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Does Lockdown Decrease the Protective Role of Ultraviolet-B (UVB) Radiation in Reducing COVID-19 Deaths?

Manuscript

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Abstract

Background. Nations are imposing unprecedented measures at large-scale to contain the spread of COVID-19 pandemic. Recent studies indicate that measures such as lockdowns may have slowed down the growth of COVID-19. However, in addition to substantial economic and social costs, these measures also limit the exposure to Ultraviolet-B radiation (UVB). Emerging observational evidence indicate the protective role of UVB and vitamin D in reducing the severity and mortality of COVID-19 deaths. In this observational study, we empirically outline the independent protective roles of lockdown and UVB exposure as measured by ultraviolet index (UVI), whilst also examining whether the severity of lockdown is associated with a reduction in the protective role.

Methods. We apply a log-linear fixed-effects model to a panel dataset of 162 countries over a period of 108 days (n=6049). We use the cumulative number of COVID-19 deaths as the dependent variable and isolate the mitigating influence of lockdown severity on the association between UVI and growth-rates of COVID-19 deaths from time-constant country-specific and time-varying country-specific potentially confounding factors.

Findings. After controlling for time-constant and time-varying factors, we find that a unit increase in UVI and lockdown severity are independently associated with 17% [-1.8 percentage points] and 77% [-7.9 percentage points] decline in COVID-19 deaths growth rate, indicating their respective protective roles. However, the widely utilized and least severe lockdown (recommendation to not leave the house) already fully mitigates the protective role of UVI by 95% [1.8 percentage points] indicating its downside.

Interpretation. We find that lockdown severity and UVI are independently associated with a slowdown in the daily growth rates of cumulative COVID-19 deaths. However, we find consistent evidence that increase in lockdown severity is associated with a significant reduction in the protective role of UVI in reducing COVID-19 deaths. Our results suggest that

lockdowns in conjunction with adequate exposure to UVB radiation might have provided even more substantial health benefits, than lockdowns alone. For example, we estimate that there would be 21% fewer deaths on average with sufficient UVB exposure while people were recommended not to leave their house. Therefore, our study outlines the importance of considering UVB exposure, especially while implementing lockdowns and may support policy decision making in countries imposing such measures.

1 Introduction

Nations are imposing unprecedented non-pharmaceutical intervention measures at large-scale to contain the spread of COVID-19 pandemic[1]. Recent studies indicate that non-pharmaceutical intervention such as lockdowns, ceasing business operations and school closures substantially may have slowed down the growth of COVID-19[1–3], indicating its protective role. Emerging observational evidence on the epidemiology of COVID-19 indicate that vitamin D deficiency might be a risk factor for COVID-19 deaths[4–7] and also indicate the protective role of the significant source of vitamin D - Ultraviolet-B radiation (UVB)[8] in reducing COVID-19 deaths. In addition to substantial economic and social costs, an unintended consequence of lockdown is the likelihood of limited exposure to UVB. However, to the best of our knowledge, no empirical study has explored the association between the severity of lockdown, the subsequent reduction in UVB exposure and the number of deaths attributed to COVID-19 (COVID-19 deaths).

In this observational study, we empirically outline the independent protective roles of lockdown and UVB as measured by ultraviolet index (UVI) and subsequently examine, whether the severity of lockdown is associated with a reduction in the protective role of UVB. After controlling for time-constant and time-varying factors, we find that a unit increase in UVI and lockdown severity are independently associated with 1.8 percentage points (p.p) and 7.9 p.p decline in COVID-19 deaths growth rate representing a decline of 17% and 77%, respectively. These declines indicate the protective roles of UVI and lockdowns. Surprisingly, the widely utilized lockdown with least severity and (e.g., recommendation to not leave the house) already practically fully mitigates the protective role of UVI by 1.8 p.p which represents a decline of 95%.

2 Association of Lockdown Severity & UVB Radiation with COVID-19 Deaths

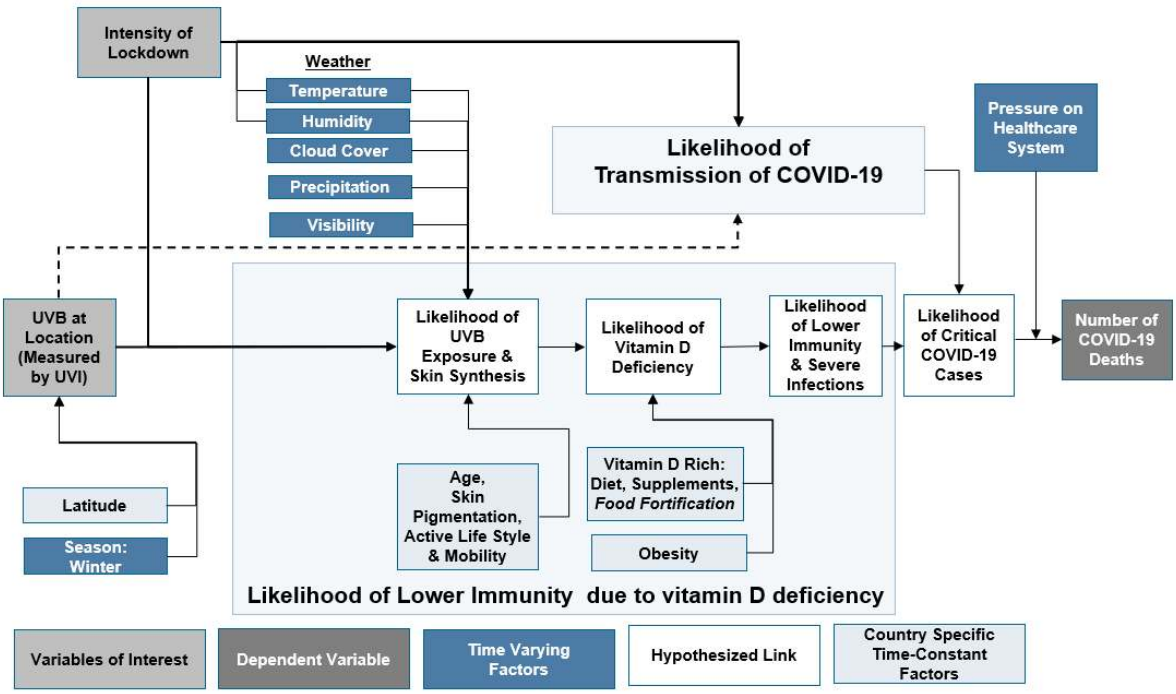
In general, non-pharmaceutical interventions such as the lockdowns aim to reduce the likelihood of transmission of the virus by limiting the movement of people, reducing the contact among individuals via restricting economic activities such as closing restaurants[2]. Some early studies indicate that such large-scale measures might have slowed down the growth rate of COVID-19 infections indicating its protective role, thereby providing direct health benefits[2,3,9]. However, the other indirect health consequences (e.g., reduced exposure to UVB radiation) of such policies are largely unknown.

In addition to substantial economic and social costs of lockdowns, an unintended health consequence of such measures may be the likelihood of limited exposure to UVB radiation. Prior studies indicate that UVB radiation plays a protective role in human health[10–14]. Humans get vitamin D via either diet (natural food, fortified food or supplements) or skin synthesis by UVB radiation exposure [15]. Likelihood of UVB exposure and subsequent vitamin D synthesis undergo substantial variation according to several time-varying and time-constant factors such as latitude[15], seasons[15], time of the day[15], lifestyle[16,17], mobility[18], age[15], skin pigmentation[15] and obesity[19]. Prior studies associate vitamin D deficiency with the likelihood of weakened immune response [20–22], infectious respiratory diseases [15,23,24] and the severity and mortality [25].

In Figure 1, we summarize these different factors explaining the potential association between the severity of lockdown and subsequent reduction in the likelihood of UVB exposure with the COVID-19 deaths. Early evidence indicates that lockdown severity[1] as well as weather factors such as temperature and humidity may reduce the likelihood of transmission of SARS-CoV-2 virus which causes COVID-19[26]. Even though UV radiation may help in reducing the likelihood of transmission by inactivating viruses in fomite transmission[27], emerging epidemiological evidence related to COVID-19 suggests a protective role of UVB and the plausible role of vitamin D in improving immunity and decreasing the likelihood of COVID-19 severity and mortality[4–8,28].

Although lockdowns might help in reducing the likelihood of transmission of SARS-CoV-2 virus[1], they potentially reduce the likelihood of UVB radiation exposure, increasing the likelihood of vitamin D deficiency as indicated in Figure 1[8]. Furthermore, emerging studies on COVID-19 indicate the association of vitamin D deficiency with COVID-19 severity and mortality [4–8]. In light of this emerging evidence, we anticipate that the severity of lockdown and UVB radiation are independently associated with a reduction in the number of COVID-19 deaths. Nevertheless, we anticipate that the increased lockdown severity will be associated with a significant reduction in the protective role of UVI in mitigating COVID-19 deaths due to a reduced likelihood of UVB radiation exposure.

Figure 1: Explanation of the Association of Severity of Lockdown & UVB Radiation with COVID-19 Deaths



Note: We extended the theoretical framework of the protective role of UVB radiation in reducing COVID-19 deaths from our former paper[8]

3 Data and Methods

3.1 Description of Data

In order to empirically estimate the independent protective roles of lockdown, UVB and the mitigating influence of lockdown severity on the protective role of UVB in reducing COVID-19 deaths, we constructed the dataset outlined in Table 1. We collected data covering 108 days from 22 January 2020 until 8 May 2020 across 162 countries of which 142 reported COVID-19 deaths before 8 May 2020 and of which 136 reported more than 20 COVID-19 infections before 8 May 2020. We focus on these 136 countries to ensure that the results are not biased by countries that are at a very early stage of COVID-19 outbreak, which would limit data points concerning COVID-19 deaths. Additionally, we drop the first 20 daily observations of every country after that country reported the first COVID-19 infection to further ensure that the observations do not bias results at the very early stage of the COVID-19 outbreak.

The corresponding country-level data consist of the cumulative daily COVID-19 deaths and infections, the daily ultraviolet index (UVI) (closely associated with UVB), and a set of control variables such as daily weather parameters such as precipitation index, cloud index, ozone level, visibility level, humidity level, as well as minimum and maximum temperature. The country-level data also consists of the severity of lockdown enforced by the country's government. We use the interaction of the lockdown severity with UVI to examine whether higher lockdown severity is associated with a reduction in the protective role of UVI in mitigating COVID-19 deaths.

Table 1: Summary of Dataset

Number of countries in the world	195
Number of countries in our dataset	162
… > 0 cumulated COVID-19 deaths before 8 May 2020	142
… > 20 cumulated COVID-19 infections before 8 May 2020	136
Covered time-period	22 January 2020 - 8 May 2020 (108 days)
Granularity of data	Daily
COVID-19 data source	https://github.com/ CSSEGISandData/COVID-19
Weather data source	https://darksky.net/
Lockdown severity data source	https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker

We present descriptive statistics of the dataset in Table 2. As of 8th of May, the cumulative COVID-19 deaths of these 136 countries were on average 2,020 and the growth rate of COVID-19 deaths on May 8 was on average 2.7% as compared to the average growth rate of COVID-19 deaths across countries and time which was 10.3%. We use cumulative COVID-19 deaths as the main dependent variable to test our hypothesis that lockdowns mitigate the protective role of UVB radiation. Based on the severity of governmental advice and restrictions, there are 4 different severity levels which could decrease skin exposure to UVB radiation ranging from no measure to requiring the population not to leave the house with minimum exceptions. On 8th of May, 15 countries had not implemented a lockdown, 35 countries recommended not to leave the house, 69 required people not to leave the house except for daily exercises, grocery shopping and essential trips, and 17 countries implemented a severe lockdown and required their people not to leave the house with minimal exceptions. UVI is on average 6.84 representing a moderate to high risk of harm from unprotected sun exposure.

Table 2: Descriptive Statistics

Variable	**Number of Countries**	**Number of Observations**	**Mean**	**Std. Dev.**	**Min**	**Max**
Cumulated COVID-19 Deaths on 8 May	136	136	2,020	8,201	1	77,180
Growth Rate of Cumulative COVID-19 Deaths on 8 May	136	136	0.027	0.050	0.000	0.400
Daily Growth Rate of Cumulative COVID-19 Deaths	136	6,050	0.103	0.256	-1	9
Time-passed by from First Reported Infection until 8 May	136	136	69.46	17.79	29	108
Daily Ultraviolet Index (UVI)	136	6,590	6.84	3.05	1	14
Daily Precipitation Index	136	6,590	0.290	0.314	0	1
Daily Cloud Index	136	6,590	0.504	0.303	0	1
Daily Ozone Level	136	6,590	308	47	236	473
Daily Visibility Level	136	6,590	15.32	2.12	0.12	16.09
Daily Humidity Level	136	6,590	0.618	0.207	0.04	1
Minimum Temperature per Day Within a Country	136	6,590	12.43	9.58	-23.45	30.87
Maximum Temperature per Day Within a Country	136	6,590	23.14	10.40	-16.41	45.82

Lockdown Severity	0	1	2	3

Description of Lockdown Severity	No measures	Recommend to not leave house	Require not to leave house with exceptions only for daily exercises, grocery shopping and 'essential' trips	Require not to leave house with minimal exceptions (e.g. allowed to leave only once every few days, or only one person can leave)
Number of Countries with Lockdown Severity at the End of Observational Period	15	35	69	17

3.2 Summary of Method

We apply a log-linear fixed-effects model to estimate the mitigating influence of lockdown severity on the association between UVI and growth-rates of COVID-19 deaths. We describe the model and the structural equation which we estimate in the supplementary material building upon Moozhipurath et al. (2020)[8] as well as Hsiang et al. (2020)[2].

In order to assess the respective protective roles of lockdown and UVI in mitigating the growth-rates of COVID-19 deaths and subsequently determine whether and which lockdown severity mitigates the protective role of UVI, we estimate three versions of the log-linear fixed-effects model. Model 1 outlines whether a unit increase in the lockdown severity mitigates the association between UVI and the growth-rates of COVID-19. Model 2 and model 3 outline whether a more severe lockdown measure (e.g., level 2 or level 3) mitigates this association more strongly as compared to a less severe lockdown (level 1).

4 Results

We estimate the protective role of lockdown severity, UVI and the mitigating influence of lockdown on UVI's protective role by using the log-linear fixed-effects model. We isolate the mitigating influence of lockdown severity from time-constant country-specific factors (see Figure 1). Further, we use the partialling-out property to isolate the mitigating influence of lockdown severity from all linear as well as some non-linear effects of time-varying factors such as weather and time, which may confound the results.

After controlling for time-constant and time-varying factors, we find that a unit increase in UVI and lockdown severity are independently associated with 1.8 percentage points (p.p) and 7.9 p.p decline in COVID-19 deaths growth rate, indicating their respective protective roles. These declines represent significant percentage reductions in the average growth-rates of COVID-19 deaths of -17% (=-0.018 / 0.103) and -77% (=-0.079/0.103).
However, we find a significant mitigating influence of lockdown severity on the protective role of UVI in reducing the growth-rates of COVID-19 deaths. A unit increase of the lockdown severity weakens the association of UVI in reducing the growth-rates of COVID-19 deaths by -33% (=0.006/-0.018). This decrease represents the average mitigation of a unit increase of the lockdown severity from 0 to 1, 1 to 2, and 2 to 3.

Surprisingly, Model 2 and Model 3 outline that the mitigation effect is mostly associated with lockdown severity of level 1 rather than level 2 or level 3 (stricter lockdowns) as the interaction of lockdown severity of level 2 or 3 with UVI is insignificant. Besides, the lockdown severity of level 1 mitigates the association of UVI and growth-rates of COVID-19 deaths by -95%, (0.018 / -0.019) and practically completely mitigating the association. Finally, all models 1 – 3 outline the significant negative association of both, lockdown severity as well as UVI, with growth-rates of COVID-19 deaths, indicating their protective roles.

We compare two scenarios to illustrate the mitigated protective role of UVI on the cumulative COVID-19 deaths. In scenario 1 UVI's protective role is not mitigated by lockdown whereas in scenario 2 UVI's protective role is fully mitigated. In order to relate the mitigated protective role with COVID-19 deaths we take the average number of COVID-19 deaths at the end of the observational period, i.e., 2,020, as cumulative COVID-19 deaths at day 0 as shown in Figure 2. In the full mitigation scenario (Scenario 2), we use the growth-rate of COVID-19 deaths in our sample, i.e., 10.3%. In Scenario 1, where UVI's role is not mitigated, we use an average growth rate of 8.5% (i.e., 10.3 p.p - 1.8 p.p). Figure 2 outlines that this mitigating influence of lockdown on the protective role of UVI translates into 1,640 or 21% fewer COVID-19 deaths after 14 days.

Figure 2: Comparison of "No Mitigation of UVI's Protective Role by Lockdown" vs. "Full Mitigation of UVI's Protective role by Lockdown" on Average Cumulative COVID-19 Deaths Across Countries

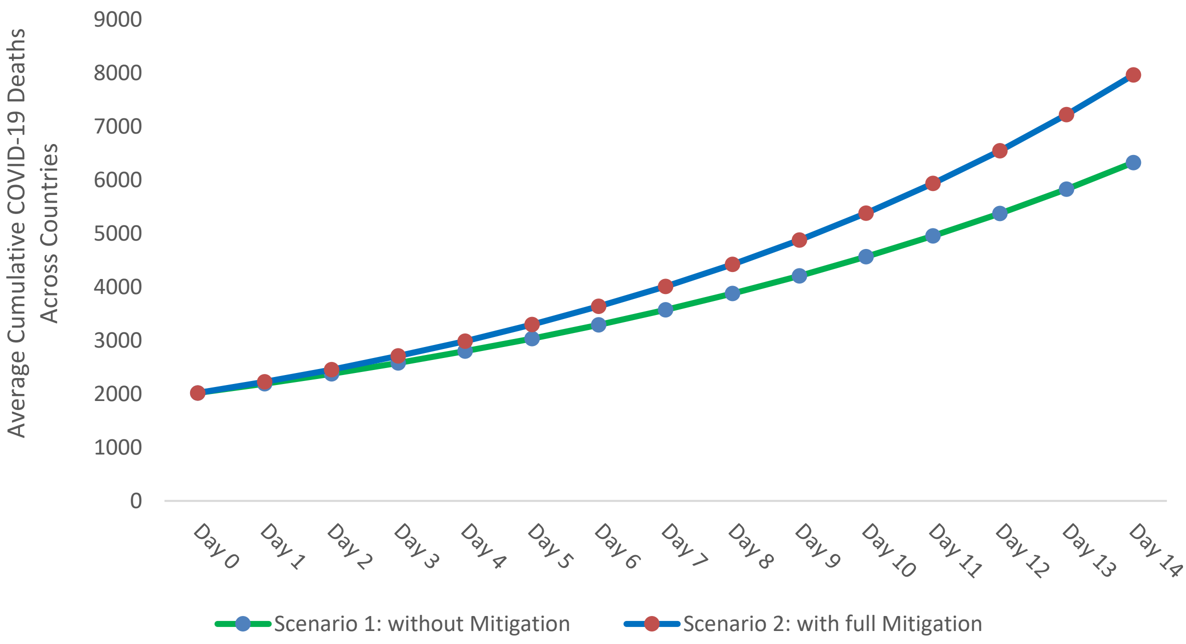


Table 3: Results of Log-Linear Fixed-Effects Model

	Model 1	Model 2	Model 3
Dependent Variables	COVID-19 Deaths	COVID-19 Deaths	COVID-19 Deaths
UVI	-0.018*** (12.60)	-0.019*** (11.47)	-0.019*** (10.75)
LD	-0.079*** (18.71)		
LD x UVI	0.006** (8.51)		
LD severity 1		-0.167** (9.74)	
LD severity 1 x UVI		0.018** (7.32)	
LD severity 2 or 3		0.003 (0.01)	
LD severity 2 or 3 x UVI		-0.006 (1.20)	
LD severity 1 or 2			-0.172*** (11.88)
LD severity 1 or 2 x UVI			0.015* (5.87)
LD severity 3			0.020 (0.27)
LD severity 3 x UVI			-0.003 (0.50)
Control Variables			
Time Trend	Linear	Linear	Linear
Country Fixed Effects	Yes	Yes	Yes
Precipitation index	Yes	Yes	Yes
Cloud index	Yes	Yes	Yes
Ozone level	Yes	Yes	Yes
Visibility Level	Yes	Yes	Yes
Humidity level	Yes	Yes	Yes
Temperature (min and max)	Yes	Yes	Yes
Number of Estimates	61 (+ 136 FE)	73 (+ 136 FE)	73 (+ 136 FE)
Number of Observations	6,049	6,049	6,049
Number of Countries	136	136	136
R-squared Within	16.86%	17.20%	17.07%

Note: +: p < 0.10, *: p < 0.05, **: p < 0.01. F-statistic for long-run coefficients in parentheses.

5 Discussion

Our empirical results indicate that although large-scale lockdowns are associated with a slowdown in the daily growth rates of COVID-19 deaths, such measures also significantly reduce the protective role of UVB in COVID-19 deaths.

We find that a unit increase in UVI and lockdown severity are independently associated with a decline in COVID-19 deaths growth rate, indicating their respective protective roles. However, the lowest lockdown severity (recommendation not to leave the house) already practically completely mitigates the protective role of UVI in reducing the growth rate of COVID-19 deaths via a reduction of 1.8 percentage points or -95% [$p < 0.01$]. Our results are consistent across different model specifications.

Our results suggest that lockdowns in conjunction with adequate exposure to UVB radiation might have provided even more substantial health benefits, than lockdowns alone. For example, we estimate that there would be 21% fewer deaths on average with sufficient UVB exposure while people were recommended not to leave their house.

While we acknowledge there may be other confounding factors posing challenges to our analysis, we used advanced statistical methods to account for such factors as much as possible. Even though we anticipate that reduced likelihood of skin synthesis due to lockdown plausibly explain these association, we may not be able to rule out the possibility of other UVB induced mediators – such as nitric oxide [10,29].

We follow a macro-level statistical backwards-looking approach which captures the real-life behaviour without making any specific assumptions regarding any epidemiological parameters[2]. Although this macro-level approach is a key strength of the study, the results cannot be interpreted as health guidance, which often comes from clinical studies[2]. Therefore, further clinical studies are needed to establish a causal relationship between UVB induced vitamin D and COVID-19 deaths.

Nations are implementing strict lockdowns to slow down COVID-19 growth. Even though the studies suggest the need for continued interventions[1,2], in addition to substantial economic and social costs, an unintended consequence of such large-scale interventions is the limited UVB exposure, plausibly increasing the risk of COVID-19 deaths. We require further studies to investigate if COVID-19 deaths can be mitigated by proper social distancing along with sensible exposure to sunlight or via vitamin D intervention. This type of intervention will be desirable from a policy maker's perspective because of its lower social and economic costs.

Further, nations may consider creating awareness among the population regarding the importance of sensible sunlight exposure while implementing lockdowns. Specifically, nations can look at assisting the vulnerable population who are at a higher risk of vitamin D deficiency – e.g., darker-skinned people living in high latitudes, people with limited mobility or indoor lifestyle (nursing home residents) and vegetarians[8]. We hope that the findings of this study can support policy decision making related to COVID-19 in countries which are currently implementing lockdowns or are considering them.

6 Declaration of Interests

RKM is a PhD researcher at Goethe University, Frankfurt. He also is an employee of a multinational chemical company involved in vitamin D business and holds the shares of the company. This study is intended to contribute to the ongoing COVID-19 crisis and is not sponsored by his company. All other authors declare no competing interests. The views expressed in the paper are those of the authors and do not represent that of any organization. No other relationships or activities that could appear to have influenced the submitted work.

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8 Author Contributions

RKM conceptualized the research idea, conducted literature research and designed theoretical framework. RKM and LK collected the data. LK designed empirical methods and analyzed the data. RKM and LK interpreted the results and wrote the article. RKM and LK reviewed and revised the article.

9 Role of the Funding Source

This study is not sponsored by any organization. The corresponding author had full access to all the data and had final responsibility for the submission decision.

10 Additional Information

Correspondence and requests for materials should be addressed to Rahul Kalippurayil Moozhipurath (rahulkm85@gmail.com).

11 Data Sharing

The data used in the study are from publicly available sources. Data regarding COVID-19 are obtained on 9th May 2020 from *COVID-19 Data Repository* by the *Center for Systems Science* *and Engineering (CSSE)* at *Johns Hopkins University* and can be accessed at https://github.com/CSSEGISandData/COVID-19. Data regarding weather is obtained from *Dark Sky* on the 9th May 2020 and can be accessed at https://darksky.net/. Data regarding lockdown severity is obtained from https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker . We will make specific dataset used in this study available for any future research. Interested researchers can contact one of the authors via email to get access to the data.

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13 Supplementary Material

13.1 Description of Methodology

We apply a fixed-effect log-linear regression model to estimate the effect of UVI on the number of COVID-19 deaths that builds upon Figure 1. The model is closely related to Moozhipurath et al. (2020)[8] as well as Hsiang et al. (2020)[2]. The major difference to Moozhipurath et al. (2020)[8] is the introduction of two additional sets of variables. Those additional sets consist of (i) variables representing the lockdown severity and (ii) variables representing the interaction of the lockdown severity and UVI. Thus, we use the following model to explain the number of COVID-19 deaths:

$$D_{i,t} = D_{i,t-1} \times e^{\gamma + \sum_{j=0}^{5}[UVI_{i,t-j}\beta_{UVI,j} + LD_{i,t-j}\beta_{LD,j} + UVI \cdot LD_{i,t-j}\beta_{UVI \cdot LD,j} + C_{i,t-j}\beta_{C,j}] + FI_{i,t}\beta_{FI} + u_i + \epsilon_{i,t}} \quad (1)$$

$D_{i,t}$ represents the cumulative COVID-19 deaths for country i at time point t (in days) and it is related to the explanatory factors via an exponential growth model on the right-hand side of the equation (1). The exponential growth model flexibly allows for different shapes of the cumulative COVID-19 deaths.

The exponential growth model consists of eight explanatory parts.

1) γ represents the daily growth rate of COVID-19 deaths from $D_{i,t-1}$ to $D_{i,t}$ that is independent of the factors presented in Figure 1. γ covers virus-specific attributes like its basic reproductive rate R_0 combined with its lethality.
2) $UVI_{i,t-j}$ represents the UVI for a country i at day t lagged by j weeks. $\beta_{UVI,j}$ reflects the effect of UVI lagged by j weeks.
3) $LD_{i,t-j}$ represents the lockdown severity LD for a country i at day t lagged by j weeks. $\beta_{LD,j}$ reflects the effect of LD lagged by j weeks. LD can either consist of one variable lagged by j weeks as in Model 1 or it can consist of 2 dummy variables as in model 2 or 3. The first dummy variable of model 2 is equal to one if the lockdown severity is at least equal to 1 whereas the second dummy variable of model 2 is equal

to one if the lockdown severity is at least equal to two. The first dummy variable of model 3 is equal to one if the lockdown severity is at least equal to 1 whereas the second dummy variable of model 3 is equal to one if the lockdown severity is at least equal to three. Similarly, $\beta_{LD,j}$ can measure the effect of unit increase in the lockdown severity as in model 1. $\beta_{LD,j}$ can also measure the effect of a specific lockdown severity as in model 2 and model 3.

4) $UVI \cdot LD_{i,t-j}$ represents the interaction of $UVI_{i,t-j}$ and the lockdown severity $LD_{i,t-j}$ for a country i at day t lagged by j weeks. $\beta_{UVI \cdot LD,j}$ reflects the effect of this interaction lagged by j weeks. We either interact UVI with variable LD for model 1 and we interact UVI with the dummy variable for model 2 and model 3. Therefore, $\beta_{UVI \cdot LD,j}$ reflects the effect of a unit increase of UVI lagged by j weeks if the lockdown severity increases by one unit as for model 1. $\beta_{UVI \cdot LD,j}$ also reflects the effect of a unit increase of UVI for model 2 and 3 if the lockdown severity is 1 as compared to when the lockdown severity is 0 as well as if the lockdown severity is 2 or 3 as compared to when the lockdown severity is 1.

5) $C_{i,t-j}$ stands for the set of control variables. This set consists of precipitation index, cloud index, ozone level, visibility level, humidity level, as well as minimum and maximum temperature for a country i at day t lagged by j weeks. The vector $\beta_{C,j}$ identifies the effect of these control variables lagged by j weeks.

6) $FI_{i,t}$ stands for the time passed by since the first reported COVID-19 infection for a country i at day t and β_{FI} identifies the associated effect.

7) u_i represents time-constant country-specific factors influencing the growth rate of cumulative COVID-19 deaths (e.g., diet related effects, population parameters about their activities and demographic composition).

8) $\epsilon_{i,t}$ consists of all the remaining factors that are not identified but also have an effect on the cumulative COVID-19 deaths (i.e., all non-linear differences of growth rates with respect to time and country-specific linear differences of growth rates with respect to time. They could be caused by a decreasing number of people who could potentially become infected or contagious, lockdowns in a country over time, mutation of the virus in a country over time, systematic false-reports of the dependent variable).

An appropriate transformation outlined in (Moozhipurath et. al 2020) results in the estimable equation

$$\Delta \ln(\ddot{D}_{i,t}) = \sum_{j=0}^{5}[\ddot{UVI}_{i,t-j}\beta_{UVI,j} + \ddot{LD}_{i,t-j}\beta_{LD,j} + \ddot{UVI \cdot LD}_{i,t-j}\beta_{UVI \cdot LD,j} + \ddot{C}_{i,t-j}\beta_{C,j}] + \ddot{FI}_{i,t}\beta_{FI} + \ddot{\epsilon}_{i,t} \quad (2)$$

γ and u_i do not appear in the equation anymore and a linear regression can identify all other coefficients. The summation of the coefficients β for each variable measures the long-term effect of a permanent unit change of the respective variable and outlines by how many percentage points the growth-rate of COVID-19 deaths changes. If $\sum_{j=0}^{5}\beta_{UVI,j} = -0.018$, then a permanent unit increase of UVI is associates with a 1.8 percentage points decline in the growth rates of COVID-19 deaths.

Equation (2) also shows why we can only use those observations where cumulative COVID-19 deaths are larger than zero. This condition explains the difference between the 6,590 observations of 136 countries in Table 2 and the 6,049 observations of 136 countries in Table 3. We listed the number of observations per country we used in the analysis in Table S3.

13.2 Model Selection

We estimated different versions of model which varied in the number of weekly lags. We decided to choose a model with 5 weekly lags because we could not find major differences with respect to the estimated coefficients when increasing the number of lags and a more parsimonious is favorable.

13.3 Robustness Checks

In order to assess the robustness of our results of the primary model - Model 1 - we isolate the mitigating influence of lockdown severity on the association of UVI and growth-rates of COVID-19 deaths from time trends in flexible ways. Models 4 – 9 in Table S1 and Table S2 isolate our findings from linear, square and exponential time trends which may be similar across countries or even country-specific. Overall, we find consistent results across model specifications. A permanent unit increase of UVI and a permanent unit increase in lockdown severity are independently associated with a -1.2 – -1.8 and -7.6 – -12.0 percentage points reduction in growth-rates of COVID-19 deaths, respectively, according to different model specifications. Results also indicate that a permanent unit increase in lockdown severity weakens the association of UVI in reducing the growth-rates of COVID-19 deaths by 0.4 – 0.6 percentage points.

Table S1: Robustness Checks with Random-Effects Model

	Model 4	Model 5	Model 6
Dependent Variables	COVID-19 Deaths	COVID-19 Deaths	COVID-19 Deaths
UVI	-0.018*** (12.96)	-0.012* (5.35)	-0.014* (6.72)
LD	-0.076*** (16.36)	-0.107*** (29.19)	-0.120*** (21.05)
LD x UVI	0.006** (8.87)	0.004 (2.60)	0.005 (2.74)
Control Variables			
Time Trend	Linear and Square	Country-specific Linear	Country-specific Linear and Square
Country Fixed Effects	Yes	Yes	Yes
Precipitation index	Yes	Yes	Yes
Cloud index	Yes	Yes	Yes
Ozone level	Yes	Yes	Yes
Visibility Level	Yes	Yes	Yes
Humidity level	Yes	Yes	Yes
Temperature (min and max)	Yes	Yes	Yes
Number of Estimates	62 (+ 136 FE)	60 (+ 136 FE + 136 TCSE)	60 (+ 136 FE + 272 TCSE)
Number of Observations	6,049	6,049	6,049
Number of Countries	136	136	136
R-squared Within	16.90%	20.85%	24.68%

Note: +: $p < 0.10$, *: $p < 0.05$, **: $p < 0.01$. F-statistic for long-run coefficient in parentheses. TCSE stands for time country-specific effects.

Table S2: Robustness Checks with Random-Effects Model

	Model 7	**Model 8**	**Model 9**
Dependent Variables	COVID-19 Deaths	COVID-19 Deaths	COVID-19 Deaths
UVI	-0.018*** (12.64)	-0.017*** (11.90)	-0.014** (6.91)
LD	-0.078*** (18.45)	-0.080*** (18.12)	-0.121*** (21.20)
LD x UVI	0.006** (8.52)	0.006** (8.48)	0.005+ (2.83)
Control Variables			
Time Trend	Linear and Exponential	Linear and Country-specific Exponential	Country-specific Linear, Square and Exponential
Country Fixed Effects	Yes	Yes	Yes
Precipitation index	Yes	Yes	Yes
Cloud index	Yes	Yes	Yes
Ozone level	Yes	Yes	Yes
Visibility Level	Yes	Yes	Yes
Humidity level	Yes	Yes	Yes
Temperature (min and max)	Yes	Yes	Yes
Number of Estimates	62 (+ 136 FE)	61 (+ 136 FE + 136 TSCE)	60 (+ 136 FE + 408 TSCE)
Number of Observations	6,049	6,049	6,049
Number of Countries	136	136	136
R-squared Within	16.86%	17.16%	25.29%

Note: +: $p < 0.10$, *: $p < 0.05$, **: $p < 0.01$. F-statistic for long-run coefficient in parentheses. TCSE stands for time country-specific effects.

Table S3: Number of Observations (Obs,) of Countries Used in Analysis

Country	Obs.	Country	Obs.	Country	Obs.	Country	Obs.
Afghanistan	47	Czechia	47	Kazakhstan	38	Russia	50
Albania	42	Denmark	53	Kenya	38	San Marino	53
Algeria	55	Djibouti	28	Korea, South	73	Saudi Arabia	45
Andorra	47	Dominican Republic	50	Kosovo	25	Senegal	37
Angola	31	Ecuador	50	Kuwait	34	Serbia	45
Argentina	48	Egypt	61	Kyrgyzstan	33	Sierra Leone	15
Australia	68	El Salvador	32	Latvia	32	Singapore	48
Austria	55	Estonia	44	Lebanon	59	Slovakia	37
Azerbaijan	50	Eswatini	22	Liberia	34	Slovenia	46
Bahrain	53	Ethiopia	33	Libya	27	Somalia	30
Bangladesh	43	Finland	48	Lithuania	48	South Africa	42
Barbados	33	France	73	Luxembourg	51	Spain	66
Belarus	38	Gabon	37	Malawi	18	Sri Lanka	41
Belgium	58	Georgia	34	Malaysia	52	Sudan	38
Benin	32	Germany	60	Mali	26	Sweden	58
Bolivia	40	Ghana	37	Mauritius	33	Switzerland	55
Bosnia and Herzegovina	46	Greece	54	Mexico	50	Syria	29
Botswana	21	Guatemala	37	Moldova	43	Taiwan*	73
Brazil	52	Guinea	23	Morocco	49	Tanzania	35
Brunei	41	Guyana	39	Netherlands	53	Thailand	68
Bulgaria	43	Haiti	31	New Zealand	40	Togo	42
Burkina Faso	41	Honduras	40	Niger	31	Trinidad and Tobago	37
Cameroon	44	Hungary	47	Nigeria	46	Tunisia	47
Canada	60	Iceland	50	Norway	54	Turkey	40
Chad	10	India	58	Oman	38	US	69
Chile	47	Indonesia	49	Pakistan	50	Ukraine	48
China	73	Iran	61	Panama	41	United Arab Emirates	49
Colombia	45	Iraq	56	Paraguay	43	United Kingdom	63
Congo (Kinshasa)	40	Ireland	51	Peru	45	Uruguay	37
Costa Rica	45	Israel	48	Philippines	73	Uzbekistan	36
Cote d'Ivoire	40	Italy	73	Poland	47	Venezuela	37
Croatia	50	Jamaica	40	Portugal	49	Yemen	8
Cuba	39	Japan	73	Qatar	41	Zambia	33
Cyprus	42	Jordan	42	Romania	47	Zimbabwe	31
Total Number of Observations				6,049			