Article

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

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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 NO2 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 (CO2), methane (CH4), and nitrous oxide (N2O); 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 (PM2.5, PM10) [15]; acidifying gases, such as ammonia (NH3) [19] and sulfur dioxide (SO2) [20]. GHG emissions, such as CO2, are mainly produced by power generation and road transport. Other GHG emissions, such as CH4, are generated by fermentation processes, fossil fuel extraction and use, landfills and waste. In addition, N2O 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 + NO2) 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 (PM2.5) [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]. NH3 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 CO2 emissions by 25%. The European Public Health Alliance (EPHA) states that, in Italy, the urban NO2 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 CO2 were registered, with a 5–10% reduction in CO2 [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\textsubscript{4}, CO\textsubscript{2}, N\textsubscript{2}O), ozone precursor gases (CO, NMVOC, NOx), aerosols (BC, PM\textsubscript{10}, PM\textsubscript{2.5}), and acidifying gases (NH\textsubscript{3}, SO\textsubscript{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\textsuperscript{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\textsuperscript{3} diesel oil, 2.6 million m\textsuperscript{3} gasoline and 600,000 m\textsuperscript{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\textsubscript{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\textsubscript{4}, CO\textsubscript{2} and N\textsubscript{2}O), ozone precursor gases (CO, NMVOC and NO\textsubscript{x}), aerosols (BC, PM\textsubscript{10} and PM\textsubscript{2.5}), and acidifying gases (NH\textsubscript{3} and SO\textsubscript{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\textsubscript{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:

\[
E(p) = \sum_{p,f,v} \left( \text{Fuel}_{f,v} \ast E_{f,p,v} \right)
\]

(1)

where \( E(p) \) is the total emission for species or pollutant \( p \), \( \text{Fuel}(f,v) \) is the fuel sold (diesel, gasoline and CNG) for type of vehicle \( v \), \( E_{f,p,v} \) 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    | 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/EEJ Joint Inventory Guide to Air Pollutant Emissions database [42], for vehicle type and pollutant (GHGs, ozone precursors, aerosols and acidifying gases). The SO\textsubscript{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\textsuperscript{−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\textsubscript{2eq} from the main GHGs (CH\textsubscript{4} and N\textsubscript{2}O) was estimated. CO\textsubscript{2eq} emissions with a 100-year horizon global warming potential (GWP100: CH\textsubscript{4} = 28 and N\textsubscript{2}O = 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\textsubscript{2}, NO\textsubscript{2} and O\textsubscript{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\textsubscript{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\textsubscript{2} retrieved from OMI data was estimated for the period of April to June 2018 and 2020 to evaluate the NO\textsubscript{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$_2$O 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$_2$O, 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.

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$_2$O 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$_2$), Bolivar ($-308$ 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, Bolivar, 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   | 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 ± 7.95 | 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  |
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 NOx 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 insights 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 en 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     | \(\text{CO}_2\) \((\text{Kg/m}^3)\) | \(\text{CH}_4\) \((\text{Kg/TJ})\) | \(\text{N}_2\text{O}\) \((\text{Kg/m}^3)\) | \(\text{CO}\) \((\text{Kg/m}^3)\) | \(\text{NMVOC}\) \((\text{Kg/m}^3)\) | \(\text{NO}_x\) \((\text{Kg/m}^3)\) | \(\text{BC}\) \((\text{Kg/m}^3)\) | \(\text{PM}_{2.5}\) \((\text{Kg/m}^3)\) | \(\text{PM}_{10}\) \((\text{Kg/m}^3)\) | \(\text{NH}_3\) \((\text{Kg/m}^3)\) | \(\text{SO}_2\) \((\text{Kg/m}^3)\) |
|-----------------------|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Personal cars         | Gasoline | 2329                           | 25.00                         | 0.15                          | 61.74                         | 7.39                          | 6.42                          | \(3 \times 10^{-3}\)          | 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                          | \(7 \times 10^{-4}\)          | 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 2018 | Gasoline 2020 | Diesel 2018 | Diesel 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      | 11,024      |
| 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          | 19,769        | 5091        | 15,555      |
| Córdoba           | 22,813        | 37,664        | 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          | 17,638        | 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     |
| SO₂        | Ultraviolet pulsed fluorescence | SO₂ Thermo Scientific 43i    |
| NO₂        | Chemiluminescence           | NOx Ecotech 9841             |
| O₃         | Absorption spectrophotometry in the ultraviolet | O₃ Ecotech 9841 |

Table A4. CO₂ 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   |

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