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The Effect of the Covid-19 Lockdown on Air Quality in Three Italian Medium-Sized Cities

Gabriele Donzelli [1,2,*], Lorenzo Cioni [3], Mariagrazia Cancellieri [4], Agustin Llopis Morales [1] and Maria M. Morales Suárez-Varela [1,5]

1 Department of Preventive Medicine and Public Health, Food Sciences, Toxicology, and Legal Medicine, School of Pharmacy, University of Valencia, Avenida Vicente Andres Estellés s/n, Burjassot, 46100 Valencia, Spain; allomo3@alumni.uv.es (A.L.M.); Maria.M.Morales@uv.es (M.M.M.S.-V.)
2 Department of Health Sciences, University of Florence, Viale GB Morgagni 48, 50134 Florence, Italy
3 Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy; lorenzo.cioni@sns.it
4 Hygiene and Public Health Unit, Department of Public Health, AUSL Imola, 40026 Bologna, Italy; m.cancellieri@ausl.imola.bo.it
5 Biomedical Research Consortium in Epidemiology and Public Health Network (CIBERESP), Avenida Monforte de Lemos, 3-5. Pabellón 11. Planta 0, 28029 Madrid, Spain
* Correspondence: gabriele.donzelli@unifi.it

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Abstract: Despite the societal and economic impacts of the COVID-19 pandemic, the lockdown measures put in place by the Italian government provided an unprecedented opportunity to increase our knowledge of the effect transportation and industry-related emissions have on the air quality in our cities. This study assessed the effect of reduced emissions during the lockdown period, due to COVID-19, on air quality in three Italian cities, Florence, Pisa, and Lucca. For this study, we compared the concentration of particulate matter PM_{10}, $PM_{2.5}$, NO_2, and O_3 measured during the lockdown period, with values obtained in the same period of 2019. Our results show no evidence of a direct relationship between the lockdown measures implemented and PM reduction in urban centers, except in areas with heavy traffic. Consistent with recently published studies, we did, however, observe a significant decrease in NO_2 concentrations among all the air-monitoring stations for each city in this study. Finally, O_3 levels remained unchanged during the lockdown period. Of note, there were slight variations in the meteorological conditions for the same periods of different years. Our results suggest a need for further studies on the impact of vehicular traffic and industrial activities on PM air pollution, including adopting holistic source-control measures for improved air quality in urban environments.

Keywords: Covid-19; lockdown; air pollution; particulate matter (PM); nitrogen dioxide; ozone

1. Introduction

Air pollution has been one of Europe's leading political concerns since the late 1970s. It continues to significantly impact the health of the European population today, particularly in urban areas. In terms of harm to human health, Europe's most serious pollutants are particulate matter (PM), NO_2, and ground-level O_3. Italy is among the European countries most affected by air pollution, with 58,600 premature deaths attributed to $PM_{2.5}$ exposure, 14,600 to NO_2 exposure, and 3000 to O_3 exposure [1].

Meteorological parameters play an important role in determining air-pollution concentrations. Generally, PM concentrations decrease with an increase in precipitation rate, wind speed, and temperature [2]. The NO_2 in our atmosphere is primarily a function of the magnitude of nitrogen oxide (NO_x) emissions and weather factors, such as sun angle, wind speed, and temperature. Meteorological variations between years can cause column NO_2 differences of ~15% over monthly timescales [3]. O_3 generally increases with increasing temperature and decreases with increasing relative humidity [4].

Road traffic is the leading cause of air pollution in cities, and it is responsible for almost a quarter of Europe's greenhouse gas emissions [5]. According to a recent report published by Legambiente, a recognized environmental organization in Italy, each year, several Italian cities exceed air-pollution limits, especially PM and O_3 pollutant levels [6]. In 2020, as in previous years, Italy's largest cities were forced to ban hundreds of thousands of vehicles from the road after days of persistent smog.

Despite the societal and economic impacts of the COVID-19 pandemic [7,8], the lockdown measures put in place by the Italian government provided an unprecedented opportunity to increase our knowledge on the contribution of transportation and industrial emissions on air quality in our cities. As expected, after Italy adopted the mandatory measures, there was a significant reduction in transport- and industry-related emissions. Recent research clearly discloses that the restrictive measures adopted during March–April 2020 brought about a significant reduction (−64.6%) in Rome's personal vehicle usage [9].

On the evening of 9 March 2020, Italian Prime Minister Giuseppe Conte imposed a national quarantine in response to the growing COVID-19 pandemic restricting people's movement, except for reasons related to basic human needs, work, and health [10]. On 22 March 2020, a new decree closed down all non-essential industries throughout the country and restricted inter-city movement further by requiring travelers to provide justification and documentation to the authorities, when moving between and within cities [11]. The restrictions lasted three months up to 3 June 2020.

This study aimed to assess the effects of the reduced emissions during the COVID-19 period on the air quality in three Italian cities, Florence, Pisa, and Lucca. For this study's purpose, we compared the concentrations of PM_{10}, $PM_{2.5}$, NO_2, and O_3 measured before, during, and after the lockdown, with the corresponding values.

2. Methods

2.1. Area of the Study

We identified three cities for this study (Figure 1), all located in Tuscany's northern region:

1. Florence, the capital city of the Tuscany region and the Province of Florence, is the most populated, with about 372,000 inhabitants that live in the municipality, but over 1,520,000 that live in the greater metropolitan area;
2. Pisa, the capital city of the Province of Pisa, has over 91,000 residents living in the municipality and about 200,000 living in the surrounding area;
3. Lucca, the capital city of the Province of Lucca, which has more than 90,000 residents.

Each of these cities has problems related to air quality, with the measured pollutant values often exceeding EU law's daily limits. In contrast, the selected cities differ amongst several characteristics, such as the number of inhabitants (http://demo.istat.it/pop2020/index.html) and geophysical attributes. While Pisa's and Lucca's population is similar, we must consider that Pisa is a city with three universities. During the day, Pisa's population practically doubles, except during the lockdown period, when the universities' activities were minimal because of the government-imposed restrictions.

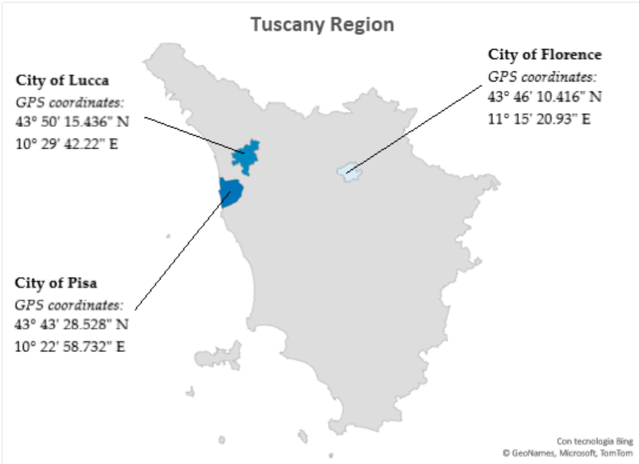

Figure 1. Map of the cities included in the study.

2.2. Air-Quality and Meteorological Data Collection and Processing

We based the data used in the following analyses from ARPAT (Agenzia Regionale per la Protezione Ambientale della Toscana, the Regional Agency for the Environmental Protection of Tuscany) website (http://www.arpat.toscana.it/temi-ambientali/aria/qualita-aria/). The analyses include measures of the four pollutants (PM_{10}, $PM_{2.5}$, NO_2, and O_3) daily average during the period from 1 January 2019, to 12 August 2020, with gaps, at times, because of unavailable data. We call these eight months the sampling period. In practice, however, we used only the data from 1 January to 12 August 2019, and the same period for the year 2020, to perform the statistical analyses. We call these two timeframes the standard periods.

We collected the data from the three cities (Firenze, Lucca, and Pisa). For each city and each pollutant, we specify the number of measuring stations in Table 1. The number of stations in each city varies according to the contaminant measured and the actual city. ARPAT provided data verification and validation by monitoring the instrumental performance and applying quality-control procedures.

Table 1. Characteristics of the air-monitoring stations included in the study.

Air-Monitoring Station	City	Station Type	Area Type	Pollutants			
				PM_{10}	$PM_{2.5}$	NO_2	O_3
FI-GRAMSCI	Florence	Traffic	Urban	✓	✓	✓	
FI-BASSI	Florence	Background	Urban	✓	✓	✓	
FI-MOSSE	Florence	Traffic	Urban	✓		✓	
FI-SETTIGNANO	Florence	Background	Suburban				✓
PI-BORGHETTO	Pisa	Traffic	Urban	✓	✓	✓	
PI-PASSI	Pisa	Background	Urban	✓	✓	✓	✓
LU-MICHELETTO	Lucca	Traffic	Urban	✓		✓	
LU-CARIGNANO	Lucca	Background	Rural				✓
LU-SAN-CONCORDIO	Lucca	Background	Urban	✓		✓	

Station type. *Traffic-measuring stations*: air-monitoring stations located in areas where the pollution level is most influenced by traffic emissions from neighboring roads with medium-high traffic intensity. *Background (or general) measuring stations*: air-monitoring stations located where the pollution level is not influenced mostly by emissions from specific sources (industries, traffic, residential heating, etc.) but rather from a combination of all sources, upwind from the station concerning the predominant wind directions at the site. Area type. *Urban fixed sampling site*: a fixed site placed in a growing or predominantly built-up area. *Suburban fixed sample site*: a fixed site placed in largely built-up areas where there are both built-up and non-urbanized areas. *Rural fixed sampling site*: a fixed site selected in areas other than those identified for urban and suburban locations. The site is defined as remote rural if it is more than 50 km away from the emission sources. PM = particulate matter.

For each pollutant, from 1 January 2019, we focused on the two standard periods dividing it further into the following subperiods:

[1 January–8 March 2019] vs. [1 January–8 March 2020] → pre-lockdown period;
[9 March–3 June 2019] vs. [9 March–3 June 2020] → lockdown period;
[4 June–12 August 2019] vs. [4 June–12 August 2020] → post-lockdown period.

We used a paired t-test to determine whether the mean difference between the two sets of observations was significant. The null hypothesis (H_0) assumed that the true mean difference between the paired samples was zero, while the alternative hypothesis (H_1) assumed that the true mean difference between the paired samples was not equal to zero. We chose the cutoff value of 0.05 to determine statistical significance. This value corresponds to a 5% (or less) chance of obtaining a result like the one that was observed if the null hypothesis was true. Regarding the main assumptions of the paired t-test, it is reasonable to assume that the observations were independent of one another. Furthermore, we tested the assumption of normality and found that the data were approximately normally distributed. Finally, we examined the relative percentage variation of the average concentrations throughout the subperiods.

For this analysis, we downloaded data on wind speed, rainfall, relative humidity, temperature, and solar irradiance for the entire period from the Meteoblue AG–Switzerland website (https://www.meteoblue.com) and from the Meteorological Archive of Tuscany website (https://www.ilmeteo.it/portale/archivio-meteo/toscana). Moreover, on 28–29 March 2020, the local environmental protection agency reported only one transport dust phenomenon from Asia and North Africa [12]. Therefore, we excluded PM_{10} and $PM_{2.5}$ values for the same days in our analysis, ensuring we considered only significant and comparable data.

To give further details concerning the meteorological data, we used the following data measured at the Pisa San Giusto, Firenze Peretola, and Lucca meteorological stations: average daily air temperature (as Celsius degrees), average daily air humidity (as a percentage value), average daily wind speed (as km/h), and average daily sea-level air pressure (as mbar). For both 2019 and 2020, we did not derive statistically significant differences. In particular, we considered the wind speed as average daily wind speed and not the wind directions during each period for the two years, 2019 and 2020, since the measuring stations are distant from each other, and since we are not interested in the directions in which the pollutants are spread but only in their values as measured by every measuring station. In all the three cases of Pisa San Giusto, Firenze Peretola, and Lucca, we found that the average daily wind speed differences between the same periods of the two years 2019 and 2020 were not statistically significant at a $\alpha = 0.05$ level.

3. Results and Discussion

3.1. Particulate Matter

Compared to the same period in 2019, PM_{10} and $PM_{2.5}$ concentrations during the pre-lockdown period are not significantly different between the air-monitoring stations across the three cities, Florence, Pisa, and Lucca. Tables 2 and 3 show that the FI-GRAMSCI monitoring station is the only air-monitoring station in which there was a statistically significant reduction of PM_{10} and $PM_{2.5}$ during the lockdown period, with a variation of about 30.8% and 50.1%, respectively. On the other hand, there was no significant difference between the remaining air-monitoring stations. This result is in line with a recent report on outdoor air pollution changes in Scotland during the COVID-19 lockdown, which showed that PM concentrations did not decline, despite reducing vehicular traffic [13]. It is very likely that the environmental response, measured as the reduction in PM concentrations, varies according to the dominant source of emission in each country and because of the specific meteorological conditions [14].

Unexpectedly, we also observed an increase in the $PM_{2.5}$ concentration at the PI-BORGHETTO monitoring station, the Pisa city center traffic station, with a variation of about 33.3%. Changes in meteorological conditions do not explain these variations, given the absence of a significant difference between the two years. We hypothesize that because people spent more time indoors during the lockdown period, the higher levels of $PM_{2.5}$ are associated with the increased use of heating systems in buildings. Moreover, we hypothesize there was only a small change in the volume of traffic in this area of the city. This hypothesis highlights that other PM sources are significantly present and that holistic source-control measures are needed for improved air quality in urban environments [15].

Figures 2 and 3 graph the PM_{10} and $PM_{2.5}$ daily mean concentrations for the three stations in which we note a statistically significant difference. Although previous studies reported a decrease of PM_{10} and $PM_{2.5}$ concentrations [16–19], we noticed that they had compared the two periods of the same year: the pre-lockdown and lockdown period. In our view, this methodology represents a bias since, every year, it is possible to observe a decrease of particulate matter concentrations due to seasonal variations [20]. However, other studies reported a reduction in PM, using a methodology similar to ours, for example, by comparing the same periods of the previous year or with averages of several prior years [21–24]. These differences should be interpreted in light of the aforementioned variations in meteorological conditions and sources of emissions between different countries and cities. Regarding the FI-GRAMSCI measuring station, we must consider that it is the critical point (hot spot) in Tuscany, with much higher values than any other air-monitoring station. Therefore, this result should be interpreted with this peculiarity in mind and confirmed with further analyses by comparing this station with similar hot-spot air-monitoring stations in other cities than Pisa, Lucca, and Florence itself. Overall, our results show no direct evidence of a relationship between the implementation of the lockdown measures and the reduction of particulate matter in urban centers, except heavy traffic areas. Further research is needed to clarify this relationship, and it would also be interesting to examine the citizens' risk perception of air pollution in the context of the current Covid-19 emergency [25].

Table 2. Output of the two-sample t-test to evaluate the lockdown effects on PM10 air concentration. The PM10 values are expressed in $\mu g \cdot m^{-3}$.

	First Period 1 January–8 March			**Second Period (Lockdown) 9 March–3 June**			**Third Period 4 June–12 August**		
	Mean (SD) 2019	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**
FI-GRAMSCI	37 (16)	36 (15)	0.635	23 (7)	16 (6)	<0.001	24 (9)	17 (4)	<0.001
FI-BASSI	23 (16)	28 (14)	0.300	14 (7)	15 (6)	0.186	19 (7)	15 (4)	0.002
FI-MOSSE	30 (18)	32 (16)	0.427	14 (8)	15 (5)	0.269	21 (8)	15 (4)	<0.001
PI-BORGHETTO	39 (17)	36 (17)	0.237	19 (8)	18 (7)	0.255	26 (9)	18 (4)	<0.001
PI-PASSI	35 (17)	33 (16)	0.223	16 (7)	17 (6)	0.982	22 (7)	15 (4)	<0.001
LU-MICHELETTO	42 (20)	42 (25)	0.996	17 (7)	19 (9)	0.141	20 (7)	18 (7)	0.131
LU-SAN-CONCORDIO	40 (18)	37 (21)	0.322	15 (7)	18 (8)	0.037	21 (7)	15 (4)	<0.001

Table 3. Output of the two-sample t-test to evaluate the lockdown effects on PM2.5 air concentration. The PM2.5 values are expressed in μg·m^{-3}.

	First Period 1 January–8 March			Second Period (Lockdown) 9 March–3 June			Third Period 4 June–12 August		
	Mean (SD) 2019	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**
FI-GRAMSCI	24 (12)	21 (13)	0.207	12 (4)	10 (4)	0.045	14 (3)	10 (3)	<0.001
FI-BASSI	19 (13)	20 (14)	0.552	9 (4)	10 (4)	0.056	12 (3)	9 (3)	<0.001
PI-BORGHETTO	25 (14)	22 (15)	0.179	8 (3)	11 (5)	<0.001	11 (3)	8 (3)	<0.001
PI-PASSI	29 (15)	26 (17)	0.245	11 (4)	12 (6)	0.437	15 (4)	10 (3)	<0.001

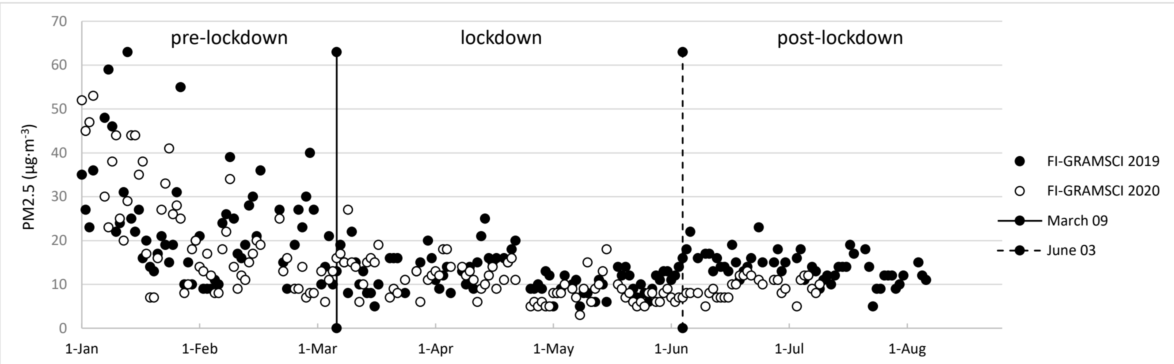

Figure 2. The daily mean concentration of PM2.5 (μg·m^{-3}). In each graph, the lockdown period is depicted between the two vertical bars.

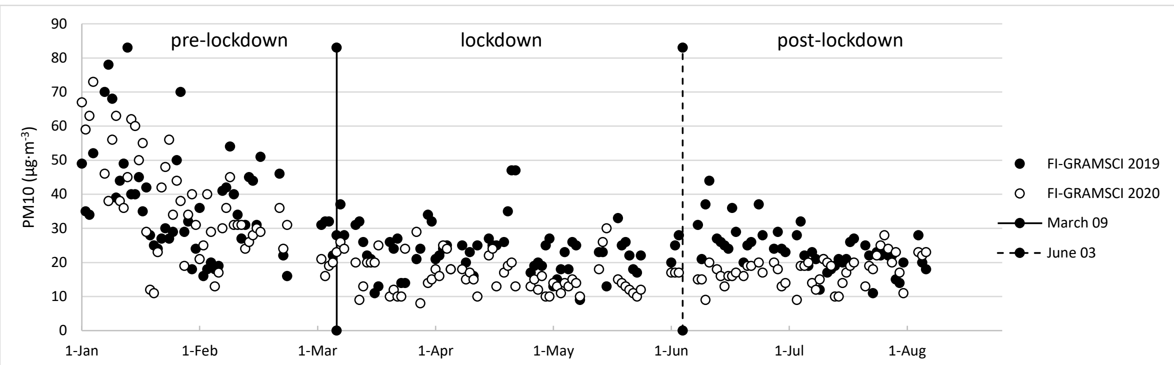

Figure 3. The daily mean concentration of PM10 (μg·m^{-3}). In each graph, the lockdown period is depicted between the two vertical bars.

3.2. Nitrogen Dioxide

NO_2 primarily gets in the air from burning fuel from cars, trucks, buses, power plants, and off-road equipment. It reacts with other chemicals in the air to form both PM and O_3, and it is harmful when inhaled due to the effect it has on the respiratory system. While we noted fluctuating NO_2 levels in different areas, the concentration of NO_2, during the lockdown was significantly less among all the air-monitoring stations across the cities included in this study. Table 4 indicates statistically significant reductions ($p < 0.05$) of NO_2 concentration during the lockdown period, compared to the same period of 2019. These results clearly indicate that reducing traffic emissions contributes to lower NO_2 concentration levels and represents a significant improvement in public health. They should motivate us to adopt new urban mobility policies to reduce pollution in our cities and protect human health even after the COVID-19 crisis [26].

Figure 4 exhibits the daily mean of NO_2 concentration during the three periods.

In detail, compared to the levels in 2019, concentrations of NO_2 decreased by 38.5%, 32.1%, 39.4%, 40.1%, 41.6%, 35.0%, and 39.4%, respectively, at the FI-GRAMSCI, FI-BASSI, FI-MOSSE, PI-BORGHETTO, PI-PASSI, LU-MICHELETTO, and LU-CARIGNANO measuring stations. These results are consistent with the findings of previously published works. For example, Nakada et al., 2020 [22], observed a decrease of up to 54.3% in NO_2 concentrations ($\mu g \cdot m^{-3}$) in the urban roads of São Paulo state, Brazil. Moreover, Collivignarelli et al., 2020, observed a drastic drop in the concentration of NO_x and NO_2 in all the areas covered by that study on air quality in Milan, Italy. Researchers also noted an apparent decrease in NO_2 levels in Rio de Janeiro, Brazil [19], in 22 cities covering different regions of India [21], the megacity Delhi, India [18], the Yangtze River Delta Region [23], and 44 cities in Northern China [24]. Satellite measurements also capture regional NO_2 concentration reductions in air quality by the TROPOspheric Monitoring Instrument (TROPOMI) on the European Space Agency's Sentinel-5 satellite [27].

Table 4. Output of the two-sample *t*-test to evaluate the effects of lockdown on NO_2 air concentrations. The NO_2 values are expressed in $\mu g \cdot m^{-3}$.

	First Period 1 January–8 March			Second Period (Lockdown) 9 March–3 June			Third Period 4 June–12 August		
	Mean (SD) 2019	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**
FI-GRAMSCI	117 (22)	110 (21)	0.081	98 (18)	60 (22)	<0.001	94 (22)	76 (13)	<0.001
FI-BASSI	61 (23)	60 (18)	0.856	36 (18)	25 (15)	<0.001	31 (9)	22 (8)	<0.001
FI-MOSSE	89 (23)	79 (18)	0.005	59 (16)	36 (16)	<0.001	46 (15)	34 (8)	<0.001
PI-BORGHETTO	85 (14)	76 (16)	0.003	58 (18)	35 (15)	<0.001	48 (13)	34 (11)	<0.001
PI-PASSI	64 (15)	55 (15)	0.001	34 (15)	20 (11)	<0.001	24 (6)	16 (4)	<0.001
LU-MICHELETTO	69 (12)	58 (12)	<0.001	45 (15)	29 (11)	<0.001	35 (11)	27 (8)	<0.001
LU-CARIGNANO	77 (17)	62 (13)	<0.001	46 (18)	28 (14)	<0.001	36 (10)	26 (8)	<0.001

As shown in Table 5, we must point out that the NO_2 concentration during 2020, is statistically lower than that of 2019, even before the lockdown. However, the variations during the lockdown are higher, leading us to deduce that the decrease in vehicular traffic positively affected the air quality. Road traffic is the principal outdoor source of nitrogen dioxide [28], and the relationship between traffic and NO_2 has been examined in many studies [29–31].

Table 5. Variations NO_2 ($\mu g{\cdot}m^{-3}$) during the three periods.

	First Period 2020 vs. 2019 1 January–8 March	Second Period 2020 vs. 2019 9 March–3 June	Third Period 2020 vs. 2019 4 June–12 August
FI-GRAMSCI	5.7%	38.5%	19.6%
FI-BASSI	1.0%	32.1%	28.3%
FI-MOSSE	11.3%	39.4%	26.2%
PI-BORGHETTO	9.7%	40.1%	29.4%
PI-PASSI	13.2%	41.6%	33.1%
LU-MICHELETTO	17.1%	35.0%	23.3%
LU-CARIGNANO	19.6%	39.4%	25.9%

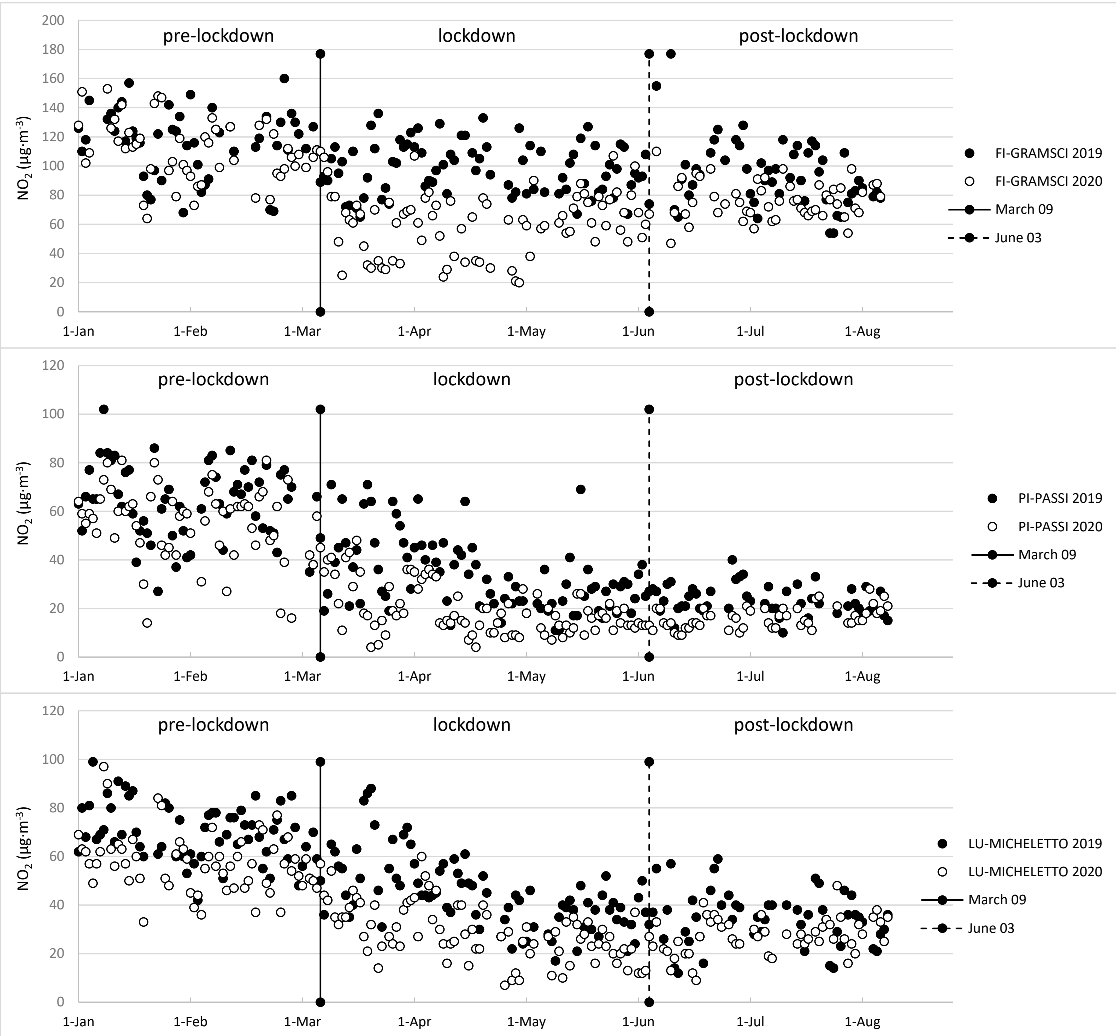

Figure 4. The daily mean concentration of NO_2 ($\mu g{\cdot}m^{-3}$). The area between the vertical bars in each graph indicates the duration of the lockdown.

3.3. Ozone

Tropospheric O_3 is a harmful air pollutant created by chemical reactions between NO_x and volatile organic compounds (VOC) in the presence of sunlight. A recent study showed that the lockdown measures caused an increase of O_3 concentrations at urban stations of four Southern European cities and Wuhan (China). This phenomenon's explanation is mainly based on the unprecedented reduction in NO_x emissions leading to a lower O_3 titration by NO [32]. On the other hand, our results show that the O_3 concentration did not show significant reductions during the period of lockdown (Table 6). Figure 5 shows the increasing ozone trend across the three periods, a typical phenomenon observed during the spring season due to the higher solar radiation [33]. However, we must point out that our data are related to background and suburban stations, and, for this reason, we cannot compare them with the aforementioned study, and we cannot draw any significant conclusions about O_3 general trends in urban areas.

Table 6. Output of the two-sample *t*-test to evaluate the effects of lockdown on O_3 air concentrations. The O_3 values are expressed in $\mu g \cdot m^{-3}$.

	Pre-Lockdown			Lockdown			Post-Lockdown		
	Mean (SD) 2019	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**	**Mean (SD) 2019**	**Mean (SD) 2020**	***p*-Value**
FI-SETTIGNANO	70 (17)	66 (16)	0.067	100 (15)	100 (17)	0.939	128 (23)	116 (25)	0.007
PI-PASSI	61 (19)	62 (20)	0.886	92 (12)	95 (14)	0.198	107 (16)	99 (15)	0.008
LU-CARIGNANO	80 (19)	70 (17)	<0.001	100 (14.0)	98.42 (17)	0.423	129 (23)	108 (18)	<0.001

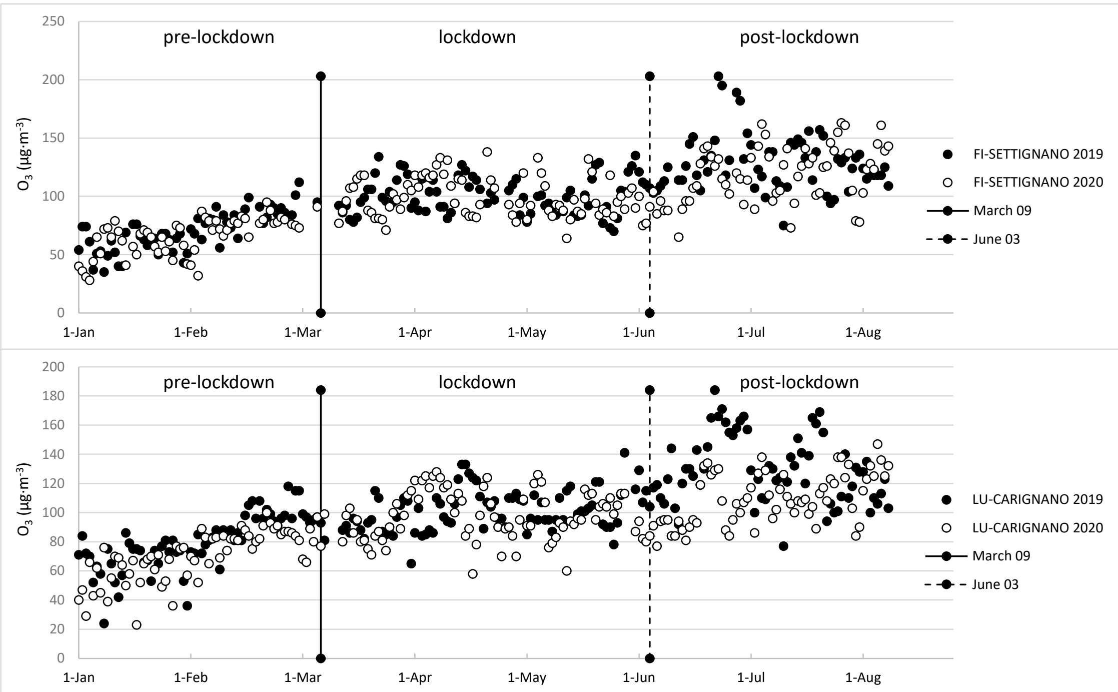

Figure 5. The daily mean concentration of O_3 ($\mu g \cdot m^{-3}$). The area between the vertical bars in each graph indicates the duration of the lockdown duration.

4. Conclusions

In this article, we assessed the impact of the Italian nationwide lockdown due to the COVID-19 outbreak on air quality in three medium-sized cities. The strict travel restrictions and limitations on the movement between and within the cities during the Italian lockdown period provided an unprecedented opportunity to assess anthropogenic activities' effect on urban air quality. More specifically, the adopted restrictive measures resulted mainly in a significant reduction in vehicular traffic and industrial activities. We aimed to evaluate the effects of these restrictive measures on the concentration of four primary air pollutants collected by the Regional Agency for the Environmental Protection of Tuscany, which are PM_{10}, $PM_{2.5}$, NO_2, and O_3. Our results did not show significant reductions in PM levels during the lockdown period, except at one monitoring station in an area of heavy traffic, which is considered a hot spot because of the consistently high levels recorded for all of Tuscany. These results are not consistent with the published studies on this topic, and we can assume that the environmental response varies according to the dominant emission source and the specific meteorological conditions. Our research field should further explore the interrelationship between the different sources of emissions and particulate matter concentration. On the other hand, the reduction in NO_2 pollution levels, consistent with other studies, was statistically significant at all the air-monitoring stations across the cities used in this study, showing a relevant traffic volume relationship. These results should motivate the politicians to adopt new urban policies to reduce pollution in our cities and protect human health even after the COVID-19 crisis. Finally, for O_3 pollutant levels, we did not observe a significant reduction during the lockdown period. However, we should take into account that none of these monitoring stations are placed in the traffic areas, and, therefore, we cannot draw significant conclusions on the trend of O3 during the lockdown period. In conclusion, we believe it is necessary to adopt holistic source-control measures for improved air quality in urban environments.

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