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Assessing correlations between short-term exposure to atmospheric pollutants and COVID-19 spread in all Italian territorial areas☆

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ABSTRACT

The spread of SARS-CoV-2, the beta coronavirus responsible for the current pneumonia pandemic outbreak, has been speculated to be linked to short-term and long-term atmospheric pollutants exposure. The present work has been aimed at analyzing the atmospheric pollutants concentrations (PM_{10}, $PM_{2.5}$, NO_2) and spatio-temporal distribution of cases and deaths (specifically incidence, mortality and lethality rates) across the whole Italian national territory, down to the level of each individual territorial area, with the goal of checking any potential short-term correlation between these two phenomena. The data analysis has been limited to the first quarter of 2020 to reduce the lockdown-dependent biased effects on the atmospheric pollutant levels as much as possible. The analysis looked at non-linear, monotonic correlations using the Spearman non-parametric correlation index. The statistical significance of the Spearman correlations has also been evaluated. The results of the statistical analysis suggest the hypothesis of a moderate-to-strong correlation between the number of days exceeding the annual regulatory limits of PM_{10}, $PM_{2.5}$ and NO_2 atmospheric pollutants and COVID-19 incidence, mortality and lethality rates for all the 107 territorial areas in Italy. A weak-to-moderate correlation seems to exist when considering the 36 territorial areas in four of the most affected regions (Lombardy, Piedmont, Emilia-Romagna and Veneto). Overall, PM_{10} and $PM_{2.5}$ showed a higher non-linear correlation than NO_2 with incidence, mortality and lethality rates. As to particulate matters, PM_{10} profile has been compared with the incidence rate variation that occurred in three of the most affected territorial areas in Northern Italy (i.e., Milan, Brescia, and Bergamo). All areas showed a similar PM_{10} time trend but a different incidence rate variation, that was less severe in Milan compared with Brescia and Bergamo.

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1. Introduction

The human fatal pneumonia that has currently spread worldwide, known as CoronaVIrus Disease-2019 (COVID-19), is caused by a very recently identified beta coronavirus named Severe Acute Respiratory Syndrome CoronaVirus type 2 (SARS-CoV-2) (Sohrabi et al., 2020). In less than 6 months, SARS-CoV-2 caused 6,194,508 confirmed cases of COVID-19 and 372,501 deaths (on May 31st, 2020) (Dong et al., 2020). Hence, the current SARS-CoV-2 pandemic is evidently much more widespread than the two previously reported coronavirus outbreaks of the *XXI* century, namely the SARS-CoV (8096 people infected with 774 deaths in 2002 – 03) and the Middle-East Respiratory Syndrome (MERS; 2494 people infected with 858 deaths in 2012) (Ahn et al., 2020). At the beginning of 2020, exactly on January 30th, the World Health Organization (WHO) declared that the Chinese outbreak of COVID-19 had to be considered a Public Health Emergency of International Concern posing a high risk to countries with vulnerable health systems (Sohrabi et al., 2020). On March 11th, 2020, the WHO (WHO Director, 2020) established that the international outbreak of a new SARS-CoV-2 coronavirus infection could be considered a pandemic, despite there being 77 countries and territories with no reported cases at that time, and 55 countries and territories with no more than 10 reported cases.

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The first epidemic spread of SARS-CoV-2 occurred in Wuhan, a main city in the Chinese region of Hubei. Then the virus moved to Europe, where it first exploded in the Milan-Bergamo-Brescia area of Lombardy in Italy, to later spread to the rest of the world.

The pandemic declaration was actually a consequence of the almost 13-fold increase in the number of cases reported outside China as 125,000 COVID-19 cases from 118 countries and territories were reported overall to the WHO itself. The first European confirmed cases of COVID-19 were reported in France (on January 24^{th}, 2020) (Stoecklin et al., 2020) and as of February 21^{st}, 2020, only 47 confirmed cases had been notified in 9 different countries of the WHO European Region (Spiteri et al., 2020). Among them, three cases were diagnosed in Italy, including a Chinese couple of tourists at the end of January in Rome, which however did not lead to a further spread of the virus. On February 20^{th}–21^{st}, 2020, the first detected cases on Italian people were reported in two Italian towns: Vo' Euganeo (territorial area of Padua, Veneto region) and Codogno (territorial area of Lodi, Lombardy region), the latter being considered as "patient 1" (Grasselli et al., 2020; Onder et al., 2020; Romagnani et al., 2020).

As a result of the pandemic spread all over the world, several studies have been focusing on the potential role of atmospheric pollutants (mainly Particulate Matters - PMs) in the diffusion of COVID-19 both in the short- and the long-term, as well as the impact of the virus on human health (Bontempi, 2020a; Coccia, 2020; Fattorini and Regoli, 2020; Frontera et al., 2020a, 2020b; Liang et al., 2020; Martelletti and Martelletti, 2020; Onder et al., 2020; Riccò et al., 2020; Wu et al., 2020; Zoran et al., 2020a, 2020b).

It is actually biologically plausible for people living in highly industrialized areas, and therefore subject to higher pollution levels, to show more severe symptoms (Bontempi et al., 2020).

Further studies have pointed out that atmospheric pollutants can indeed act as virus carriers and boost pandemic diffusion (Del Buono et al., 2020; Sterpetti, 2020; Setti et al., 2020; SIMA, 2020). Yet, as stated in a recent work (Bontempi, 2020a), there is no scientific evidence that PMs can act as a means of transport of the virus, thus promoting its diffusion.

Another study (Bontempi, 2020b) suggests that parameters other than environmental pollution, such as trade-related aspects, should be assessed as a possible source of virus diffusion at the onset of the pandemic in Italy.

A pandemic is actually a very complex phenomenon and several variables (confounding factors) should be considered in the analysis to describe any possible correlation in a rigorous way (Bontempi et al., 2020).

As reported by (Heederik et al., 2020), scientific research has been adopting different methodological approaches to this problem. The first approach relies on the use of confounders in the analysis, whereas other studies have opted for leaving confounders out of the scope of investigation.

A recent study carried out in the United States (Wu et al., 2020) on 1783 counties looked at several confounders to analyze the correlation of COVID-19 with the average long-term exposure (2000–2016) to average air pollution levels ($PM_{2.5}$). The confounding factors included population size, ethnicity, hospital beds, number of individuals tested for COVID-19, weather, socioeconomic and behavioral variables (e.g. income, obesity, smoking habits), days since the first reported case of COVID-19, population age distribution, and days since the issuance of the stay-at-home order in each state. There are only few other studies based on the use of confounders and the related sensitivity analysis (Isaifan, 2020; Liang et al., 2020; Zhu et al., 2020).

Further works on this subject have merely pointed out the need to consider other variables besides atmospheric pollution, such as temperature and relative humidity (Sajadi et al., 2020; Scafetta, 2020). Many studies conducted in Europe about the association between COVID-19 diffusion and long-term exposure to pollutants, did not consider the effects of confounding factors in their analyses (Bontempi 2020a; Coccia 2020; Fattorini and Regoli, 2020; Frontera et al., 2020a, 2020b; Ogen, 2020; Travaglio et al., 2020; Zoran et al., 2020a, 2020b). Moreover, several studies have also pointed out the connection among climate change, atmospheric pollution and human health (Orru et al., 2017; Kinney, 2018; Ravindra et al., 2019).

Finally, further works have been trying to predict the behavior of some COVID-19 related variables through the use of exponential models as well as dynamic SIR-based models (Chen et al., 2020; Fanelli and Piazza, 2020; Remuzzi and Remuzzi, 2020; Reno et al., 2020).

Confounders have been left out of the scope of the present analysis due to the lack of reliable data sources. When writing the manuscript, there were actually no data available about the confounding factors of interest at the same spatio-temporal resolution of COVID-19 and atmospheric pollutants variables used in the present analysis.

Focusing on the Italian case, the present work has examined the possibility of there being a non-linear correlation between short-term exposure to $PM_{2.5}$, PM_{10}, and NO_2 atmospheric pollutants in the first quarter of 2020 (including the start of the virus spread in Italy) and COVID-19 diffusion variables, i.e. incidence, mortality and lethality rates. The analysis used the Spearman correlation coefficient to assess non-linear, monotonic correlations for the whole Italian national territory down to the level of each individual territorial area ($n = 107$ territorial areas), including four of the most affected regions ($n = 36$ territorial areas), i.e. Lombardy, Piedmont, Emilia-Romagna and Veneto. Data analysis has been limited up to March 31^{st}, 2020 with the aim of reducing as much as possible the lockdown-dependent biased effects on the levels of the three atmospheric pollutants under investigation. Finally, PM_{10} profiles have been further analyzed along with the incidence rate variation for three of the most affected territorial areas in Northern Italy (i.e., Milan, Brescia, and Bergamo) in March 2020.

2. Materials and methods

2.1. Data sources

As reported in Table 1, data were only collected from reliable institutional and well-referenced sources, in order to reduce as much as possible the uncertainty due to mixing different data sources. The reference links to access raw data are also indicated.

Data collection for the short-term exposure to atmospheric pollutants and COVID-19 related variables has been limited up to March 31^{st}, 2020 with the aim of minimizing the lockdown-dependent biased effects. Furthermore, COVID-19 incidence rate has only been examined up to the end of the national lockdown on June 2^{nd}, 2020.

Starting from February 24^{th}, 2020, data have been daily updated providing useful information about the epidemic spread in Italy on a regional scale and in the different territorial areas as well. Several COVID-19 related variables are available at regional level, whereas only the total cases are reported for the territorial areas. Therefore, COVID-19 deaths by territorial area have been extracted from a joint report published by the Italian National Institute of Statistics (ISTAT) and the Italian National Institute of Health (ISS) (ISTAT, 2020a). The report provides an integrated view of the COVID-19 epidemic spread in Italy and total mortality data from February 20^{th} to March 31^{st}, 2020.

Besides the lethality rate, the present analysis has also considered incidence and mortality rates as COVID-19 variables; for this reason, data on the population living in Italy as of January 1^{st},

Table 1
Publicly available data sources used in the analysis.

Parameter	Source	Data
COVID-19 total cases	Civil Protection Department of the Italian Government, Presidency of the Council of Ministers. GitHub repository: https://github.com/pcm-dpc/COVID-19, ICPD (Civil Protection Department GitHub data repository), 2020b; ICPD (Civil Protection Department of the Italian Government), 2020a	Daily updated total cases for Italian regions and territorial areas from February 24th, 2020 to present date
COVID-19 deaths	Italian National Institute of Statistics (ISTAT) & Istituto Superiore di Sanita (ISS) report https://www.istat.it/it/files//2020/05/Istat- ISS_- eng.pdf	COVID-19 deaths in Italy from February 20th to March 31st, 2020
Atmospheric pollutant concentrations: $PM_{2.5}$, PM_{10}, NO_2	Copernicus Atmosphere Monitoring Service (CAMS) air quality forecasts https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-europe-air-quality-forecasts?tab=overview	Daily averaged air quality forecasts and analysis from January 1st to March 31st, 2020 for all territorial areas in Italy
Air quality regulatory limits	World Health Organization (WHO) guidelines https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1	WHO air quality indices for particulate matters and nitrogen dioxide
Population	Italian National Institute of Statistics (ISTAT) http://dati.istat.it	Population living in each territorial area as of January 1st, 2020

2020 at the level of each individual territorial area have been provided by the Italian National Institute of Statistics (ISTAT, 2020b).

Air quality variables ($PM_{2.5}$, PM_{10}, and NO_2), collected from the Copernicus Atmosphere Monitoring Service (CAMS) (CAMS, 2020), represent a combination of 9-models forecasts and observation data provided by the European Environment Agency (EEA) (EEA, 2020a, b).

The CAMS dataset has a higher spatial resolution of $0.1^\circ \times 0.1^\circ$ degrees (approximately 10 km) and a temporal resolution of 1 h. The gathering procedure from the CAMS dataset consists in extracting a specific sub-domain related to each of the 107 territorial areas across the whole Italian territory, thus avoiding any overlap. Grid points fall inside each sub-domain and represent the time evolution of pollutant concentrations. Multivariate time series were therefore considered for the analysis, by averaging pollutant levels both spatially (across all the sub-domain grid points) and temporally (every 24-h). A total of 3 pollutants time series were then extracted for each of the 107 territorial areas within the time period January 1st - March 31st, 2020.

The Italian state territory is divided into 20 regions and 107 territorial areas (ISTAT, 2020c), which include both provinces (n = 93) and metropolitan areas (n = 14). Hence, the reference to territorial areas along this manuscript indicates the overall sub-regional level of data and analyses. In order to get a clear starting point of the COVID-19 spread in Italy, the authors decided to focus the attention on the first period of the outbreak, from February 20th to March 31st, 2020.

To check the correlation among COVID-19 incidence, mortality and lethality rates and the main air quality indicators, i.e., $PM_{2.5}$ and PM_{10} particulate matters as well as NO_2, a series of analyses based on scatter plots has been performed, to fix the following pivotal parameters: *i)* short-term exposure to the three mentioned air quality indicators, usually associated with human health effects above all at the respiratory level, within the first quarter of 2020 (91 days from January 1st, 2020 on) as reference exposure period, and *ii)* number of days (at least 45) exceeding the annual regulatory limits for each indicator, setting the worst case as the pivotal exceeding period in the whole analysis. Notably, exceeding the annual regulatory limits for 45 days means having a higher exposure to each atmospheric pollutant for at least 50% of the period under consideration, that is the first quarter of 2020.

The present analysis was performed on all 107 Italian territorial areas and revealed that almost all atmospheric pollutants under investigation exceeded the annual regulatory limits (see Table 2) for half of the first quarter of 2020, that is 45 days out of 91 from January 1st to March 31st, 2020.

Furthermore, the analysis of short-term exposure to $PM_{2.5}$, PM_{10}, and NO_2 was targeted on the 36 territorial areas in four of the most affected Italian regions, i.e., Lombardy, Piedmont, Emilia-Romagna and Veneto.

Table 2
WHO air quality regulatory limits. Pollutants concentrations are expressed in $\mu g/m.^3$.

WHO guidelines	$PM_{2.5}$	PM_{10}	NO_2
Hourly concentration limit	–	–	200
Daily concentration limit	25	50	–
Annual concentration limit	10	20	40

2.2. Incidence rate

The *incidence rate per 100,000 inhabitants* in the period from February 24th to March 31st, 2020, has been calculated for all 20 regions and 107 territorial areas as the *ratio* of the *total number of COVID-19 cases* (from the Italian Civil Protection repository) to the *population at risk* during the period. The analysis considered the whole population at risk as of January 1st, 2020, (see population reference in Table 1).

The *incidence rate variation* for day *t* was calculated as:

$$ir\_variation_t = ir_t - ir_{t-1}$$

PM_{10} profiles have been smoothed by means of a 7-day moving average, which means that every value in the time series is computed as the average of values over the previous 7 days. The *i-th* PM_{10} value of the time series is actually replaced by the mean value computed on the previous 7 days, including the *i-th* value. In addition to providing a smoothing effect on the time-series, the use of a 7-day moving average allows keeping track of the continued exposure to PM_{10} concentrations over the previous 7 days.

By using a 7-day lag-time, the value reported on the *i-th* day would have been the accurate value occurred 7 days earlier, without considering any other effect resulting from the continued exposure over the previous 7 days.

2.3. Mortality rate

The *mortality rate per 100,000 inhabitants* in the period from February 24th to March 31st, 2020 has been calculated for all 20 regions and 107 territorial areas as the *ratio* of the *total number of COVID-19 deaths* (from the ISTAT-ISS report) to the *population at risk* during the period.

2.4. Lethality rate

The *lethality rate* in the period from February 24^{th} to March 31^{st}, 2020 has been calculated for all 20 regions and 107 territorial areas as the *percentage ratio* between the *total number of COVID-19 deaths* (from the ISTAT-ISS report) and the *total number of COVID-19 cases* (from the Italian Civil Protection repository).

2.5. Air quality index (AQI)

The *Air Quality Index (AQI)*, an indicator used to monitor air pollution in a particular area (EEA, 2020a, b), varies according to the number of considered pollutants and air quality regulatory limits. The *AQI* has been evaluated as the *maximum among air pollutants concentrations*. The analysis performed in this work used the World Health Organization (WHO) guidelines for particulate matters ($PM_{2.5}$, PM_{10}) and nitrogen dioxide (NO_2) (WHO, 2005) (Table 2).

On this basis, a counter variable has been computed for each territorial area, accounting for the number of days that exceeded the annual regulatory limits for the selected pollutants in the period from January 1^{st} to March 31^{st}, 2020.

2.6. Statistical analysis

Data sources have been integrated using the Python 3.6.5 programming language and analyzed with data science, statistical and plotting libraries (pandas, geopandas, numpy, scipy stats library and scikit-learn). The Spearman correlation coefficient was used in this work to assess non-linear, monotonic correlations between the number of days exceeding regulatory limits for the selected pollutants and COVID-19-related variables at the level of territorial areas. The statistical significance of the Spearman coefficient was also evaluated.

3. Results

3.1. COVID-19 initial spread and air quality index (AQI): the Italian country standpoint

Data reported by ISTAT (ISTAT, 2020a) stated that on March 31^{st}, 2020, the national lethality rate of COVID-19 corresponded to 12.64% (14,324 deaths, 113,312 total confirmed cases).

The number of days exceeding the annual regulatory limits (see Table 2) of particulate matters ($PM_{2.5}$ and PM_{10}) and NO_2 (see Fig. 1, panels A, B and C) has been calculated to determine the level of pollution across the Italian territorial areas in the period from January 1^{st} to March 31^{st}, 2020. Most territorial areas in Northern Italy exceeded the limits for several days in a row throughout the first quarter of 2020. Notably, the number of exceeding days for each individual atmospheric pollutant was higher than 45, that is at least 50% of the analyzed period.

A careful analysis immediately pointed out the overlap of the low AQI (Fig. 1, panel D) with the incidence rate distribution at regional level (Fig. 1, panel E) down to the level of territorial areas (Fig. 1, panel F). The AQI was calculated for the first quarter of 2020, from January 1^{st} to March 31^{st}, based on the levels of individual pollutants (Fig. 1, panels A–C). Overall, air quality distribution at the national level (Fig. 1, panel D) provided evidence of low air quality levels (i.e. low AQI) mainly concentrated in the same territorial areas of Northern Italy, including a few territorial areas of Tuscany, Lazio and Campania, mainly due to $PM_{2.5}$ levels (Fig. 1, panel A).

COVID-19 incidence rate at the level of both territorial areas (Fig. 1, panel E) and regions (Fig. 1, panel F) showed an unequal distribution that, at first glance, roughly reflects the distance from the first epidemic epicenters located in Northern Italy, in the period from February 20^{th} to March 31^{st}.

3.2. Exceeding annual regulatory limits of atmospheric pollutants and COVID-19 spread in Italy: the situation in the first quarter of 2020

The potential short-term correlation between atmospheric pollutants and COVID-19-related variables has been assessed based on the number of days exceeding the annual regulatory limits (see Table 2) of atmospheric pollutants ($PM_{2.5}$, PM_{10}, NO_2) in the first quarter of 2020 and the distribution of COVID-19 incidence, mortality and lethality rates in the period from February 20^{th} to March 31^{st}, 2020. The analysis concerned all Italian territorial areas (Fig. 2), including four of the most affected regions in Northern Italy (Lombardy, Piedmont, Emilia-Romagna, and Veneto) (Fig. 3).

As reported in Fig. 2, such limits were overrun in 42 territorial areas out of 107 in the case of $PM_{2.5}$ (Fig. 2, panels A, D and G), in 17 territorial areas out of 107 for PM_{10} (Fig. 2, panels B, E, and H), and finally in 3 territorial areas out of 107 for NO_2 (Fig. 2, panels C, F, and I). The territorial areas of Novara, Milan, and Monza-Brianza exceeded the annual concentration limits of all three atmospheric pollutants for at least 45 days, whereas 14 territorial areas (Alessandria, Varese, Como, Bergamo, Brescia, Pavia, Cremona, Mantua, Verona, Padua, Piacenza, Reggio nell'Emilia, Modena, and Lodi) exceeded the annual concentration limits of both $PM_{2.5}$ and PM_{10} for at least 45 days. Other 31 territorial areas exceeded the annual limit for 45 days only in the case of $PM_{2.5}$.

To suggest the hypothesis of a potential correlation among variables, a statistical non-parametric test was carried out based on the data reported in Figs. 2 and 3.

Table 3 shows the results of the statistical Spearman correlation test and the related level of significance.

The correlation test results for the 107 territorial areas show that the magnitude of the Spearman coefficients ranges from 0.41 to 0.63, thus highlighting moderate-to-strong positive correlations (see Table 3, rows 2A-2I). In particular, when considering incidence and mortality rates, $PM_{2.5}$ and PM_{10} concentrations exhibit a stronger correlation compared with NO_2, whereas when the lethality rate is considered, the correlation strength is almost the same among pollutants.

Moreover, the statistical analysis of the short-term exposure to $PM_{2.5}$, PM_{10}, and NO_2 was further targeted on the 36 territorial areas mostly affected by COVID-19 (Fig. 3). In this case, the magnitude of the Spearman coefficients ranges from 0.32 to 0.49, thus highlighting weak-to-moderate positive correlations (Table 3, rows 3A-3I). The correlation of *PMs* with incidence, mortality and lethality rates is higher than the correlation with NO_2.

3.3. Daily mean atmospheric pollutants and COVID-19 incidence rate variation in three territorial areas: Milan, Brescia, and Bergamo

As expected, the particulate matter profiles ($PM_{2.5}$ and PM_{10}) of three of the most affected territorial areas in Lombardy (Milan, Brescia, and Bergamo) mostly overlapped in the first quarter of 2020 (Fig. 4, panels A–C).

Based on the results of the previous statistical analysis that suggest a positive and statistically significant correlation between PM_{10} and the incidence rate, PM_{10} profiles (Fig. 5) of the territorial areas shown in Fig. 4 have been overlapped with the incidence rate variation in the period from March 1^{st} to March 31^{st}.

PM_{10} profiles were mostly above the annual regulatory limits showing a common trend for all three territorial areas considered, that is a very similar PM_{10} pattern but with slightly different concentrations. After a rapid initial increase, the COVID-19 incidence rate variation was roughly stable in Brescia and Bergamo since

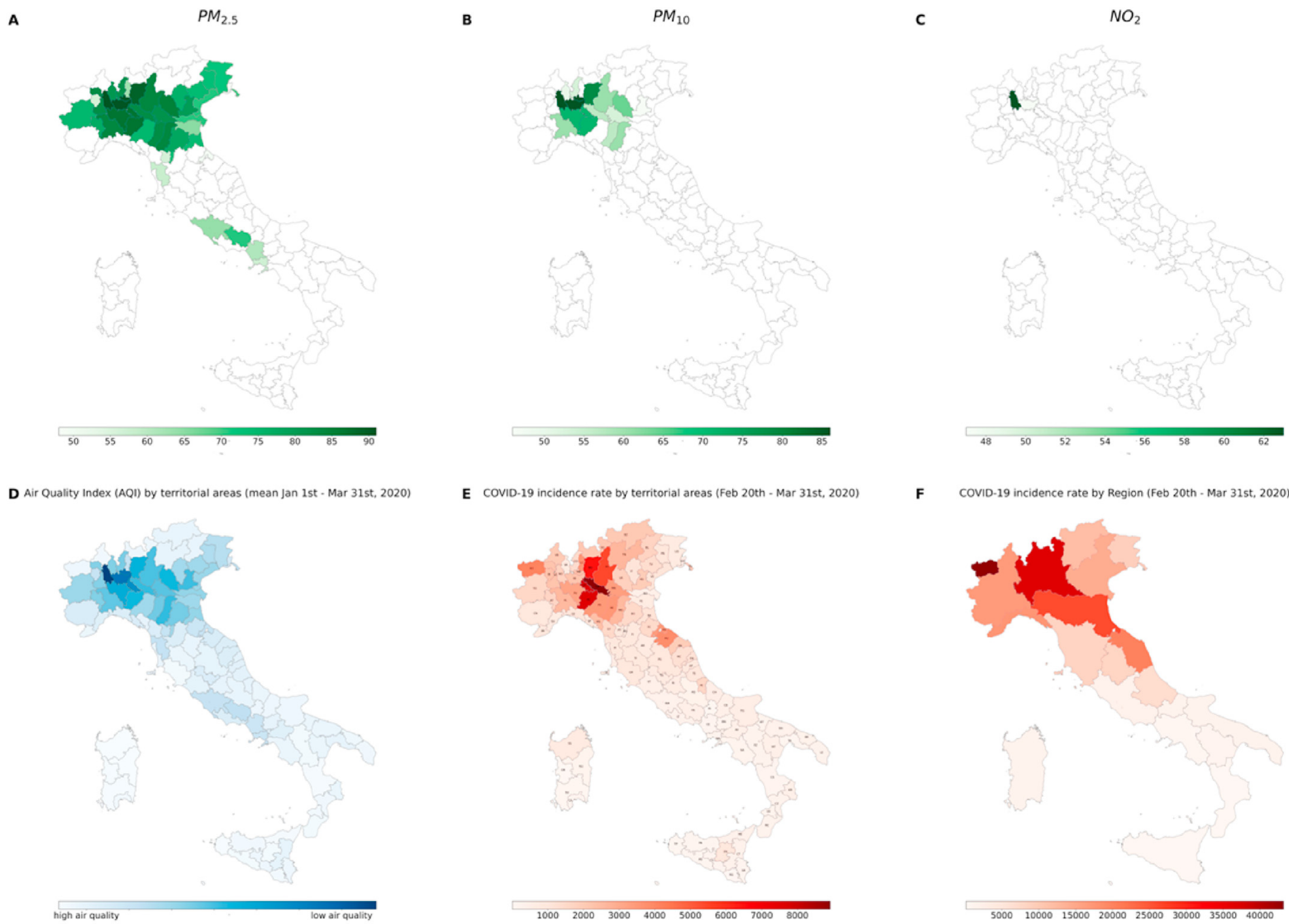

Fig. 1. Air quality indicators, air quality index (AQI) and COVID-19 spread in the 107 Italian territorial areas: Panels A, B, and C, report the number of days (at least 45) that exceeded the annual regulatory limits in the period from January 1st to March 31st, 2020, in all 107 Italian territorial areas, with reference to $PM_{2.5}$ (panel A), PM_{10} (panel B) and NO_2 (panel C). Panel D reports the AQI for each territorial area (measured as in section 2.5), and the average index in the period from January 1st to March 31st, 2020. Panels E and F report the COVID-19 incidence rate (per 100,000 inhabitants) at territorial and regional level, respectively, in the period from February 20th to March 31st, 2020. Data references are available in Table 1.

March 10th–11th (Fig. 5, panels B and C) until the end of the month, whereas in Milan the same effect occurred since March 19th (Fig. 5, panel A). PM_{10} levels increased since March 8th onwards, achieving a peak on March 21st-22nd in all the considered territorial areas, which however corresponds to a decline in the incidence rates on the same day or in the following days.

Moreover, by extending the incidence rate monitoring period (Fig. 6) up to the last lockdown day (June 2nd, 2020), it can be observed that the outbreak dynamics are different in the three territorial areas considered in Fig. 5. The cumulative incidence rates reported for Milan, Brescia and Bergamo (Fig. 6) showed that in Milan they were much lower than in Brescia and Bergamo. In particular, as regards time trends, the cumulative incidence rates in Brescia (Fig. 6, blue line) and Bergamo (Fig. 6, orange line) first showed an exponential increase until the end of March, which was then followed by a more moderate, steady, linear increase. In Milan (Fig. 6, green line), the initial increase of the incidence rate was at much lower levels, as evidenced by the lower slope of the green line, and it was followed by a continuous but moderate increase.

4. Discussion

The main goal of this work was to check for possible correlations among atmospheric pollutants, acting as boosting factors, and COVID-19 outbreak in a very short-term period, i.e., the first quarter of 2020. $PM_{2.5}$, PM_{10}, and NO_2 pollution data have been collected to assess the number of days exceeding the annual regulatory limit for each pollutant. Hence, air quality data have been correlated with COVID-19 incidence, mortality and lethality rates all over Italy.

The analysis covered all the 107 territorial areas in Italy down to a 4-region subset of 36 territorial areas, including some of the most affected regions (Lombardy, Piedmont, Emilia-Romagna and Veneto), without claiming to single out any causal effect.

The results of the statistical analysis suggest moderate-to-strong correlations when considering the 107 territorial areas and weak-to-moderate correlations when the analysis is limited to 36 territorial areas in the 4-region subset, which corresponds to about one third of the whole national territory.

It is worth mentioning that the present study contains several major differences compared with other studies on the Italian

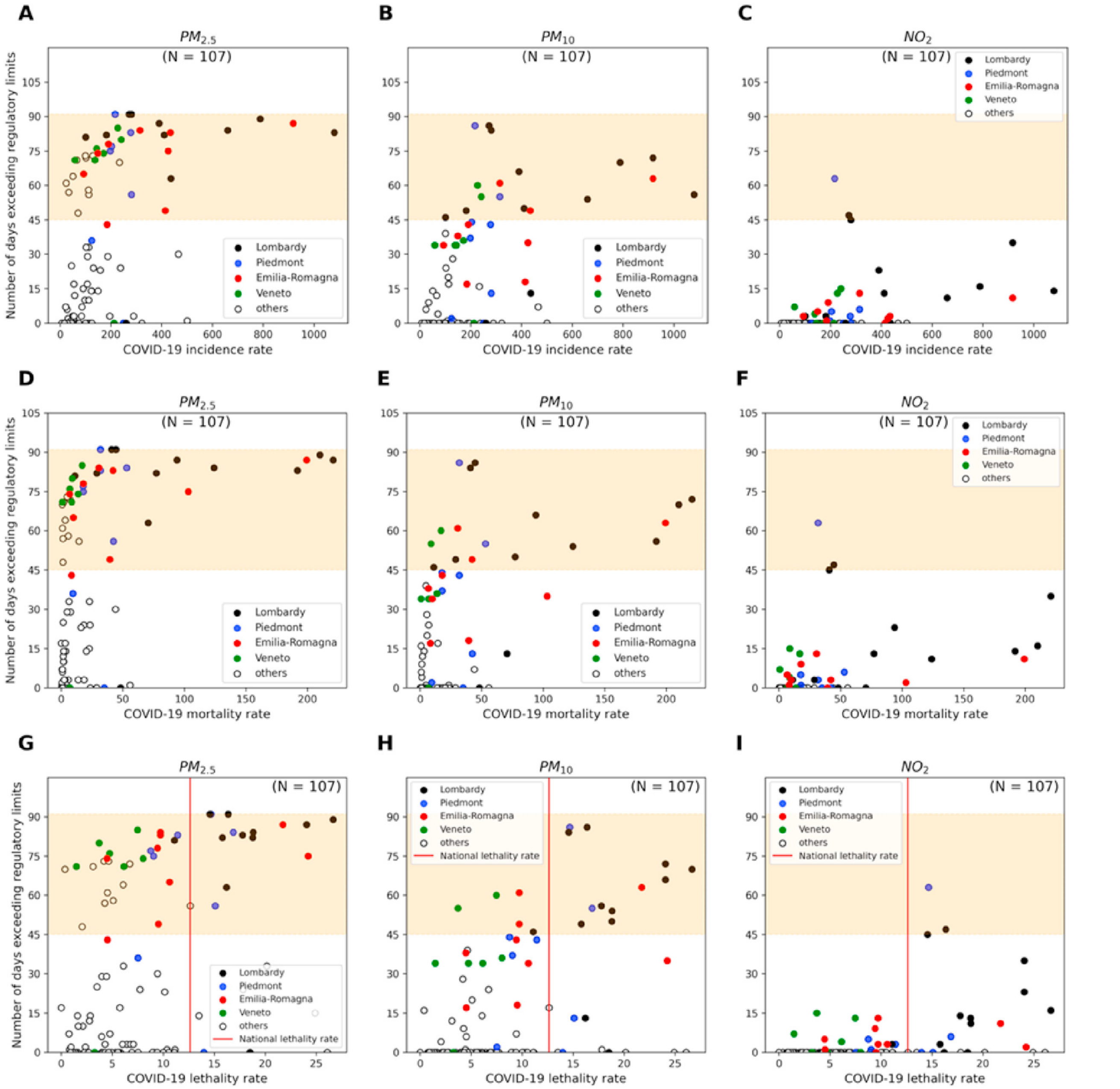

Fig. 2. Scatter plots for all 107 Italian territorial areas: number of days exceeding the annual regulatory limits (y-axis) for $PM_{2.5}$, PM_{10}, and NO_2, from January 1st to March 31st, with respect to: COVID-19 incidence rates (panels A–C, x-axis), COVID-19 mortality rates (panels D–F, x-axis), and COVID-19 lethality rates (panels G–I, x-axis), in the period from February 20th to March 31st. Incidence and mortality rates are reported for 100,000 inhabitants. Data references are available in Table 1.

country that were reported in a recently published systematic review on the role of air pollution in COVID-19 spread and lethality (Copat et al., 2020). In particular, none of these papers looked at the overall effect of potential confounders, nor used the non-parametric statistical analysis, i.e., the Spearman coefficient. Only the Pearson linear coefficient was used to infer conclusions based on geographical correlations, whereas some studies only used a descriptive analysis. Furthermore, as far as the geographical selection of the areas is concerned, only 71 Italian territorial areas were considered in (Fattorini and Regoli, 2020), whereas only 66 administrative Italian regions were considered in (Ogen, 2020); further studies (Zoran et al., 2020a; 2020b) merely focused on the territorial area of Milan or performed the analysis at regional level only (Frontera et al., 2020a, b); finally, another study (Bontempi 2020a) only considered 7 provinces in Lombardy and 6 provinces in Piedmont. All the aforementioned studies did not consider $PM_{2.5}$, PM_{10} and NO_2 at the same time, except for one (Fattorini and Regoli, 2020). Last but not least, several studies (Coccia, 2020; Fattorini and Regoli, 2020; Frontera et al., 2020a, b; Ogen, 2020; Zoran et al., 2020a, 2020b) relied on the confirmed COVID-19 cases or deaths, without scaling the values based on the population in each province.

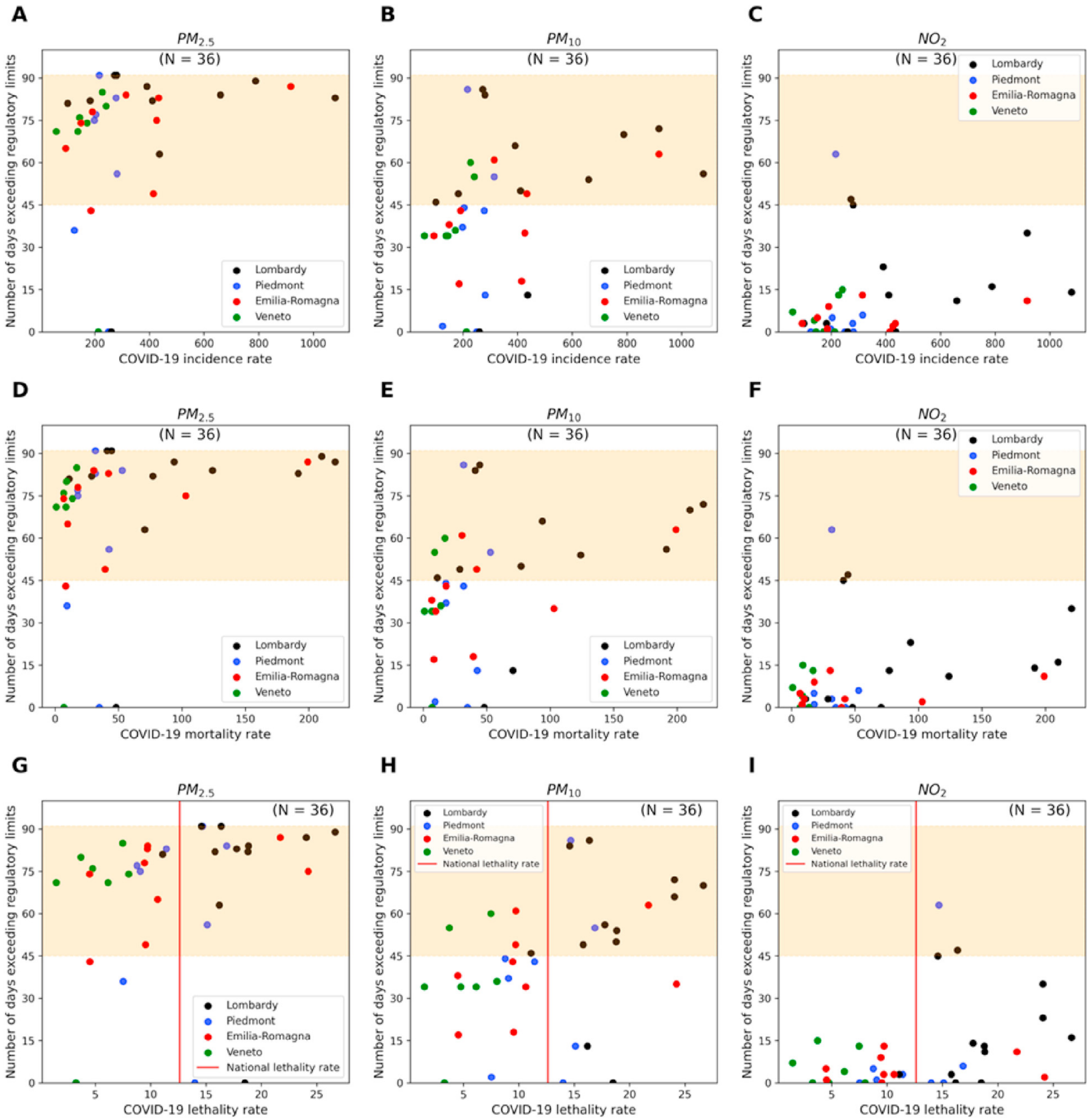

Fig. 3. Scatter plots for the 36 territorial areas in four of the most affected Italian regions: number of days exceeding the annual regulatory limits (y-axis) for $PM_{2.5}$, PM_{10}, and NO_2, from January 1st to March 31st, with respect to: COVID-19 incidence rates (panels A–C, x-axis), COVID-19 mortality rates (panels D–F, x-axis) and COVID-19 lethality rates (panels G–I, x-axis), in the period from February 20th to March 31st. Incidence and mortality rates are reported for 100,000 inhabitants. Data references are available in Table 1.

The authors are also aware that the analysis is limited due to the missing evaluation of confounding factors and region-based COVID-19 outbreak dynamics. High levels of incidence rate can be attributed to a series of alternative factors other than air pollution, which can explain the spread and lethality of COVID-19 from different perspectives, such as trade (Bontempi, 2020b), weather (Orru et al., 2017; Kinney, 2018; Ravindra et al., 2019), socio-economic conditions (Cazzolla-Gatti et al., 2020; Wu et al., 2020), and healthy-related variables (Cazzolla-Gatti et al., 2020).

The analysis of confounding factors is actually very challenging (Bontempi, 2020b; Cori and Bianchi, 2020; Heederik et al., 2020) mainly due to the lack of high-quality data in the reference period. Reliable data sources should be available for each confounder and have the same spatio-temporal resolution of the COVID-19 variables and atmospheric pollutants levels used in the analysis. As an example, a recently published paper (Cazzolla-Gatti et al., 2020) on the effect of long-term exposure to atmospheric pollutants on COVID-19 variables in Italy, focused on several confounders but the final dataset resulted in a mixture of different spatially distributed data sources at the level of regions and territorial areas.

In the present study, all the considered variables have always been analyzed in a coherent way to avoid mixing different data

Table 3
Statistical correlation among COVID-19 and $PM_{2.5}$, PM_{10}, and NO_2 atmospheric pollutants in all Italian territorial areas ($n = 107$) and a 4-region subset ($n = 36$). The Spearman coefficient and the level of significance are reported for all scatter plots presented in Figs. 2 and 3 and for COVID-19 incidence, mortality and lethality rates.

Territorial areas	Figure	Spearman	Significance	Pollutant	Variable
$n = 107$	2A	0.63	$p < 0.01$	PM_{10}	Incidence rate
	2B	0.61	$p < 0.01$	$PM_{2.5}$	
	2C	0.55	$p < 0.01$	NO_2	
	2D	0.59	$p < 0.01$	PM_{10}	Mortality rate
	2E	0.59	$p < 0.01$	$PM_{2.5}$	
	2F	0.55	$p < 0.01$	NO_2	
	2G	0.41	$p < 0.01$	PM_{10}	Lethality rate
	2H	0.45	$p < 0.01$	$PM_{2.5}$	
	2I	0.45	$p < 0.01$	NO_2	
$n = 36$	3A	0.45	$p < 0.01$	PM_{10}	Incidence rate
	3B	0.42	$p < 0.05$	$PM_{2.5}$	
	3C	0.32	$p < 0.10$	NO_2	
	3D	0.49	$p < 0.01$	PM_{10}	Mortality rate
	3E	0.45	$p < 0.01$	$PM_{2.5}$	
	3F	0.35	$p < 0.05$	NO_2	
	3G	0.48	$p < 0.01$	PM_{10}	Lethality rate
	3H	0.43	$p < 0.01$	$PM_{2.5}$	
	3I	0.33	$p < 0.05$	NO_2	

sources with different spatio-temporal resolutions. The analyses have been separately performed, at both regional and territorial area level.

A new methodological approach is then required to determine the context and sort out the key parameters to consider, as recently stated in (Bontempi, 2020b). This approach should promote international research and involve political authorities that have to rely on multidisciplinary scientific committees. In this way, research efforts would be more effective, and the correct dissemination of the relevant and suitable information would not only concern the scientific community but also a wider audience, including the general population and policymakers.

Therefore, due to the sensitivity of these issues, confounders were left out of the scope of the analysis in this initial phase, adopting a methodological approach based on the "go slow to go fast" paradigm, as recently suggested in (Heederik et al., 2020).

The investigation will be extended in the future to account for confounding factors and outbreak dynamics. As a matter of fact, the comparison of the data presented in Figs. 4 and 5 suggests that confounding factors be considered to justify why the almost identical PM_{10} profiles observed in Milan, Brescia, and Bergamo during the first quarter of 2020 did not produce similar COVID-19 incidence rate variations. In addition, confounders might justify the differences in the statistical significance of correlations found when comparing a 4-region subset (n = 36 territorial areas) with the whole Italian country (n = 107 territorial areas).

Finally, as recently investigated in several studies (Orru et al., 2017; Kinney, 2018; Ravindra et al., 2019), climate change negatively affects human health and its potential role in the pandemic

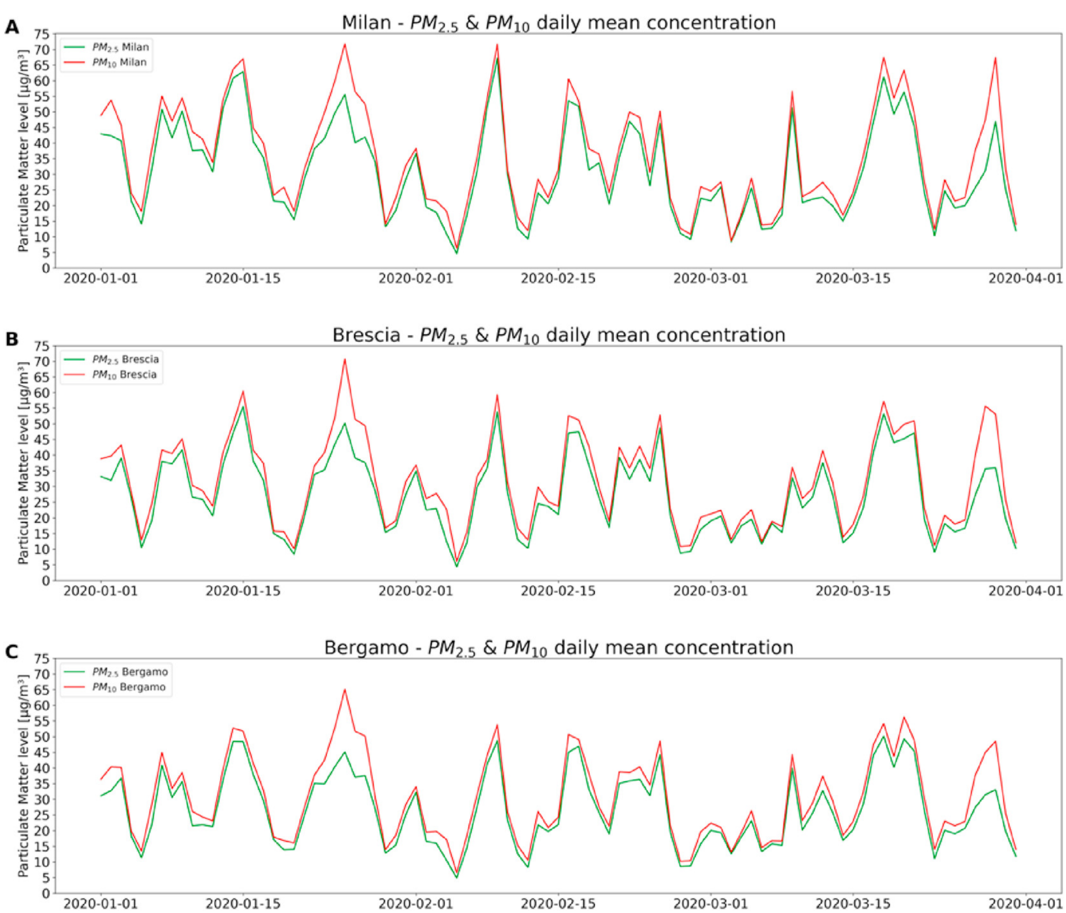

Fig. 4. Profiles of $PM_{2.5}$ (green line) and PM_{10} (red line) atmospheric pollutant levels in three of the most affected territorial areas in Lombardy, from January 1st to March 31st (x-axis). Panels A, B and C, report the concentrations for Milan, Brescia, and Bergamo, respectively. The y-axis reports the absolute levels of *PMs* in µg/m^3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

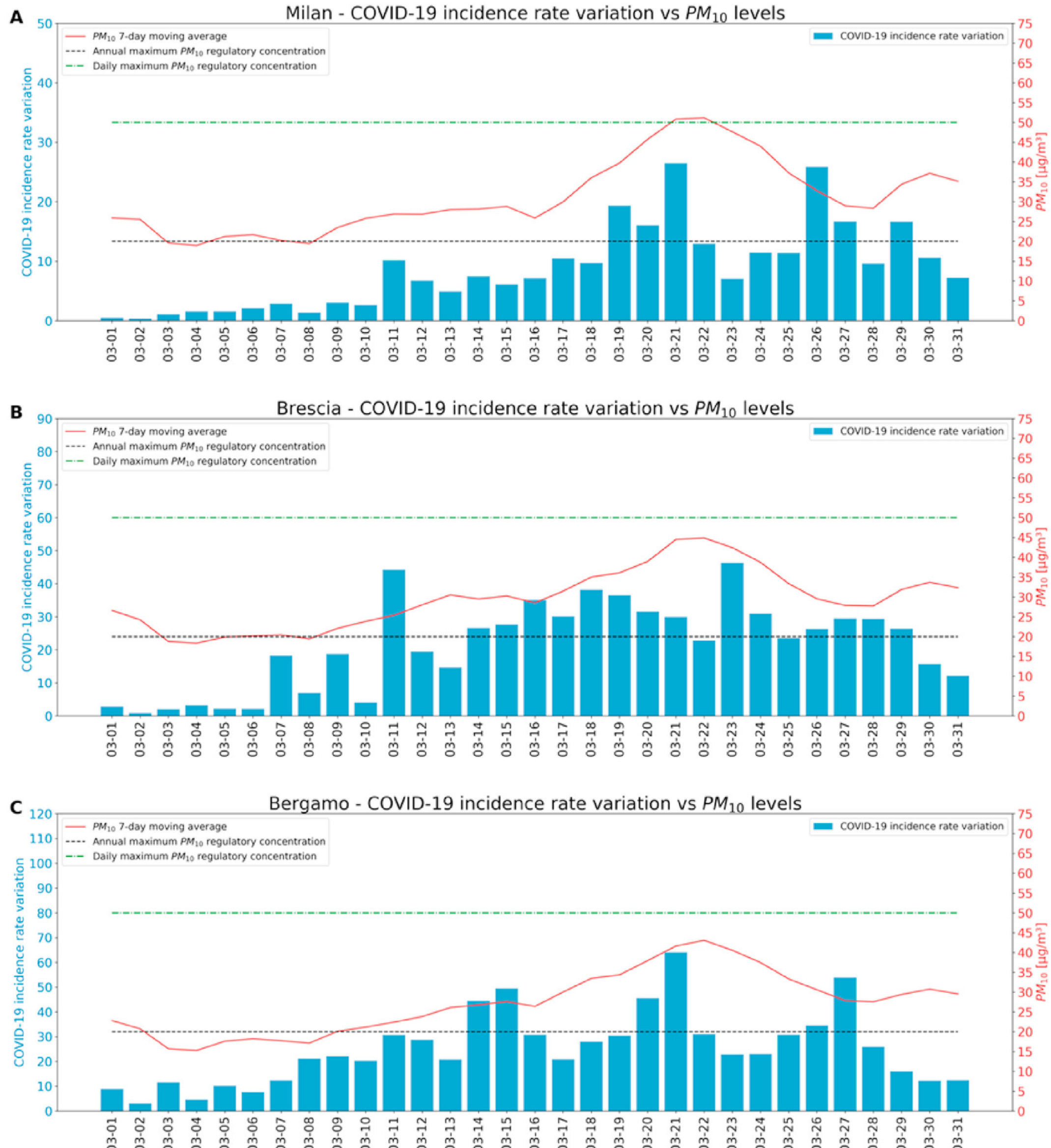

Fig. 5. Profile of the *PM10* atmospheric pollutant levels (using a 7-day moving average) and COVID-19 incidence rate (per 100,000 inhabitants) variation in three of the most affected territorial areas in Lombardy, from March 1st to March 31st. Panels A, B and C, report the PM_{10} concentrations for Milan, Brescia, and Bergamo, respectively. PM_{10} profiles are represented by a red line with values on the y-axis, right side. Incidence rate variations are represented by blue bars with values on the y-axis, left side. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

spread deserves further investigation.

5. Conclusions

The present work analyzed the 3-month short-term potential effect of three well-known atmospheric pollutants, $PM_{2.5}$, PM_{10}, and NO_2, on the whole Italian country, down to the level of each single territorial area. The results of the statistical analysis suggest the hypothesis of a correlation among the short-term exposure to each atmospheric pollutant and COVID-19 incidence, mortality and lethality rates. When considering the whole Italian country (107 territorial areas), moderate-to-strong correlations were observed, whereas weak-to-moderate correlations were found when the analysis was limited to four of the most affected regions in Northern Italy (36 territorial areas forming the 4-region subset).

In particular, when considering the incidence and mortality rates in the whole Italian country (107 territorial areas), $PM_{2.5}$ and PM_{10} concentrations exhibited a stronger correlation compared with NO_2. On the other hand, when considering the lethality rate, the correlation strength was almost the same among the pollutants under investigation. The correlation of *PMs* with the incidence, mortality and lethality rates is more pronounced compared with NO_2

In the case of the 4-region subset (36 territorial areas).

This preliminary study, inspired by the “go slow to go fast” paradigm (Heederick et al., 2020), helped assume the presence of potential correlations between short-term exposure (3 months) to particulate matters and several COVID-19-related variables in Italy.

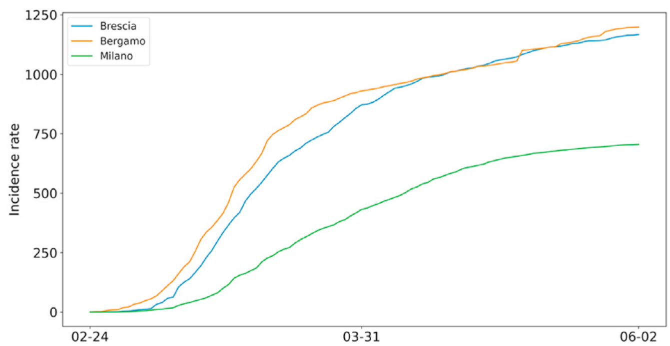

Fig. 6. COVID-19 incidence rate (for 100,000 inhabitants) registered for each day in the period from February 24th to June 2nd (x-axis), in Milan (in green), Bergamo (in orange) and Brescia (in blue). The incidence rate values are reported on the y-axis. Data references are available in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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