Interrupted time series analysis of world nitrogen dioxide Sentinel 5-P satellite concentrations during COVID-19 lockdown

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Introduction

- The coronavirus disease (COVID-19) has caused global changes in human behavior patterns and economic activity, both due to personal choices and public health policies to slow the disease's spread.[1]
- Nitrogen dioxide (NO_2) is a pollutant that has been found to have adverse effects on human health, both independently and in conjunction with other air pollutants.[2]
  - NO_2 is emitted by anthropogenic sources including vehicle combustion and industrial processes. NO_2 is often used as a proxy for measuring traffic-related air pollution (TRAP). Thus, it is a strong choice for evaluating the effects of lockdown, which severely limited human mobility.
  - Both short- and long-term exposures to NO_2 are have been shown to negatively impact health via a variety of biological pathways.
- Recent studies have aimed to quantify the impact of the COVID-19 lockdown on NO_2 concentrations on local, regional, national, and global scales using both ground and satellite data.[3]
  - These papers used a variety of mechanisms and data sources; most concluded that NO_2 did decrease over lockdown in the relevant study region. However, NO_2 trends seasonally towards higher concentrations in the winter and lower in the summer. Because seasonal trends predict a decrease in NO_2 in the northern hemisphere that temporally coincides with lockdown, it can be difficult to distinguish seasonality and lockdown effects.
- This study attempts to address these challenges and validate recent findings. We present a novel angle in the following ways:
  1. **Satellite-obtained tropospheric NO_2 column density**[4] is used for an **interrupted time series analysis (ITS)**, including historical data for comparison.
  2. **The study stratifies NO_2 spatially by urban and rural areas,** which allows for the impact of lockdown to be assessed in highly populated areas where behavioral changes due to lockdown measures were likely magnified.
  3. **The scope of the study is global**; individual countries in IHME GBD (Institute for Health Metrics Evaluation Global Burden of Diseases, Injuries, and Risk Factors Study) super regions with high urban NO_2 concentrations are chosen for further analysis.

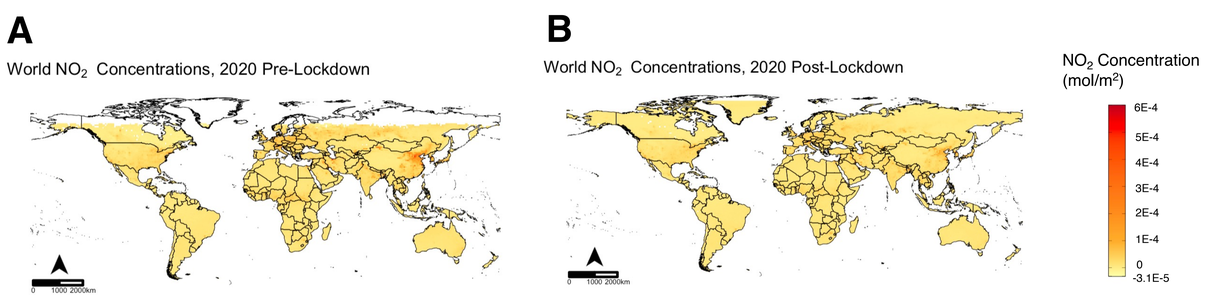

Figure 1. World NO_2 tropospheric column density averaged over 6 weeks pre-lockdown (A) and averaged over 6 weeks post-lockdown (B), with lockdown defined as Jan. 30th 2020, the day WHO declared COVID-19 a public health emergency. By visual inspection, a decrease in NO_2 occurs between A and B, especially over East Asia and Europe.

Objectives

- **Determine** whether **NO_2 levels decreased during the COVID-19 lockdown** using an interrupted time series analysis, filtering data by country and by urban-rural divide.
- **Analyze** the **relative effects of different pandemic-related restrictions on NO_2** in selected countries with a high baseline NO_2.

Methods

Data Retrieval

- Used rgee R package to obtain and clean Earth Engine Sentinel 5-P weekly 2019—2020 offline NO_2 satellite data (1.0 arc degrees resolution).
- Extracted urban and rural NO_2 concentrations by country with World Urban Area shapefile from the North American Cartographic Information Society.
- Obtained OxGCRT COVID Policy Tracker data and filtered for 8 containment closure policy indexes and 1 overall stringency index.

Country Selection

- Countries in R dataset wrld_simpl filtered for Area > 4,000,000 hectares
- Urban Area shapefile used to extract urban NO_2 concentrations by country from NO_2 raster data.
- Top 3 countries from each IHME GBD region sorted by 2019 urban NO_2 averages chosen for further analysis.

Analysis

- ITS linear model created with interaction terms allowing for change of intercept and slope after interruption. Modeled actual and counterfactual situations for 2019 and 2020.
- ITS model interaction terms used to detect significant decreases in NO_2 over lockdown date.
- Model applied to 21 selected countries at 9 lockdown indexes.

Validation

- Obtained 2020 EPA AirData NO_2 daily monitor measures from 4 Philadelphia locations.
- Extracted 2020 Earth Engine satellite data at coordinates of each monitor.
- Created linear model for satellite vs. ground data for individual monitors and a Philadelphia average.

Results

Urban NO_2 Concentrations During Lockdown

Significance of Varying Lockdown Measures on Ambient NO_2

		p value								
	Average Urban NO2 (mol/m^2)	School Closures	Workplace Closures	Cancelled Public Events	Restrictions on Gatherings	Public Transport Closures	Stay at Home Orders	Internal Travel Restrictions	International Travel Restrictions	Overall Lockdown Stringency Index
Central Europe, Eastern Europe, and Central Asia										
Poland	3.55e-05	**0.021**	**0.010**	**0.007**	0.071	0.686	0.071	**0.021**	**0.003**	**0.004**
Slovakia	3.55e-05	0.176	0.088	0.309	0.432	0.206	0.432	0.467	0.304	0.088
Czechia	3.48e-05	0.120	**0.000**	0.120	0.086	0.948	**0.005**	**0.043**	0.734	0.202
High-income										
South Korea	6.63e-05	0.748	0.785	0.405	0.577	NA	0.583	0.583	0.933	0.583
Germany	4.90e-05	**0.014**	0.137	0.151	**0.008**	NA	**0.006**	**0.012**	0.151	**0.012**
Japan	4.19e-05	0.909	0.860	0.920	NA	NA	**0.030**	0.860	0.088	NA
Latin America and Caribbean										
Panama	1.75e-05	**0.001**	**0.012**	**0.001**	**0.001**	0.820	**0.002**	0.084	0.367	**0.002**
Guatemala	1.72e-05	0.067	0.231	0.124	0.108	0.231	0.738	0.211	0.066	0.067
Brazil	1.70e-05	0.579	0.992	0.579	0.912	0.623	0.992	0.904	0.992	0.904
North Africa and the Middle East										
Iraq	5.64e-05	0.512	0.333	0.512	0.512	0.110	0.110	0.194	0.620	0.512
Egypt	4.07e-05	0.814	0.570	0.572	0.506	0.506	0.506	0.506	0.770	0.465
Syria	3.84e-05	0.139	0.263	**0.045**	**0.045**	0.188	**0.038**	0.111	0.822	**0.045**
South Asia										
India	4.09e-05	0.572	0.652	0.572	0.498	0.935	0.754	0.652	0.754	0.411
Pakistan	4.06e-05	0.550	0.345	0.948	0.948	0.345	0.345	0.345	0.332	0.948
Bangladesh	4.05e-05	0.206	0.345	0.206	0.345	0.345	0.345	0.345	0.897	0.345
Southeast Asia, East Asia, and Oceania										
China	8.89e-05	**0.001**	**0.001**	**0.000**	**0.000**	**0.001**	**0.001**	**0.001**	0.530	**0.001**
North Korea	3.52e-05	NA	NA	NA	NA	NA	NA	NA	0.822	NA
Malaysia	2.68e-05	0.548	0.255	0.665	0.407	NA	0.255	0.255	0.846	0.255
Sub-Saharan Africa										
South Africa	3.17e-05	0.169	0.178	0.460	0.460	0.178	0.178	0.273	**0.049**	0.169
Congo	2.29e-05	0.506	0.506	0.506	0.506	0.817	0.506	0.506	0.307	0.506
Nigeria	2.25e-05	0.362	0.211	0.211	0.211	0.381	0.481	0.381	0.481	0.216

Bolded *p values signify p<.05*

Missing *p values signify that the index date either falls outside the study period, the type of lockdown never occurred, or there is no date in data set.*

Philadelphia EPA Monitor vs Sentinel Satellite NO_2, 2020

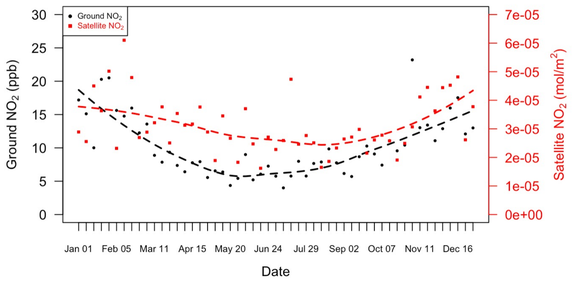

Figure 2. (above) Weekly satellite NO_2 data (red) is plotted along with ground monitor data (black) against time. Models for the overall Philadelphia average data (shown here) and individual monitor data return $p < 0.05$.

Table 1 (left). Shown are ITS model outputs for urban areas of 21 countries, stratified by IHME region. The ITS model created is as follows:

```
Call:
lm(formula = NO2_Concentration ~ no_of_weeks * year2020 + covid_lockdown *
    year2020 + no_of_weeks * covid_lockdown * year2020, data = x)
```

p values are included for the interaction term containing all three predictors (no_of_weeks:year2020:covid_lockdown).

Change in NO_2 levels in urban vs. rural areas in China before and after Jan 22nd, 2020, the date public events were cancelled

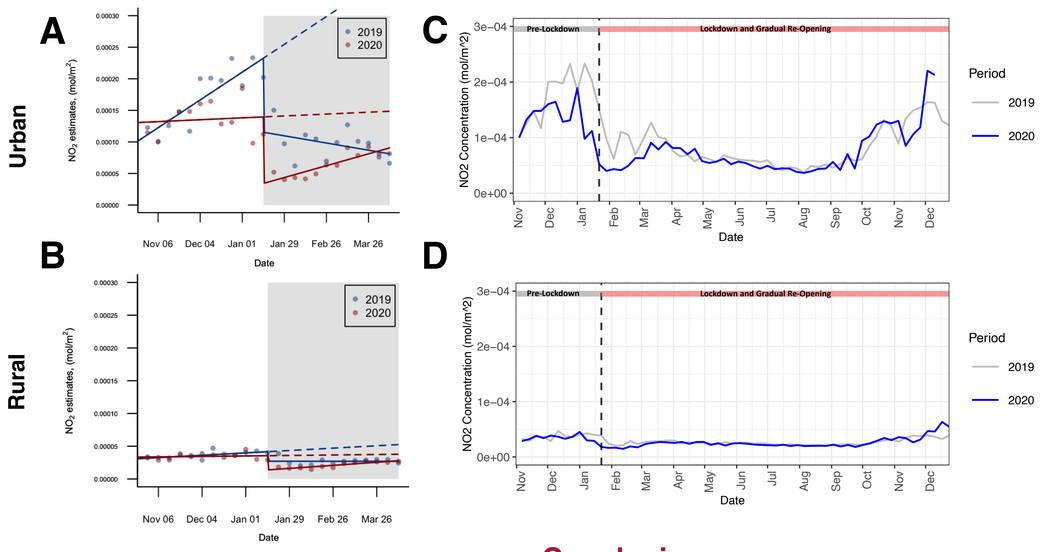

Figure 3. (left) ITS models comparing urban (A) and rural (B) NO_2 concentrations over 12 weeks pre- and post-lockdown. Corresponding full-year data is also shown (C, D). Plots were created for all countries and lockdown indexes; only China with cancelled public events as lockdown is shown. Dotted lines model the counter-factual situation and solid lines model actual concentrations in 2019 and 2020.

Conclusion

- Though **China had the most distinct change** in levels during lockdown in urban areas, driving the worldwide pattern, **all lockdown indexes** had a statistically significant effect on NO_2 concentrations in **at least one country.**
- **Significant rural-urban disparities** in NO_2 concentrations emphasize risk factors of urban living—exposure to outdoor air pollution has an additive effect for densely populated areas already vulnerable to heightened disease transmission.
- Moving forward, post-COVID-19 policies to improve air quality without economic shutdown can be driven by the **relative environmental impacts of lockdown measures**.

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