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Air pollution: a more serious health problem than COVID-19 in 2020

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As a global pandemic, Coronavirus disease 2019 (COVID-19) poses a serious threat to people's health. However, by comparing the deaths caused by COVID-19 and deaths from air pollution in 183 countries, our results show that air pollution was even more of a serious health problem than COVID-19 in 2020. The relative roles of air pollution and COVID-19-attributable deaths across countries were affected by $PM_{2.5}$ exposure, population age structure, societal development and government policies. The countries with less strict policies during the early stages of COVID-19, to ensure stable economic development, paid more to control COVID-19 deaths in the subsequent stages, and hence showed large GDP reduction percentages in 2020. Our results indicate that the COVID-19 is a serious killer but also that the mortality caused by air pollution is high, which underline the concurrent need to control the dispersion of COVID-19 and improvement of air quality.

Introduction

The coronavirus disease 2019 (COVID-19), caused by severe newly discovered acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has changed the lives of everyone in the world. Declared as a worldwide pandemic on 11 March 2020 by the World Health Organization (WHO), COVID-19 spread quickly across the globe. By 8 April 2021, WHO reported more than 132.7 million confirmed cases infected with COVID-19, and with more than 2.8 million deaths from the disease (https://covid19.who.int/). Clinical characteristics of COVID-19 are highly variable, ranging from none to life-threatening illness, while the most common radiological findings are a ground-glass opacity in the lungs (Lotfi *et al.* 2020, Krishnan *et al.* 2021). Although the transmission mechanisms of COVID-19 from person to person remained uncertain, SARS-CoV-2 is believed to be transmitted through both direct and indirect contact (Borak 2020, Lotfi *et al.* 2020, Morawska and Cao 2020, Kutter *et al.* 2021). Thus, new infections could occur when the person is exposed to virus-containing aero-

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sol particles, which are exhaled by an infected person through coughing, sneezing, or even talking or breathing (Lotfi *et al.* 2020). To control the spread of COVID-19, countries implemented strict social distancing policies, e.g. school closures, workplace closures, cancellation of public events, restrictions on public gatherings and so on, proved to be successful in reducing the transmission of COVID-19 (Nouvellet *et al.* 2021). Without the successful control mechanisms, the death toll due to the pandemic would have been catastrophic.

At the same time, air pollution-attributable deaths, which are mainly caused by exposure to aerosol particles, did not raise an alarm (Das and Horton 2018, Landrigan *et al.* 2018). Air pollution is a global problem, and around 90% of people breathe air that exceeds WHO guideline limits (https://www.who.int/health-topics/air-pollution#tab=tab_1). Air pollution is linked to a wide range of diseases, such as respiratory, cardiovascular and pulmonary disease. In 2015 alone, 19% of cardiovascular deaths, 24% of ischemic heart disease deaths, 21% of stroke deaths, and 23% of lung cancer deaths were attributed to air pollution (GBD 2015 Mortality and Causes of Death Collaborators 2016). Killing around 7 million people worldwide each year — divided between the outdoor and indoor pollution, air pollution is one of the largest health and environmental problems (https://www.who.int/health-topics/air-pollution#tab=tab_1). In addition to the harmful effects on human health, air pollution causes economic costs including direct medical expenditures, indirect health related expenditures, diminished economic productivity, and losses in output resulting from premature death (Hunt *et al.* 2016, Dechezleprêtre *et al.* 2019). However, these economic costs are largely invisible and are often not recognized to be caused by pollution (Landrigan and Fuller 2015, Hunt *et al.* 2016). Unfortunately, there are views that pollution and disease are the unavoidable consequences of economic development, which contribute to the neglect of air pollution impacts (Landrigan *et al.* 2018).

Recent studies bring air pollution into the public eye by pointing out that SARS-CoV-2 was present on outdoor particulate matter and that the increase of air pollution supports the spread of COVID-19 (Copat *et al.* 2020, Fattorini and Regoli 2020, Setti *et al.* 2020, Wu *et al.* 2020, Zhu *et al.* 2020, Travaglio *et al.* 2021). These studies highlighted the important contribution of air pollution in triggering the COVID-19 spread and increasing its lethality (Copat *et al.* 2020). However, up-to-date knowledge of the relationship between air pollution and COVID-19 is still limited. Most of the earlier studies focused on certain countries or regions, and therefore the connections between air pollution and COVID-19 at the global scale is still lacking. In this study, we utilize global open data sets with the aim to provide a direct comparison between the deaths caused by air pollution and COVID-19 on the global scale. Then we explore the governing and potentially confounding factors affecting the interconnected global distribution of air pollution and COVID-19-attributable deaths in order to raise global awareness of air pollution.

Methods

To investigate the relationship between air pollution and COVID-19 mortality and the possible confounding factors at the global scale, a comprehensive data set was compiled from a suite of public sources, including global data sets on aerosol mass concentrations ($PM_{2.5}$) reported by WHO (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/concentrations-of-fine-particulate-matter-(pm2-5)); deaths and death rates associated with ambient and indoor air pollution in 2016 reported by WHO (https://www.who.int/data/gho/data/themes/theme-details/GHO/air-pollution) and from 2015 to 2019 reported by Health Effects Institute (2020); data on population, population density, hospital beds per 1000 capita, gross domestic product (GDP) per capita, human development index (HDI), government stringency index (OSI), as well as deaths and death rates associated with COVID-19 in 2020 from Our World in Data (https://ourworldindata.org/coronavirus); GDP from 2019 to 2020 (https://www.imf.org/external/datamapper/datasets/WEO); prevalence of tobacco use reported by WHO (https://www.who.int/data/gho/data/themes/theme-details/GHO/tobacco-control);

data on carbon dioxide emissions from 2019 to 2020 (Le Quéré *et al.* 2021). The data is summarized in the Supplementary Information Table S1 and the data details are illustrated in Supplementary Text S1. In short, death rates in this study are deaths per 100 000 capita per year. HDI is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and having a decent standard of living (http://hdr.undp.org/en/content/human-development-index-hdi). To address the relative roles of air pollution and COVID-19-associated deaths, we used the parameter *R*:

$$R = \frac{\text{Air pollution-attributable deaths}}{\text{Deaths due to COVID-19}} \quad (1)$$

In the calculations, we used values from 2016 as the estimated air pollution-attributable deaths. Here, the total deaths due to air pollution are the sum of ambient air pollution-attributable deaths and indoor air pollution-attributable deaths. Air pollution-attributable deaths overall remained at the same level from 2015 to 2019 (see Fig. S1a and Supplementary Text S2 in Supplementary Information). This justifies the use of values from 2016 in the analysis, although it may cause uncertainties in individual countries, which are mostly within 20% (see Supplementary Information Fig. S1b). It is also noted that the uncertainties can also be contributed by the underestimated of the reported COVID-19 deaths, which differ between countries due to the testing capacity, reporting policy, as well as problems in the attribution of the cause of death (Dyer 2021, Karlinsky and Kobak 2021).

OSI was calculated to track and compare policy responses to COVID-19, and a higher OSI score indicates a stricter response (i.e. 100 indicates the strictest response; Hale *et al.* 2021). It is noted that OSI simply records the strictness of government policies, while the effectiveness of the government policies can still be affected by other factors. For example, compared with nations with high levels of cultural tightness, nations with high levels of cultural looseness are estimated to have higher number of deaths (Gelfand *et al.* 2021).

To better investigate the influence of government policy on COVID-19 spread, we defined the OSI in different stages of the pandemic as follows: OSI_{d1} is the OSI when the given country has the first death due to COVID-19; OSI_{tc1} is the OSI when the number of people infected with COVID-19 reached 1 per million capita in the given country. With the same logic, OSI_{tc10} is the OSI when the number of people infected with COVID-19 reached 10 per million capita in the given country.

Based on the time difference of the government response to the elevated COVID-19 infections, we then define a parameter, *P*, to scale the government control measures to the speed of the spread of COVID-19 case load in the early stage of COVID-19:

$$P = OSI_{tc10} \times (Date_{tc10} - Date_{tc1}), \quad (2)$$

where $Date_{tc10}$ and $Date_{tc1}$ are the dates when the number of people infected with COVID-19 reached 10 and 1 per million capita in a given country, respectively. The smaller the differences between these two dates, the quicker the spread speed of COVID-19 was in the early stage in the given country. On one hand, the *P* value is low, when at the same time the government stringency index is low and the spread speed of COVID-19 in the early stage is high. On the other hand, high *P* values can be reached with high stringency and slow development of the case load.

Results and Discussion

Deaths due to COVID-19 and air pollution

In 2020, COVID-19 caused a loss of 1.8 million lives globally. The deaths from COVID-19 varied from 1 to 345 955 in 183 countries with the death rates varying from 0.02 to 168.50 per 100 000 persons. In general, more COVID-19 deaths occurred in the countries with higher death rates (see Supplementary Information Fig. S2). On one hand, based on these results, it is undoubted that the COVID-19 is a serious threat to human life and without the stringent

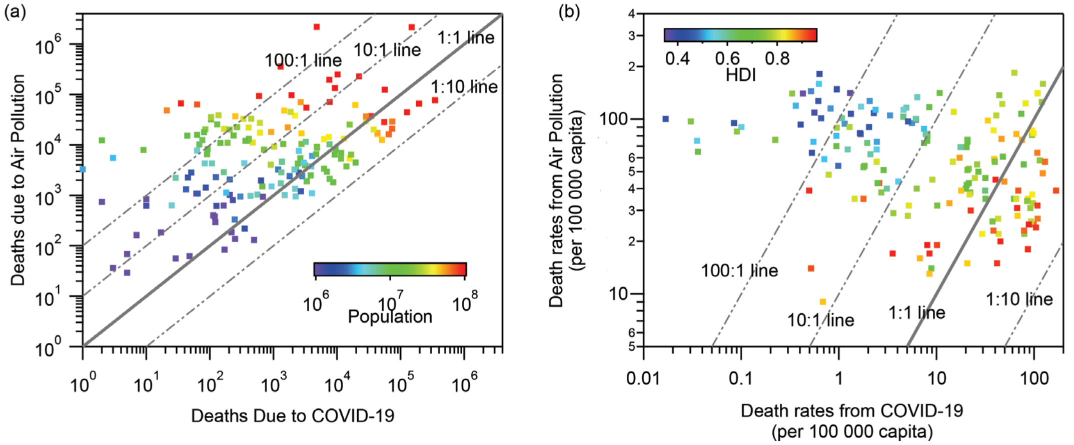

Fig. 1. Scatter plots of (**a**) deaths due to air pollution versus deaths due to COVID-19, coloured by population; and (**b**) death rates from air pollution versus death rates from COVID-19, coloured by human development index (HDI).

control mechanisms, the death rate would have been considerably higher. On the other hand, the loss of life due to air pollution was 6.6 million people in the world, which was 2.7 times higher than deaths caused by COVID-19.

We plotted the absolute values for the annual accumulated deaths due to air pollution as a function of deaths due to COVID-19 (Fig. 1). Generally, the number of deaths in a country scale as a function of population and therefore this reveals a correlation between the absolute deaths due to COVID-19 and air pollution. A general correlation was found, although the different countries with a certain population range span the full scale of amounts of death due to COVID-19 while the deaths due to air pollution remain constant. However, the picture changes when we plot the death rates and colour the markers of the countries as a function of their HDI. The death rates from COVID-19 and air pollution seem to show a weak negative correlation driven by socioeconomic differences, while a positive correlation is observed when we focus on these countries with the HDI higher than 0.8, suggesting the possible relationship between air pollution and COVID-19 lethality in these countries that have similar living standards (Fig. 1b). It is noted that in most of the countries, the deaths from air pollution are higher than deaths caused by COVID-19. Deaths due to air pollution were even 100 times higher in 24 countries, e.g. Togo, Chad, China, Mongolia.

As a metric for further comparison, we calculated *R* for each country (Fig. 2). Overall, there are greater than ten thousand-fold differences between countries with the value of *R*, which varied from 0.2 to 6180.0. The small values indicate dominance of COVID-19-associated deaths while the large values underline the role of air pollution as a more important cause of death in relative terms. More than 70% countries had *R* values higher than 1. The countries in North America and South America showed *R* values mostly lower than 1 (e.g., USA: 0.2, Brazil: 0.3). In Europe, there were considerable variability. Some countries had a low *R*, (e.g., Sweden: 0.2, UK: 0.3) while some others exhibited a medium *R* (e.g., Germany: 1.1, Finland: 1.8). With the value of 0.2, Sweden had the lowest *R* in the world, attributing to the high COVID-19 death rates associated with loose government policies (Claeson and Hanson 2021). The parameter OSI_{tc1}, which was found to negative correlate with the COVID-19 death rates in the next section, was 0 in Sweden, suggesting that the transmission of COVID-19 in the early stage might have been out of control. On the contrary, *R* was generally higher than 1 in African and Asian countries and was even higher than 100 in countries in central Africa and eastern Asia (e.g., Togo, China, Thailand, Burundi). These results indicated that air pollution caused more deaths than COVID-19 particularly across central Africa and eastern Asia in 2020.

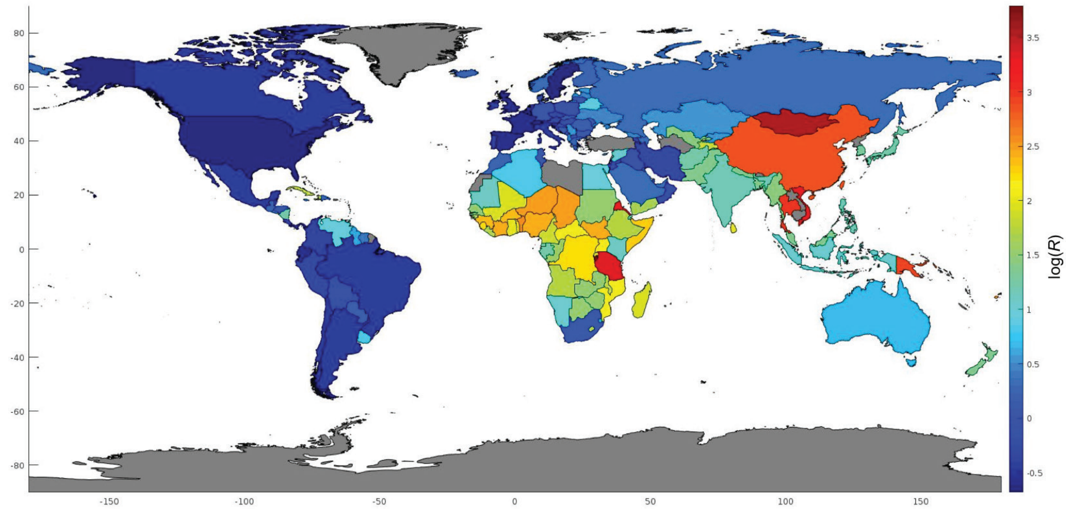

Fig. 2. Global map of the ratio between deaths due to air pollution and COVID-19 (*R*). The map is coloured by log(*R*). When there was no data, the area was coloured grey.

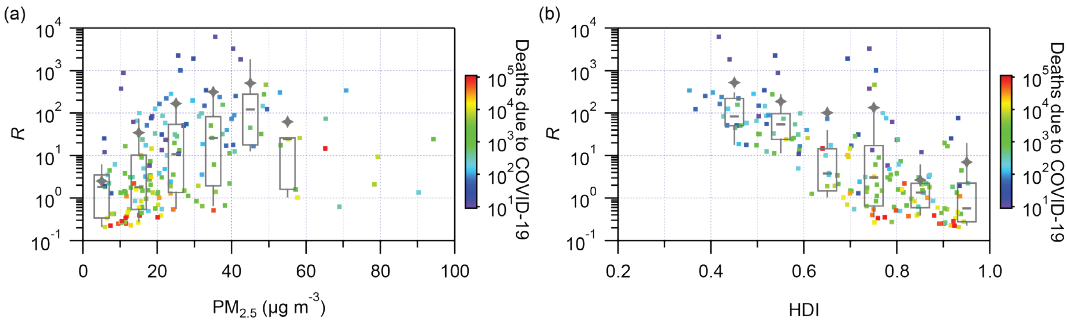

Fig. 3. Ratio between deaths due to air pollution and COVID-19 (*R*) versus (**a**) $PM_{2.5}$ and (**b**) human development index (HDI) coloured by deaths due to COVID-19.

Dependency of the deaths associated with air pollution and COVID-19

Further detailed analysis shows that the varying of the *R* parameter in different countries is associated with overall $PM_{2.5}$ exposure of the population and HDI (Fig. 3 and Figs. S3 and S4 in Supplementary Information). Other contributing factors were age structure of the population, and stringency of the government policies towards controlling the COVID-19 dispersion (see Supplementary Information Figs. S5 and S6, Supplementary Texts S3 and S4).

The parameter *R* in different countries were binned into six categories based on the annual $PM_{2.5}$ mass concentrations (Fig. 3a). The results show that with the increase of $PM_{2.5}$ exposure, the air pollution attributable death rate rose while the COVID-19 mortality decreased (see Supplementary Information Fig. S3). The decreasing of COVID-19 mortality is mainly caused by the fact that countries with lower $PM_{2.5}$ have an older population age and looser government policies, leading to higher risk from COVID-19 (see Supplementary Information Figs. S4 and S5). Indeed, the COVID-19 mortality showed an increasing trend with the $PM_{2.5}$ mass concentration for the countries with a low population median age. When the death rates from COVID-19 were lower than 20, the deaths due to COVID-19 were higher in countries that had a higher level of pollution. These results likely indicate that air pollution enhanced the COVID-19 lethality. On one hand, aerosol particles could act as a medium for COVID-19 transmission; and on the other hand, high pollution exposure could contribute to COVID-19 severity by compromising the lungs' immune response to the infection or by exacerbating underlying respiratory or cardiovascular diseases (Brandt *et al.* 2020, Greenhalgh *et al.* 2021). Thus, *R* increased with an increasing $PM_{2.5}$ exposure level until $PM_{2.5}$ reached 50 μg m^{-3} (Fig. 3a). Parameter *R* lower than unity was mostly observed in countries where the $PM_{2.5}$ concentration was lower than 20 μg m^{-3}. This is a consequence of the low death rates from air pollution and concurrent high death rates from COVID-19. The median value of *R* was larger than 100 in the $PM_{2.5}$ range, from 40–50 μg m^{-3}. This result suggests that the people exposed to high $PM_{2.5}$ levels have a much greater health risk from air pollution than from the COVID-19. When $PM_{2.5}$ was higher than 50 μg m^{-3}, *R* dropped slightly, but this can be a consequence of a small set of countries in this $PM_{2.5}$ exposure level. We then note that some of these countries, which include Iraq, Kuwait, Bahrain, Saudi Arabia, and Qatar, had a relatively low death rates from air pollution, although the $PM_{2.5}$ exposure was high. These countries have a significantly higher GDP per capita (> $10 000), suggesting that overall health, well-being, healthcare and high medical standards in these nations significantly reduce the risk of mortality from respiratory illness associated with air pollution (see Supplementary Information Fig. S7).

Our analysis shows that *R* decreased with an increasing HDI level (Fig. 3b). It was unexpected that the high deaths with particularly high death rates from COVID-19 were observed in some high HDI countries, where people typically have high living standards and high heath care standards (see Supplementary Information Fig. S4). Further analysis showed that higher COVID-19 mortality was associated with the elder age structure and looser government policies connected to the control of the COVID-19 dispersion (see Supplementary Texts S3 and S4; Fuller *et al.* 2021). In the high HDI countries, the population age structure had a relative higher contribution of elder people, and sometimes looser restrictions were implemented in the early stage of COVID-19 spread (see Supplementary Information Figs. S6 and S8). On the other hand, risk from air pollution decreased with the increase of HDI. In this case, median *R* decreased from 27.4 to 0.6 when HDI increased from 0.4 to 0.9. In general, when the HDI was lower than 0.6, almost all countries had *R* larger than 10. This is indicative of the fact that the people in the low HDI countries had a much greater health risk due to the air pollution than from COVID-19. In the middle HDI countries (0.6 < HDI < 0.8), *R* was mostly higher than unity. The *R* values lower than unity were mainly observed in the countries with both the high HDI and high COVID-19 death rates.

Besides, there was a considerable impact of the prevalence of current tobacco use in the *R* parameter as well (see Supplementary Information Fig. S9 and Supplementary Text S5). Tobacco use seems to increase the death rates due to both air pollution and COVID-19, while the value of *R* decreased with the increasing tobacco use.

Variability of the air pollution and COVID-19-associated deaths in classified data

We grouped different countries based on their *R* values into five categories (C) as follows: C-I, *R* <= 0.5; C-II, 0.5 < *R* <= 1; C-III, 1 < *R* <= 10; C-IV, 10 < *R* <= 100; C-V, *R* > 100 (Fig. 4 and Table S2 in Supplementary Information).

The category, C-V, which includes a total of 24 countries (e.g., Togo, Chad, China, Mongolia), showed low death rates due to COVID-19 (median: 0.4) and concurrent very high death rates due to air pollution (median: 174.0). These countries, in which the age structure favours the youngest population (median age: 18.7 years), implemented the strictest government policies in the early stage of COVID-19 (median OSI_{tc1}: 61.1), succeeded in controlling the epidemic (median COVID-19-associated death rate: 68). The highest death rates from air pollution in these countries are associated with the highest pollution exposure ($PM_{2.5}$ median: 33.1 μg m^{-3}) and the lowest living

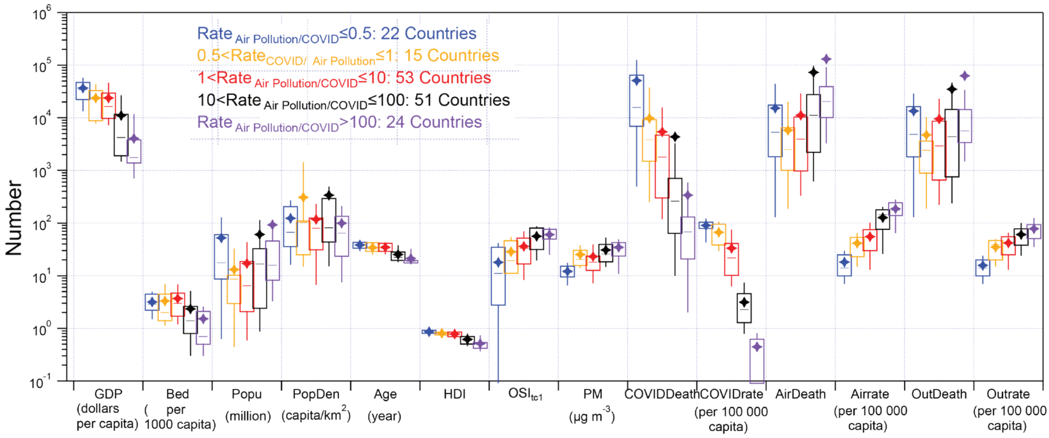

Fig. 4. The statistics of factors under five different categories according to the ratio between deaths from air pollution and COVID-19. GDP means Gross domestic product (GDP) per capita; Bed is the hospital beds per thousand capita; Popu is the total population of the country; PopDen is the population density of the country; Age is the median age of the country; HDI is the human development index of the country; OSItc1 is the government stringency index when the total COVID-19 case reached 1 per million capita in the given country; PM is the $PM_{2.5}$ exposure of the country; COVIDDeath is the total deaths due to COVID-19; COVIDrate is the deaths from COVID-19 per 100 000 capita; AirDeath is the total deaths associated with air pollution; Airrate is the deaths due to air pollution per 100 000 capita; OutDeath is the deaths due to ambient air pollution; Outrate is the deaths due to ambient air pollution per 100 000 capita.

standards (HDI median value: 0.5) including low income (GDP median: 1768.20 dollars per capita), low healthcare standards (0.7 hospital beds per thousand capita). China (*R* value: 456.8) and Thailand (*R* value: 1005.5), are the only two countries with HDI higher than 0.7 and median population age larger than 35.0 years, linked to the extremely low COVID-19 mortality (see Supplementary Information Table S2).

The next group (C-IV) consisted of 51 countries, e.g., India, New Zealand, Yemen, Cuba. The death rates caused by air pollution in C-IV countries were 17.2% lower than that in C-V, resulting from the lower $PM_{2.5}$ (median: 25.9 µg m^{-3}) exposure and better healthcare standards (median HDI: 0.6). The median death rates due to COVID-19 are 4.3 times higher in C-IV countries than C-V countries. Higher COVID-19 mortality in C-IV could be partly associated with the more aged population structure, larger population density and looser government policies (median OSI_{tc1}: 57.4; see Supplementary Information Fig. S4).

In the categories C-III and C-II, we had 53 (e.g., Germany, Qatar, Finland, Australia) and 15 countries (e.g. Iran, Austria, Bolivia, Hungary), respectively. In general, the countries in the C-III and C-II have similar pollution exposure levels (median $PM_{2.5}$: ~20 µg m^{-3}) and good living standards (median HDI: 0.8). These countries had comparable death rates due to the air pollution. The reason that the countries within C-II showed lower *R* is that these countries had higher COVID-19 death rates despite the countries in both categories having comparable living standards and similar age structures. The difference between these two categories seem to originate from the different government stringencies. The countries in C-II had looser government policies (median OSI_{tc1}: 19.4 in C-II and 33.3 in C-III) concurrently with slightly lower healthcare standards (2 in C-II and 3 in C-III hospital beds per thousand capita) and slightly larger population density (102.9 in C-II and 80.1 in C-III) plausibly influencing the rate of COVID-19 dispersion within the population.

For category C-I, we classified 22 countries (e.g., Sweden, USA, UK, Canada). C-I had high death rates from COVID-19 and concurrently very low death rates from air pollution, associated with the very low $PM_{2.5}$ concentration (median: 11.5 µg m^{-3}) and high HDI (median: 0.9). The high COVID-19 deaths could be linked, on one hand to the population age

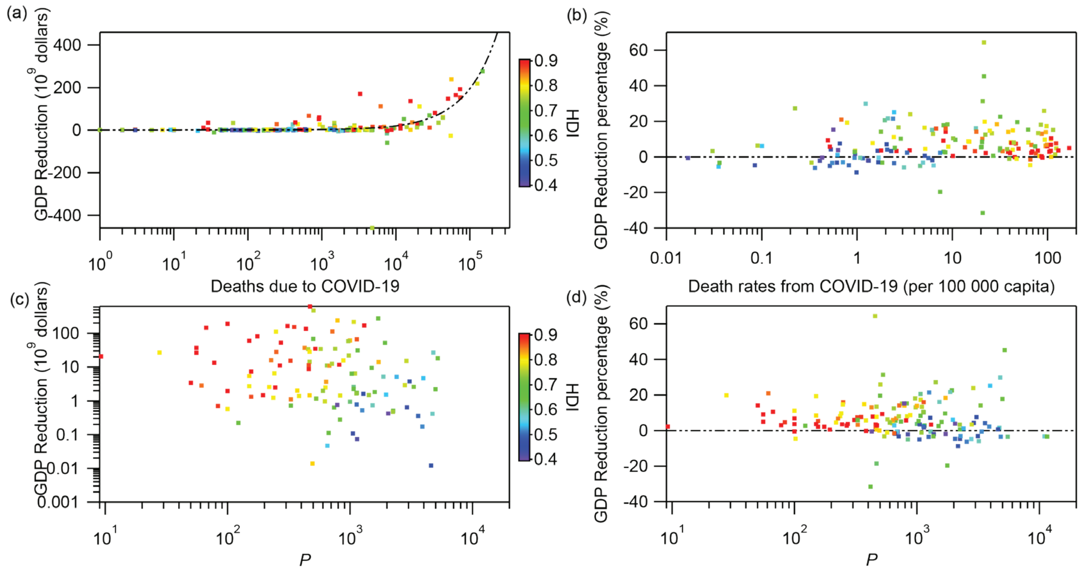

Fig. 5. The connection (**a**) between GDP reduction and deaths due to COVID-19 in 2020; (**b**) GDP reduction percentage and death rates from COVID-19 in 2020; (**c**) between GDP reduction and *P* value in 2020; (**d**) GDP reduction percentage and *P* value in 2020. These dots are coloured by human development index (HDI).

structure and on the other hand to the government policies. The median age of 39.7 years in category C-I was the highest. Meanwhile, these countries had the lowest stringency index (median OSI_{tc1}: 11.1) in the early stage of COVID-19 spread.

Time for a decisive action to tackle air pollution

Due to strong governmental control and regulation for limiting the dispersion of the COVID-19, only 37 countries had more deaths due to COVID-19 than due to air pollution. As a side effect, these restrictions had economic impacts that influenced the lifestyle of the population, at least during the most stringent governmental control periods. On a global scale, the CO_2 emissions from fossil fuel use and GDP decreased in 2020. A positive correlation between the COVID-19 death rates and annual CO_2 reduction percentage in 2020 (see Supplementary Information Fig. S10). The countries with the high COVID-19 death rates imposed stricter measures to control the outbreak of COVID-19 in the later stage of the pandemic (see Supplementary Information Fig. S11), leading to large CO_2 reduction percentage in 2020 compared to 2019. Consistently, these countries showed a larger GDP reduction in 2020 when the COVID-19 deaths were higher (Fig. 5). The absolute GDP reduction increased from few to hundreds billion dollars with the increasing of deaths from COVID-19 from 1000 to 100 000. While the influence on GDP is only a minor for the countries that had the deaths from COVID-19 below 1000. Indeed, the GDP reduction percentage compared to 2019 showed an increasing trend with the death rates from COVID-19. In general, when the death rates from COVID-19 were below 10 per 100 000 capita, GDP in 2020 increased in the countries with low HDI. While when the death rates from COVID-19 were higher than 10, the GDP in 2020 showed an obvious reduction percentage compared to 2019. We then connected the observed GDP reduction with the parameter *P*, which describes the time dependency of the governmental stringency index during the initial COVID-19 pandemic. The results show that the high absolute GDP reduction with high reduction percentage was observed under low *P* values (Fig. 5). These results are indicative of the fact that the countries, which had looser policies in the early stage of COVID-19 in order to ensure stable economic

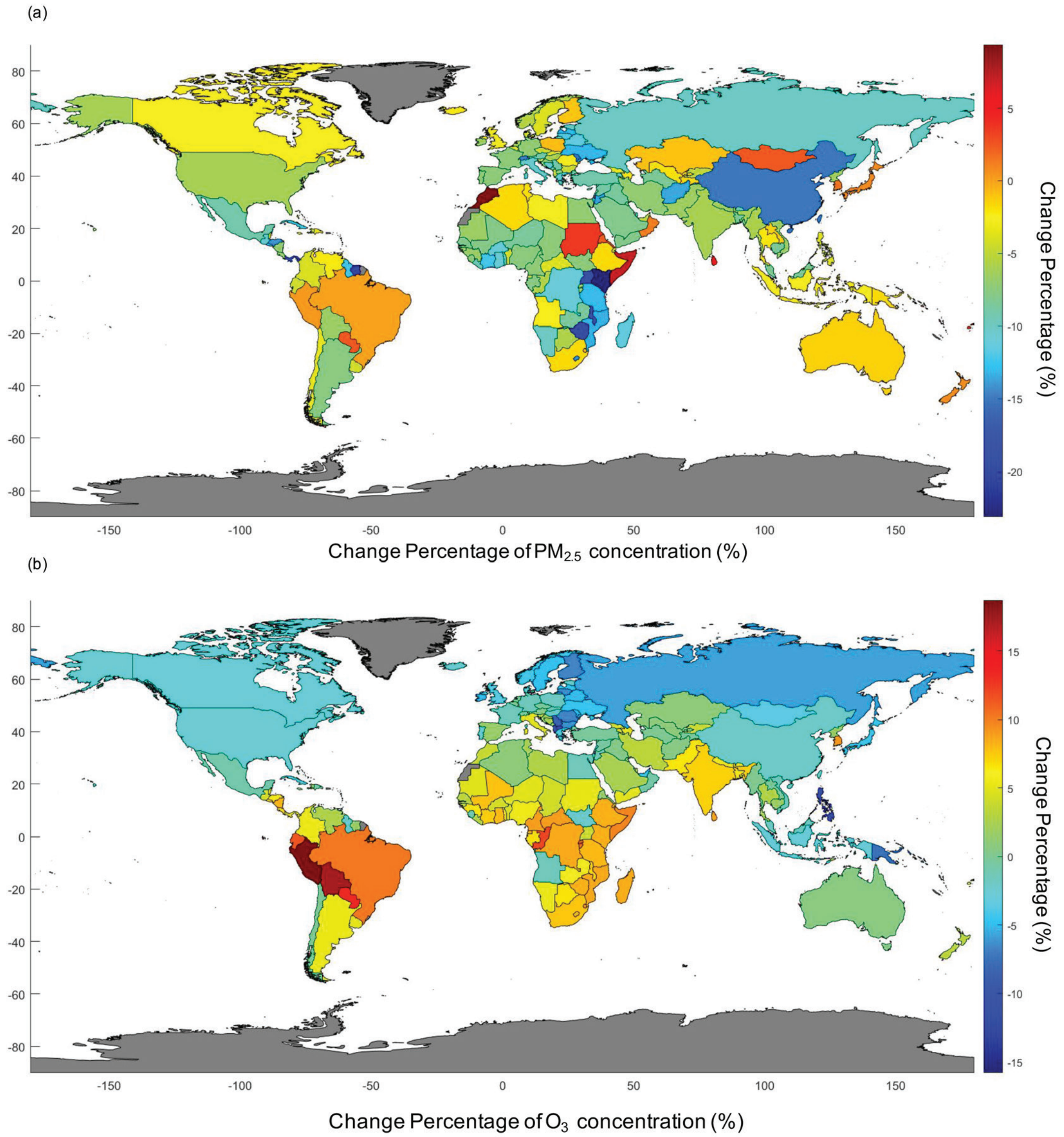

Fig. 6. Global map of (**a**) the change percentage of $PM_{2.5}$ concentration from 2015 to 2019; and (**b**) the change percentage of O_3 concentration from 2015 to 2019. When there was no data, the area was also coloured as grey.

development, seem to have paid more to control the COVID-19 deaths in the following stage, and hence showed large CO_2 and GDP reduction percentages in 2020.

It is crucial to control dispersion of COVID-19, but concurrently it is time for decisive actions towards improving the air pollution. In the last 5 years, the proportion of global population using solid fuels decreased from 51.1% in 2015 to 48.6% in 2019, which improved indoor air quality. Correspondingly, the absolute number of deaths and relative death rates connected to household air pollution reduced by 10.5% and 18.0%, respectively. However, the total deaths related to air pollution remained stable (around 6.6 million) during the last 5 years. This is associated with the increase of deaths due to ambient air pollution from 4.1 million in 2015 to 4.4 million in 2019 (see Supplementary Information Fig. S12). Thus, ambient air pollution-attributable deaths contributed to 62% of deaths from air pollution globally in 2019. In fact, the good news is that the average annual population-weighted $PM_{2.5}$ showed a slightly decreasing trend after 2015 (Fig. 6a and S12b in Supplementary Information). There are 40 countries that showed a $PM_{2.5}$ reduction higher than 10%, and only 20 countries had an increasing trend. Yet the global $PM_{2.5}$ median concentration of 42.6 µg m^{-3} in 2019 was still much higher than the WHO guideline annual pollution limit. Thus, the death rates attributable to ambient $PM_{2.5}$ showed a negligeable reduction (4.0%) from 2015 to 2019, which is surmounted by the increasing total population. In addition, concentration of secondary pollutants, such as ozone, increased continuously from 2015 to 2019 with the rate of 0.24 ppb/year, also contributing to the increasing of deaths attributable to ambient air pollution (Fig. 6b). The increasing trend of O_3 was more significant in South America and Africa, exceeding rates of 10% from 2015 to 2019.

By implementing decisive action, China was able to control COVID-19 dispersion in 2020. Concurrently, China has gained remarkable achievements in reducing air pollution during the last 5 years. From 2015 to 2019, ambient $PM_{2.5}$ reduced by 15%, and O_3 concentration also showed a decreasing trend in China (Fig. 6). At the same time, the GDP per capita increased by more than 26% from 2015 to 2019, and GDP per capita in 2020 also was ~200 dollars more than that in 2019. Such a success suggests that it is possible to achieve balance between economic development and environmental protection.

Conclusions

In this study, we explored the connections between air pollution and COVID-19-associated deaths and death rates at a global perspective. Based on a suite of comprehensive data on the air pollution exposure, economic data and data related to the spatiotemporal variability of deaths associated with COVID-19, we were able to conclude the following:

1) On the absolute scale, air pollution caused more loss of life during the pandemic in 2020 than the COVID-19, especially in Africa and Asia.
2) The ratio of deaths associated with air pollution and with COVID-19 in 2020 varied with $PM_{2.5}$ exposure and human development index (HDI). In general, air pollution was a more serious health problem than COVID-19 in low HDI countries, where people exposed to high $PM_{2.5}$ pollution. Air pollution enhanced the COVID-19 lethality while tobacco use was found to increase the death rates due to both air pollution and COVID-19.
3) Thanks to the imposed governmental regulations and policies as well as changes in the people's lifestyles, the dispersion of the COVID-19 was reduced and controlled effectively. Negative correlation was found between COVID-19 mortality and OSI in the early stage of COVID-19 in 2020. Our results further indicate that the countries, which have looser policies in the early stage of COVID-19 in order to ensure stable economic development, seem to pay more to control high COVID-19 deaths in the following stage, and hence show large CO_2 and GDP reduction percentage in 2020.
4) We categorized the countries based on the ratio of deaths associated with air pollution and with COVID-19 in 2020. Air pollution-attributable deaths were 100 times higher than COVID-19 deaths in 24 countries, e.g., Togo, Chad, China, Mongolia. Only 37 countries had more deaths from COVID-19 than air pollution, e.g., Sweden, USA, UK.
5) Air pollution is a long-term health problem, and the total deaths related to air pollution remained stable (around 6.6 million) in last 5 years. This is attributed to the increasing contribution of ambient air pollution. $PM_{2.5}$ concentration showed a decreasing trend in last 5 years, while it is still the dominant pollutant. O_3 concentration increased in recent 5 years. In South America and Africa, the increasing trend of O_3 was even higher than 10%.

Our analysis underlines the concurrent need to control the dispersion of COVID-19 and improvement of air quality. The earlier the action, the better. This is valid not only for COVID-19 but also air pollution.

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