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Social distancing measures following COVID-19 epidemics had positive environmental consequences

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At the time of this communication (March 12, 2020), there have been 126,660 cases of COVID-19 reported worldwide, with 68,305 individuals having recovered and 4,641 deaths registered. The speed of the disease's spatial diffusion was unprecedented: the first reported case was documented on December 8, 2019 in Wuhan, and by January 28, 2020, there were more than 800 cases internationally. Though the majority was concentrated in China, the virus had spread to Japan, South Korea, the U.S.A., Taiwan, Hong Kong, Macau, Singapore and Vietnam. In an attempt to contain the spread of the virus, beginning on January 23, residents of Wuhan were placed under quarantine, immediately followed by the cities of Huanggang and Ezhou. Authorities went on to cancel Chinese New Year celebrations.

As a result of the slowdown of economic and social activities,[1] pollution began to contract. Satellite-based observations detected a contraction of 10-30% in NO_2 and $PM_{2.5}$.[2,3] Our analysis suggests that voluntary and imposed social distancing measures to fight COVID-19 could substantially impact pollution depending on the pollutants considered.

We have analysed 151 monitoring stations located across major Chinese cities in 31 provinces that track the concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO in order to gather data before and after the outbreak of COVID-19. In the analysis that follows, the heterogeneous effects of the

COVID-19 outbreak on concentrations of $PM_{2.5}$, PM_{10}, NO_2 are computed through regression models, the details of which appear in the supplementary materials, where we also report estimates for O_3, SO_2 and CO. To estimate our models, we have used daily data regarding pollution concentration and the number of COVID-19 cases while controlling for a series of spatial and time fixed effects as well as province/region-specific time trends.

In the cities of Wuhan and Beijing, our data indicate a very diverse pattern in the concentration of pollutants after the outbreak of the disease. In Wuhan, all pollutants, except for ozone and sulphur dioxide, decreased substantially. Meanwhile, Beijing shows contractions only in NO_2 and PM_{10}, with the concentration of all other pollutants increasing over the time period under consideration. In Wuhan, the number of confirmed cases contributed to reducing the emissions of PM10, O3 and NO2 by 6.55, 5.86 and 6.58 μ/m^3, respectively, while reducing PM2.5 by 17.9 μ/m^3. Il should also be noted that our estimates show an increase in CO concentration of 3.6 μ/m^3.

Moreover, according to data on Wuhan's primary pollutants, the emission levels for PM2.5 and O3 on March 8 had returned to the same historical trend for the month, while emissions of PM10 and NO2 were still 10% and 7% lower than their monthly averages, respectively.

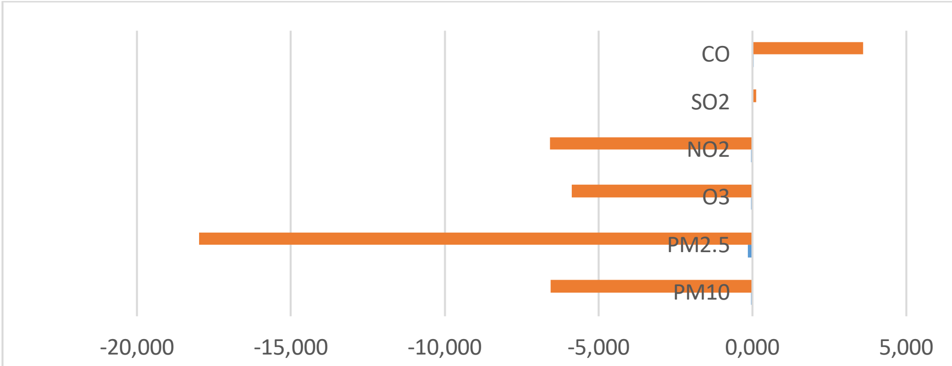
The spread of COVID-19 in Italy has followed a similar pattern to the Chinese case with 10,390 cases and 827 deaths reported so far, mostly affecting the Northern region of Lombardy. Since March 3, 2020, authorities implemented a series of restrictive measures on people's movement first across Northern regions and subsequently extended to the whole Italian territory, regardless of the number of COVID-19 cases.

Based on our preliminary evidence, the impact of the disease's diffusion has been sizeable in the city of Milan. PM_{10} declined by an average of 14 μ/m^3 after February 22, a pattern comparable to

$PM_{2.5}$ and NO_2 concentrations, which reduced by 25 μ/m^3 and 9 μ/m^3, respectively. In this case, it also should be noted that, since the outbreak of COVID-19, concentrations of PM_{10} and $PM_{2.5}$ have been 30% below the historical trend for this time of year, and NO_2 emissions have been 13% below the historical monthly trend.

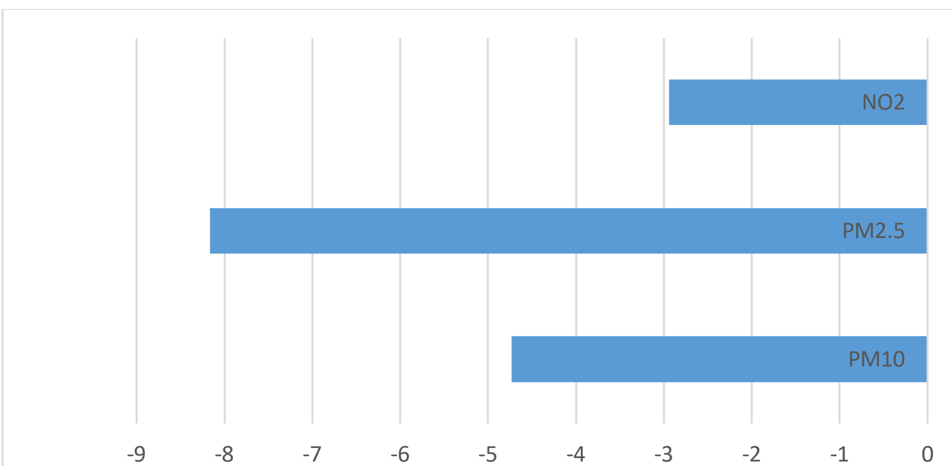
The epidemic is taking a devastating toll in terms of lives lost, likely having negative repercussions for local and national economies.[4] Although this large-scale natural experiment does not allow us to distinguish between the effects of a slowdown in social contact[5,6] and the contraction of production, our results point to a positive and substantial role for voluntary and imposed social distancing not only in terms of containing COVID-19, but also in terms of air quality—with potentially broader health implications.

Figure 1: The effects of the COVID-19 outbreak in Beijing and Wuhan



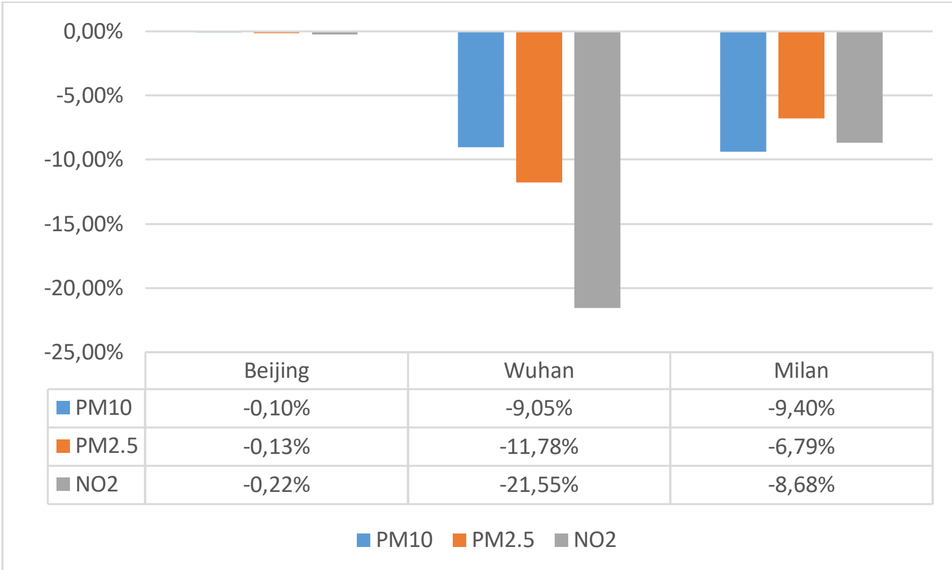
	PM10	PM2.5	O3	NO2	SO2	CO
Wuhan	-6,551	-17,973	-5,865	-6,585	0,126	3,601
Beijing	-0,052	-0,142	-0,046	-0,052	0,001	0,028

Figure 2: The effects of the COVID-19 outbreak in Milan



	PM10	PM2.5	NO2
Series1	-4,730509677	-8,16423871	-2,940587097

Figure 3: Percentage change in pollutants concentration with respect to the pre-epidemics 2019-2020 average



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[5] The *Lancet* Editorial, COVID-19: too little, too late?, *The Lancet*, Volume 395, ISSUE 10226, P755, March 07, 2020.

[6] RM Anderson, H. Heesterbeek, D. Klinkenberg, TD Hollingsworth, How will country-based mitigation measures influence the course of the COVID-19 epidemic?, *The Lancet*, Online First

Supplementary materials

Methodology

In the case of China, our spatial unit of observation is the province. Meanwhile, to estimate the impact of the COVID-19 outbreak, we have estimated several versions of the following regression:

$$Pollutant_{t,p} = \alpha + \beta COVID_{t,p} + \delta_t + \gamma_p + \text{f(trend)} + \varepsilon_{t,p},$$

where the dependent variable stands for the average daily concentration in terms of mg/m3 of one of the following pollutants: PM10, PM2.5, O3, NO2, SO2 or CO. Our treatment variable is $COVID_{t,p,}$ measuring either the number of cases detected in province p at time *t*, the number of deaths or the number of recovered individuals. This variable takes the value of 0 before the outbreak of the disease on 8 December 2020. δ_t and γ_p indicate full sets of day-of-the-year- and province-specific fixed effects. These dummy variables are of paramount importance because they capture day-specific regularities in China (e.g., the Chinese New Year's Day) or time-invariant characteristics at the province level. $\varepsilon_{t,p}$ is an iid error term, so that, by using the Panel Least Squares estimator, we retrieve an estimate for parameter β that measures the impact of the COVID-19 outbreak on pollution concentrations.

Equation (1) is estimated by using data from 2014 to 2020 and by using information from the following months: November, December, January and February.

It should be further mentioned that in several specifications of Equation (1), we include province-specific quadratic time trends to account for possible local temporal trends in the concentration of pollutants, that is, the function *f(trend)* in equation (1).

In the case of Milan, we include additional historical daily weather controls for each Italian region. Therefore, we estimate the following regression:

(2) $$Pollutant_{t,r} = \alpha + \beta COVID_{t,r} + \delta_t + \gamma_r + \text{f(trend)controls}_{t,r} + \varepsilon_{t.r},$$

where the dependent variable measures the daily concentration of one of the following pollutants: PM10, PM2.5, O3, NO2, SO2 or CO. Our treatment variable is $COVID_t$, measuring either the number of cases detected in each Italian region, *r* at time *t*, the number of deaths, or the number of hospitalized individuals. This variable takes the value of 0 before the outbreak of the disease, that is, before 22 February 2020. Among the controls, we include maximum and minimum daytime temperature and millimetres of precipitation. Also, in this case, $\varepsilon_{t,r}$ is an iid error term, so that by using the Panel Least Squares estimator, we retrieve an estimate for parameter β that measures the impact of the COVID-19 outbreak on pollution concentrations.

Data

As for the number of confirmed cases, hospitalizations and deaths for COVID-19, we have used data made available by the Italian Ministry of Health and Protezione Civile. Both institutions provide data at the regional and provincial levels. We have also utilised data from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.[1] These data are available through an associated dashboard at the following URL: https://www.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6 GitHub data repositories are also available at https://github.com/pcm-dpc/COVID-19 and https://github.com/CSSEGISandData/COVID-19.

Data on pollution come from the World Air Quality Index project. The Air Quality Index is based on measurements of particulate matter (PM2.5 and PM10), Ozone (O3), Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2) and Carbon Monoxide (CO) emissions. Most of the stations on the map monitor both PM2.5 and PM10 data, but there are few measuring only PM10. The World Air Quality Index is a collaborative project integrating data from public monitoring stations with private devices in order to provide unified and global air quality information. Data are available at this URL: https://waqi.info/. As of March 2020, real-time air quality information is available from more than 12,000 stations in 1000 major cities in 100 countries. The air quality information provides official pollution levels for the EPAs (Environmental Protection Agencies) of each country.

In order to maintain a high level of consistency, only data from stations with both particulate matter readings (PM2.5/PM10) are published. The AQI standard for every published station is based on the US EPA Instant-Cast standard.

The data published on the World Air Quality Index is real-time, and therefore, invalid by the time of publication. However, in order to ensure a high level of accuracy for each AQI figure, we use several machine learning processing solutions. For instance, we verified data consistency, in real-time, with neighbouring stations, allowing the automatic detection of defective monitoring stations; if needed, they were removed from the map. Data on pollution levels for China became available in January 2014. To test the quality of pollution data in China, we also used data regarding the monthly concentration of NO2 in Beijing collected by the Tropospheric Monitoring Instrument (TROPOMI) on ESA's Sentinel-5 satellite from 2014 to 2018.

Finally, to test the quality of pollution data in Milan, we utilised data on the concentration of PM10, PM2.5, O3, NO2 and SO2 from the monitoring stations managed by the Agenzia Regional per la Protezione Ambientale (ARPA), the public body responsible for environmental monitoring in the region of Milan. ARPA is also the source of weather variables (min-max temperatures, precipitations) in Milan.

Definition of Pre- and Post-Covid-19 spread in Italy and China

To allow for a meaningful comparison of the emission levels before and after the onset of the novel coronavirus, we have considered historical daily weather variables for major Chinese cities for the months of December, January, February and March, since 2014. This approach has allowed us to compare the emission levels for each city to its historical average during the time period.

The COVID-19 virus started its diffusion in the province of Hubei on the 21st of January 2020 and reached its peak around February 15th. Our empirical strategy therefore considers the 21st of January as the start of the post-virus period.

In Italy, the onset of the novel coronavirus occurred one month later (with its peak yet to be reached as of the 9th of March). The first date on the number of cases and deaths for COVID-19 was published on the 22nd of February. As a result, our methodology uses this date as the first of the post-virus period.

Results

Tables S1-S3 report regression estimates (1) by using three indicators of the spread of COVID-19: the number of confirmed cases, hospitalisations and deaths. Tables S4-S6 report regression estimates (2) by using the aforementioned three indicators of the spread of COVID-19.

Table S1: Effects of daily cases of COVID-19 on air pollutants in China

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	PM10	PM2.5	O3	NO2	SO2	CO
Cases	-0.000191**	-0.000524***	-0.000171***	-0.000192***	3.67e-05	0.000105**
	(8.27e-05)	(8.93e-05)	(1.94e-05)	(2.33e-05)	(4.04e-05)	(5.03e-05)
Constant	135.4***	175.6***	21.43***	41.07***	37.91***	42.10**
	(11.23)	(8.853)	(2.754)	(3.164)	(2.879)	(16.27)
Observations	17,437	17,588	15,699	17,533	17,535	17,292
R-squared	0.434	0.486	0.492	0.603	0.678	0.220
Province FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Province*Trend	YES	YES	YES	YES	YES	YES
Province*Trend^2	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S2: Effects of daily hospitalisations of COVID-19 on air pollutants in China

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	PM10	PM2.5	O3	NO2	SO2	CO
Hospitalisations	- 0.000450**	- 0.00113***	- 0.000384***	- 0.000445***	0.000104	0.000283**
	(0.000210)	(0.000225)	(5.00e-05)	(5.42e-05)	(9.39e-05)	(0.000120)
Constant	135.4***	175.6***	21.43***	41.07***	37.91***	42.10**
	(11.23)	(8.853)	(2.754)	(3.164)	(2.879)	(16.27)
Observations	17,437	17,588	15,699	17,533	17,535	17,292
R-squared	0.434	0.486	0.492	0.603	0.678	0.220
Province FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Province Month Trend	YES	YES	YES	YES	YES	YES
Province Month Quad Trend	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S3: Effects of daily deaths for COVID-19 on air pollutants in China

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	PM10	PM2.5	O3	O3	O3	CO
Confirmed Deaths	-0.00461**	-0.0122	-0.00406***	-0.00450***	0.000697	0.00236**
	(0.00189)	(0)	(0.000458)	(0.000482)	(0.000903)	(0.00103)
Constant	135.4***	175.6	21.43***	41.07***	37.91***	42.10**
	(11.23)	(0)	(2.754)	(3.164)	(2.879)	(16.27)
Observations	17,437	17,588	15,699	17,533	17,535	17,292
R-squared	0.434	0.486	0.492	0.603	0.678	0.220
Province FE						YES
Time FE						YES
Province Month Trend						YES
Province Month Quad Trend						YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S4: Effects of daily cases of COVID-19 on air pollutants in Milan

VARIABLES	(1) PM10	(2) PM2.5	(3) NO2
Confirmed Cases	-0.0259***	-0.0447***	-0.0161***
	(0.00917)	(0.0154)	(0.00309)
Temp Min	-1.879***	-2.279***	-1.499***
	(0.234)	(0.572)	(0.156)
Temp Max	0.448**	-0.895*	0.871***
	(0.194)	(0.478)	(0.145)
Precipitation	-0.370***	-0.867***	0.0369
	(0.0916)	(0.267)	(0.0386)
Constant	49.14***	128.6***	38.26***
	(1.815)	(4.458)	(1.280)
Observations	621	618	620
R-squared	0.230	0.163	0.153

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S5: Effects of daily hospitalisations for COVID-19 on air pollutants in Milan

VARIABLES	(1) PM10	(2) PM2.5	(3) NO2
Hospitalisations	-0.522***	-0.700***	-0.183***
	(0.0891)	(0.247)	(0.0385)
Temp Min	-1.879***	-2.279***	-1.501***
	(0.234)	(0.572)	(0.156)
Temp Max	0.444**	-0.907*	0.863***
	(0.193)	(0.478)	(0.145)
Precipitation	-0.370***	-0.866***	0.0384
	(0.0917)	(0.266)	(0.0386)
Constant	49.19***	128.8***	38.32***
	(1.810)	(4.456)	(1.282)
Observations	621	618	620
R-squared	0.233	0.164	0.151

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S6: Effects of daily deaths for COVID-19 on air pollutants in Milan

	(1)	(2)	(3)
VARIABLES	PM10	PM2.5	N02
Deaths	-0.724***	-1.339***	-0.495***
	(0.279)	(0.483)	(0.0945)
Temp Min	-1.878***	-2.279***	-1.499***
	(0.234)	(0.572)	(0.156)
Temp Max	0.449**	-0.891*	0.873***
	(0.194)	(0.479)	(0.145)
Precipitation	-0.370***	-0.867***	0.0365
	(0.0916)	(0.267)	(0.0386)
Constant	49.13***	128.6***	38.25***
	(1.816)	(4.460)	(1.280)
Observations	621	618	620
R-squared	0.230	0.163	0.154

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table S7: Average Pollution Levels in Beijing, Wuhan and Milan Before and After the Diffusion of COVID-19

	(1)	(2)	(3)
Pre COVID-19	PM10	PM2.5	NO2
Beijing	50.54	107.83	23.52
Wuhan	72.40	152.6	30.56
Milan	50.32	120.32	33.89
Post COVID-19			
Beijing	42.94	142.65	14.52
Wuhan	53.11	144.30	14.63
Milan	30.16	70.33	30.50

Data use 21-01-2020 as the date for the commencement of COVID spread in China, reaching a peak on 15-02-2020. In Italy, the diffusion started on 24-02-2020. Pollutant levels are expressed in μ/m^3.

Data quality check

To check the data's quality, we have investigated alternative sources and correlated them with the AQI data.

As for the case of China, we have investigated the correlation between AQI data and data on the concentration of NO2 in Beijing available at monthly levels from 2014 to 2018. As can be seen in figure S1, the linear correlation is equal to 0.94.

As for Milan, we were able to estimate equation (2) by using official data provided by ARPA for the same pollutants used when obtaining estimates for tables S4-S6. As reported in table 9, differences in point estimates are relatively small.

Figure S1: Correlation between AQI and NASA data for NO2 in Beijing

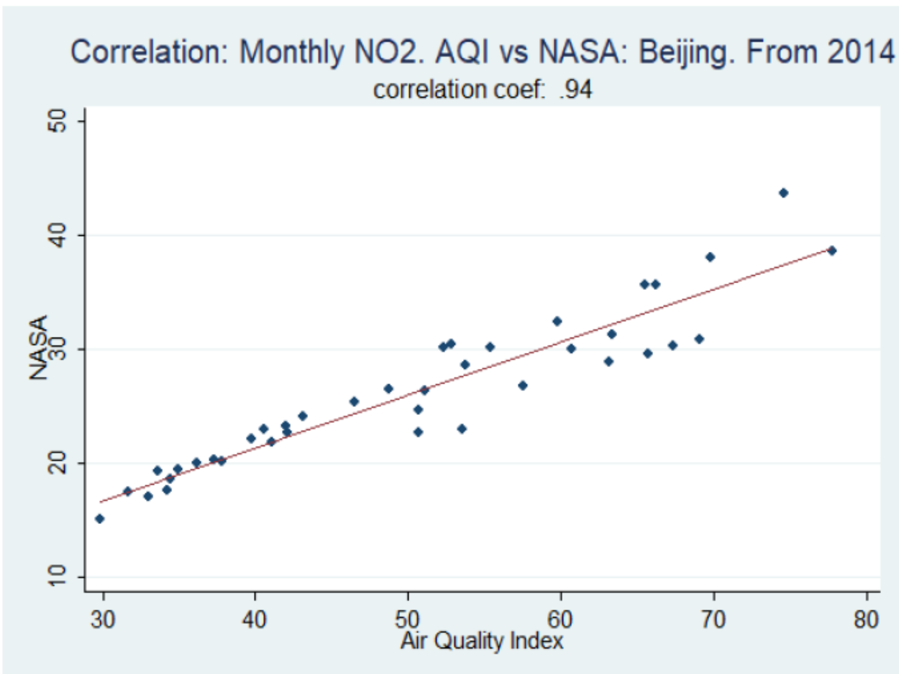
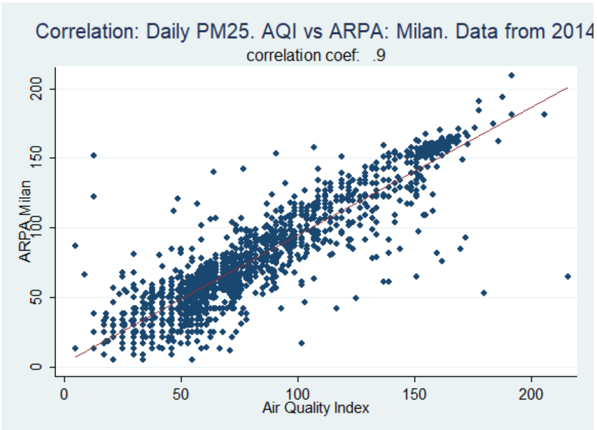
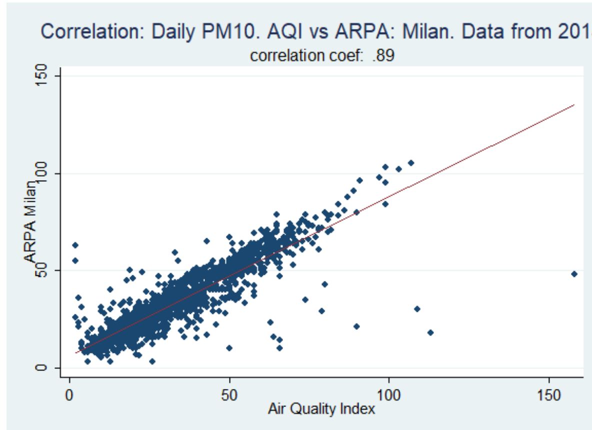


Figure S2: Correlation between AQI and ARPA data for PM_{10}, $PM_{2.5}$ and NO_2 in Milan





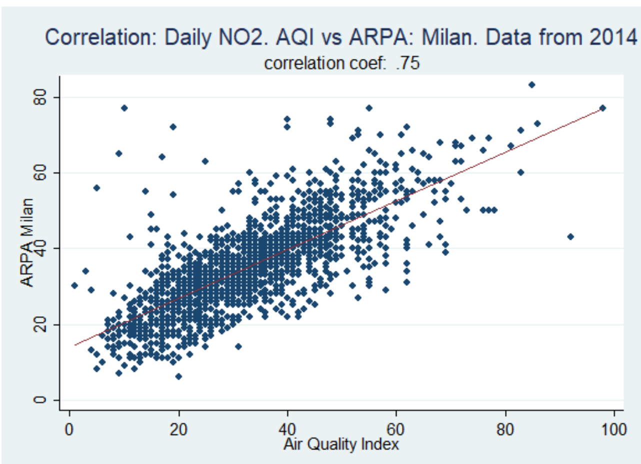


Table 8: Effects of daily cases of COVID-19 on air pollutants in Milan: Official ARPA data

VARIABLES	(1) PM10	(2) PM25	(3) NO2	(4) O3	(5) SO2
Confirmed Cases	-0.0352***	-0.0602***	-0.0107***	0.0262***	0.00174**
	(0.0102)	(0.0175)	(0.00389)	(0.00999)	(0.000819)
Temp Min	-1.960***	-2.428***	-2.014***	-0.632***	-0.00357
	(0.250)	(0.533)	(0.203)	(0.115)	(0.0195)
Temp Max	0.651***	-0.494	1.464***	0.857***	0.0498***
	(0.208)	(0.474)	(0.176)	(0.103)	(0.0179)
Precipitation	-0.412***	-1.049***	-0.00256	0.125***	-0.0193***
	(0.107)	(0.188)	(0.0940)	(0.0355)	(0.00679)
Constant	47.50***	127.8***	29.88***	2.621***	2.027***
	(1.957)	(4.406)	(1.526)	(0.884)	(0.161)
Observations	613	614	600	622	602
R-squared	0.228	0.168	0.196	0.131	0.042

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

[1] E. Dong, H. Du, L. Gardner, An interactive web-based dashboard to track COVID-19 in real time, *The Lancet Infectious Disease*, Published Online February 19, 2020.

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