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LETTER

Health impacts of smoke exposure in South America: increased risk for populations in the Amazonian Indigenous territories

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Abstract

Smoke particulate matter emitted by fires in the Amazon Basin poses a threat to human health. Past research on this threat has mainly focused on the health impacts on countries as a whole or has relied on hospital admission data to quantify the health response. Such analyses do not capture the impact on people living in Indigenous territories close to the fires and who often lack access to medical care and may not show up at hospitals. Here we quantify the premature mortality due to smoke exposure of people living in Indigenous territories across the Amazon Basin. We use the atmospheric chemistry transport model GEOS-Chem to simulate $PM_{2.5}$ from fires and other sources, and we apply a recently updated concentration dose-response function. We estimate that smoke from fires in South America accounted for ∼12 000 premature deaths each year from 2014–2019 across the continent, with about ∼230 of these deaths occurring in Indigenous lands. Put another way, smoke exposure accounts for 2 premature deaths per 100 000 people per year across South America, but 4 premature deaths per 100 000 people in the Indigenous territories. Bolivia and Brazil represent hotspots of smoke exposure and deaths in Indigenous territories in these countries are 9 and 12 per 100 000 people, respectively. Our analysis shows that smoke $PM_{2.5}$ from fires has a detrimental effect on human health across South America, with a disproportionate impact on people living in Indigenous territories.

1. Introduction

Air pollution from fires is detrimental to public health. Smoke particulate matter from biomass burning in the Amazon Basin can travel great distances, affecting air quality across several countries in South America (Bourgeois *et al* 2015, Bencherif *et al* 2020). Many studies examining the impact of smoke on public health have tended to focus on one season or have relied on hospital admission data (Butt *et al* 2020, 2021, de Souza *et al* 2020, Nawaz and Henze 2020, Ye *et al* 2021). These approaches may miss the impact of smoke on populations without access to hospitals and neglect the changes in premature mortality due to long-term smoke exposure. Here we use the chemical transport model GEOS-Chem and an updated concentration response function (CRF) to calculate the excess mortality due to exposure to smoke fine particulate matter

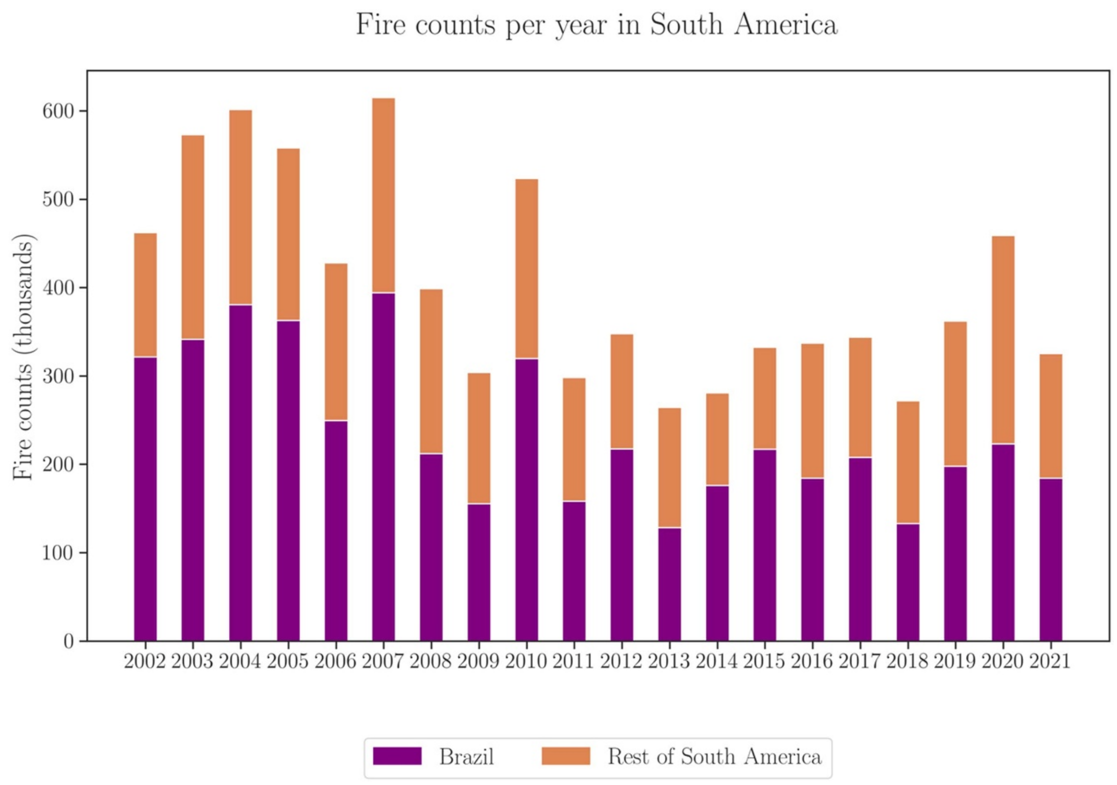

Figure 1. Fire counts in thousands per year in South America, as observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite for 2002–2021. The contributions of fire counts in Brazil are shown in purple.

($PM_{2.5}$) in South America for 2014–2019, with a particular focus on people living in Indigenous territories in the Amazon Basin. Our study has significance given that these populations live in close proximity to fires and that rates of biomass burning in the Amazon has recently surged (Barlow *et al* 2019, de Souza *et al* 2020, Human Rights Watch *et al*, 2020, da Silva *et al* 2021).

Fire activity in the Amazon Basin is driven largely by human activity and variations in climate (Nepstad *et al* 2014, Aragão *et al* 2018, Barlow *et al* 2019, Dos Reis *et al* 2021). Charcoal records show that small fires were introduced to the tropical rainforest roughly 4500 years ago as a crop management tool, changing the composition and structure of the natural forest (Maezumi *et al* 2018a, 2018b). In recent decades, human intervention—e.g. mining, logging, and agricultural land use—has significantly degraded the Amazon forest, amplifying fire risk (Pivello *et al* 2021). Fires have also been deliberately set to clear land or manage crops. Using visibility observations as a proxy for fire activity, van Marle *et al* (2017) found that fire emissions across the Amazon Basin were relatively low from the mid-1970s to the late 1980s, but increased rapidly over the 1990s. In 2004, the Brazilian government implemented new regulations to reduce illegal deforestation in an effort to sustainably develop the region (Garrett *et al* 2021). From 2005 to 2013, deforestation rates in the Amazon region declined by 70% in response to these regulations, and fire counts decreased by ∼60% (Aragão *et al* 2018, Barlow *et al* 2019, Nepstad *et al* 2014; https://queimadas.dgi.inpe.br/queimadas/portal-static/estatisticas_paises/). However, these trends have reversed. The National Institute of Space Research (INPE) estimated that roughly 10 000 sq km of the Brazilian Amazon were cleared from July 2018 to August 2019, a 34% increase from the previous year (Garrett *et al* 2021, INPE, 2022). In 2020, fire activity increased by ∼74% from the 2013 low (figure 1), and in 2021, deforestation in this region increased to ∼13 000 km^2 per year, almost double the rate in 2012 (INPE, (Inst. Nac. Pesqui. Espac.) 2022).

Climate variability can also influence fire activity in the Amazon region. Observations suggest that the dry season has lengthened by about a month since the 1970s (Debortoli *et al* 2015, Espinoza *et al* 2016, 2019), and this trend, compounded by relatively frequent drought years (2005, 2010, 2015), has increased the incidence of fires (Aragão *et al* 2014, Aragão *et al* 2018, Marengo *et al* 2017, Brando *et al* 2019, Silveira *et al* 2020). The forest fragmentation resulting from years of human intervention in the region means that agriculture fires and other deliberately set fires can more easily 'escape,' increasing the area burned, especially during drought years (Fernandes *et al* 2017).

The continued burning in the Amazon Basin poses a threat to public health (Molina *et al* 2015, Reddington *et al* 2018). Observations of aerosol optical depth (AOD) from the Moderate Resolution Imaging

Spectroradiometer (MODIS) suggest that smoke $PM_{2.5}$ from fires in the Amazon Basin contributes significantly to aerosol loading across the continent (Castro Videla *et al* 2013, Della Ceca *et al* 2018), and previous studies have shown that exposure to smoke $PM_{2.5}$ can lead to premature mortality and respiratory disease (Johnson *et al* 2012, Liu *et al* 2015, Reid *et al* 2016). Recent reviews have found that $PM_{2.5}$ from wildfires can also impact other health outcomes such as cardiovascular disease, cancer, neuropsychological diseases, metabolic dysfunction, birth outcomes, mental health, loss of work days, and increase in medical costs (Grant and Runkle 2022, Yu *et al* 2022). In particular, smoke pollution may have a disproportionate impact on Indigenous populations, given their proximity to the fires and their limited access to healthcare, medicine, basic hygiene materials, and clean water. Food insecurity and a relative lack of immunity compared to other populations may also contribute to a greater susceptibility among Indigenous people to complications from respiratory diseases, as was documented during the COVID-19 pandemic (Human Rights Watch (HRW) 2020, da Silva *et al* 2021). For August 2019, municipal data suggest that hospital admissions of people living in Indigenous territories in the Legal Brazilian Amazon over the age of 50 increased by 25% for respiratory problems compared to July, possibly because greater smoke exposure coincided with an increase of fires in the region (de Souza *et al* 2020). However, the health impacts of smoke on Indigenous people in the region may not be well documented due to the lack of healthcare infrastructure.

Most previous studies examining the health impacts of smoke exposure in South America have focused on the years before 2015, examined just 1–2 years of fire seasons (typically July to November), or relied on hospital data. For example, Reddington *et al* (2015) found that the 2001–2012 decrease in fire activity accounted for 400–1700 fewer premature deaths each year across South America. Butt *et al* (2020) estimated that the 2012 fires led to 16 800 premature deaths across the continent, while Butt *et al* (2021) further found that the enhancement in fire activity in 2019 accounted for 3400 additional deaths, compared to 2012. Ye *et al* (2021) determined that a 10 $\mu g\ m^{-3}$ incremental increase in smoke $PM_{2.5}$ in South America was associated with a 1.6% increase in all-cause hospital admissions during 2000–2015. Extending these earlier studies, Nawaz and Hanze (2020) estimated smoke-related deaths across four fire seasons, from 2016–2019, but that study focused just on Brazil.

For this study, we use the chemical transport model GEOS-Chem to quantify the distribution of smoke across the continent and its impact on public health from 2014 to 2019. We build on previous studies by examining the impact of smoke $PM_{2.5}$ on public health for a six-year time period across all of South America as well as in the Amazonian Indigenous territories. We also use an updated CRF from the meta-analysis of Vodonos *et al* (2018), which has been used in studies examining excess mortality due to $PM_{2.5}$ worldwide and regionally (Marais *et al* 2019, Vodonos and Schwartz 2021, Vohra *et al* 2021). InfoAmazonia estimated that most Indigenous villages are between 200 km to 700 km away from intensive care units (Geraque 2020). The application of a CRF allows us to estimate the health impact of smoke exposure without having to rely on hospital admission data, which may not be accurate for Indigenous populations due to the lack of medical facilities near Indigenous territories.

2. Data and methods

2.1. In-situ and satellite observations

We use surface and satellite observations to validate simulated $PM_{2.5}$ from GEOS-Chem. Information on the observations used and steps taken for the validation can be found in the supplement (S1).

2.2. GEOS-Chem

We use GEOS-Chem v.12.8.1 (DOI: 10.5281/zenodo.3837666), a 3D global atmospheric chemical transport model, driven by assimilated meteorological fields from the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2; Gelaro *et al* 2017, https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). We perform two sets of six-year nested grid simulations, with and without fire emissions, at $0.5° \times 0.625°$ spatial resolution for 2014–2019. We define smoke $PM_{2.5}$ as the difference between the two simulations with and without fire emissions. More details on the GEOS-Chem simulations are in the supplement (S2).

GEOS-Chem has been previously used to estimate premature mortality from surface $PM_{2.5}$ at both global and regional levels (Eastham and Barrett 2016, Koplitz *et al* 2016, Marais *et al* 2019, Vohra *et al* 2021). These past studies have examined excess mortality due to $PM_{2.5}$ exposure from a range of sources, including fossil fuel combustion (Marais *et al* 2019, Vohra *et al* 2021), aviation (Eastham and Barrett 2016), and biomass burning (Koplitz *et al* 2016).

2.3. Datasets and premature mortality analysis

For population data, we rely on the Gridded Population of the World, version 4, revision 11 (GPWv4.11; Center for International Earth Science Information Network—CIESIN, 2018). This dataset has a spatial resolution of 2.5 arc-minute, about 4.6 km at the equator. To estimate the population in Indigenous territories in the Amazon Basin, we mask the GPWv4.11 gridded population using shapefiles from the Amazonian Network of Georeferenced Socio-Environmental Information (RAISG; www.amazoniasocioambiental.org/). The RAISG shapefiles of Indigenous territories are those recognized by each country (www3.socioambiental.org/raisg2015/metadados/raisg_tis_territorios_indigenas.html). For all our analyses, we use 2015 estimates for population, which yields ∼5.8 million people living in Indigenous territories, or ∼1.4% of the total population in South America. We estimate the total population of each country by masking the GPWv4.11 gridded population with country shapefiles; these total populations include the people living in Indigenous territories in the Amazon Basin. For the baseline mortality, we use the 2016 global burden of disease estimates from the World Health Organization (WHO 2018).

To calculate excess mortality due to smoke exposure, we apply the updated CRF from Vodonos *et al* (2018). Further details can be found in the supplement (S3).

3. Results

Figure 1 shows the time series of fire counts in South America from MODIS from 2002 to 2021. Since 2002, annual fire counts have risen above 600 000 twice, in 2004 and 2007. Fire counts generally decreased from 2004–2013, to a low of 264 000 in 2013. Then from 2013 to 2020, fire activity increased rapidly, with fire counts reaching ∼459 000 in 2020, the highest value since 2010. About 56% of all fires in South America from 2014–2021 occurred in Brazil.

We focus here on fire activity and smoke exposure during the years 2014–2019. We find that GEOS-Chem can adequately capture the seasonality of AOD at 500 nm as observed at the AERONET sites (figure S1), with AOD values over the Amazon Basin as much as 0.3 greater during the dry season there, compared to the wet season. The normalized mean biases of GEOS-Chem compared to AERONET are −36% during January–May and −34% during July–November. Validation of model results outside the Amazonian wet and dry seasons yields similar results (not shown). In particular, GEOS-Chem underestimates AOD by 0.1–0.4 at five sites in Colombia during January-May, perhaps because the model cannot accurately capture the anthropogenic emissions from nearby cities or because it underestimates smoke from fires occurring in this region at this time of year. Figure S2 shows that AOD from GEOS-Chem correlates with the seasonal values at the AERONET sites with an r of 0.81 during the dry season but only 0.54 during the wet season. Consistent with the comparison with AERONET, we find that GEOS-Chem also underestimates AOD at 550 nm as observed by MODIS (figure S3), especially in fire-prone regions. During January-May, the underestimates are greatest in Colombia, Venezuela, and northern Brazil, and during July-November they are greatest in western Brazil, Paraguay, eastern Peru, and Bolivia.

We also validate our model results with the few available *in-situ* concentrations of $PM_{2.5}$ outside of São Paulo (figure S4). We find that the GEOS-Chem values during the Amazonian dry season correlate with observed $PM_{2.5}$ with an r of 0.57 and a normalized mean bias of −25%. Compared to the site data, GEOS-Chem appears to underestimate $PM_{2.5}$ during the wet season, with a normalized mean bias of −65%, but this mismatch between observed and modeled $PM_{2.5}$ could be due to high humidity affecting the sensors (Ardon-Dryer *et al* 2020, Stavroulas *et al* 2020). The mismatch could also arise from the challenge of comparing point measurements with modeled values in coarse grid cells.

We find that transport processes can carry smoke $PM_{2.5}$ across a wide region of South America. GEOS-Chem yields enhancements in total $PM_{2.5}$ of 5–70 $\mu g\ m^{-3}$ in the Amazon during the dry season there, compared to the wet season (figure 2), with smaller enhancements of 5–30 $\mu g\ m^{-3}$ across large areas of Peru, Bolivia, northern Brazil, Paraguay, and Argentina. These seasonal differences in $PM_{2.5}$ concentrations are more pronounced during the drought years of 2015 and 2016 compared to non-drought years (2014, 2017–2019) (figure 2). Fires account for 5%–40% of increase in $PM_{2.5}$ during the wet season and 5%–90% during the dry season. From January to May, fire activity shifts north to Colombia and Venezuela, with modest increases in smoke $PM_{2.5}$ of ∼15 $\mu g\ m^{-3}$. Surface $PM_{2.5}$ is also enhanced at that time of year over the Atlantic Ocean north of Brazil, due to the transport of dust and smoke from Africa (Ansmann *et al* 2009). Figure S5 isolates the contribution of smoke to the seasonal differences of $PM_{2.5}$ seen in figure 2, revealing smoke concentrations of 30–50 $\mu g\ m^{-3}$ in the Amazon Basin (figure S5).

Figure 3 shows that Indigenous territories in the Amazon Basin are particularly affected by the smoke enhancement in surface $PM_{2.5}$ during the dry season. Many small territories are scattered throughout the Brazilian Amazon and Bolivia, suggesting that populations living in these areas experience disproportionately large smoke exposures. We estimate monthly mean smoke exposures in three Brazilian cities—São Paulo in eastern Brazil and Porto Velho and Rio Branco in western Brazil—as well as in Karipuna, an Indigenous territory in western Brazil (figures S5 and S6). In São Paulo, monthly mean $PM_{2.5}$ ranges between 30 and 70 $\mu g\ m^{-3}$, mainly driven by anthropogenic emissions such as industrial and

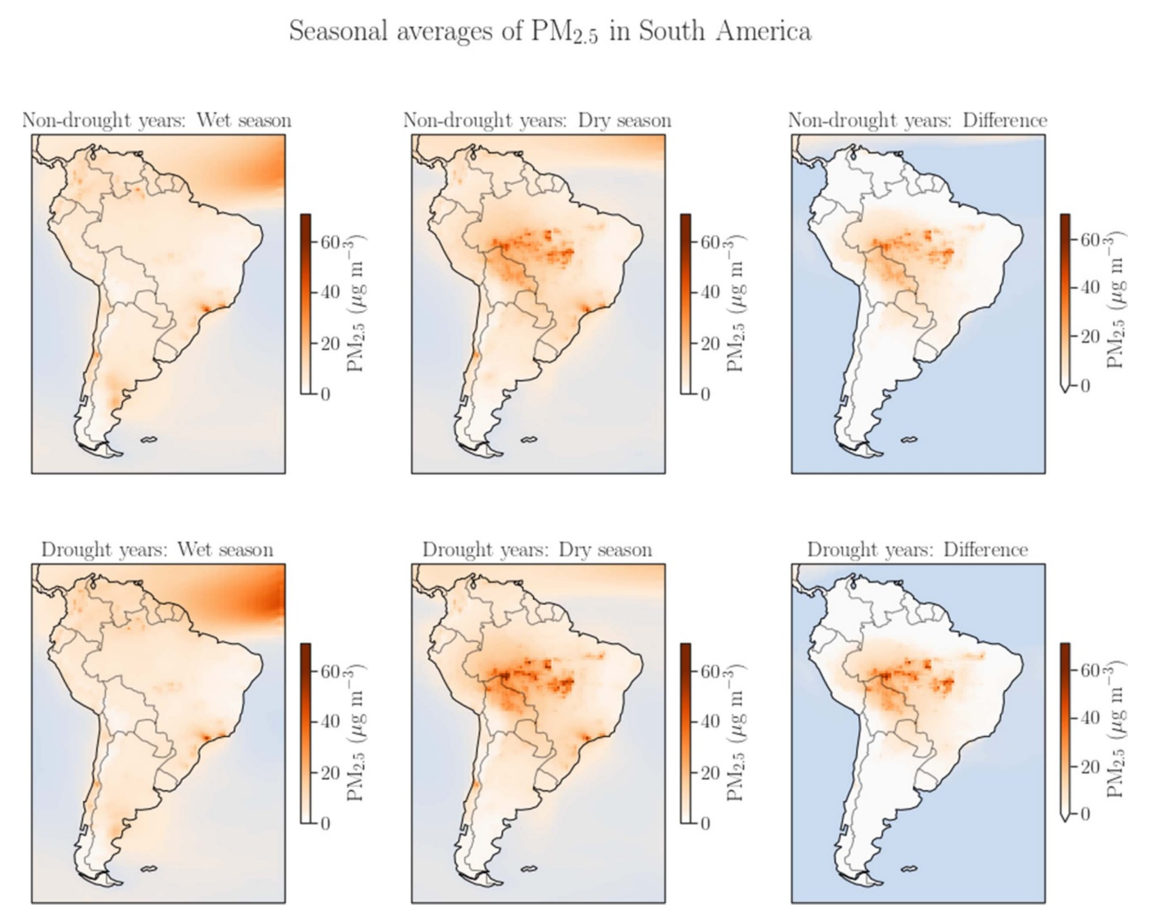

Figure 2. Simulated $PM_{2.5}$ concentrations, in units of μg m^{-3}, from GEOS-Chem, averaged over four non-drought years (2014, 2017–2019, top row) and over two drought years (2015 and 2016, bottom row). Values for the Amazonian wet season (15 January to 15 May) are shown at left, and for the dry season (15 July to 15 November) in the center column. Right hand panels show the seasonal differences.

transportation sources and not by fire emissions. In contrast, surface $PM_{2.5}$ concentrations in Porto Velho and Rio Branco, two cities located much closer to the fires, exhibit a seasonality that matches that of the fires in the Amazon, with monthly mean concentrations ranging from 30 to 80 μg m^{-3} during the dry season. In Karipuna, monthly mean concentrations are quite high, ranging between 80 and 100 μg m^{-3} during the dry season and reaching nearly 200 μg m^{-3} in 2019, when fire activity near this territory was particularly intense. Given that the WHO guidelines for daily $PM_{2.5}$ exposure are set to 15 μg m^{-3} (World Health Organization 2021), these large monthly mean concentrations suggest significant health effects from smoke exposure in Porto Velho, Rio Branco, and Karipuna.

On average, the Indigenous territories in the Amazon experience 1.1 $\pm$ 0.4 μg m^{-3} greater concentrations of annual mean total $PM_{2.5}$ compared to the whole of South America during 2014–2019, and 0.64 $\pm$ 0.21 μg m^{-3} greater smoke $PM_{2.5}$ (figure S7). The distribution of annual mean concentrations of total $PM_{2.5}$ in all gridcells across South America reveals that 90% of these averages fall below 15 μg m^{-3} in both South America and the Indigenous territories (figure S8). However, outliers can reach annual mean values as high as 50 μg m^{-3} in some years and gridcells when taking all of South America into account, and as high as 30 μg m^{-3} in the Indigenous territories. We find that the population-weighted, annual mean smoke exposure is greatest in Bolivia and Paraguay, at 2.2 $\pm$ 0.75 μg m^{-3} and 2.09 $\pm$ 0.44 μg m^{-3} (not shown). In addition, population-weighted smoke concentrations are greater for people living in Amazonian Indigenous territories, particularly in Bolivia and Brazil where concentrations of smoke experienced in these territories are $\sim$1.5–1.75 μg m^{-3} greater than the country averages (figure S9).

Figure 4 presents a time series of the annual number of premature deaths attributable to smoke exposure in South America and in the Amazonian Indigenous territories. For South America we find that $\sim$12 000 deaths per year are attributable to smoke $PM_{2.5}$ exposure for 2014–2019, with a 95% confidence interval (CI) of 3100–20 700; in Indigenous territories, the number of deaths per year is $\sim$230 (CI: 60–390). Using alternative CRFs from Krewski *et al* (2009) and the US Environmental Protection Agency (2010), excess mortality can reach as high as $\sim$22 600 deaths per year in South America and $\sim$500 for Indigenous territories

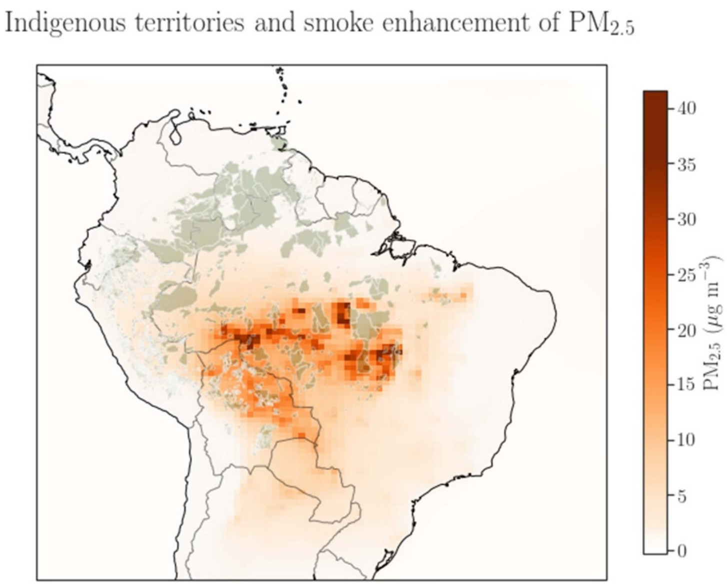

Figure 3. Simulated surface smoke $PM_{2.5}$ concentration, in units of μg m^{-3}, averaged over 2014–2019 for the Amazonian dry season (July 15 to November 15). $PM_{2.5}$ is shown in shades of orange and red; Indigenous territories within the Amazon Basin are shaded green. Boundaries for these territories are from the Amazonian Network of Georeferenced Socio-Environmental Information (RAISG; www.amazoniasocioambiental.org/).

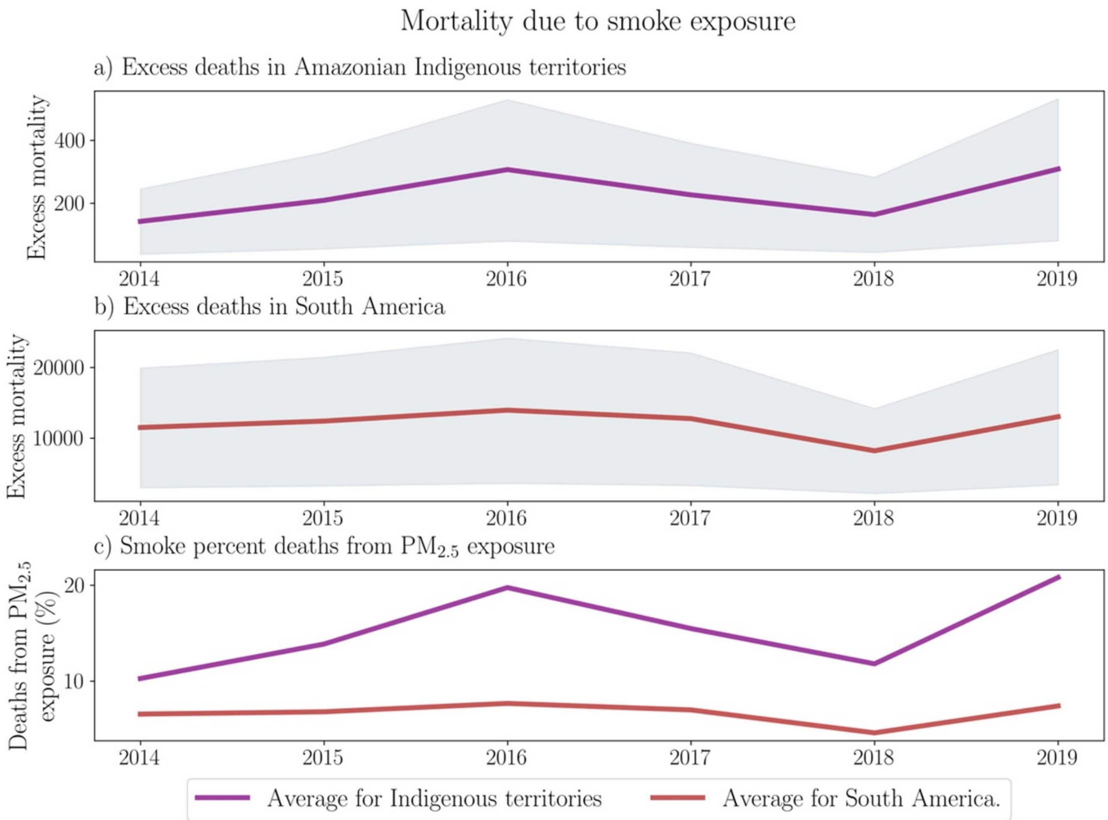

Figure 4. Time series of annual excess mortality due to smoke $PM_{2.5}$ exposure for 2014–2019. Top panel shows the excess deaths in the Amazonian Indigenous territories, and middle panel shows the excess deaths across all of South America. Gray contours in top and middle panels represent the 95% confidence intervals. Bottom panel shows the percentage of all $PM_{2.5}$-related deaths that can be traced to smoke exposure. Purple lines denote the percentage in Indigenous territories and red lines the percentage across all of South America. Mortality estimates are calculated using the concentration response function of .Vodonos *et al* (2018)

(figure S10). Figure 4 also shows the contribution of smoke exposure to all $PM_{2.5}$-related premature deaths. We find that of these premature deaths, 6.7% across South America can be attributed to smoke exposure, while 15.3% of $PM_{2.5}$-related deaths in Indigenous territories are from smoke. These values suggest an outsized influence of smoke exposure on Indigenous people compared to other populations.

We find that smoke exposure leads to the greatest excess mortality for the general population in Brazil, Argentina, and Colombia; for populations living in Indigenous territories, Peru and Bolivia lead with the most excess deaths (figure S11). For example, summed over the 2014–2019 time period, exposure to smoke $PM_{2.5}$ from fires accounts for ∼39 000 deaths in Brazil and ∼500 deaths in Indigenous territories in Peru (figure S11). Of the five countries with the largest Indigenous populations, the rate of mortality due to smoke $PM_{2.5}$ exposure is greater for the Indigenous population in all but one (Venezuela). On average the percent population at risk of premature death due to smoke across South America is 0.002%, and for people in Indigenous territories is 0.004% (figure S12). This translates to two smoke-related deaths per 100 000 people per year across South America as a whole, but double that rate—four premature deaths per 100 000 people per year—in Indigenous lands (table S1).

4. Discussion and conclusions

We use a combination of the chemical transport model GEOS-Chem and an updated CRF from Vodonos *et al* (2018) to estimate premature mortality from smoke exposure from fires in South America, which occur mainly in the Amazon Basin. We find smoke enhances seasonal mean $PM_{2.5}$ concentrations by up to 40 $\mu g\ m^{-3}$ during the Amazonian dry season between 2014–2019 (figure 3). Monthly mean concentrations in Indigenous territories can reach much higher values. For example, in 2019, the September mean concentration at Karipuna, an Indigenous territory in western Brazil, reached nearly 200 $\mu g\ m^{-3}$. On an annual average, the Amazonian Indigenous territories experience $1.1 \pm 0.4\ \mu g\ m^{-3}$ greater total $PM_{2.5}$ and $0.64 \pm 0.21\ \mu g\ m^{-3}$ greater smoke $PM_{2.5}$ than the whole of South America (figure S7). The greatest excess mortality at the country-level is in Brazil, Argentina, and Colombia, probably because these countries have the largest total populations in South America. For people living in Indigenous territories, those in Peru and Bolivia experience the most excess deaths due to their close proximity to smoke (figure S11). We further estimate that ∼12 000 premature deaths occur annually in South America due to exposure to smoke $PM_{2.5}$, including ∼230 deaths in the Amazonian Indigenous territories. Our results suggest that people living in these Indigenous territories are twice as likely to die prematurely from smoke exposure, compared to the population across South America.

Our results are well within the range of past estimates of smoke-related deaths in South America, which range from 5000 to 17 000 premature deaths per year (Johnston *et al* 2012, Reddington *et al* 2015, Butt *et al* 2020, Nawaz and Henze 2020). These studies relied on older CRFs and did not analyze the impacts on the Indigenous communities. For Butt *et al* (2020, 2021) used a similar exposure-outcome approach as we do here, but they relied on the Global Exposure Mortality Model (GEMM) from Burnett *et al* (2018) to estimate relative risk. The GEMM model includes data from 41 studies and focuses on five causes of death in people aged 25 years and older. In contrast, the meta-analysis from Vodonos *et al* (2018) considered 53 studies, has higher sensitivity of mortality to a unit change of $PM_{2.5}$ than does GEMM, and accounts for all-cause mortality in people aged 15 years and older.

Our estimates for premature mortality from smoke exposure for different populations in South America could be improved in future work. Our $PM_{2.5}$ concentration estimates are limited by the spatial resolution ($0.5° \times 0.625°$), and future work should consider having a finer resolution when looking at specific locations. Also, our analysis does not represent a full accounting of the health burden of the Indigenous community, since we do not consider people identifying as Indigenous living outside the Amazonian territories. For this study we estimate the health impact on the people living in Indigenous territories in the Amazon Basin, and we do not differentiate between people based on identifying as Indigenous or non-Indigenous. We also do not incorporate differences in populations such as ethnicity, socioeconomic status, income, education, and underlying comorbidities, which could increase vulnerability to adverse health outcomes related to air pollution. Also, the methods we use to estimate people living in the Amazonian Indigenous territories yield a total population of ∼5.8 million people, which may be an underestimate (Butler 2019). In Brazil, however, we calculate that 443 000 people live in these territories, consistent with government estimates of 464 000 for 2019 (Souza, Oviedo, and dos Santos, 2020). We also do not have base mortality estimates for individual Indigenous territories as we do for each country. Neither Vodonos *et al* (2018) nor Burnett *et al* (2018) included cohort studies from South America when developing their CRFs, indicating the need for a detailed analysis of the association between $PM_{2.5}$ and health on this continent. The CRFs here also do not take into account the possibility that $PM_{2.5}$ from wildfires may incur a different degree of harm than $PM_{2.5}$ from other sources, or how this might be affected by changes in chemical composition as the wildfire plume ages (Atwi *et al* 2022). For this work, we focused on the health impacts from annual mean smoke exposures; the acute health consequences of short-term smoke exposures may also be significant. Additionally, discussion of health impacts could be broadened from purely mortality estimates to examination of morbidity, missed days of school/work, and burdens of health costs. Finally, to gain a greater understanding of the ways that fire activity affects public health and welfare, future work should more closely involve the people living in the Amazonian Indigenous territories. We recommend that governments provide financial assistance to monitor air quality, such as deploying reference monitors and well-calibrated, low-cost sensors in Indigenous territories to study the impact of short- and long-term exposure of smoke.

In response to deforestation regulations, fire counts in Brazil decreased by ∼70% from 2004 to 2011 (Aragão *et al* 2018, Barlow *et al* 2019). Since 2013, however, this downward trend in fire activity has reversed. Given these recent increases in fire activity in the Amazon Basin, our results imply significant and disproportionate consequences for Indigenous people. Fire not only affects air quality, however, but also impacts food security in these communities through the destruction of tropical vegetation. By exacerbating erosion, fire can also contaminate waterways, distributing debris, toxins, and harmful nutrients throughout the watershed (Human Rights Watch, 2020). Since 2000, deforestation, fires, road construction, and land use changes have led to a drier, less fire-resistant Amazon Basin, a trend that will persist if deforestation continues increasing (Boulton *et al* 2022). Previous research has suggested substantial benefits when Indigenous communities are granted 'treatment as a state' provisions to create environmental policy and regulate natural resources separately from state governments (Diver *et al* 2019, Hart-Fredeluces *et al* 2021). For example, such communities have limited deforestation and the spread of escaped fires, and they have acted as stewards for biodiversity, water quality and other environmental assets (Nepstad *et al* 2006, Diver *et al* 2019, Dos Santos *et al* 2021, Hart-Fredeluces *et al* 2021). While Indigenous territories account for relatively few fires in the Amazon Basin (Dos Reis *et al* 2021), our work indicates that the people living in these territories experience significantly greater health risks from smoke-related $PM_{2.5,}$ compared to the general population.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/Z06WGF.

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Data access statement

Data will be published in the Dataverse public repository prior to acceptance.

Author contributions

E X B and L J M designed the research with help from J J B and M C C. E X B performed the GEOS-Chem and public health calculations with assistance from S D E and J J B. Validation of simulated $PM_{2.5}$ from GEOS-Chem with Purple Air was conducted by G R with assistance from D M W. E X B and L J M wrote the paper with input from L V, A A, and all other authors.

Conflict of interest

The authors declare no competing interests.

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References

Ansmann A, Baars H, Tesche M, Müller D, Althausen D, Engelmann R, Pauliquevis T and Artaxo P 2009 Dust and smoke transport from Africa to South America: lidar profiling over cape verde and the Amazon rainforest *Geophys. Res. Lett.* **36** L11802

Aragão L E O C *et al* 2018 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions *Nat. Commun.* **9** 1–12

Aragão L E O C, Poulter B, Barlow J B, Anderson L O, Malhi Y, Saatchi S, Phillips O L and Gloor E 2014 Environmental change and the carbon balance of Amazonian forests *Biol. Rev.* **89** 913–31

Ardon-Dryer K, Dryer Y, Williams J N and Moghimi N 2020 Measurements of $PM_{2.5}$ with PurpleAir under atmospheric conditions *Atmos. Meas. Tech.* **13** 5441–58

Atwi K *et al* 2022 Differential response of human lung epithelial cells to particulate matter in fresh and photochemically aged biomass-burning smoke *Atmos. Environ.* **271** 118929

Barlow J, Berenguer E, Carmenta R and França F 2019 Clarifying Amazonia's burning crisis *Glob. Change Biol.* **26** 319–21

Bencherif H *et al* 2020 Investigating the long-range transport of aerosol plumes following the Amazon fires (August 2019): a multi-instrumental approach from ground-based and satellite observations *Remote Sens.* **12** 3846

Boulton C A, Lenton T M and Boers N 2022 Pronounced loss of Amazon rainforest resilience since the early 2000s *Nat. Clim. Change* **12** 271–8

Bourgeois Q, Ekman A M L and Krejci R 2015 Aerosol transport over the Andes from the Amazon basin to the remote Pacific Ocean: a multiyear CALIOP assessment *J. Geophys. Res. Atmos.* **120** 8411–25

Brando P M, Paolucci L, Ummenhofer C C, Ordway E M, Hartmann H, Cattau M E, Rattis L, Medjibe V, Coe M T and Balch J 2019 Droughts, wildfires, and forest carbon cycling: a pantropical synthesis *Annu. Rev. Earth Planet. Sci.* **47** 555–81

Burnett R *et al* 2018 Global estimates of mortality associated with longterm exposure to outdoor fine particulate matter *Proc. Natl Acad. Sci. USA* **115** 9592–7

Butler R A 2019 People in the Amazon rainforest *Mongabay* (available at: https://rainforests.mongabay.com/amazon/amazon_people.html) (Accessed 28 March 2022)

Butt E W *et al* 2020 'Large air quality and human health impacts due to Amazon forest and vegetation fires *Environ. Res. Commun.* **2** 095001

Butt E W, Conibear L, Knote C and Spracklen D V 2021 Large air quality and public health impacts due to Amazonian deforestation fires in 2019 *GeoHealth* **5** e2021GH000429

Center for International Earth Science Information Network—CIESIN, C. U 2018 Gridded population of the world, version 4 (GPWv4): population density adjusted to match 2015 revision UN WPP Country Totals, Revision 11′. Palisades (New York: NASA Socioeconomic Data and Applications Center (SEDAC)) (available at: https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11) (Accessed 4 March 2022)

da Silva L L, Nascimento P E, Araújo O C G and Pereira T M G 2021 The articulation of the indigenous peoples of Brazil in facing the Covid-19 pandemic *Front. Sociol.* **6** 611336

de Souza A A, Oviedo A and Dos Santos T M 2020 Impactos na qualidade do ar e saúde humana relacionados ao desmatamento e queimadas na Amazônia Legal Brasileira *Instituto Socioambiental* pp 1–21 (available at: https://acervo.socioambiental.org/sites/default/files/documents/prov085.pdf)

Debortoli N S, Dubreuil V, Funatsu B, Delahaye F, de Oliveira C H, Rodrigues-Filho S, Saito C H and Fetter R 2015 Rainfall patterns in the Southern Amazon: a chronological perspective (1971–2010) *Clim. Change* **132** 251–64

Della Ceca L S, García Ferreyra M F, Lyapustin A, Chudnovsky A, Otero L, Carreras H and Barnaba F 2018 Satellite-based view of the aerosol spatial and temporal variability in the Córdoba region (Argentina) using over ten years of high-resolution data *ISPRS J. Photogramm. Remote Sens.* **145** 250–67

Diver S, Ahrens D, Arbit T and Bakker K 2019 Engaging colonial entanglements: "treatment as a state" policy for indigenous water co-governance *Glob. Environ. Politics* **19** 33–56

Dos Reis M, Graça P M L D A, Yanai A M, Ramos C J P and Fearnside P M 2021 Forest fires and deforestation in the central Amazon: effects of landscape and climate on spatial and temporal dynamics *J. Environ. Manage.* **288** 112310

Dos Santos A M, Silva C F A D, Rudke A P and Oliveira Soares D D 2021 Dynamics of active fire data and their relationship with fires in the areas of regularized indigenous lands in the Southern Amazon *Remote Sens. Appl.: Soc. Environ.* **23** 100570

Eastham S D and Barrett S R H 2016 Aviation-attributable ozone as a driver for changes in mortality related to air quality and skin cancer *Atmos. Environ.* **144** 17–23

Espinoza J C, Ronchail J, Marengo J A and Segura H 2019 Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017) *Clim. Dyn.* **52** 5413–30

Espinoza J C, Segura H, Ronchail J, Drapeau G and Gutierrez-Cori O 2016 Evolution of wet-day and dry-day frequency in the western Amazon Basin: relationship with atmospheric circulation and impacts on vegetation *Water Resour. Res.* **52** 8546–60

Fernandes K, Verchot L, Baethgen W, Gutierrez-Velez V, Pinedo-Vasquez M and Martius C 2017 Heightened fire probability in Indonesia in non-drought conditions: the effect of increasing temperatures Environ. Res. Lett. **12** 054002

Garrett R D, Cammelli F, Ferreira J, Levy S A, Valentim J and Vieira I 2021 Forests and sustainable development in the Brazilian Amazon: history, trends, and future prospects *Annu. Rev. Environ. Resour.* **46** 625–52

Gelaro R *et al* 2017 The modern-era retrospective analysis for research and applications, version 2 (MERRA-2) *J. Clim.* **30** 5419–54

Geraque E 2020 Far from ICUs and ventilators, indigenous people from the Amazon try to shield themselves from the virus *InfoAmazonia* (available at: https://infoamazonia.org/en/2020/05/11/distantes-de-utis-e-respiradores-indigenas-da-amazonia-tentam-se-blindar-do-virus/) (Accessed 20 April 2022)

Grant E and Runkle J D 2022 Long-term health effects of wildfire exposure: a scoping review *J. Clim. Change Health* **6** 100110

Hart-Fredeluces G M, Ticktin T and Lake F K 2021 Simulated Indigenous fire stewardship increases the population growth rate of an understorey herb *J. Ecol.* **109** 1133–47

Human Rights Watch (HRW) 2020 Instituto de Pesquisa Ambiental da Amazônia (IPAM) and Instituto de Estudos para Politicas de Saúde (IEPS) *The air is unbearable': Health impacts of deforestation-related fires in the Brazilian Amazon* (available at: www.hrw.org/report/2020/08/26/air-unbearable/health-impacts-deforestation-related-fires-brazilian-amazon#) (Accessed 2 February 2022)

INPE, (Inst. Nac. Pesqui. Espac.) 2022 Projeto PRODES: monitoramento do desmatamento da floresta Amazônica Brasileira por satélite (available at: www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes) (Accessed 28 April 2022)

Johnston F H, Henderson S B, Chen Y, Randerson J T, Marlier M, DeFries R S, Kinney P, Bowman D M J S and Brauer M 2012 Estimated global mortality attributable to smoke from landscape fires *Environ. Health Perspect.* **120** 695–701

Koplitz S N *et al* 2016 Public health impacts of the severe haze in Equatorial Asia in September-October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure *Environ. Res. Lett.* **11** 9

Krewski D *et al* 2009 *Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality* (Boston, MA: Health Effects Institute)

Liu J C *et al* 2015 A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke *Env. Res.* **136** 120–32

Maezumi S Y, Alves D, Robinson M, de Souza J G, Levis C, Barnett R L, Almeida de Oliveira E, Urrego D, Schaan D and Iriarte J 2018b The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon *Nat. Plants* **4** 540–7

Maezumi S Y, Robinson M, de Souza J, Urrego D H, Schaan D, Alves D and Iriarte J 2018a New insights from pre-Columbian land use and fire management in Amazonian dark earth forests *Front. Ecol. Evol.* **6** 1–23

Marais E A, Silvern R F, Vodonos A, Dupin E, Bockarie A S, Mickley L J and Schwartz J 2019 Air quality and health impact of future fossil fuel use for electricity generation and transport in Africa *Environ. Sci. Technol.* **53** 13524–34

Marengo J A, Fisch G F, Alves L M, Sousa N V, Fu R and Zhuang Y 2017 Meteorological context of the onset and end of the rainy season in Central Amazonia during the GoAmazon2014/5′ *Atmos. Chem. Phys.* **17** 7671–81

Molina L T *et al* 2015 Earth's future pollution and its impacts on the South American cryosphere *Earth's Future* **3** 345–69

Nawaz M O and Henze D K 2020 Premature deaths in Brazil associated with long-term exposure to $PM_{2.5}$ from Amazon fires between 2016 and 2019′ *GeoHealth* **4** 8

Nepstad D *et al* 2006 Inhibition of Amazon deforestation and fire by parks and indigenous lands *Biol. Conserv.* **20** 65–73

Nepstad D *et al* 2014 Slowing Amazon deforestation through public policy and interventions in bee and soy supply chains *Science* **344** 1118–23

Pivello V R *et al* 2021 Understanding Brazil's catastrophic fires: causes, consequences and policy needed to prevent future tragedies *Perspect. Ecol. Conserv.* **19** 233–55

Reddington C L *et al* 2018 Biomass burning aerosol over the Amazon: analysis of aircraft, surface and satellite observations using a global aerosol model *Atmos. Chem. Phys.* **19** 1–32

Reddington C L, Butt E W, Ridley D A, Artaxo P, Morgan W T, Coe H and Spracklen D V 2015 Air quality and human health improvements from reductions in deforestation-related fire in Brazil *Nat. Geosci.* **8** 768–71

Reid C E, Brauer M, Johnston F H, Jerrett M, Balmes J R and Elliott C T 2016 Critical review of health impacts of wildfire smoke exposure *Environ. Health Perspect.* **124** 1334–43

Silveira M V F *et al* 2020 Drivers of fire anomalies in the Brazilian Amazon: lessons learned from the 2019 fire crisis *Land* **9** 516

Stavroulas I, Grivas G, Michalopoulos P, Liakakou E, Bougiatioti A, Kalkavouras P, Fameli K, Hatzianastassiou N, Mihalopoulos N and Gerasopoulos E 2020 Field evaluation of low-cost PM sensors (Purple Air PA-II) under variable urban air quality conditions, in Greece *Atmosphere* **11** 926

US Environmental Protection Agency 2010 Quantitative health risk assessment for particulate matter. US Environmental Protection Agency (available at: www3.epa.gov/ttn/naaqs/standards/pm/data/PM_RA_FINAL_June_2010.pdf) (Accessed 4 March 2022)

van Marle M J E, Field R D, van der Werf G R, Estrada de Wagt I A, Houghton R A, Rizzo L V, Artaxo P and Tsigaridis K 2017 Fire and deforestation dynamics in Amazonia (1973–2014) *Glob. Biogeochem. Cycles* **31** 24–38

Videla F C, Barnaba F, Angelini F, Cremades P and Gobbi G P 2013 The relative role of Amazonian and non-Amazonian fires in building up the aerosol optical depth in South America: a five year study (2005–2009) *Atmos. Res.* **122** 298–309

Vodonos A, Awad Y A and Schwartz J 2018 The concentration-response between long-term PM 2.5 exposure and mortality; A meta-regression approach *Env. Res.* **166** 677–89

Vodonos A and Schwartz J 2021 Estimation of excess mortality due to long-term exposure to $PM_{2.5}$ in continental United States using a high-spatiotemporal resolution model *Environ. Res.* **196** 110904

Vohra K, Vodonos A, Schwartz J, Marais E A, Sulprizio M P and Mickley L J 2021 Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: results from GEOS-Chem *Environ. Res.* **195** 110754

WHO 2018 *Global Health Estimates 2016: Deaths by Cause, Age, Sex, by Country and Region, 2000–2016*

World Health Organization 2021 *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 And PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide* (Geneva: World Health Organization)

Ye T, Guo Y, Chen G, Yue X, Xu R, Coêlho M D S Z S, Saldiva P H N, Zhao Q and Li S 2021 Risk and burden of hospital admissions associated with wildfire-related $PM_{2.5}$ in Brazil, 2000–15: a nationwide time-series study *Lancet Planet. Health* **5** e599–e607

Yu Y, Zou W W, Jerrett M and Meng Y-Y 2022 Acute health impact of convectional and wildfire-related $PM_{2.5}$: a narrative review *Adv. Environ.* 100179