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

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Supplementary material for this article is available [online](#)

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

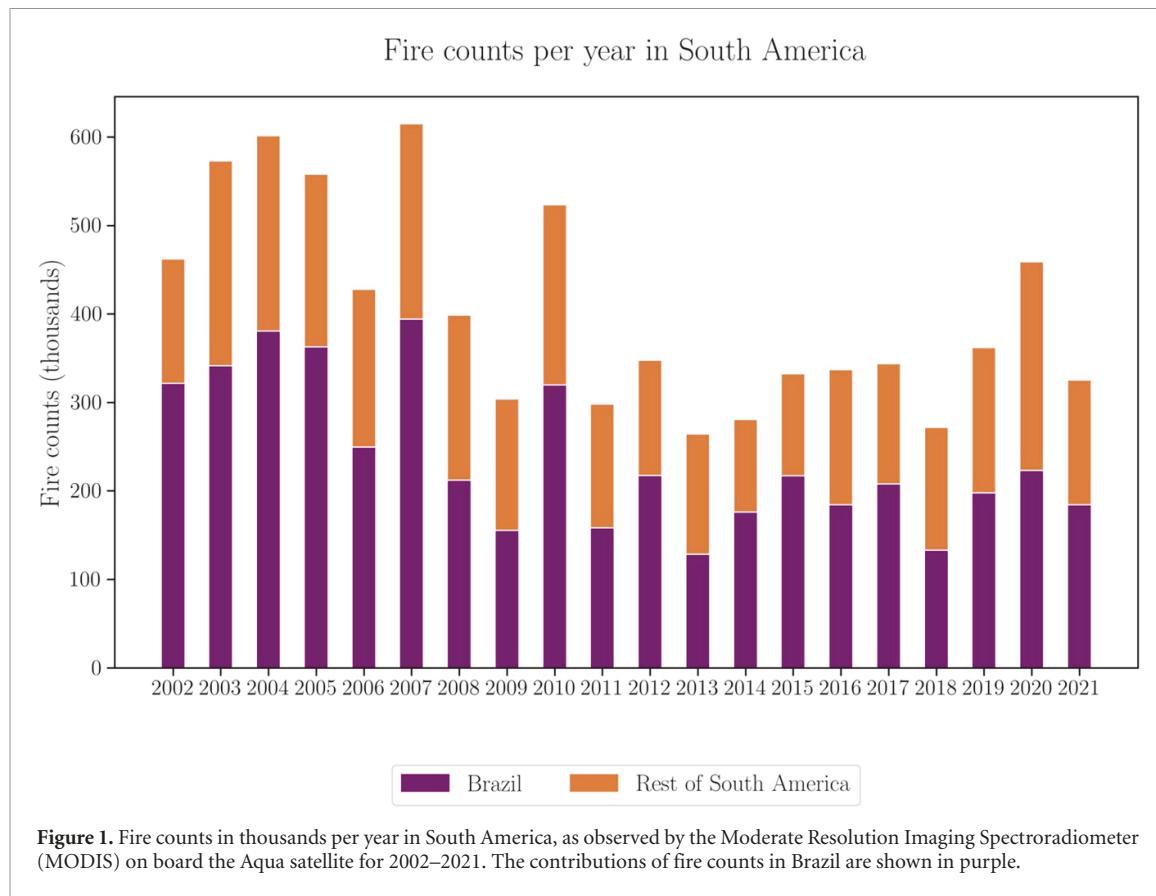


Figure 1. Fire counts in thousands per year in South America, as observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite for 2002–2021. The contributions of fire counts in Brazil are shown in purple.

(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 km² 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 $10 \mu\text{g m}^{-3}$ 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](https://doi.org/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 $0.5^\circ \times 0.625^\circ$ 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 $\sim 1.4\%$ 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

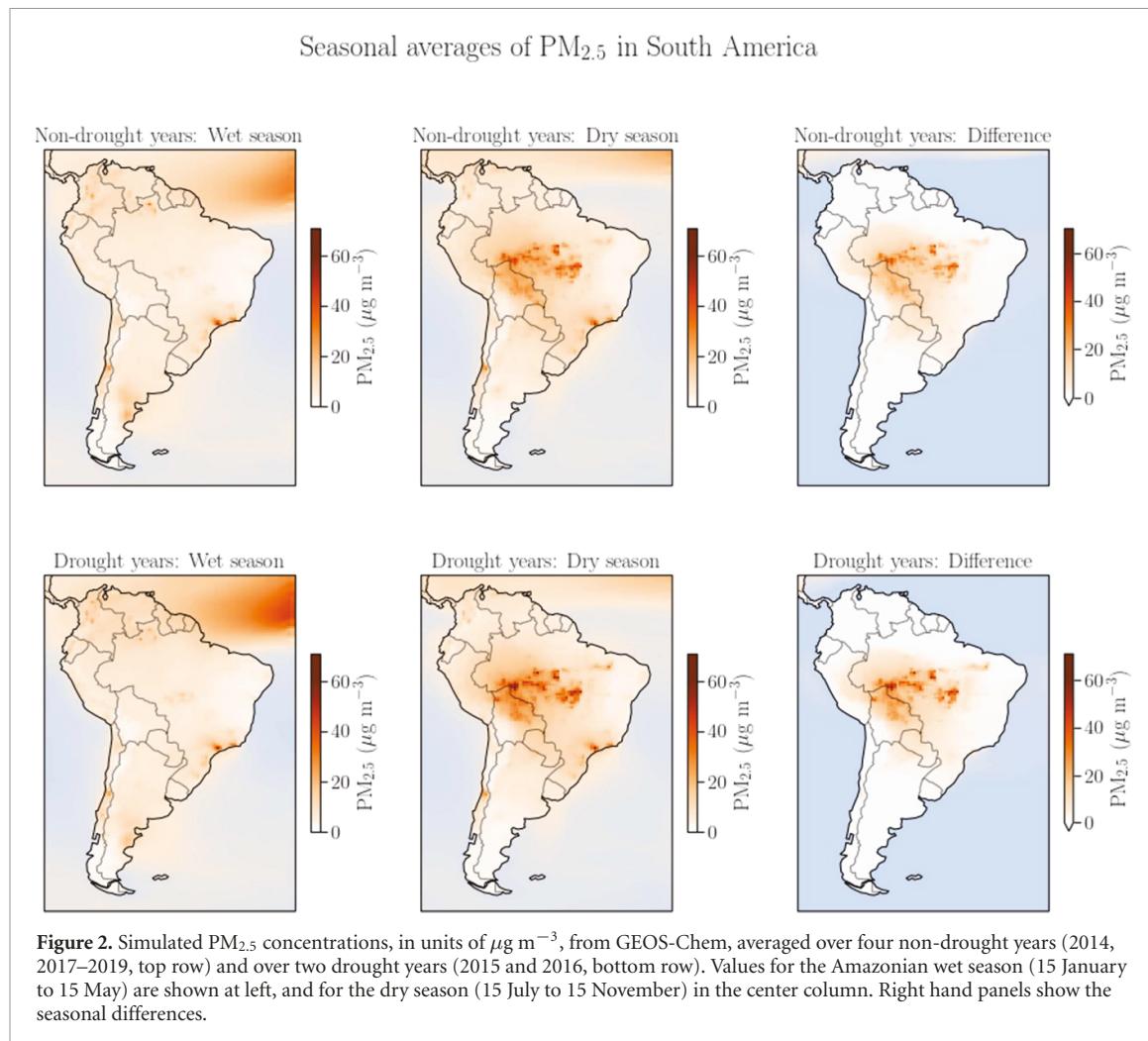
Figure 1 shows the time series of fire counts in South America from MODIS from 2002 to 2021. Since 2002, annual fire counts have risen above 600 000 twice, in 2004 and 2007. Fire counts generally decreased from 2004–2013, to a low of 264 000 in 2013. Then from 2013 to 2020, fire activity increased rapidly, 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 $\mu\text{g m}^{-3}$ in the Amazon during the dry season there, compared to the wet season (figure 2), with smaller enhancements of 5–30 $\mu\text{g m}^{-3}$ 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 $\sim 15 \mu\text{g m}^{-3}$. 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 $\mu\text{g m}^{-3}$ 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 $\mu\text{g m}^{-3}$, mainly driven by anthropogenic emissions such as industrial and



transportation sources and not by fire emissions. In contrast, surface $\text{PM}_{2.5}$ 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 $80 \mu\text{g m}^{-3}$ during the dry season. In Karipuna, monthly mean concentrations are quite high, ranging between 80 and $100 \mu\text{g m}^{-3}$ during the dry season and reaching nearly $200 \mu\text{g m}^{-3}$ in 2019, when fire activity near this territory was particularly intense. Given that the WHO guidelines for daily $\text{PM}_{2.5}$ exposure are set to $15 \mu\text{g m}^{-3}$ (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 $1.1 \pm 0.4 \mu\text{g m}^{-3}$ greater concentrations of annual mean total $\text{PM}_{2.5}$ compared to the whole of South America during 2014–2019, and $0.64 \pm 0.21 \mu\text{g m}^{-3}$ greater smoke $\text{PM}_{2.5}$ (figure S7). The distribution of annual mean concentrations of total $\text{PM}_{2.5}$ in all gridcells across South America reveals that 90% of these averages fall below $15 \mu\text{g m}^{-3}$ in both South America and the Indigenous territories (figure S8). However, outliers can reach annual mean values as high as $50 \mu\text{g m}^{-3}$ in some years and gridcells when taking all of South America into account, and as high as $30 \mu\text{g m}^{-3}$ in the Indigenous territories. We find that the population-weighted, annual mean smoke exposure is greatest in Bolivia and Paraguay, at $2.2 \pm 0.75 \mu\text{g m}^{-3}$ and $2.09 \pm 0.44 \mu\text{g m}^{-3}$ (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 $\sim 1.5\text{--}1.75 \mu\text{g m}^{-3}$ 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 $\text{PM}_{2.5}$ exposure for 2014–2019, with a 95% confidence interval (CI) of 3100–20 700; in Indigenous territories, the number of deaths per year is ~ 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 ~ 500 for Indigenous territories

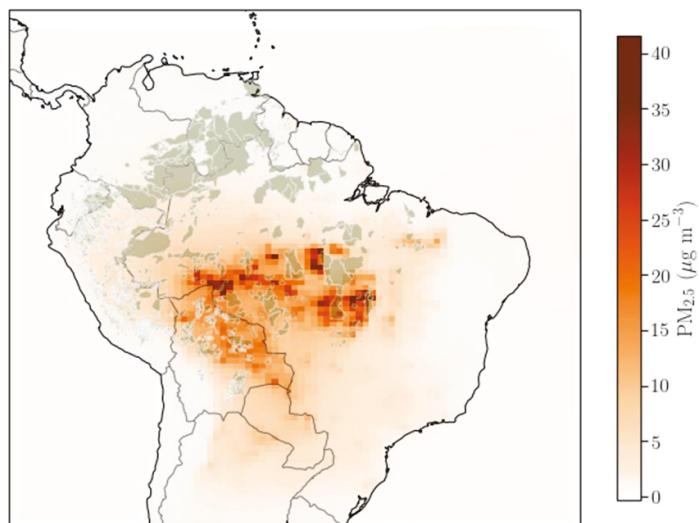
Indigenous territories and smoke enhancement of PM_{2.5}

Figure 3. Simulated surface smoke PM_{2.5} concentration, in units of $\mu\text{g m}^{-3}$, 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/).

Mortality due to smoke exposure

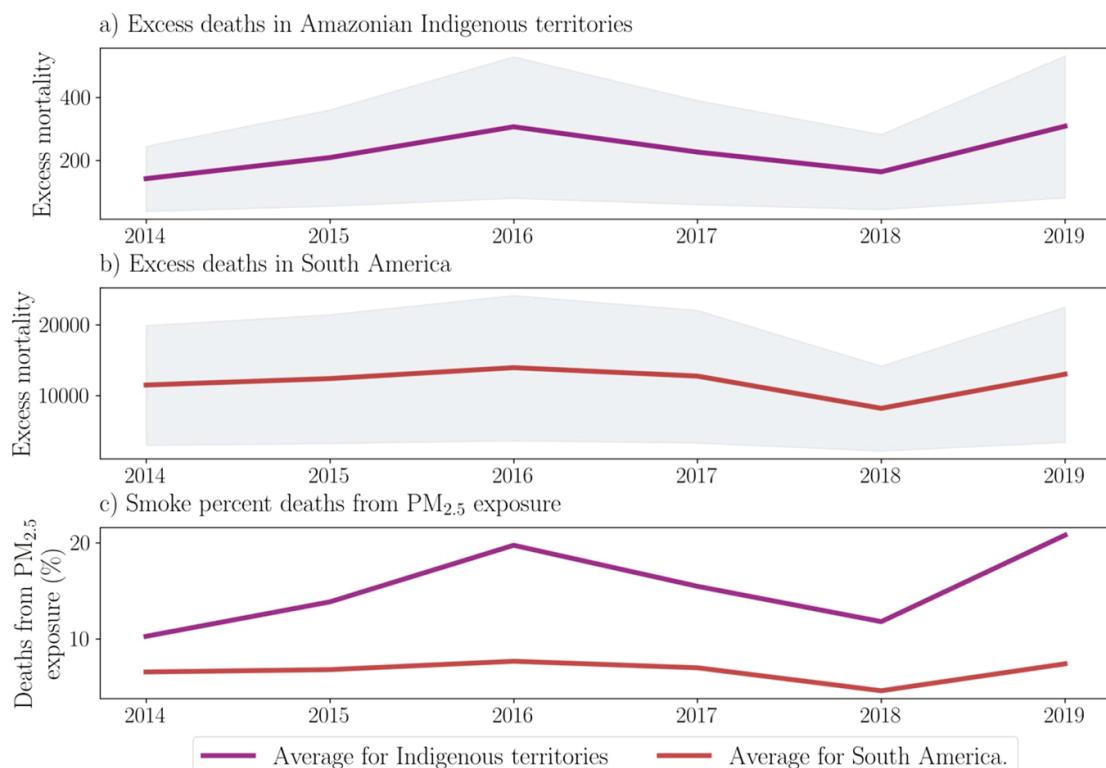


Figure 4. Time series of annual excess mortality due to smoke PM_{2.5} exposure for 2014–2019. Top panel shows the excess deaths in the Amazonian Indigenous territories, and middle panel shows the excess deaths across all of South America. Gray contours in top and middle panels represent the 95% confidence 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 $\mu\text{g m}^{-3}$ 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 $\mu\text{g m}^{-3}$. On an annual average, the Amazonian Indigenous territories experience $1.1 \pm 0.4 \mu\text{g m}^{-3}$ greater total PM_{2.5} and $0.64 \pm 0.21 \mu\text{g m}^{-3}$ 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 ($0.5^\circ \times 0.625^\circ$), 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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