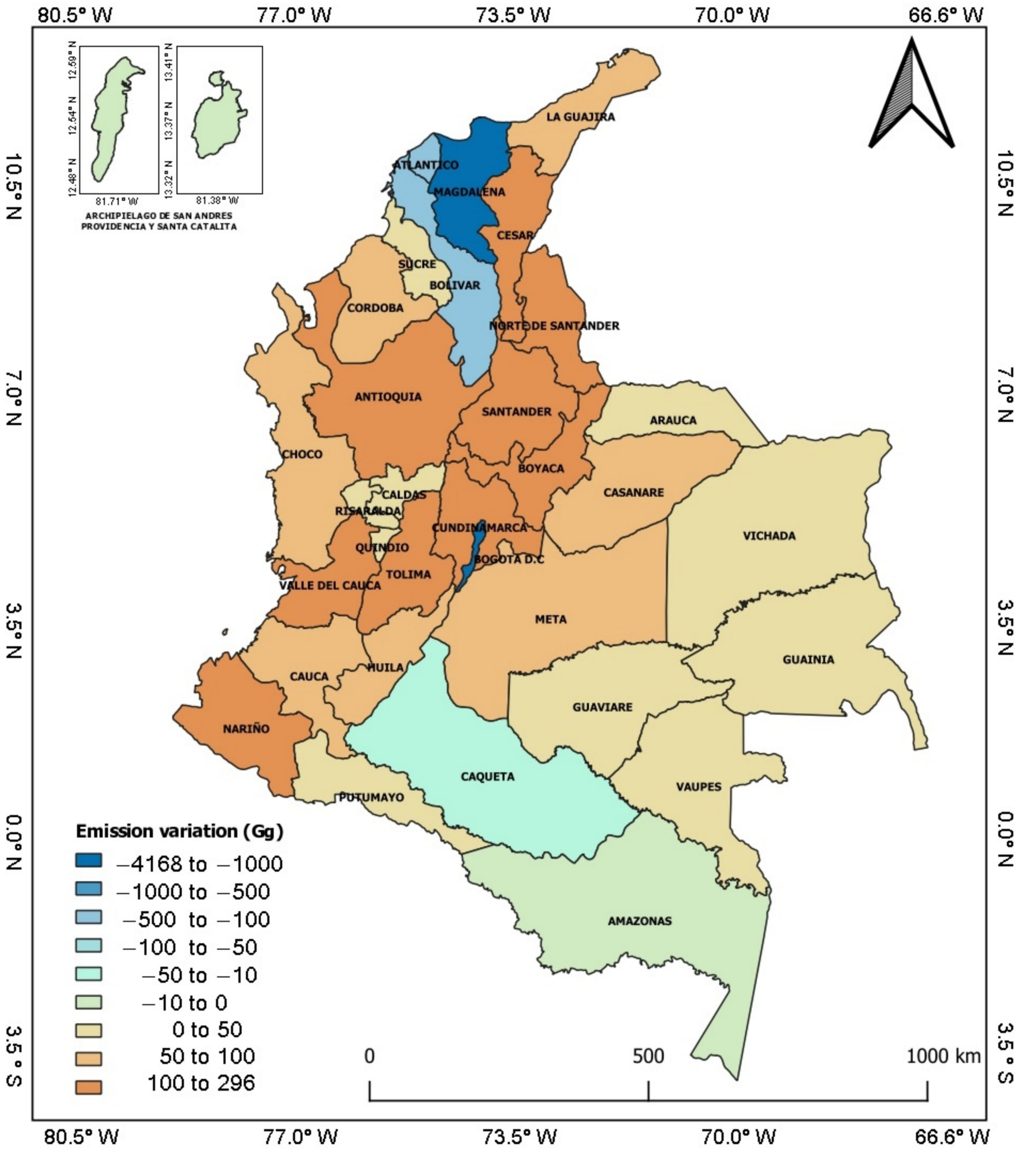

Figure 5. Spatial distribution of mean levels of tropospheric NO_2 through internal political and territorial divisions (departments) between April and June 2018 and 2020. Source: Time averaged map of NO_2 tropospheric column (30% cloud screened) daily 0.25 deg. (OMI OMNO2dv003) $1/cm^2$.

4. Discussion

The Colombian government's restrictions to curb the spread of the COVID-19 pandemic have had a significant impact in several sectors of its economy due to the cessation of some activities [58]. Our results showed reductions for the four groups of pollutants analyzed. In particular, a total of 6010 Gg were eliminated, mainly in seven territorial subdivisions of Colombia where close to 50% of the national population live [59]. One of the positive impacts identified is the emissions reduction from decreased road transport. This is registered by recent studies on air quality improvements carried out in Sao Paulo (Brazil), which reported high reductions of air pollutant concentrations during its partial lockdown due to the decrease in vehicular traffic in analyzed areas [60]. In Barcelona (Spain), the most significant reductions were estimated for pollutants related to traffic emissions [61]. Emissions in China caused by road transport have been affected by the lockdown, generating a reduction of the pollutants associated with this sector [62]. Therefore, the lockdown significantly reduced the air pollution (air pollutants and warming gases) in most cities across the world [26].

Emissions of the four pollutant groups selected in this study depend on the consumption of fossil fuels, which during the lockdown decreased in accordance with the lower vehicle traffic in Colombia. According to Colombian government reports, diesel and gasoline consumption experienced a drop of 50% and 65%, respectively, since mid-March when the lockdown began [63]. Furthermore, the Mercantile Exchange Colombia did not register increases in the consumption data for CNG [50]. This led to a reduction in the estimated emissions of the four pollutant groups studied, with the most variation in GHGs, specifically CO_2. It is consistent with recent studies that affirm the first sector with the greatest reduction in global emissions of CO_2 during isolation was transportation [64].

The emissions reduction of ozone precursor gases (CO, NMVOC, NOx) registered in this study is consistent with the highest reduction of CO and NO_2 that occurred in China due the lockdown measures taken to control the COVID-19 pandemic, which dramatically reduced the number of vehicles on the road, and consequently led to an improvement in air quality due most likely to reduced emissions from some sectors (such as the transportation linked to the NO_2 emissions). This occurred chiefly in those provinces with large fleet vehicular and secondary industries, which suggests that the reduced emissions from the transportation and industrial sectors caused a decrease in concentrations of these gases [18]. In addition, it was reported that NO_2 emissions were reduced by up to 60% in the city of Santander (Spain) [32]. Other studies found a 20–30% reduction in emissions of NO_2 in China, Spain, France, Italy, and the USA due to the lockdown [9] and a drastic reduction of NO (up to −77.3%), NO_2 (up to −54.3%), and CO (up to −64.8%) in Sao Paulo (Brazil). In the case of NO, one recent study demonstrated that heavy-duty diesel trucks are the major sources of this pollutant [65]. While the NMVOC emissions reduction was −22% in this study, other research has shown a $PM_{2.5}$ emissions reduction of −17% [23].

Aerosol reductions (BC, PM_{10}, $PM_{2.5}$) in our study were consistent with recent studies. Chinese researchers carried out an analysis of $PM_{2.5}$ data in cities such as Beijing, Shanghai, Guangzhou, and Wuhan during COVID-19 and found a pronounced reduction in air pollution attributed to the reduction of emissions in transportation and industrial sectors [18]. As well, it was observed over the major cities of India, such as Delhi, Mumbai, Hyderabad, Kolkata and Chennai, that a decline in $PM_{2.5}$ during the lockdown period registered a significant improvement in air quality, which provides important information to the cities' administration about the implementation of regulations [14]. Other studies conducted during the lockdown suggested the main sources of atmospheric particulate matter PM_{10} and $PM_{2.5}$ (include fossil fuel combustion, motor vehicle exhaust emissions, industrial production, secondary particulate matter generation, among others) experienced a significant reduction up to −48.9% in three of China's provinces [66]. The decline in $PM_{2.5}$ emissions due to the lockdown to control the spread of SARS-CoV-2 in New York, Los Angeles, Zaragoza, Rome, Dubai, Delhi, Mumbai, Beijing and Shanghai reflected the positive changes that contributed to improve air quality [67]. BC emissions reduction can be attributed to on-road diesel sources [68], so the mitigation of transportation-related BC emissions decreased the global emissions significantly [69].

In this study, acidifying gases (NH_3, SO_2) also showed a significant emissions reduction, up to −23% for NH_3. Other studies found that decreasing emissions were identified in Kannur district, India (−16%), due to a complete shutdown of traffic and industrial activities [70], as NH_3 emissions come mainly from heavy-duty diesel vehicles [65]. In addition, SO_2 emissions registered a decrease (−19%), which was identified in China as a decrease attributed to lower emissions from traffic and coal combustion [62]. Kannur, India, reported decreased emissions (−62%), and a diurnal variation most pronounced during peak traffic hours was absent during the lockdown owing to the roads being deserted [70].

Figure 4 shows NO_2 emissions increased in the northern Colombian region due to events of long-range pollution transport, like regional biomass burning beginning at the end of March, during the lockdown, according to recent studies [33,34]; the air quality improvement shown in this period was partially annulled by the impact of these events.

Despite an emissions reduction in the four pollutant groups selected, an increase of ozone concentration was observed in urban areas of Bogotá. This result was consistent with recent studies, in which Sao Paulo (Brazil) urban areas, highly influenced by road transportation, had an increase of approximately 30% in ozone emissions [60]. The increase of ozone concentration is related to nitrogen monoxide decreases, which may cause a reduction in ozone consumption during the photochemical reactions [61,71]. Moreover, VOCs are often the limiting precursors for O_3 production in urban areas [23,31]. O_3 levels increased up to 57%, probably due to lower titration of O_3 by NO (titration, $NO + O_3 = NO_2 + O_2$), and the decrease of NOx added to the increase of solar irradiation and temperatures in this period of the year [61]; ozone levels are a major concern in tropical cities, where the temperature and insolation favor the atmospheric processes leading to O_3 formation [31]. In this sense, recent studies also showed that reductions in $PM_{2.5}$ during the COVID-19 pandemic favored the formation of O_3 due to a reduction in NO_x levels due to reduced transport and an increase in solar radiation [31,72]. On the other hand, the increase in ozone seems to be associated with the decrease in $PM_{2.5}$, because the sinking of hydroperoxy radicals is slowed down, and therefore, ozone production accelerates [73].

Therefore, these results showed that a reduction in the transport sector contributed to lower emissions of the four pollutant groups (GHGs, ozone precursors, aerosols and acidifying gases), but was not able to cut down ozone concentrations, which leads us to consider other strategies aimed at reducing emissions and the reactivity in the troposphere, such as fuel composition and the control of vehicular emission systems. However, these results indicate that today, more than ever, we must take measures that are focused on individual behavioral changes.

Previous studies recommend high-impact actions for emissions savings >0.8 Mg CO_2 eq per year for countries, with potential contribution to systemic change and substantial reduction in annual emissions, such as living without vehicles (2.4 Mg CO_2 eq saved per year) and opting for more efficient vehicles or switching to electric cars (1.19 Mg CO_2 eq saved per year) [74]. Using the cleanest available technology (electric cars) results in significant reductions. Despite the fact that these actions can be effective, the dependence of people on the use of conventional cars is increasingly noticeable, and it is evidenced by the vehicle fleet records in Colombia. Therefore, governments should consider the adoption of incentives to use fewer polluting vehicles [75]. Also, Wynes et al. [74] show significant emissions reductions through moderate-impact actions (emissions savings 0.2–0.8 Mg CO_2 eq per year), such as replacing gasoline-burning vehicles with hybrid cars, and even the use of public transportation, which reduces emissions by 26–76% [76], as well as biking and walking. In Colombia, incentive measures should encourage the use of CNG or hybrid vehicles, as natural gas represents the lowest emissions compared to the other fuels under study.

The changes in air pollution during the COVID-19 lockdown can provide insight into the achievability of air quality improvement when there are significant restrictions in emissions related to the sectors with the greatest impact, thus giving regulators better ability to control air pollution [13]. However, it is likely that most of the changes observed in 2020 in terms of emissions are temporary, since no structural changes are reflected in the economic or transport systems [8]. Moreover, several studies have shown that poor air quality is related to increases in infections and mortality due to COVID-19 [77–80]. This would indicate that a reduction in emissions and improvements in air quality could also reduce the rate of infection and mortality due to COVID-19 [47,81–85]. Thus, it would be expected that prevention measures (such as social distancing and lockdowns, among others) are actually more profitable than a cure [78,86,87].

5. Conclusions

The effect of restricted human activities due to the COVID-19 pandemic in Colombia since mid-March of 2020 was studied by analyzing emissions variations of eleven criteria pollutants, comparing the first half of 2020 with values obtained in the same period of 2018.

In general, the air quality improved during the COVID-19 lockdown, and it was apparently caused by reductions in emissions of some human activities, such as in the transportation sector. Lifting the lockdown and the normalization of activities in the productive sectors may reverse the reduction of global air pollution and even increase air pollution levels if researchers, decision makers, productive sectors, and governments do not articulate efforts to maintain the economy with minimum emissions. COVID-19 has allowed us to analyze the positive impacts of the measures adopted during the lockdown, specifically those that have generated reductions in pollution emissions with evident consequences for the air quality. Thus, it is important to identify the impact of low, moderate and high actions on reducing emissions, with emphasis in the agricultural and energy sectors, and especially the contributions of the transport sub-sector. The circumstances under which we have lived, and the measures adopted during the pandemic, taking in consideration changes for improving environmental conditions, can be the subject of dialogue at the next conference of the United Nations for Climate Change, COP26. Additionally, future work may use more detailed methodologies, such as tier 3 [42,88], to achieve high-resolution spatial inventories in Colombia.

Author Contributions: Conceptualization, Y.C.-C. and T.R.B.-O.; data curation, Y.C.-C., L.C.M.-R. and T.R.B.-O.; formal analysis, Y.C.-C., L.C.M.-R. and T.R.B.-O.; investigation, Y.C.-C., L.C.M.-R. and T.R.B.-O.; methodology, Y.C.-C., L.C.M.-R. and T.R.B.-O.; writing—original draft preparation, Y.C.-C., L.C.M.-R. and T.R.B.-O.; project administration, Y.C.-C.; software, L.C.M.-R.; supervision, Y.C.-C. and T.R.B.-O.; visualization, Y.C.-C., L.C.M.-R. and T.R.B.-O.; writing—original draft, Y.C.-C., L.C.M.-R. and T.R.B.-O.; funding acquisition, Y.C.-C. All authors have read and agreed to the published version of the manuscript.

Funding: The work of T.R.B.-O. was funded in part by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) (National Council for Scientific and Technical Investigations), the National Agency of Scientific and Technological Promotion (ANPCyT) (Agencia Nacional de Promoción Científica y Tecnológica) under project PICT 2016 1115, and Universidad Tecnológica Nacional (UTN) (National Technological University) in Argentina. T.R.B.-O. also thanks GORE-FNDR-V Región in Valparaíso and Programa de Asignación Rápida de Recursos para Proyectos de Investigación Sobre el Coronavirus (COVID−19) (project CO-VID0581-2020), ANID, Ministerio de Ciencia, Tecnología, Conocimiento e Innovación, both in Chile. Y.C.-C. and L.M.R. thank the grants and fund research (AA N° 014-2015, AA N° 031-2016, Res N° 0388-2017, Res N° 0709-2017, Res N° 0119-2018, Res N° 0305-2018 and Res N°0347-2020) from Universidad del Magdalena (Santa Marta, Colombia).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Acknowledgments: We would like to thank Viverlys Diaz-Gutierrez for her help to graph Figure 4. We also would like to thank NASA's Aura Mission scientific teams, and their associated personnel, for the production of the data used in this research effort.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Emission factors by vehicle classification and fuel type.

Vehicle Type	Fuel	CO_2 * (Kg/m^3)	CH_4 ** (kg/TJ)	N_2O ** (Kg/m^3)	CO * (Kg/m^3)	NMVOC * (Kg/m^3)	NO_x * (Kg/m^3)	BC * (Kg/m^3)	$PM_{2.5}$ * (Kg/m^3)	PM_{10} * (Kg/m^3)	NH_3 * (Kg/m^3)	SO_2 + (kg/TJ)
Personal cars	Gasoline	2329	25.00	0.15	61.74	7.39	6.42	3×10^{-3}	0.02	0.02	0.81	3.57
	Gas Oil	2678	3.90	0.07	2.81	0.59	10.95	0.53	0.93	0.93	0.05	2.91
	CNG	1972	92.00	0.06	60.90	9.81	10.93	-	-	-	0.06	-
Light commercial vehicles	Gasoline	2329	25.00	0.14	111.94	10.72	9.72	7×10^{-4}	0.01	0.01	0.49	3.57
	Gas Oil	2678	3.90	0.05	6.25	1.30	12.60	0.71	1.28	1.28	0.03	2.91
	CNG	1972	92.00	-	4.10	0.14	9.35	-	0.01	0.01	-	-
Heavy duty vehicles	Gas Oil	2678	3.90	0.04	6.41	1.62	28.20	0.42	0.79	0.79	0.01	2.91
	CNG	1972	92.00	-	4.10	0.19	9.35	-	0.01	0.01	-	-
Motorcycles	Gasoline	2329	25.00	0.04	39.54	96.58	4.88	0.18	1.62	1.62	0.04	3.57

* EMEP/EEA air pollutant emission inventory guidebook 2019 [42]. ** 2006 IPCC Guidelines for National Greenhouse Inventories [41].
+ 2016 UPME FECOC calculator (Colombian fuel emission factors) [43].

Table A2. Fuel sales (m^3) by department for March to June 2018 and 2020.

Departments	Gasoline		Diesel	
	2018	2020	2018	2020
Amazonas	1167	1808	1167	491
Antioquia	154,614	195,364	154,614	206,015
Arauca	2456	13,591	2456	11,024
San Andrés y Providencia	1844	2397	1844	621
Atlántico	73,855	46,499	73,855	53,498
Bogotá D.C.	1,112,981	184,188	892,924	144,130
Bolívar	118,597	45,119	124,428	73,072
Boyacá	25,132	39,383	21,619	53,587
Caldas	17,596	24,280	11,606	19,639
Caquetá	8680	14,167	22,570	6439
Casanare	7751	15,883	12,365	37,034
Cauca	18,299	41,413	11,317	22,147
Cesar	30,871	59,565	59,162	112,311
Choco	6606	19,768	5091	15,555
Córdoba	22,813	37,646	16,226	36,267
Cundinamarca	74,089	88,491	74,260	165,606
Guainía	956	3576	670	696
Guaviare	2257	4270	1314	2293
Huila	21,200	34,236	16,067	26,438
La Guajira	3781	31,629	10,080	16,893
Magdalena	268,517	22,459	320,757	18,756
Meta	19,924	34,320	22,967	47,797
Nariño	33,581	72,836	21,191	46,554
Norte de Santander	14,744	68,938	21,411	67,054
Putumayo	7304	17,838	6064	7558
Quindío	11,741	16,622	7083	13,289
Risaralda	20,316	29,554	14,635	22,211
Santander	45,700	63,675	42,618	65,638
Sucre	11,014	18,367	6122	14,021
Tolima	28,855	38,160	26,876	60,583
Valle del Cauca	106,590	143,532	84,913	163,125
Vaupés	183	458	244	93
Vichada	572	2877	636	1887

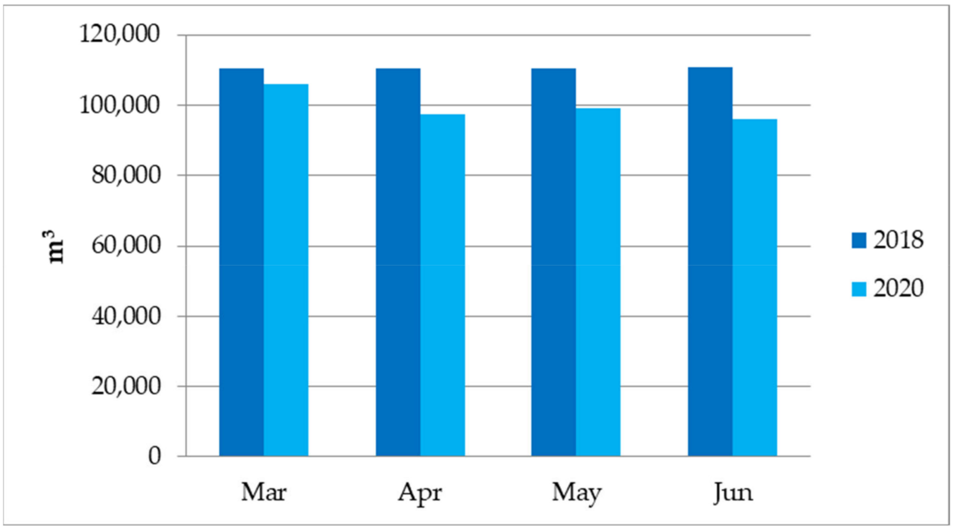

Figure A1. Fuel consumption from March to June 2018 and 2020. GNG sales data was only available at the national level.

Table A3. Equipment used by BAQMD to monitor air quality in Bogota city [54]. Note that only the equipment that measures the parameters (pollutants) used in this comparison is shown.

Pollutants	Measurement Principle Used	Equipment
CO	Infrared absorption spectrophotometry	CO Thermo Scientific 48i
SO_2	Ultraviolet pulsed fluorescence	SO_2 Thermo Scientific 43i
NO_2	Chemiluminescence	NOx Ecotech 9841
O_3	Absorption spectrophotometry in the ultraviolet	O_3 Ecotech 9841

Table A4. CO_2 emissions (Gg) by departments from March to June 2018 and 2020.

Departments	2018	2020
Amazonas	5.84	5.53
Antioquia	774.15	1006.71
Arauca	12.30	61.18
San Andrés y Providencia	9.23	7.25
Atlántico	369.79	251.56
Bogotá D.C.	4983.45	814.97
Bolívar	609.43	300.76
Boyacá	116.43	235.23
Caldas	72.06	109.14
Caquetá	80.65	50.24
Casanare	51.17	136.16
Cauca	72.93	155.77
Cesar	230.33	439.49
Choco	29.02	87.70
Córdoba	96.59	184.80
Cundinamarca	371.42	649.57
Guainía	4.02	10.19
Guaviare	8.78	16.09
Huila	92.40	150.54
La Guajira	35.80	118.91
Magdalena	1484.36	102.54
Meta	107.91	207.93
Nariño	134.96	294.31
Norte de Santander	91.67	340.13

Table A4. *Cont.*

Departments	2018	2020
Putumayo	33.25	61.79
Quindío	46.31	74.30
Risaralda	86.51	128.31
Santander	220.57	324.08
Sucre	42.05	80.33
Tolima	139.18	251.11
Valle del Cauca	475.65	771.13
Vaupés	1.08	1.31
Vichada	3.04	11.75

References

1. Aylward, B.; Liang, W. Report of the WHO-China Joint Mission on Coronavirus Disease 2019 (COVID-19). *WHO-China Jt. Mission Coronavirus Dis.* **2020**, *2019*, 16–24.
2. World Health Organization (WHO) Coronavirus disease 2019 Situation Report 51 11th March 2020. *World Health Organ.* **2020**, *2019*, 2633. [CrossRef]
3. Wang, C.; Horby, P.W.; Hayden, F.G.; Gao, G.F. A novel coronavirus outbreak of global health concern. *Lancet* **2020**, *395*, 470–473. [CrossRef]
4. JHU Coronavirus Resources Center. Available online: https://coronavirus.jhu.edu/map.html (accessed on 25 April 2020).
5. Wilder-Smith, A.; Freedman, D.O. Isolation, quarantine, social distancing and community containment: Pivotal role for old-style public health measures in the novel coronavirus (2019-nCoV) outbreak. *J. Travel Med.* **2020**, *27*, taaa020. [CrossRef] [PubMed]
6. McKibbin, W.; Fernando, R. The Global Macroeconomic Impacts of COVID-19. *Brook. Inst.* **2020**, 1–43. [CrossRef]
7. May, B. World Economic Prospects Monthly. *Econ. Outlook* **2020**, *44*, 1–33. [CrossRef]
8. Le Quéré, C.; Jackson, R.B.; Jones, M.W.; Smith, A.J.P.; Abernethy, S.; Andrew, R.M.; De-Gol, A.J.; Willis, D.R.; Shan, Y.; Canadell, J.G.; et al. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **2020**, *10*, 647–654. [CrossRef]
9. Muhammad, S.; Long, X.; Salman, M. COVID-19 pandemic and environmental pollution: A blessing in disguise? *Sci. Total Environ.* **2020**, *728*, 138820. [CrossRef]
10. IPCC Proposed outline of the special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate cha. *Ipcc Sr15* **2018**, *2*, 17–20.
11. Dantas, G.; Siciliano, B.; França, B.B.; da Silva, C.M.; Arbilla, G. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Sci. Total Environ.* **2020**. [CrossRef]
12. O'Reilly, K.M.; Auzenbergs, M.; Jafari, Y.; Liu, Y.; Flasche, S.; Lowe, R. Effective transmission across the globe: The role of climate in COVID-19 mitigation strategies. *Lancet Planet. Health* **2020**, *4*, e172. [CrossRef]
13. Sharma, S.; Zhang, M.; Anshika; Gao, J.; Zhang, H.; Kota, S.H. Effect of restricted emissions during COVID-19 on air quality in India. *Sci. Total Environ.* **2020**. [CrossRef] [PubMed]
14. Singh, R.P.; Chauhan, A. Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Qual. Atmos. Health* **2020**, *13*, 921–928. [CrossRef] [PubMed]
15. Pant, P.; Harrison, R.M. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmos. Environ.* **2013**, *77*, 78–97. [CrossRef]
16. Ly, B.T.; Kajii, Y.; Nguyen, T.Y.L.; Shoji, K.; Van, D.A.; Do, T.N.N.; Nghiem, T.D.; Sakamoto, Y. Characteristics of roadside volatile organic compounds in an urban area dominated by gasoline vehicles, a case study in Hanoi. *Chemosphere* **2020**, *254*, 126749. [CrossRef]
17. Fameli, K.M.; Kotrikla, A.M.; Psanis, C.; Biskos, G.; Polydoropoulou, A. Estimation of the emissions by transport in two port cities of the northeastern Mediterranean, Greece. *Environ. Pollut.* **2020**, *257*, 113598. [CrossRef]
18. Wang, Y.; Yuan, Y.; Wang, Q.; Liu, C.; Zhi, Q.; Cao, J. Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions. *Sci. Total Environ.* **2020**, *731*, 139133. [CrossRef]
19. Tournadre, B.; Chelin, P.; Ray, M.; Cuesta, J.; Kutzner, R.D.; Landsheere, X.; Fortems-Cheiney, A.; Flaud, J.-M.; Hase, F.; Blumenstock, T.; et al. Atmospheric ammonia (NH_3) over the Paris megacity: 9 years of total column observations from ground-based infrared remote sensing. *Atmos. Meas. Tech.* **2020**, *13*, 3923–3937. [CrossRef]
20. Puliafito, S.E.; Bolaño-Ortiz, T.; Berná, L.; Pascual Flores, R. High resolution inventory of atmospheric emissions from livestock production, agriculture, and biomass burning sectors of Argentina. *Atmos. Environ.* **2020**, *223*, 117248. [CrossRef]
21. Janssens-maenhout, G. Supplement of EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data* **2019**, *11*, 959–1002. [CrossRef]

22. Janssens-Maenhout, G.; Crippa, M.; Guizzardi, D.; Dentener, F.; Muntean, M.; Pouliot, G.; Keating, T.; Zhang, Q.; Kurokawa, J.; Wankmüller, R.; et al. HTAP-v2.2: A mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution. *Atmos. Chem. Phys.* **2015**, *15*, 11411–11432. [CrossRef]
23. Huang, X.; Zhang, Y.; Wang, Y.; Ou, Y.; Chen, D.; Pei, C.; Huang, Z.; Zhang, Z.; Liu, T.; Luo, S.; et al. Evaluating the effectiveness of multiple emission control measures on reducing volatile organic compounds in ambient air based on observational data: A case study during the 2010 Guangzhou Asian Games. *Sci. Total Environ.* **2020**, *723*, 138171. [CrossRef] [PubMed]
24. Franco, J.F.; Pacheco, J.; Belalcázar, L.C.; Behrentz, E. Characterization and source identification of VOC species in Bogotá, Colombia. *Atmósfera* **2015**, *28*, 1–11. [CrossRef]
25. Xue, R.; Wang, S.; Li, D.; Zou, Z.; Chan, K.L.; Valks, P.; Saiz-Lopez, A.; Zhou, B. Spatio-temporal variations in NO_2 and SO_2 over Shanghai and Chongming Eco-Island measured by Ozone Monitoring Instrument (OMI) during 2008–2017. *J. Clean. Prod.* **2020**, *258*, 120563. [CrossRef]
26. Anjum, N. Good in The Worst: COVID-19 Restrictions and Ease in Global Air Pollution. *Preprints* **2020**. [CrossRef]
27. Kheirbek, I.; Haney, J.; Douglas, S.; Ito, K.; Matte, T. The contribution of motor vehicle emissions to ambient fine particulate matter public health impacts in New York City: A health burden assessment. *Environ. Health A Glob. Access Sci. Source* **2016**, *15*, 89. [CrossRef]
28. Chang, Y.; Zou, Z.; Deng, C.; Huang, K.; Collett, J.L.; Lin, J.; Zhuang, G. The importance of vehicle emissions as a source of atmospheric ammonia in the megacity of Shanghai. *Atmos. Chem. Phys.* **2016**, *16*, 3577–3594. [CrossRef]
29. Huang, Y.; Zhou, J.L.; Yu, Y.; Mok, W.; Lee, C.F.C. Uncertainty in the Impact of the COVID-19 Pandemic on Air Quality in Hong Kong, China. *Atmosphere* **2020**, *11*, 914. [CrossRef]
30. Musselwhite, C.; Avineri, E.; Susilo, Y. Editorial JTH 16 –The Coronavirus Disease COVID-19 and implications for transport and health. *J. Transp. Health* **2020**, *16*, 4–7. [CrossRef]
31. Siciliano, B.; Dantas, G.; Cleyton, M.; Arbilla, G. Increased ozone levels during the COVID-19 lockdown: Analysis for the city of Rio de Janeiro, Brazil. *Sci. Total Environ.* **2020**, *737*, 139765. [CrossRef]
32. Aloi, A.; Alonso, B.; Benavente, J.; Cordera, R.; Echániz, E.; González, F.; Ladisa, C.; Lezama-Romanelli, R.; López-Parra, Á.; Mazzei, V.; et al. Effects of the COVID-19 lockdown on urban mobility: Empirical evidence from the city of Santander (Spain). *Sustainbility* **2020**, *12*, 3870. [CrossRef]
33. Mendez-Espinosa, J.F.; Rojas, N.Y.; Vargas, J.; Pachón, J.E.; Belalcazar, L.C.; Ramírez, O. Air quality variations in Northern South America during the COVID-19 lockdown. *Sci. Total Environ.* **2020**, *749*, 141621. [CrossRef] [PubMed]
34. Arregocés, H.A.; Rojano, R.; Restrepo, G. Impact of lockdown on particulate matter concentrations in Colombia during the COVID-19 pandemic. *Sci. Total Environ.* **2020**, 142874. [CrossRef] [PubMed]
35. DANE Departamento Administrativo Nacional de Estadística (DANE). Available online: https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion (accessed on 18 January 2021).
36. Economics, T. Colombia—Economic Forecasts—2020–2022 Outlook. Available online: https://tradingeconomics.com/colombia/forecast (accessed on 30 July 2020).
37. Runt Runt—Registro Único Nacional de Tránsito. Available online: https://www.runt.com.co/runt-en-cifras/parque-automotor (accessed on 1 July 2020).
38. IDEAM. *Inventario Nacional y Departamental de Gases Efecto Invernadero. Tercera Comunicación Nacional de Cambio Climático*; IDEAM: Bogota, Colombia, 2016; ISBN 9789588971254.
39. Hao, H.; Wang, H.; Ouyang, M. Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet. *Energy* **2011**, *36*, 6520–6528. [CrossRef]
40. Bebkiewicz, K.; Chłopek, Z.; Lasocki, J.; Szczepański, K.; Zimakowska-Laskowska, M. Analysis of emission of greenhouse gases from road transport in Poland between 1990 and 2017. *Atmosphere* **2020**, *11*, 387. [CrossRef]
41. Eggleston, H.S.; Miwa, K.; Srivastava, N.; Tanabe, K. *IPCC 2006 IPCC Guidelines for National Greenhouse Inventories—A primer, Prepared by the National Greenhouse Gas Inventories Programme*; Iges: Hayama, Japan, 2006; ISBN 4-88788-032-4.
42. EMEP. *EEA Report No 13/2019*; EMEP: Geneva, Switzerland, 2019; ISBN 978-92-9480-098-5.
43. FECOC Unidad de Planeación Minero Energética—UPME. Available online: http://www.upme.gov.co/Calculadora_Emisiones/aplicacion/calculadora.html (accessed on 26 July 2020).
44. Puliafito, S.E.; Allende, D.G.; Castesana, P.S.; Ruggeri, M.F. High-resolution atmospheric emission inventory of the argentine energy sector. Comparison with edgar global emission database. *Heliyon* **2017**, *3*, 489. [CrossRef] [PubMed]
45. Puliafito, S.E.; Allende, D.; Pinto, S.; Castesana, P. High resolution inventory of GHG emissions of the road transport sector in Argentina. *Atmos. Environ.* **2015**, *101*, 303–311. [CrossRef]
46. Puliafito, S.E.; Bolaño-Ortiz, T.R.; Berná Peña, L.L.; Pascual-Flores, R.M. Dataset supporting the estimation and analysis of high spatial resolution inventories of atmospheric emissions from several sectors in Argentina. *Data Br.* **2020**, *29*, 105281. [CrossRef]
47. Bolaño-Ortiz, T.R.; Puliafito, S.E.; Berná-Peña, L.L.; Pascual-Flores, R.M.; Urquiza, J.; Camargo-Caicedo, Y. Atmospheric Emission Changes and Their Economic Impacts during the COVID-19 Pandemic Lockdown in Argentina. *Sustainability* **2020**, *12*, 8661.
48. Ministry of Mines and Energy Information System of Liquid Fuels of Colombia-SICOM. Available online: https://www.sicom.gov.co/index.php/boletin-estadistico (accessed on 18 January 2021).
49. Ministry of Mines and Energy Information System of Liquid Fuels of Colombia-SICOM. Available online: https://www.sicom.gov.co/sicom/identificacionAction.do?method=pRedirectHttps (accessed on 1 July 2020).

50. GMGNC Manager of the Natural Gas Market in Colombia-GMGNC. Available online: https://www.bmcbec.com.co/informes/informes-mensuales (accessed on 20 November 2020).
51. UPME Plan de Acción Indicativo de Eficiencia Energética 2017–2022; Bogotá, 2016; pp.1–157. Available online: https://www1.upme.gov.co/DemandaEnergetica/MarcoNormatividad/PAI_PROURE_2017-2022.pdf (accessed on 20 July 2020).
52. PROMIGAS Promigas S.A. E.S.P. Available online: http://www.promigas.com/Es/Noticias/Paginas/Revista-Magasin/Edicion-27/Pagina-69.aspx (accessed on 23 July 2020).
53. Myhre, G.; Shindell, D.; Bréon, F.-M.F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.J.-F.; Lee, D.; Mendoza, B.; et al. Anthropogenic and Natural Radiative Forcing: Supplementary Material. *Clim. Chang.* **2013**. [CrossRef]
54. Secretary of Environment Bogotá, Bogotá Air Quality Monitoring Network—RMCAB. Available online: http://201.245.192.252:81/home/map (accessed on 4 September 2020).
55. OMI National Aeronautics and Space Administration. Available online: https://www.nasa.gov/mission_pages/aura/spacecraft/omi.html (accessed on 24 July 2020).
56. Acker, J.G.; Leptoukh Eos, G. Trans. AGU. In Proceedings of the Online Analysis Enhances Use of NASA Earth Science Data; AGU: Washington, DC, USA, 2007; pp. 14–17.
57. De Souza, C.D.R.; Silva, S.D.; Da Silva, M.A.V.; de D'Agosto, M.A.; Barboza, A.P. Inventory of conventional air pollutants emissions from road transportation for the state of Rio de Janeiro. *Energy Policy* **2013**, *53*, 125–135. [CrossRef]
58. Undp Undp in Latin America and the Caribbean. Available online: https://www.latinamerica.undp.org/content/rblac/en/home/library/crisis_prevention_and_recovery/social-and-economic-impact-of-covid-19-and-policy-options-in-arg.html (accessed on 29 July 2020).
59. DANE Statistics by Demography and Population in Colombia. Available online: https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion (accessed on 19 January 2021).
60. Nakada, L.Y.K.; Urban, R.C. COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. *Sci. Total Environ.* **2020**, 139087. [CrossRef] [PubMed]
61. Tobías, A.; Carnerero, C.; Reche, C.; Massagué, J.; Via, M.; Minguillón, M.C.; Alastuey, A.; Querol, X. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Sci. Total Environ.* **2020**, *726*, 138540. [CrossRef] [PubMed]
62. Silver, B.; He, X.; Arnold, S.R.; Spracklen, D.V. The impact of COVID-19 control measures on air quality in China. *Environ. Res. Lett.* **2020**, *15*. [CrossRef]
63. Dinero Dinero. Available online: https://www.dinero.com/pais/articulo/consumo-de-gasolina-en-colombia-en-junio-de-2020/290275 (accessed on 24 July 2020).
64. Liu, Z.; Ciais, P.; Deng, Z.; Lei, R.; Davis, S.J.; Feng, S.; Zheng, B.; Cui, D.; Dou, X.; Zhu, B.; et al. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **2020**, *11*, 5172. [CrossRef]
65. He, L.; Zhang, S.; Hu, J.; Li, Z.; Zheng, X.; Cao, Y.; Xu, G.; Yan, M.; Wu, Y. On-road emission measurements of reactive nitrogen compounds from heavy-duty diesel trucks in China. *Environ. Pollut.* **2020**, *262*, 114280. [CrossRef]
66. Xu, K.; Cui, K.; Young, L.H.; Wang, Y.F.; Hsieh, Y.K.; Wan, S.; Zhang, J. Air quality index, indicatory air pollutants and impact of covid-19 event on the air quality near central china. *Aerosol Air Qual. Res.* **2020**, *20*, 1204–1221. [CrossRef]
67. Chauhan, A.; Singh, R.P. Decline in PM2.5 concentrations over major cities around the world associated with COVID-19. *Environ. Res.* **2020**, *187*, 109634. [CrossRef]
68. de Miranda, R.M.; Perez-Martinez, P.J.; de Fatima Andrade, M.; Ribeiro, F.N.D. Relationship between black carbon (BC) and heavy traffic in São Paulo, Brazil. *Transp. Res. Part D Transp. Environ.* **2019**, *68*, 84–98. [CrossRef]
69. Chen, W.T.; Lee, Y.H.; Adams, P.J.; Nenes, A.; Seinfeld, J.H. Will black carbon mitigation dampen aerosol indirect forcing? *Geophys. Res. Lett.* **2010**, *37*, 1–5. [CrossRef]
70. Resmi, C.T.; Nishanth, T.; Satheesh Kumar, M.K.; Manoj, M.G.; Balachandramohan, M.; Valsaraj, K.T. Air quality improvement during triple-lockdown in the coastal city of Kannur, Kerala to combat Covid-19 transmission. *PeerJ* **2020**, *8*, e9642. [CrossRef] [PubMed]
71. De Fatima, M.; Kumar, P.; Dias, E.; Freitas, D.; Yuri, R.; Martins, J.; Martins, L.D.; Nogueira, T.; Perez-martinez, P.; Maura, R.; et al. ~ o Paulo: Evolution over the last 30 Air quality in the megacity of S a years and future perspectives. *Atmos. Environ.* **2017**, *159*, 66–82. [CrossRef]
72. Sicard, P.; De Marco, A.; Agathokleous, E.; Feng, Z.; Xu, X.; Paoletti, E.; Rodriguez, J.J.D.; Calatayud, V. Amplified ozone pollution in cities during the COVID-19 lockdown. *Sci. Total Environ.* **2020**, *735*, 139542. [CrossRef] [PubMed]
73. Li, K.; Jacob, D.J.; Liao, H.; Shen, L.; Zhang, Q.; Bates, K.H. Anthropogenic drivers of 2013–2017 trends in summer surface ozone in China. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 422–427. [CrossRef]
74. Wynes, S.; Nicholas, K.A. The climate mitigation gap: Education and government recommendations miss the most effective individual actions. *Environ. Res. Lett.* **2017**, *12*, 074024. [CrossRef]
75. Andrade-Castañeda, H.J.; Arteaga-Céspedes, C.C.; Segura-Madrigal, M.A. Emisión de gases de efecto invernadero por uso de combustibles fósiles en Ibagué, Tolima (Colombia). *Corpoica Cienc. y Tecnol. Agropecu.* **2017**, *18*, 103–112. [CrossRef]
76. Chester, M.; Pincetl, S.; Elizabeth, Z.; Eisenstein, W.; Matute, J. Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environ. Res. Lett.* **2013**, *8*. [CrossRef]

77. Anderson, R.M.; Heesterbeek, H.; Klinkenberg, D.; Hollingsworth, T.D. How will country-based mitigation measures influence the course of the COVID-19 epidemic? *Lancet* **2020**, *395*, 931–934. [CrossRef]
78. Goscé, L.; Johansson, A. Analysing the link between public transport use and airborne transmission: Mobility and contagion in the London underground. *Environ. Health* **2018**, *17*, 84. [CrossRef]
79. Filippini, T.; Rothman, K.J.; Goffi, A.; Ferrari, F.; Maffeis, G.; Orsini, N.; Vinceti, M. Satellite-detected tropospheric nitrogen dioxide and spread of SARS-CoV-2 infection in Northern Italy. *Sci. Total Environ.* **2020**, *739*, 140278. [CrossRef]
80. Saha, B.; Debnath, A.; Saha, B. Analysis and finding the correlation of air quality parameters on the spread and deceased case of COVID-19 patients in India 2020. 2020, Research Square. Available online: https://assets.researchsquare.com/files/rs-34647/v1/d82c5de9-56a1-435b-a1e4-6ca206b8838f.pdf (accessed on 18 January 2021).
81. Bolaño-Ortiz, T.R.; Camargo-Caicedo, Y.; Puliafito, S.E.; Ruggeri, M.F.; Bolaño-Diaz, S.; Pascual-Flores, R.; Saturno, J.; Ibarra-Espinosa, S.; Mayol-Bracero, O.L.; Torres-Delgado, E.; et al. Spread of SARS-CoV-2 through Latin America and the Caribbean region: A look from its economic conditions, climate and air pollution indicators. *Environ. Res.* **2020**, *191*, 109938. [CrossRef] [PubMed]
82. Bolaño-Ortiz, T.R.; Pascual-Flores, R.M.; Puliafito, S.E.; Camargo-Caicedo, Y.; Berná-Peña, L.L.; Ruggeri, M.F.; Lopez-Noreña, A.I.; Tames, M.F.; Cereceda-Balic, F. Spread of COVID-19, Meteorological Conditions and Air Quality in the City of Buenos Aires, Argentina: Two Facets Observed during Its Pandemic Lockdown. *Atmosphere* **2020**, *11*, 1045. [CrossRef]
83. Bashir, M.F.; Bilal, B.M.A.; Komal, B. Correlation between environmental pollution indicators and COVID-19 pandemic: A brief study in Californian context. *Environ. Res.* **2020**, 109652. [CrossRef]
84. Travaglio, M.; Popovic, R.; Yu, Y.; Leal, N.; Martins, L.M. Links between air pollution and COVID-19 in England. *medRxiv* **2020**. [CrossRef]
85. Ogen, Y. Assessing nitrogen dioxide (NO_2) levels as a contributing factor to coronavirus (COVID-19) fatality. *Sci. Total Environ.* **2020**, *726*, 138605. [CrossRef]
86. Mankia, K.; Di Matteo, A.; Emery, P. Prevention and cure: The major unmet needs in the management of rheumatoid arthritis. *J. Autoimmun.* **2020**, *110*, 102399. [CrossRef]
87. Brianti, M.; Magnani, M.; Menegatti, M. Optimal choice of prevention and cure under uncertainty on disease effect and cure effectiveness. *Res. Econ.* **2018**, *72*, 327–342. [CrossRef]
88. EMEP EMEP/EEA air pollutant emission inventory guidebook—2016—European Environment Agency. *EEA Reports* **2016**. [CrossRef]