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Long time series analysis of air quality data in the Veneto region (Northern Italy) to support environmental policies

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HIGHLIGHTS

- Italy has infringed on the EU law regarding ambient air quality.
- One of the more polluted Italian areas is the Po Valley, including the Veneto region.
- A long time series of the air quality data region was statistically analysed.
- Only nitrogen oxide concentrations were significantly reduced during the last ten years.
- Environmental policies have mainly addressed traffic emissions.

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ABSTRACT

The world population is demonstrating an increasing awareness about the ecological impacts of air quality, including impacts on human health. The Veneto region and, more generally, the Po Valley (NE Italy), are characterised by frequent exceedance of limit values for air quality, in particular particulate matter (PM_{10}), which causes these areas to be listed as hotspots; thus, this region has some of the worst air pollution in Europe.

The aim of the current research was to analyse a 10 year-long time series of air quality data (2011–2021) in the Veneto region to investigate the influence of selected factors on air quality, such as natural processes (meteorological conditions), environmental policies, and health emergency measures due to the COVID-19 pandemic.

Generally, the considered pollutants, PM_{10}, NO, and NO_2, presented a decreasing trend during the last ten years. The reduction in nitrogen oxides was clearly improved after the implementation of a specific environmental protocol (the "New Agreement of Po Valley Basin"). Conversely, the PM_{10} concentration seemed to be affected by other important emission sources, such as domestic heating systems, agricultural activities, and animal farms, which are not as strongly regulated as emission sources such as traffic.

The 2020 lockdown mainly influenced nitrogen oxide concentrations.

1. Introduction

Many epidemiological studies report direct associations between exposure to ambient air pollutants and short- and long-term effects on human health (e.g., Horne et al., 2018; Turner et al., 2020; Khomenko et al., 2021; World Health Organization, 2021). Air pollution also impairs visibility (Hyslop, 2009), may damage building and cultural heritage materials (Di Turo et al., 2016), and directly and indirectly affects the climate (Seinfeld and Pandis, 2016). European Air Quality (AQ) legislation has significantly reduced emissions of air pollutants across Europe since the 1970s (Turnock et al., 2016). Among the legislative measures adopted in the European Union (EU), Directive

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2008/50/EC (EC Working Group on Guidance for the Demonstration of Equivalence, 2010) introduced ambitious and increasingly stringent air quality objectives that are still in force in Europe for improving human health and environmental quality. The directive set limit values and thresholds for most air pollutants, also specifying ways to assess targets. Furthermore, the Directive listed possible corrective actions if the limit standards are not met. In Italy, the European air quality directives were transposed by the Legislative Decree n.155/2010, which established a uniform legislative framework to assess and manage air quality with specific reference to the development of regional or interregional plans for reducing the risk of exceeding the limits and target values.

Despite the increasingly stringent standards and the implementation of abatement measures mandated by the EU, current air quality standards are still breached in some European locations (European Environment Agency, 2021), i.e., so-called hotspots. The Po Valley (Northern Italy) is a major hotspot for air pollution, where high-density anthropogenic emission sources extend over a $46 \cdot 10^3$ km^2-wide plain/hilly territory hosting approx. 16 million inhabitants. Beyond the complex emission scenario, the topographic characteristics of the plain and the orographic setup of the Alpine and Apennine Mountain chains favour air stagnation events and frequent wintertime thermal inversions in the Po Valley, leading to the consequent build-up of air pollutants (e.g., Pernigotti et al., 2012; Pecorari et al., 2013; Perrino et al., 2014; Caserini et al., 2017). As a result, major cities in the Po Valley suffer from air pollution. For instance, the cities of Brescia and Bergamo (Lombardy) and Vicenza (Veneto) rank first, second and fourth in Europe for death incidence caused by high $PM_{2.5}$ levels, respectively (Khomenko et al., 2021).

The Veneto region is the highest in the eastern part of the Po Valley, i.e., the region that borders the Adriatic Sea. Reports from the local environmental agency (ARPAV, 2015, 2021a) and trend analysis over 2008–2014 (Masiol et al., 2017) indicated that nitrogen oxides, PM_{10} (particulate matter with an aerodynamic diameter not greater than 10 μm) and ozone are critical pollutants in the Veneto region, due to the frequent breaching the EC limit and target values.

In 2014, the European Commission opened an infringement proceeding for Italy regarding its tendency to systematically and persistently exceed the limit values for PM_{10} at several sites, many of which are in the Po Valley. Despite some advocacies presented by Italy for defence (European Court of Justice, 2020a), the European Court of Justice rejected the appeal of the Italian Republic in 2020 (European Court of Justice, 2020b), stating that Italy had not adopted appropriate measures to ensure compliance with the limit values for PM_{10}.

Several actions are currently implemented in the Po Valley, including the Veneto region by competent authorities to lower air pollution, including the following.

1. Measures on stationary emission sources such as industrial activities are primarily contained in Directive (2010)/75/EU (European Parliament and Council of the European European Parliament Council of the European Union, 2008).
2. Structural measures of environmental policies, such as the "New Agreement of the Po Valley Basin" (Italian Minister of Environment et al., 2017), signed in 2017, which was derived directly by indications of Directive (2008)/50/CE and Legislative Decree n.155/2010, state that if exceedances of air quality limit values occur in one or more areas inside zones or agglomerations, the regions concerned must adopt a plan that provides measures to be applied to address the main emission sources.
3. Periodic measures were adopted by municipalities during the winter season on traffic restrictions and heating system limitations to reduce air pollution.

In addition, health emergency measures due to the COVID-19 pandemic, which are not directly involved in air quality measures, have definitely affected relevant emission sources such as industrial activities and traffic (Lonati and Riva, 2021; Ciarelli et al., 2021; Bontempi et al., 2022).

A major challenge for research and policymakers is the identification and quantification of the real effects of AQ policies. However, there is no general consensus on the effectiveness of the past and current AQ mitigation measures adopted across the Veneto region. Additionally, the concurrent effects of factors driving changes in air pollution at the regional level are still unclear, including the effects due to the implementation of EU directives, the effects of economic changes or the impacts of climate change.

Under this view, the current study aims to answer this gap by analysing long time series of air quality data in the Veneto region during the 2011/2021 period to quantify the effects of past mitigation strategies and to support future environmental policies. The long-term air quality data are matched with local meteorology, environmental policies (e.g., periodic traffic limitations and the application of the "New Agreement of the Po Valley Basin"), and health emergency measures due to the recent COVID-19 pandemic.

Maintaining long-term monitoring is fundamental to developing informed evaluations and decisions that define cost-effective policies for the 21st century. Therefore, this study provides key information on air quality status over a major European hotspot for air pollution and will help highlight future research needs, possible future steps on AQ policies, and improvements of the regional monitoring network. Additionally, the current study will provide important tools for policymakers to drive the next generation of AQ mitigation measures at the regional level that may be applicable to other hotspots in Europe.

2. Materials and methods

2.1. Study design

The methodological approach carried out in the present study was structured into four phases: scale of analysis definition; data acquisition; statistical data processing; and data interpretation. In the first phase, the spatial and temporal scales were defined: the whole Veneto region was identified, and the period from 2011 to 2021 was selected for the analysis. The time of the study was further divided into subperiods to analyse the effects of the implementation of specific regulations such as the "New Agreement of the Po Valley Basin" and emergency health measures related to COVID-19.

In the second phase, the following data were collected: air quality data from 15 stations, meteorological data from 9 stations, ordinances of traffic restrictions, number of circulating vehicles per Euro-classification – i.e., the European categories to classifies vehicles emissions –, and data about road, vessel and air traffic reductions during the 2020 lockdown.

Subsequently, in the third phase, several statistical models were carried out to analyse the persistence of air quality data and potential correlations with external factors. Finally, the results were interpreted in the fourth phase to derive potential indications to support environmental policies.

2.2. Description of the study area

The central and southern zones of the Veneto region, together with the Piedmont, Lombardy and Emilia-Romagna regions, are part of the Po Valley. The geographical area between the Alps, the northern Apennines and the Adriatic Sea represents an areological basin with homogeneous conditions from the land-use, anthropogenic pressure, and climatic perspectives, i.e., it is characterised by a high concentration of traffic, productive activities, settlements and population density and by weather conditions that promote the stagnation of pollutants (ARPAV, 2016) (Fig. 1). The Veneto region has a mainly flat territory (nearly 56%), while mountainous areas occupy 29%, and hills occupy 15%.

The Veneto region has some geographically homogeneous areas in terms of altitude, orographic, and climate characteristics, e.g., the

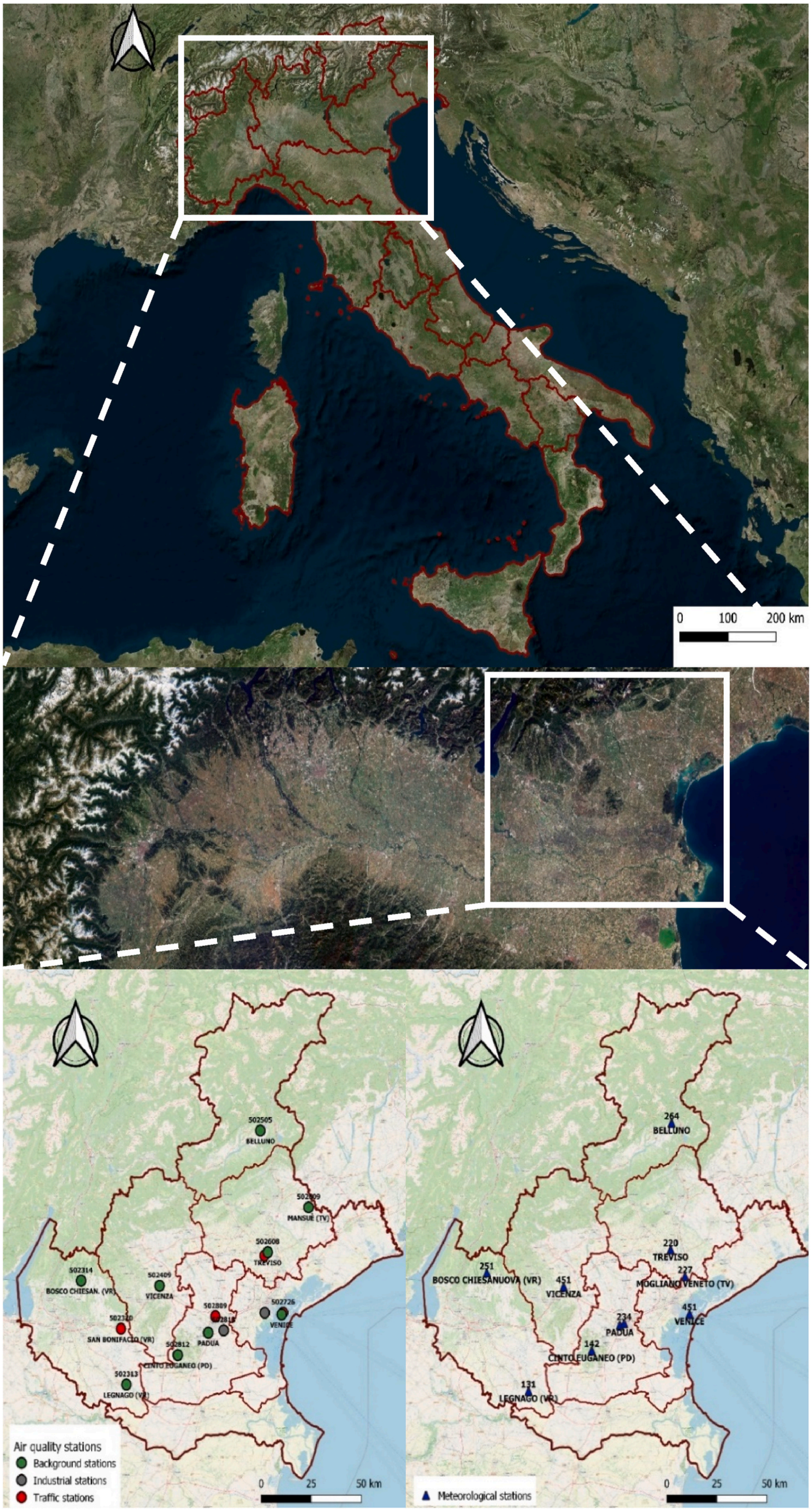

Fig. 1. *Location of the Po Valley inside Italy [open source* (European Space Agency, 2019)*:]. The first white rectangle includes, from the left to the right and from the top to the down, Piedmont, Lombardy, Veneto and Emilia-Romagna, the four Regions of Po Valley Basin. The second white rectangle shows the location of Veneto region. The last figures from the top are the maps of air quality and meteorological stations of Veneto Region selected for this work. Codes of the considered Provinces in the Veneto region: BL: Belluno; TV: Treviso; VR: Verona; VI: Vicenza; PD: Padua; VE: Venice.*

Alpine region, the pre-Alpine and subalpine belts, the high and low plains, the Lagoon of Venice and the Polesine belt.

The population of the Veneto region as of 1 January 2021 was 4,852,453 inhabitants (ISTAT, 2021), and most of the population was concentrated on the edge of the major traffic routes of Verona, Padua and Venice Provinces. The population density was approximately 267.7 inhabitants/km^2. Veneto is one of the most industrialised Italian regions, with an industrial fabric based on a large number of small and medium-sized enterprises widespread throughout the territory. At the edges of the "central axes", Verona and Venice represent two relevant industrial and commercial areas.

Due to its morphological characteristics and its position related to the winds, the Veneto region has a large variety of climates, from alpine climate in the high basin of the Piave River to the Mediterranean climate in the Garda Lake basin and along the coastline. Mists are common, and precipitation is abundant, especially in the alpine and pre-alpine zones.

The main anthropogenic emissions of the Veneto region include nonindustrial combustion (mainly heating systems), road traffic emissions, and industrial emissions (Bassan et al., 2017).

Moreover, the presence of three important airports, an industrial harbour and main cruise ship terminals may affect the regional emissions scenario.

2.3. Data acquisition

2.3.1. Acquisition of air quality data

Air quality data were collected from 15 monitoring stations spread throughout the Veneto region and managed by the regional environmental protection agency (ARPAV, Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto) (see Fig. 1, green, red and grey circles).

Following the European Environmental Agency (EEA) criteria (Larssen et al., 1999), air quality monitoring stations were classified according to the type of station and type of zone (see Supplementary Material, Table A.1) into urban background stations, rural background stations, traffic stations and industrial stations.

The Veneto region and ARPAV implemented a review process of the monitoring network to meet the standards imposed by Legislative Decree n. 155/2010 and finally identified the stations that were suitable for the regional air quality evaluation program.

All of the stations selected in the current project are reported in Table 1, including 6 urban background stations, 3 rural background stations, 4 traffic stations and 2 industrial stations. All of them belong to the ARPAV Evaluation Program, except for "Rio Novo" (Venice).

Air quality analysis refers to the daily concentrations of PM$_{10}$ [μg/m^3], nitrogen monoxide (NO [μg/m^3 at 293 K]), and nitrogen dioxide (NO$_2$ [μg/m^3 at 293 K]) at all stations except in "Granze" (ID 502813), where only PM$_{10}$ data are available.

The networks and the individual stations are subjected to regular checks and maintenance according to specific quality procedures to ensure high performance (EN 14211, 2012; EN 12341, 2014; EN 16450, 2017). The quality system is guaranteed by the local environmental protection agency (ARPAV) with periodic participation in quality assurance programs. The laboratory measurements are controlled by the national accreditation body according to EN ISO/IEC 17025. The sampling and analysis methods used, minimum data captured and minimum time covered are those indicated in the European directives (Commission Directive, 2015/1480), national laws (Decreto 30-03-2017) or guidelines (JRC, 2008a,b; EC Working Group on Guidance for the Demonstration of Equivalence, 2010; ISPRA, 2014).

For the purpose of this work, only stations with more than 10 years of monitoring data were selected, except for two stations, "Strada Sant'Agnese" (Treviso) (ID 502612) and "Rio Novo" (Venice) (ID 502726), which were activated in 2015 and 2017, respectively, and they were selected because they are close to two emission sources potentially affecting the local air quality: the Airport of Treviso and the Harbour of Venice, respectively.

2.3.2. Meteorological data

The ARPAV has 175 meteorological stations scattered across the Veneto region (ARPAV, 2010). Among them, only stations that refer to the same municipality in which the air quality station is located were selected (see Table A.2 in Supplementary data and Fig. 1).

For the purpose of this work, the daily average temperature [°C], daily amount of precipitation [mm] and daily average wind speed [m/s] were analysed.

Correlation analysis between air quality data and meteorological factors is largely used in the literature(e.g., Battista and de Lieto Vollaro, 2017); however, rainfall data were not considered in the previous studies.

Table 1

Selected air quality monitoring stations.

ID	Name/locality	Municipality	Province	Type of station	Type of zone	Year of Activation	Altitude [m a.s.l.]	Measured parameters [μg/m3] or [ng/m3]
502505	Parco Città di Bologna	Belluno	BL	Background	Urban	2004	378	NO$_x$, NO, NO$_2$, O$_3$ PM10, PM2.5, B(a)P
502313	Via Togliatti	Legnago	VR	Background	Urban	2001	13	NO$_x$, NO, NO$_2$, O3, PM10
502808	Mandria	Padua	PD	Background	Urban	1999	9	NO$_x$, NO, NO$_2$, O$_3$, PM10, PM2.5, Benzene, B(a)P, Pb, As, Ni, Cd
502409	Quartiere Italia	Vicenza	VI	Background	Urban	1998	36	NO$_x$, NO, NO$_2$, O$_3$, PM10, PM2.5, B(a)P, Pb, As, Ni, Cd
502608	Via Lanceri di Novara	Treviso	TV	Background	Urban	2004	15	NO$_x$, NO, NO$_2$, O$_3$, PM10, PM2.5, BTEX, B(a)P, Pb, As, Ni, Cd
502717	Sacca Fisola	Venice	VE	Background	Urban	1994	0	SO2, NO$_x$, NO, NO$_2$, PM10, O$_3$, Pb, As, Ni, Cd
502314	Zambelli	Bosco Chiesanuova	VR	Background	Rural	2007	814	SO2, NO$_x$, NO, NO$_2$, CO, O$_3$, PM10, B(a)P, Pb, As, Ni, Cd
502812	Parco Colli Euganei	Cinto Euganeo	PD	Background	Rural	2008	12	NO$_x$, NO, NO$_2$, O$_3$, PM10
502609	Via Cornarè	Mansuè	TV	Background	Rural	2004	8	NO$_x$, NO, NO$_2$, O$_3$, PM10, PM2.5
502809	Arcella	Padua	PD	Traffic	Urban	2007	11	SO$_2$, NO$_x$, NO, NO$_2$, CO, PM10, B(a)P
502612	Strada Sant'Agnese	Treviso	TV	Traffic	Urban	2015	15	SO2, NO$_x$, NO, NO$_2$, CO, PM10
502726	Rio Novo	Venice	VE	Traffic	Urban	2017	0	NO$_x$, NO, NO$_2$, CO, O$_3$, PM10
502310	Via Fiume	San Bonifacio	VR	Traffic	Urban	1985	30	NO$_x$, NO, NO$_2$, O$_3$, PM10
502813	Granze	Padua	PD	Industrial	Urban	2005	8	PM10, B(a)P, Pb, As, Ni, Cd
502723	Malcontenta - Marghera	Venice	VE	Industrial	Suburban	2008	1	SO2, NO$_x$, NO, NO$_2$, PM10, PM2.5, B(a)P, Pb, As, Ni, Cd

2.3.3. *Data on emission reduction measures*

2.3.3.1. New Agreement of the Po valley basin. The "New Agreement of the Po Valley Basin" (Italian Minister of Environment et al., 2017) provides the application of common modalities to identify situations of persistent PM_{10} accumulation, allocating the task to realise technical tools to identify these critical situations to the regional Agencies for Environmental Protection.

Two levels of alert are provided: level 1 alert is actuated if there are 4 consecutive days of PM_{10} limit value exceedance – set at 50 μg/m^3 by Legislative Decree n.155/2010 – while level 2 alert is actuated with 10 consecutive days of exceedance of the same limit value (ARPAV, 2021a).

Since the signing of this important deal, municipalities have been basing their traffic restriction ordinances on ARPAV reports. If a level 1 alert is reached, the following measures must be adopted.

- circulation is forbidden for all Euro-4 private diesel vehicles during weekdays and from 8.30 a.m. to 6.30 p.m.;
- use of domestic woody biomass heat generators with an emission class lower than 3 stars is forbidden if another heating system is present;
- open domestic burnings are totally forbidden.

With a level 2 alert, circulation restriction is extended for commercial vehicles during weekdays from 8.30 a.m. to 12.30 p.m.

The alert activation mechanism for traffic restrictions is reported in Table A.3 (ARPAV, 2021b) (Supplementary materials).

2.3.3.2. Winter weekday traffic (WWTR) restrictions and traffic-restricted Sundays (TRS). In the last 10 years and before the New Agreement was signed (2017), specific measures to reduce atmospheric pollution were adopted, such as winter weekday traffic restrictions (WWTR, restrictions for old vehicles during the weekdays in winter) and traffic-restricted Sundays (TRS, restrictions for all vehicles during some Sundays decided by each municipality) (also called ecological Sundays), and these measures are applied locally and without coordination by municipalities. After the implementation of the Agreement, even if TRSs were not explicitly mentioned, they were still applied in a few cities.

During the winter season, generally from October/November to March/April, circulation was forbidden for Euro-0, Euro-1 and Euro-2 vehicles on weekdays.

Ordinances were acquired by emailing the environmental office of the involved municipalities. Every office provided the list with the ordinances from 2011 to 2021, in which all the measures for air pollution mitigation were reported, including traffic limitation during the winter period (WWTR), New Agreement measures, and traffic-restricted Sundays (TRS).

Belluno, Cinto Euganeo, Mansuè and Bosco Chiesanuova never activated any traffic restrictions or TRSs; conversely, in Padua, Treviso, Venice, Vicenza, Legnago and S. Bonifacio from 2011 to 2021, from October to March, there were approximately 110 days of WWTRs per year for Euro-0, Euro-1 and Euro-2 cars. From 2018, with the implementation of the "New Agreement of the Po Valley Basin", the restrictions were extended to Euro-3 vehicles.

A total of 59 local traffic restriction TRSs were retrieved: 15 for Padua, 20 for San Bonifacio, 4 plus 3 odd-even strategy weekends for Treviso, 8 for Venice and 9 for Vicenza (see Table A.4 in Supplementary data).

The deadline for the implementation of the New Agreement was the end of 2018, but all analysed municipalities applied their measures starting in October 2017, except Treviso. Moreover, the COVID-19 lockdown influenced pollutant concentrations.

Following these two considerations, for each time series, four partitions were defined.

- the first one between 2011 and 2015;
- the second one between 2015 and October 2017 (it was the period used as a comparison for the non-COVID period);
- the third one between October 2017 and February 2020 (pre-COVID period), when lockdown started;
- the fourth one, from February 2020 to May 2021.

For each partition, a linear regression line based on the moving averages of the time series was plotted, and its slope was calculated to evaluate if and how air quality improved after the activation of the mentioned agreement (see Section 3.2).

To analyse the effectiveness of TRSs, first, the concentration of pollutants during TRSs was compared with that measured on contiguous days of the same week; then, if a relevant effect was detected, nonrestricted weekends before each ecological Sunday were also considered for comparison.

2.3.4. *Emission reduction data during the 2020 lockdown*

By analysing the air quality data for the period between March 2020 and June 2020 and comparing them with the values for the same period of the previous years, it was possible to understand the effects of the 2020 lockdown that represented a unique, but unwanted, scenario at the national scale, in which specific emissions, such as traffic emissions, completely ceased.

A special focus was dedicated to air and vessel traffic reduction during the 2020 lockdown due to the presence of two air monitoring stations near Treviso International Airport "A. Canova" and in the centre of Venice city, respectively, the "Strada Sant'Agnese" (Treviso) (ID 502612) and "Rio Novo" (Venice) (ID 502726) stations.

This analysis was carried out considering the emission reductions reported in a preliminary ARPAV report about the lockdown effect (Liguori et al., 2020). The detailed timetable of the restrictions is reported in Table A.6 (Supplementary materials) and could be divided into the following periods according to the implementation of more stringent restrictions: 1st-9th March; 10th-24th March; and 25th-31st March.

For the industrial sector, referring to the variation data in natural gas volumes transported provided by SNAM (one of the most important natural gas distributors) and to the variation data in electrical energy demand provided by TERNA (responsible for the high voltage network in Italy), the following estimation of emission reduction between 2019 and 2020 was considered: 1% in the period from 1st – 9th March; −12% in the period from 10th – 24th March; and −27% in the period from 25th – 31st March.

Moreover, considering NO_x emission data provided by the major thermal power plants of the industrial zone of Marghera, the percentage variations between 2020 and 2019 were −16% in January, −21% in February and 1% in March.

Road traffic was the major anthropic component that showed a clear reduction relative to the lockdown period. The national travel reduction was approximately 80% compared to the pre-COVID-19 period for light vehicles and approximately 40% for heavy vehicles.

The national and regional travel percentage variations between 2019 and 2020 were −42% and −41% in the period from 1–9 March, −68% and −65% in the period from 10–24 March, and −73% and −70% in the period from 25–31 March, respectively.

Vessel traffic had a smaller reduction for two reasons: trade vessel traffic has its own reaction time with respect to national and international closure situations, and noncore activities were closed only from 25 March 2020; additionally, the first bimester was not characterised by significant passenger naval traffic. In fact, the naval movements to Venice Port in February 2019 and 2020 were 196 and 191 (−3%), respectively, and that in March was 226 versus 186 (−16%).

From March 7, 2020, air traffic rapidly decreased, and on March 10, 2020, there were no flights at all at Treviso Airport; in total, the reduction in the number of flights was equal to −73% in March 2020 with respect to March 2019.

2.4. Statistical methods

The statistical analysis of the data was carried out by several methods that are reported and discussed in the following paragraphs. Each statistical method was selected based on the type of data available and the specific targets.

All statistical elaborations were performed using R (R Development Core Team, 2021), and to properly run the program, a preliminary missing data imputing procedure was implemented.

The available datasets presented some missing values due to instrumental failures, blackouts, maintenance operations or other issues, and those values were discarded following ARPAV audit protocols. To properly run the subsequent analyses, a method for missing data imputation was selected, taking into account both the trend and the seasonality effects of the time series so that an appropriate value could be input (Moritz and Bartz-Beielstein, 2017).

On average, considering each time series and for each monitoring location, only 2.7% of observations were missing, therefore the gap filling method selected is not expected to introduce any significant additional uncertainty in the analysis. Table A.7 in the Supplementary materials provides a complete list of the missing values for each monitoring location, and two examples of the data filling methodology are shown in Figures A.1 and A.2 in the Supplementary materials.

2.4.1. Cross-correlation function

This method was used to find correlations between air quality and meteorological data to determine how these natural external factors influenced pollutant concentrations in the atmosphere.

Cross-correlation is a method by which the degree of similarity between two time series can be quantified.

Its general concept is used in a variety of advanced analysis techniques where the aim is to gain insights into the relationships existing between two time series.

2.4.2. Time-series decomposition with moving averages and a trend fit line

In this work, the moving averages method was applied to evaluate the time-series trend of air quality data from 2011 to 2021. Usually, data present some noise that needs to be removed. The first step was determining if the model was additive or multiplicative: additive models can be identified as having a relatively stable frequency over time, while multiplicative models exhibit a change in frequency over time.

The time series analysed in this work were additive, and they could be described with the following equation:

$$y_i = T_i + S_i + \varepsilon_i$$

where.

- y_i: output of the model
- T_i: trend component of the model
- S_i: seasonal component of the model
- ε_i: noise/remainder.

The second step was the identification of the trend using a moving average filter. It was decided to use a moving average of length equal to the number of days in one year (365). This means that at each point, an average of the daily observations for the 6 months before and the 6 months after the i-th observation was calculated.

The moving average was calculated for each element from July 2nd, 2011, until there were no longer 183 leading values (i.e., 6 months) remaining. Each time it advanced to the next element, the whole window shifted. The result of these moving averages yielded the overall trend of the data where a large part of the residual noise was eliminated.

A linear regression model was then developed on the smoothed data to find the increase/reduction percentages of the contaminants at the various stations. The model is in the form:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

where the coefficients β_0 and β_1 denote the intercept and the slope of the line, respectively, y_i is the predicted (smoothed) concentration of the pollutant, and x_i indicates the progressive number of days in the interval considered. It is important to emphasise that the observations did not lie on the straight line but were rather scattered around it; thus, the "error" term (ε) did not imply a mistake but rather a deviation from the underlying straight-line model (Hyndman and Athanasopoulos, 2018).

2.4.3. Boxplot and inferential analyses

Analysis through boxplots was carried out to analyse the effects of TRSs and emissions reductions during the 2020 lockdown.

Due to the low number of TRSs, a punctual analysis was carried out: PM_{10}, NO and NO_2 data from Friday (two days before Sunday) to Tuesday (two days after Sunday) in which an ecological Sunday was scheduled were considered. Then, if precipitation greater than 7 mm/day occurred during one of these 5 days (Guo et al., 2016), that weekend was excluded because rain influences the PM_{10} concentration, and it can be considered a confounding variable (see Section 3.1).

Together with descriptive information concerning pollutant concentrations through visual inspection of boxplots, appropriate statistical tests were carried out to provide inferential conclusions regarding the effectiveness of the ecological Sundays policy. To this end, repeated-measures ANOVA was employed (Crowder and Hand, 2020). This technique serves the same purpose as the well-known ANOVA procedure (Montgomery, 2019), that is, it is used to identify statistically significant differences among the means of two or more groups to be compared. However, while the traditional ANOVA technique assumes independent groups, repeated-measures ANOVA presumes the existence of some dependency (e.g., temporal or spatial) between the groups being compared. In this case, the dependency is imputable to the persistence of the pollutant concentration on subsequent days. One assumption of the repeated-measures ANOVA is that data are normally distributed. If this assumption was violated for some of the pollutants, $\log_{10}()$--transformation was employed to ensure data normality.

As already stated, the purpose of repeated-measures ANOVA is to identify the presence of at least one group that has a mean significantly different from the others. However, to identify which comparisons are significant (i.e., which groups are different), the analyst must proceed with pairwise comparisons. In this context, a well-known issue concerns the increase in the false positive rate when pursuing multiple inferences (Benjamini and Hochberg, 1994). Therefore, in this article, we employed the false discovery rate (FDR) technique to adjust the p-values and consequently control the FDR, ensuring proper conclusions from the statistical tests.

If at least one pairwise comparison was found to be significant in the selected period (i.e., the mean pollutant concentration was different on at least one of the days), the analysis proceeded by comparing the TRSs with the non-restricted Sundays from the preceding weekend. This was done because some human-related activities naturally decline on Sundays (e.g., lower traffic levels); thus, the idea was to evaluate whether the TRSs presented a concentration of pollutants that was lower not only than the contiguous days in the same week but also than the concentration registered on the preceding Sunday. To do that, we carried out permutation tests considering paired (i.e., dependent) data, testing the alternative hypothesis that the concentration of pollutants on the TRS was significantly lower than the concentration on the Sunday preceding the event (Pesarin and Salmaso, 2010). We opted for permutation tests since these are flexible nonparametric tests that do not make assumptions on the size or distribution of data and do not even assume that the distribution of the considered groups is approximately equal (unlike other common nonparametric tests such as the Mann–Whitney *U* test) (Pesarin and Salmaso, 2010).

One final analysis was executed regarding the 2020 lockdown effects. Boxplots were made for urban background stations to highlight the differences between PM_{10}, NO and NO_2 concentrations in 2017–2019 and 2020 during March, April, and May. A permutation test considering the alternative hypothesis that the concentration of pollutants during 2020 was lower than that during 2017–2019 was also carried out for each station. In this case, the groups were assumed to be independent since the data were collected from different years.

2.4.4. *Second-order regression model*

To quantify the effect of the 2020 COVID-19 lockdown on pollutant concentrations, a second-order model was developed using the pollutant data for each location. The model was developed considering data from January to June in 2017–2019, and predictions were carried out during the same period in 2020. Therefore, an overprediction or underprediction of the pollutant concentration in the lockdown period of 2020 was attributed to the investigation of possible effects related to COVID-19 restrictions on human activities (Venter et al., 2020).

A second-order model takes the following form:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j$$

where β_0, β_i, β_{ii} and β_{ij} are the regression coefficients with $i,j = 1,2, \ldots,k$, and x_i and x_j are the k input variables.

Such a model can quantify the effect of several predictors as well as quadratic effects and interactions among different input variables. In this paper, the k predictors were related to weather conditions (i.e., average temperature, average wind speed, precipitation level) and the day of the year. Furthermore, to include only significant effects in the models, a backwards stepwise elimination procedure was employed, which retained only those variables that were statistically significant (p-value $\leq 5\%$). In regression tasks when prediction is one of the objectives, the adjusted R-squared (adj-Rsq) is a relevant metric, as it indicates how much variation in y is explained by the terms in the model. The range is from 0 (0%) to 1 (100%), and higher values indicate a better fit. One last remark is that to protect from violations of the assumption of homogeneity of variances (homoscedasticity), the pollutant concentration data were transformed using the $\log_{10}()$-transformation prior to model fitting.

A similar approach was adopted by Venter et al. (2020). In their work, the authors used historical relationships between weather and daily pollutant time series in a linear regression model to estimate what the pollutant levels would have been during the COVID-19 lockdown dates. The model was trained considering pollutant concentration values and meteorological parameters from 2017 to 2019, and it was used to predict pollutant concentrations for March, April, May and June 2020, taking into account the observed meteorological data in that period. The results were then analysed using scatterplots and boxplots to assess eventual lockdown effects. One difference between this work and the one presented by Venter et al. (2020) is that here we also investigated the effects of quadratic and interaction terms, while a simpler approach only considering the main effects was preferred by Venter et al. (2020).

3. Results and discussion

3.1. *Analysis of correlations between air quality data and meteorological factors*

The correlations between atmospheric pollutants (PM_{10}, NO and NO_2) and meteorological factors (average wind speed, daily precipitation quantity, and average daily temperature) are reported in Table B.1 of the Supplementary materials. Plots related to the cross-correlation values of a single station for each type and with seasonal differentiation are reported in the Supplementary materials (Figures B.1 – B.12).

A negative correlation of pollutants with precipitation and wind speed was generally found at all stations, mainly during the winter season. The investigated rural background stations presented lower correlation values, likely because they already presented low pollutant concentrations, so atmospheric events had minor effects.

In Fig. 2, the cross-correlations for urban background stations with a lag of three days are reported. The results pointed out the effects and the time extension of wet deposition: a windy or rainy day could influence pollutant concentrations, mainly PM_{10}, not only on the same day in which meteorological events occur but also on the following three days, and this fact confirmed the persistent nature of the air pollutants. Wind affected both particulate matter and gases; in contrast, the rainfall washout effect was more visible only on PM_{10} (see Fig. 2).

The negative correlation between pollutants and temperature was very high. During the warm periods of the year, the build-up of air pollutants was lower for several reasons, including a general shutdown of heating systems, an increase in photochemical reactions in the atmosphere (Cichowicz et al., 2017), a higher mixing layer height, and the dispersive effect of sea/land breezes in the more coastal areas (Squizzato et al., 2012).

The negative correlation between pollutant concentration and temperature was verified for all seasons except summer. During summer, the concentrations of PM_{10} and NO_2 in general tend to be positively correlated with the average daily temperature, meaning that the pollutant concentration tends to be higher on the hottest days (see Figures B4, B6, B.7, B.9, B.10, B.12 in the Supplementary materials). This result implies that during summer a lower pollutant concentration is detected on cooler days, which are usually rainy days (see Figure B.13 in the Supplementary materials). As already pointed out, to a precipitation event corresponds a washout effect of pollutants; therefore, the decrease in pollutant concentration on cooler days in summer might be explained by the presence of precipitation events, which also lower the temperatures. This occurrence also explains the positive correlation of pollutant concentration with the average daily temperature during summer.

Comparable results were found by Masiol et al. (2014); using bivariate level-plots and a cross-correlation function analysis, they showed that most pollutants in Mestre Venice, a major city of the Veneto region, were characterised by highly positive or negative correlations with meteorological conditions, especially temperature, precipitation, and wind speed data, particularly between ozone and solar radiation and between air pollutants mainly linked to traffic, such as CO, NO_x, BTEX and PM_{10}, and wind speed.

Battista and de Lieto Vollaro (2017) found correlations between most of the considered pollutants (NO, NO_2, O_3, CO) and weather variables (air temperature, solar radiation, wind direction and wind speed, but not rainfall, which was not considered in that work) in Rome, considering an urban background station.

The results for nitrogen oxides could be compared, and their data were generally in agreement with this work.

3.2. *Analysis of the time-series trend of air quality data during the investigated periods*

Table 2 shows the percent reduction/increase in PM_{10}, NO and NO_2 for each partition of time, averaged for each type of station. Tables and graphs of the single stations are illustrated in the Supplementary materials, while in Fig. 3, the moving averages and trends for the three pollutants investigated at all of the urban background stations are reported.

It is important to highlight that the concentration values used to calculate the percentages were those obtained through the linear regression model fitted to the moving-averaged data.

3.2.1. *Rural background stations*

The NO and PM_{10} concentrations did not show major reductions in the last two partitions, highlighting that concentration values were far below limit values and mitigation measures were not necessary. Another possible reason is that if concentration values were already low, it would

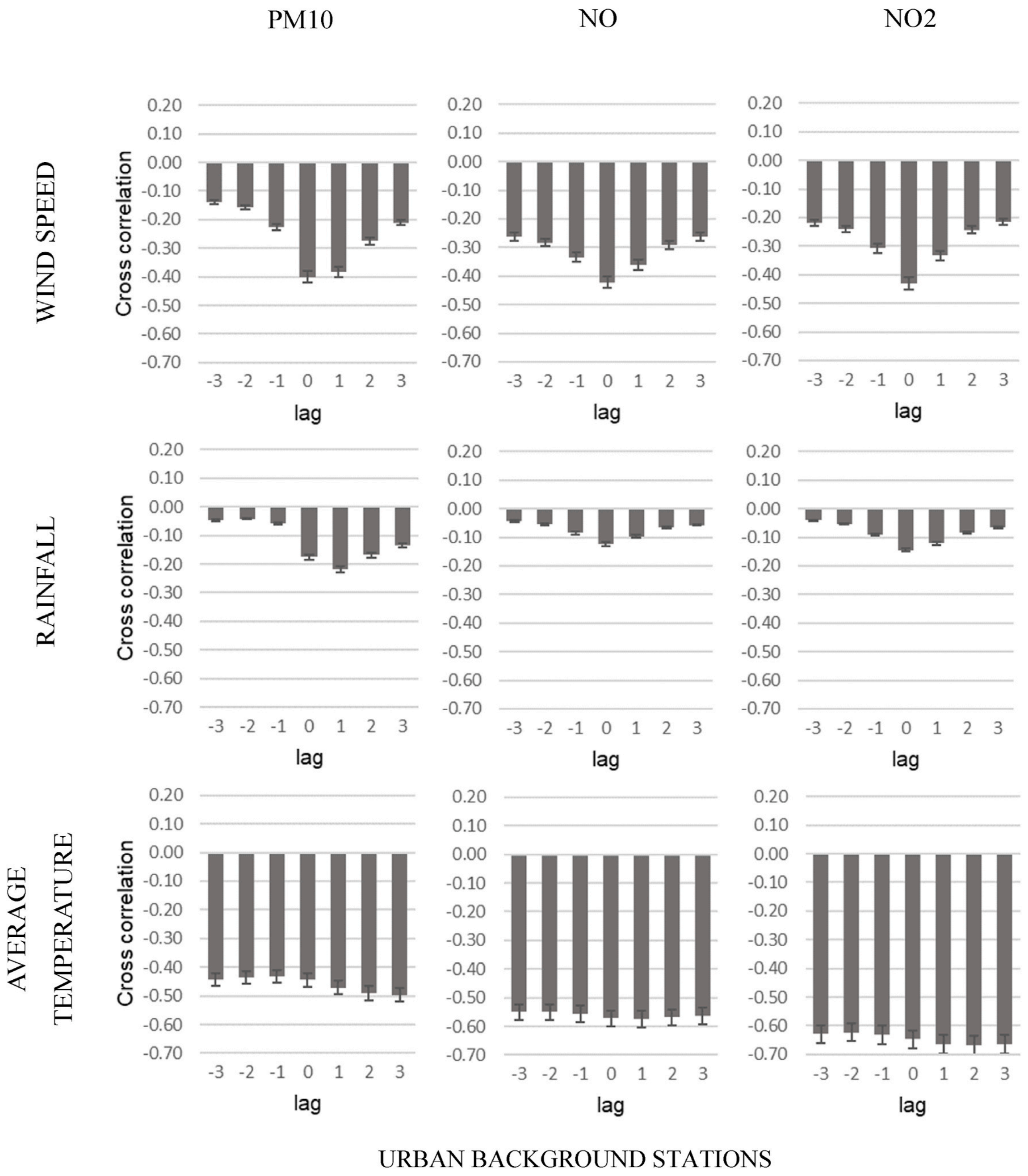

Fig. 2. Cross-correlation function between the three pollutants (PM10, NO and NO_2) and wind speed, rainfall and average temperature for the urban background stations. These plots consider a lag of up to three days.

be difficult to have large reductions. Regardless, the time-series trend between 2011 and 2021 showed a reduction for all the pollutants, with values of −20.5% for PM10, -48.4% for NO, and −24.4% for NO_2 (plots with each rural background station are in the Supplementary materials, Figures C.1, C.4, C.7).

3.2.2. *Urban background stations*

The improvement after the implementation of the Agreement was quite low regarding PM_{10} (−6.6% for partition 2 and -8.7% for partition 3). Since restriction measures in urban areas are mainly oriented to particulate matter concentration, the result should have been better.

Good reduction percentages were obtained for nitrogen oxides for partition 3, and for the whole time series, the overall reductions were −16.2% for PM_{10}, -35.0% for NO, and −19.5% for NO_2.

3.2.3. *Traffic and industrial stations*

Regarding traffic stations, the reduction trend of the time series was confirmed; in particular, NO and NO_2 showed great decreases (−43.1% for NO and −38.1% for NO_2), while the PM_{10} reduction was approximately −19.9%. At this type of station, the greatest nitrogen oxide reduction for partition 3 was −30.0% for NO and −22.1% for NO_2. These results show how nitrogen monoxide has a dominant primary nature and is mainly emitted by traffic, since significant concentrations of NO were detected near traffic stations (Liguori et al., 2020). In fact, the only station that did not detect a noteworthy reduction was Sacca Fisola (Fig. 3, Tables C2, C3) (from 15.63 to 15.49 μg/m^3), located in the centre of Venice, a station not directly influenced by maritime traffic limitations.

Industrial stations confirmed the reduction trend of the overall time series for all pollutants.

Table 2
Percentage reductions of PM10, NO, NO_2 by station type for each partition time and for the whole time series.

Station type	Partition 1 (2011–2015)			Partition 2 (2015–2017)			Partition 3 (2017–2020)			Partition 4 (2020–2021)			Time-series trend (2011–2021)		
	PM10%	NO %	NO2%	PM10%	NO %	NO2%	PM10%	NO %	NO2%	PM10%	NO %	NO2%	PM10%	NO %	NO2%
Rural background	−25.5%	−33.5%	-6.1%	−14.8%	−32.5%	-6.8%	1.0%	−15.1%	−15.6%	-3.2%	-4.4%	-9.7%	−20.5%	−48.4%	−24.4%
Urban background	−22.9%	−29.4%	−10.2%	-6.6%	−10.3%	-3.4%	-8.7%	−15.7%	−15.5%	-5.0%	−26.6%	-8.2%	−16.2%	−35.0%	−19.5%
Traffic	−34.4%	−24.9%	−15.4%	-9.9%	−13.6%	−12.4%	-8.5%	−30.0%	−22.1%	-3.3%	−14.4%	-2.1%	−19.9%	−43.1%	−38.1%
Industrial	−22.0%	−8.8%	−13.6%	-4.13%	-5.0%	−20.0%	−12.01%	−29.4%	-0.6%	-3.80%	−15.7%	-9.6%	-9.40%	−33.2%	−25.2%

3.3. Analysis of the effects of TRSs

Only 5 municipalities implemented this measure over the study period. The New Agreement does not include ecological Sundays; in fact, Venice ordered its last ecological Sunday in 2014, Treviso's was in 2016, San Bonifacio's was in 2017, and only Padua and Vicenza continued until 2019.

In the last ten years in the 5 municipalities involved, 59 ecological Sundays were implemented, but due to the reasons previously reported (Section 2.4.3), only 31 were considered for statistical analysis: 11 in San Bonifacio, 7 in Padua, 6 in Vicenza, 4 in Venice and 2 plus 1 odd-even strategy weekend in Treviso.

To compare TRSs with nonrestricted Sundays, 31 weekends before each TRS were considered, taking into account the meteorological situation, discarding rainy weekends and considering previous suitable weekends.

Industrial and rural background stations were not considered because the zones in which they are localised are not involved in the ecological Sundays ordinances.

Regarding the three pollutants considered, no statistically significant differences between the two days before and after Sunday were registered for PM_{10} in the urban background and traffic station and for NO in the urban background station.

In the other cases (Fig. 4), the situation was similar: on Sunday, the mean (red dot in Fig. 4) values decreased significantly, but then the concentrations returned to the previous values on the following days.

A further analysis was carried out for these last cases in which the TRSs presented statistically lower mean pollutant concentrations than the contiguous days in the same week.

A comparison between TRSs (TRS = 1) and normal Sundays (TRS = 0) (see Figure D4 in the Supplementary materials) highlighted that a decrease in nitrogen oxides for the urban background stations during the restricted Sundays corresponded to an increase in concentrations for the traffic stations. This fact showed that the traffic was not reduced; rather, it moved from the city centres to the suburbs.

3.4. Analysis of emission reductions during the COVID-19 lockdown

An analysis through boxplots and ANOVA was performed considering all the stations to highlight the different distributions during the COVID-19 lockdown months in the previous years and in 2020 (see section E in the Supplementary materials).

Tables 3–5 show the medians and means of the PM_{10}, NO, and NO_2 concentrations 2017–2019 and 2020 for each type of station.

Figure E1 shows the distribution of the daily PM_{10}, NO, and NO_2 concentrations from 23rd February to 17th May for 2017–2019 (first boxplot) and 2020 (second boxplot) for the urban background stations.

For PM_{10}, the median and mean did not present a strong decrease, mainly because road traffic was strongly reduced by restrictions adopted in that period (see Table A6); however, road traffic is only one source of particulate matter emissions. Other significant emissions, such as those from domestic heating systems, could be increased due to the COVID-19 lockdown because people stayed at home; moreover, agricultural activities were not affected by restrictions. Therefore, the concentration decrease determined by traffic limitations due to the pandemic could be balanced by an increase in the use of domestic heating systems (Liguori et al., 2020). This circumstance is confirmed by the results of statistical tests (Figure E1 to E.4 in Supplementary materials), which show how only one monitoring station ("Padua" - ID 50288) registered a statistically significant decrease in PM_{10}. In fact, in some cases (e.g., Legnago), the mean pollutant concentration during lockdown in 2020 was higher than the average computed over 2017–2019.

Nitrogen monoxide has only a primary origin, and the concentrations detected by traffic stations could be useful for highlighting the impact of road traffic restrictions.

As expected, the "Rio Novo" (ID 502726) station (Venice), which is

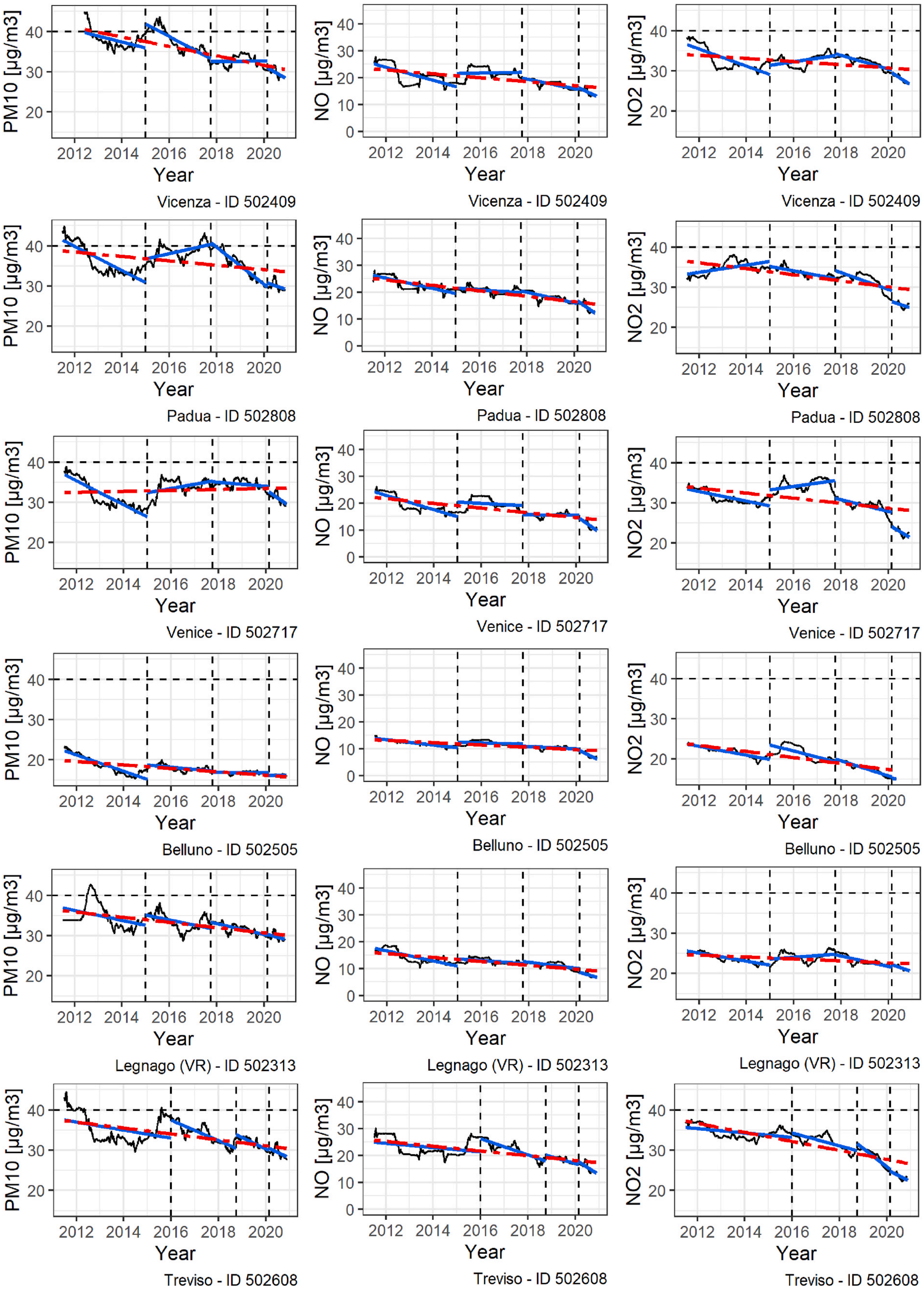

Fig. 3. PM10, NO, NO_2 moving-averages curve (black curve), with the trend fit lines for each partition (blue lines) and for the whole period (red dash-dotted line) in urban background stations. Horizontal dotted lines represent annual law limits for PM10 and NO_2.

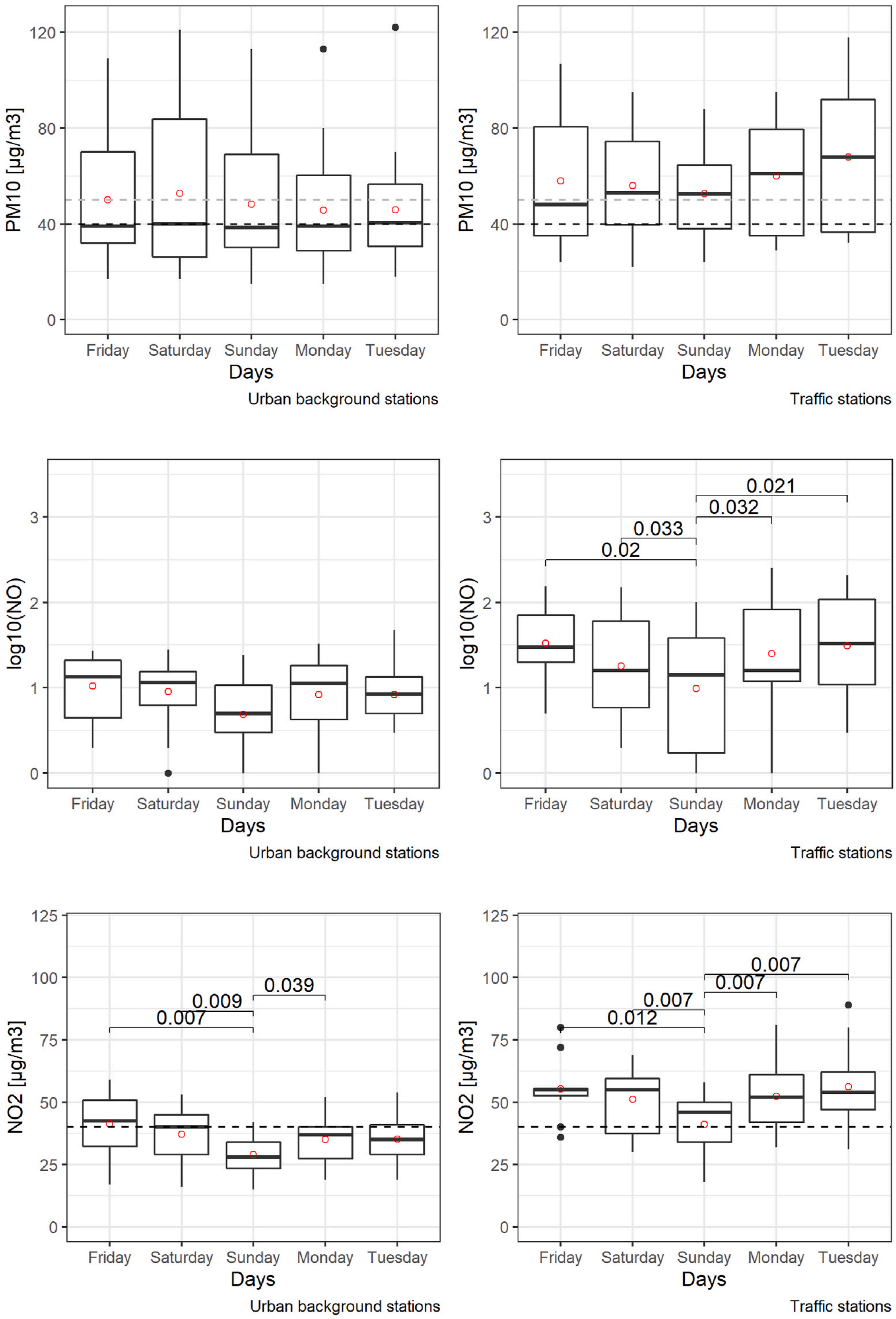

Fig. 4. Boxplots with PM10 (first row), $\log_{10}(NO_x)$ (second row) and NO_2 (third row) distributions during traffic-restricted Sundays for each type of station investigated. The $\log_{10}()$ transformation is employed to ensure data normality. Horizontal dashed lines represent annual mean law limits for NO_2 and PM10 (40 μg/m^3). Grey dashed lines in PM10 graphs represent the daily average limit (50 μg/m^3), which is to not exceed more than 35 times in a year. Statistically significant comparisons (α = 0.05) are indicated in the plots, and the corresponding p-values (adjusted for multiplicity) are reported.

Table 3
PM10 medians and means comparison between March, April and May 2020 and same months in 2017-19, for all types of station.

PM10	Median 2017–2019 [μg/m3]	Median 2020 [μg/m3]	Difference [%]	Mean 2017–2019 [μg/m3]	Mean 2020 [μg/m3]	Difference [%]
Rural background	22.11	19.00	−14.1%	23.20	23.53	1.4%
Urban background	25.28	20.83	−17.6%	28.28	26.49	−6.3%
Traffic	28.89	24.39	−15.6%	31.80	31.17	−2.0%
Industrial	29.67	24.33	−18.0%	32.48	30.88	−5.0%

Table 4
NO medians and means comparison between March, April and May 2020 and same months in 2017-19, for all types of station.

NO	Median 2017–2019 [µg/m3]	Median 2020 [µg/m3]	Difference [%]	Mean 2017–2019 [µg/m3]	Mean 2020 [µg/m3]	Difference [%]
Rural background	1.78	1.67	−6.2%	2.06	1.70	−17.5%
Urban background	5.28	1.33	−74.7%	7.06	2.92	−58.7%
Traffic	9.67	3.33	−65.5%	11.80	5.95	−49.6%
Industrial	22.00	4.00	−81.8%	23.95	6.09	−74.6%

Table 5
NO_2 medians and means comparison between March, April and May 2020 and same months in 2017-19, for all types of station.

NO_2	Median 2017–2019 [µg/m3]	Median 2020 [µg/m3]	Difference [%]	Mean 2017–2019 [µg/m3]	Mean 2020 [µg/m3]	Difference [%]
Rural background	9.89	7.33	−25.8%	11.16	8.50	−23.8%
Urban background	25.61	14.83	−42.1%	26.16	17.02	−34.9%
Traffic	32.11	19.33	−39.8%	32.71	20.82	−36.3%
Industrial	36.83	18.00	−51.1%	38.73	19.76	−49.0%

influenced by Venice Port activities, and the "Strada Sant'Agnese" (502612) station (Treviso), which is situated close to the Treviso Airport, reported very relevant reductions due to the closure of Venice Port and Treviso Airport during the lockdown period. This result highlights that vessel and air traffic are responsible for the greatest part of the NO concentrations in those areas (see Figure E3 in the Supplementary materials).

The lockdown effect was visible in the urban background, traffic and industrial stations (Figures E1, E.3, E.4 in Supplemental material), with a median reduction between 66% and 82% (Table 4), confirming that NO concentrations showed the clearest signal linked to traffic restrictions. Rural background stations registered a lower but still statistically significant reduction (except from "Cinto Euganeo" - ID 502812).

Nitrogen dioxide has both primary and secondary origins, and the main emission source is traffic.

Usually, higher concentrations were observed near traffic stations, but at background stations, NO_2 presence was also relevant (Liguori et al., 2020).

The lockdown months in 2020 were characterised by significantly lower NO_2 concentrations than those in 2017–2019 at all monitoring stations (Figures E.1 to E.4 in Supplementary material) and the reductions in median concentration ranged from −26% at rural background stations to −51% at industrial stations (Table 5).

The median concentrations were always higher at traffic stations with respect to the corresponding background station.

A second-order regression model considered data from urban background and traffic stations in Padua (IDs 502808 and 502809), Venice (IDs 502717 and 502726) and Treviso (IDs 502608 and 502612), as well as the Legnago (VR) (ID 502313) urban background station and the San Bonifacio (VR) (ID 502310) traffic station, both located in Verona Province. Urban background stations that were not correlated with traffic stations in the same area of interest were not selected.

For each monitoring station, the model was developed considering the first 180 days in 2017–2019, and then it was used to predict pollutant concentrations in the same period in 2020. Furthermore, since the predictors of the model are the day of the year and daily weather conditions, the influence of those factors on pollutant concentration was considered. Therefore, the eventual differences between predicted values and observed values are solely attributable to the lockdown effect.

The blue lines represent predicted values, and the red lines show observed values (see Figure E.5 to E.10). The two vertical dashed lines highlight the lockdown period between 23rd February and 17th May. Each graph reports the R-squared value, which represents how much variability the model is able to explain. Generally, all graphs present acceptable R-squared values; thus, the predictions are considered reliable, and in line with other similar applications in the literature (Venter et al., 2020).

To avoid problems of heteroskedasticity (see Section 2.4.4), the model was run with $\log_{10}$ values of the pollutant concentrations, and then the plots were reconverted to clearly visualise the results. Both types of results are reported in the Supplementary material (Figures E5 to E10).

Some observed outliers were present at the end of March 2020 at all stations (from day 87 to day 89 of the year), and they identified high concentrations detected due to the transport of desertic sands from the Caspian Sea caused by strong winds from eastern quadrants.

Regardless, the PM_{10} concentrations in 2020 were generally in line with the model predictions, except for an accumulation event that occurred during the second week of March. On the other hand, NO and NO_2 predictions were in line with the observed values only before the lockdown, while after the beginning of the restrictions the models tended to consistently overpredict data. This result is the effect of the lockdown, as the models predict the pollutant concentration that would have been registered if no lockdown was put in place. In general, second-order regression plots confirm the results obtained from the boxplots.

This analysis may provide a follow-up to the study provided by ARPAV in May 2020 (Liguori et al., 2020). That study analysed PM_{10}, NO and NO_2, concluding that there were concentration reductions for all three compounds, but it highlighted that the PM_{10} value reduction may have been caused by meteorological conditions, which favoured pollutant dispersion in March 2020. Thus, uncertainties remained about the correlation between lockdown and air quality situations, particularly for particulate matter, but this work's results generally agreed with the ARPAV results.

3.5. *Limitations and scalability of the results*

The findings of this article are obtained based on a rigorous statistical analysis; however, some assumptions and limitations of the statistical techniques employed can be mentioned. First, the results of the analyses are heavily affected by the quality of the data. It is worth mentioning that all the measuring devices are subject to regular checks and maintenance (Section 2.3), and data are carefully checked by ARPAV protocols to meet EC Directive requirements.

Second, missing data may affect the results in many ways. However, a low percentage of missing data (2.7% of the total data) was present, and an appropriate data inputting technique was employed. Furthermore, whenever possible, descriptive results were supported by inferential results from the execution of statistical tests. Great attention was paid to the assumptions of each statistical procedure, and appropriate data transformation techniques were employed to ensure that all the assumptions of the parametric procedures were verified (e.g., logarithmic transformation to ensure data normality and homoscedasticity). If some of the assumptions of the parametric tests could not be verified, robust nonparametric permutation tests were preferred to provide reliable inferential conclusions in these situations. A regression approach based on second-order regression models was employed for prediction of the pollutant concentration in the lockdown periods. Even though the results, in terms of goodness of fit, were similar to other similar applications in the literature (Venter et al., 2020), it is worth mentioning that the R-squared values were never extremely high (i.e. R-squared>90%), underlining how some potentially significant predictors were not considered in the analyses and how the models chosen could not provide a complete and thorough explanation of the variance observed in the data.

Based on the outcomes of this research, policy makers must start to identify the main steps needed to further improve AQ across the Veneto region. Although the results of this study are scaled over the eastern part of the Po Valley, a European region with a peculiar emission scenario, and climatic topographic characteristics, the adopted methodologies may be further extended to other European areas affected by air pollution. It would be desirable to further extend the methodologies adopted in the current study at least to the whole Po Valley, to obtain a comprehensive overview of the trends across the largest air pollution hotspot in Europe. An extension of this study would also allow the identification of possible spatial changes in the trends due to different emission scenarios and mitigation policies adopted within the Po Valley. Additionally, a more extended analysis will help identify the possible effects of polluted air mass transport in, out, and within the Po Valley.

4. Conclusions

The Veneto region and the Po Valley are generally characterised by situations where the air quality limit values for many pollutants are frequently exceeded. The infringement procedure towards Italy for the systematic and persistent exceedance of PM_{10} limit values has led the Po Valley basin to sign a New Agreement, with the aim of improving air quality.

An extended time-series analysis, which included the 2020 lockdown, permitted us to obtain relevant results that can efficiently support environmental policies. They are presented and discussed as follows.

- PM_{10}, NO, and NO_2 presented high negative cross-correlations with air temperature, confirming that air quality was better during summer. The same situation occurred with wind: the higher the daily average wind speed was, the lower the pollutant concentrations were. Rainfall instead had effects mainly on particulate matter, and interestingly, a rainfall event could affect PM_{10} values for the following three days.
- Environmental policy measures in recent years have acted mainly on the traffic sector. As evidence, the percentage of circulating vehicles in the Veneto region involved in traffic restrictions before and after the implementation of the Agreement of Po Valley was approximately 18% and 50%, respectively (See Table A5 in Supplementary data).
- Nitrogen oxide concentrations were reduced significantly, principally after implementing the Agreement of the Po Valley basin in 2017. However, the reduction in the particulate matter concentration was not as reassuring. This result indicates that other direct and indirect emission sources, such as domestic heating systems, agricultural activities, and animal farms, should be regulated with the same rigor as traffic sources.
- Ecological Sundays were not able to significantly affect air quality in terms of PM10. Regardless, they maintain an essential educational role in empowering the community to respect the environment.
- The 2020 lockdown effects were mainly linked to reducing nitrogen oxides; conversely, PM_{10} did not decrease significantly. This result provides proof that traffic is not the principal emission source of particulate matter; rather, other sources are important and should be monitored and regulated.

In summary, the analysis of long-term data has allowed us to depict the mechanisms that influence air quality in the Po Valley and to highlight how the current containment measures promoted by environmental policies, primarily aimed at the traffic sector are only partially effective in improving air quality. In particular, to achieve the PM_{10} targets, it is necessary to integrate the current air quality improvement plans with more stringent measures aimed at controlling emissions from domestic heating systems and from crop and animal production, as well as to promote energy efficiency policies in buildings and more sustainable agricultural practices.

CRediT authorship contribution statement

Alberto Pivato: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Luca Pegoraro:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Mauro Masiol:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Erick Bortolazzo:** Methodology, Software, Writing – original draft, Writing – review & editing. **Tiziano Bonato:** Methodology, Writing – review & editing. **Gianni Formenton:** Methodology, Writing – review & editing. **Giovanna Cappai:** Methodology, Writing – original draft, Writing – review & editing. **Giovanni Beggio:** Methodology, Writing – review & editing. **Rosa Arboretti Giancristofaro:** Methodology, Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2023.119610.

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