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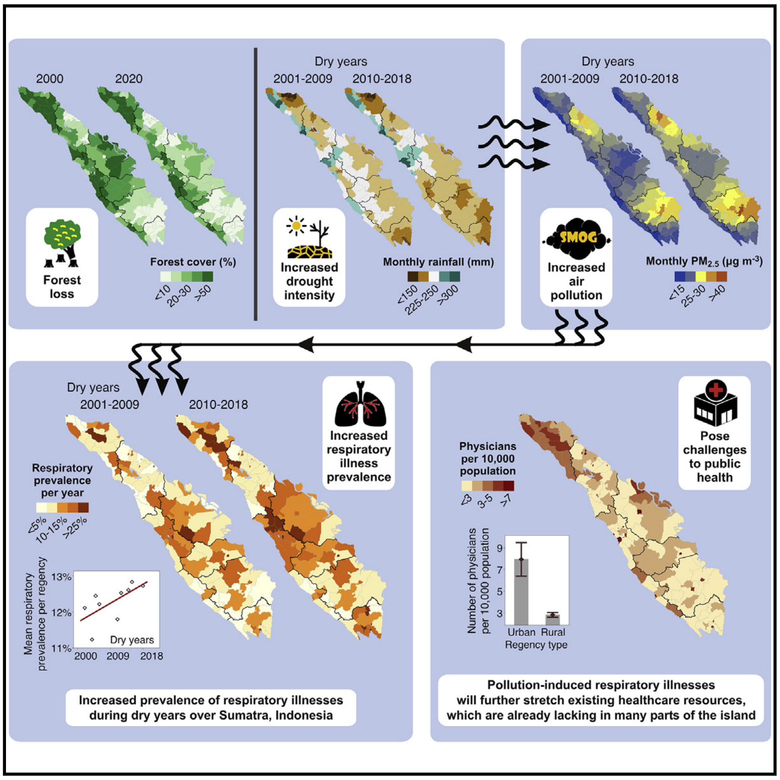
Deterioration of respiratory health following changes to land cover and climate in Indonesia

Graphical abstract



Highlights

- We link respiratory illnesses to land fires and air pollution in Sumatra, Indonesia
- Prevalence of respiratory ailments increased by 8.5% during dry years
- Respiratory ailments are more prevalent in deforested areas, particularly peatland
- Fire-induced air pollution will present a challenge to public health in the future

Authors

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In brief

Land fires occur frequently in Sumatra, Indonesia. However, the magnitude of the health impacts of these fires, especially on respiratory health, and the connection between human activities, pollution, and health are unknown. We linked healthcare attendance for respiratory illnesses with changes in land cover, climate, socioeconomic factors, land fires, and air pollution. We found respiratory ailments increased during dry years and in deforested areas, particularly in peatland. We show how fire-induced air pollution can pose more challenges to public health.

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Deterioration of respiratory health following changes to land cover and climate in Indonesia

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SCIENCE FOR SOCIETY Respiratory illnesses are among the most common diseases globally and are worsened by exposure to air pollution. The risk of pollution causing severe illness is greatest in developing countries where land-use change, healthcare provisions, and weather patterns complicate the study of pollution and health. Resolving the links between human activities, pollution, and health and the magnitude of health impacts can help reveal solutions to reverse current trends.
Sumatra, Indonesia, is famed for its land fires causing transboundary haze. We tracked changes in land cover, climate, socioeconomic factors, and air pollution and linked this information to healthcare attendance over 18 years. We found respiratory ailments increased during dry years and in deforested areas, particularly where fires spread into peatlands. Using data on healthcare facilities, we show how air pollution can further affect respiratory illnesses in the future, posing more challenges to public health.

SUMMARY

Air pollution associated with agricultural activities and land-cover change poses significant health problems in developing countries. However, studies on the respiratory health impacts of these activities are scarce. Sumatra, Indonesia, is a region well known for its frequent land fires and haze. Here, we link data on healthcare attendances for respiratory illnesses between 2001 and 2018 with biophysical and socioeconomic variables known to be important drivers of respiratory ailments. We show that the prevalence of respiratory illnesses increased by 8.5% during dry years over the last two decades. This was largely attributed to changes in rainfall patterns and land cover. Increasingly severe drought during El Niño events, combined with reduced forest cover and increased land degradation on peatland, has further escalated fires with concomitant air pollution impacts on respiratory health. Our study highlights the need to explicitly incorporate health costs of environmental damage into land-use planning and public health interventions.

INTRODUCTION

Respiratory illnesses, such as chronic obstructive pulmonary disease (COPD), asthma, and acute respiratory tract infection (ARI), are among the most common diseases worldwide.[1] In 2017, these illnesses affected 545 million people, an increase of 40% since 1990[2] and representing a global prevalence of 7%. Respiratory diseases accounted for 4 million deaths in 2017 (an increase of 18% since 1990) and were the third leading cause of death after cardiovascular diseases and neoplasms.[2] Although smoking has been the most prevalent risk factor in high-income countries, exposure to ambient air pollution has been the major cause of respiratory diseases in low- and middle-income countries.[2] Resource constraints typical of healthcare systems in these countries further exacerbate the impacts of pollution on human health and well-being.[3–5] Respiratory diseases, such as ARI, can have long-term detrimental effects on fetal development, infants, and children, predisposing them to chronic diseases and morbidity later in life.[6,7] Air pollution in developing countries is associated with socioeconomic factors including poverty, trade, and weak enforcement of environmental laws and standards,[8,9] and it is sourced largely from factories, transport, household solid-fuel combustion, and open burning for agricultural purposes.[5,10–13]

Open burning has been practiced for thousands of years across tropical regions to clear land for agriculture or of crop residues after harvest.[14,15] However, rapid changes from traditional agroforestry systems to extensive monoculture over recent decades have altered fire regimes and have led to more widespread and intense burning.[15–17] Complex interactions between changes in land management, vegetation degradation condition, soil type (i.e., peat and non-peat soil), and climate are increasing the number of landscape fires, especially in dry years during the El Niño-Southern Oscillation (ENSO).[18–20] Landscape fires cause highly elevated particulate matter concentrations over short periods of time.[21–23] During the 2015 El Niño episode, for example, the total particulate matter emissions from fires in Southeast Asia were estimated to be 1.8 Tg over a 2-month period, equating to 2.2 times the annual average between 2002 and 2014.[21] Tropical peatlands that have been deforested, drained, and degraded are more vulnerable to fires during dry seasons,[24–28] and peatland fires release much larger amounts of carbon dioxide and fine particulate matter compared with fires on other soils.[16,22,29–31]

Despite tropical fire events causing severe air pollution and having profound repercussions on health, sparse hospital or healthcare records are unable to provide reliable estimates of the number of people affected.[32–34] Recent advancements in satellite-derived data and modeling between aerosol emissions and relative health risk have enabled the approximation of broad-scale health implications of large-scale fires.[35–37] Nonetheless, uncertainty remains about the real magnitude of impact of these fires on human health. This is especially the case for impacts on the respiratory system across different geographical areas and time periods. Such knowledge would guide tangible public health intervention and land-use planning at the sub-national level.[32–34]

Here we explore the relationship between healthcare attendance for respiratory illnesses and changing interannual tropical land-cover and climate patterns using data from Sumatra, Indonesia (Figure S1), a region known for its frequent land fire episodes. We link data on healthcare attendance for respiratory illnesses between 2001 and 2018 collected by local health agencies (Figure S2) with biophysical and socioeconomic variables known to have important effects on respiratory health (Table S1). Pathways through which change in biophysical and socioeconomic conditions leads to negative respiratory outcomes underlies our analytical framework (Figure S3, Table S2). Respiratory illnesses captured include asthma, COPD, ARI, bronchitis, pneumonia, nasopharyngitis, and influenza. The biophysical variables investigated include the annual rainfall variability (Figure S4), land-cover change (Figure S5), soil type, fire occurrences (Figure S6), and total fine particulate matter concentration ($PM_{2.5}$) from all pollution sources (Figure S7), and the socioeconomic variables include poverty rates and human population density (Figure S8). We specifically answer the following questions: (1) how have rainfall patterns in Sumatra changed over recent decades? (2) How has deforestation and land degradation affected the fire and $PM_{2.5}$ response to rainfall variability and change? (3) What are the associations between respiratory cases and the change in climate, environment, and socioeconomic conditions? By linking multiple datasets, we reconstruct detailed interannual spatiotemporal distribution of respiratory illnesses over the last two decades across Sumatra's 131 regencies (or kabupaten). Using data on the number of physicians in public hospitals and healthcare facilities across Sumatran regencies,[38] we further show how pollution-induced respiratory illnesses can exacerbate local public health challenges.

RESULTS

Sumatra's changing climate patterns

Sumatra's rainfall fluctuates each year and is driven largely by the El Niño (warm) and La Niña (cool) events in the tropical Pacific.[39] Based on rainfall data obtained from the Climate Hazards Group Infra-Red Precipitation with Station (CHIRPS) data,[40] we estimated that the mean annual rainfall over the island between 2000 and 2019 was 235 mm/month (Figure 1A). El Niño phases (in 2002, 2004, 2006, 2014, 2015, 2018, and 2019) typically cause prolonged dry spells, and the annual rainfall during these dry years could be as low as 200 mm/month on average (Figure 1A). On the other hand, La Niña phases (in 2000, 2007, 2008, 2010, 2016, and 2017) typically cause wet weather conditions, and the annual rainfall during these wet years could be as high as 255 mm/month on average (Figure 1A).

The CHIRPS data reveal that there has been a change in rainfall patterns across Sumatra over the last two decades. The interannual rainfall variability was larger after 2010 compared with previous years (95% confidence interval [CI] 220–245 mm for the 2000–2009 period and CI 205–253 mm for the 2010–2019 period, F-test $p < 0.001$; Figure 1B), suggesting that rainfall patterns became more erratic. Moreover, during dry years (when average rainfall is below 235 mm/month, usually coinciding with El Niño events), the mean monthly rainfall reduced by 0.95 mm per year ($p < 0.001$) between 2000 and 2019 (Figures 1C and S9A; Table S3). Conversely, during wet years (when the average rainfall was above 235 mm/month, usually coinciding with La Niña events), the mean monthly rainfall increased marginally by 0.27 mm per year ($p = 0.165$) over the same period (Figures 1C and S9A; Table S3). When considering the seasonal variation in rainfall, we obtained different patterns for dry months (May to October) compared with wet months (November to April). In dry months, the mean monthly rainfall during dry years between 2000 and 2019 reduced significantly by 1.53 mm per year ($p < 0.001$), but during wet years it increased significantly by 0.52 mm per year ($p = 0.03$) (Figure S9B; Table S3). On the other hand, in wet months the mean monthly rainfall remained relatively constant during both dry years and wet years over the 2000–2019 period (Figure S9C; Table S3). This indicates that the region had become increasingly dry during dry years but wetter during wet years, especially in the dry months, and this pattern confirms the broader regional climate change patterns outlined in the latest Intergovernmental Panel on Climate Change (IPCC) report.[41]

Deforestation, climate change, fire, and air pollution

Sumatra lost 25% of its natural forest in the last two decades (Figure 2A). Regencies with a high proportion of peatland were more likely to be deforested during this period (Figure 2B). Deforestation

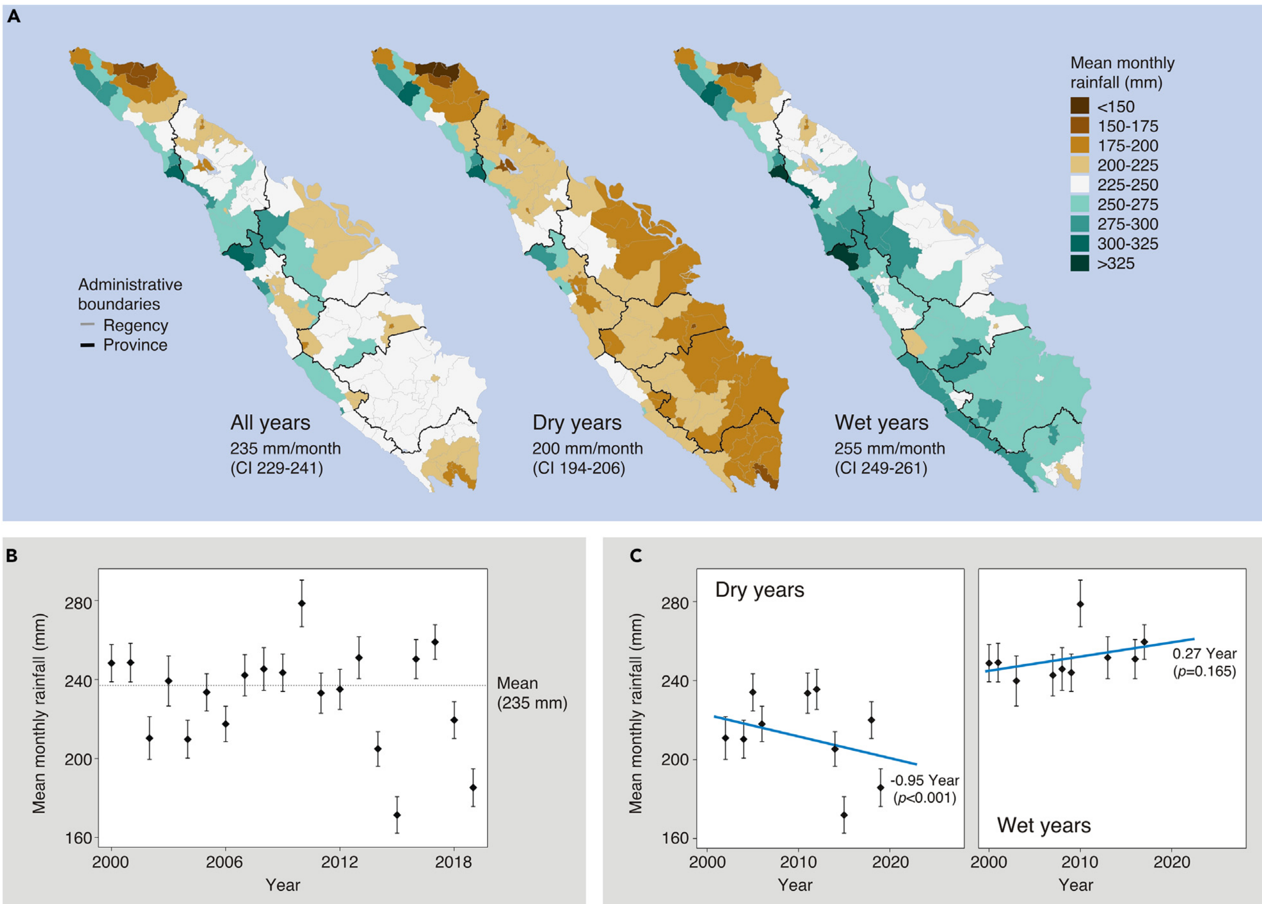

Figure 1. Rainfall distribution and the trends through time

(A) Rainfall distribution across regencies in Sumatra, averaged across all years, dry years (when the average rainfall in a given year is below 235 mm per month; usually coincides with the El Niño event), and wet years (when the average rainfall in a given year is above 235 mm per month; usually coincides with the La Niña event).

(B) The annual trends in mean monthly rainfall across regencies between 2000 and 2019 (with 95% confidence interval [CI] error bars). Rainfall variability is higher after 2010 compared with previous years.

(C) The annual trends in mean monthly rainfall across regencies between 2000 and 2019 (with 95% CI error bars) broken down by dry years and wet years. The regression line shows a significantly decreasing trend for dry years, but a marginally increasing trend for wet years.

was also more prevalent in regencies with a higher proportion of their land allocated to timber and agro-industrial concessions (Figure 2C).

Deforestation and the subsequent land degradation were associated with increased fire occurrences, especially during dry years between 2000 and 2019, but the extent differed between areas on peat soil and mineral soil (Figure 3A). In degraded peatland, the density of fire increased by 0.08 per 1,000 km^2 per year ($p < 0.001$) (Figure 3A; Table S4) following the observed decline in rainfall (Figure 1C), whereas, in degraded mineral soil, fire density had been relatively constant (Figure 3A). In contrast, the fire density in forested areas on peat soil or mineral soil remained relatively low (Figure 3A) despite a reduction in rainfall during dry years. This demonstrates that, in an undisturbed state, tropical peatlands have a high degree of fire resistance, as the entire peat layers, together with the living forest biomass, is nearly permanently moist. However, when peat forests are cleared and subsequently degraded (typically through drainage via canal construction), peatland can no longer sustain its water table against increasing drought intensity, which then leads to increased risk of fire.[16,25,29,42] During wet years between 2000 and 2019, fires were rare regardless of soil type, and the annual density of fires has marginally decreased (Figure 3A; Table S4) following the observed marginal increase in rainfall (Figure 1C).

The density of fires between 2000 and 2019 over Sumatran regencies was positively correlated with the concentration of $PM_{2.5}$, but this relationship varied by soil type and level of forest cover (Figure S10; Table S5). Non-forest areas tend to have higher density of fires than in forest areas due to more extensive human activities and land degradation. However, the ratio between $PM_{2.5}$ concentration and fire density was higher for forest areas compared with non-forest areas, as tropical forest burning produces greater emissions of $PM_{2.5}$ due to higher biomass density compared with fires in savannah, grassland, or crop residue burning in non-forested areas. This suggests that the locations of fire do not necessarily correspond to the locations where there will be the greatest impact on air quality associated with fires.[43,44]

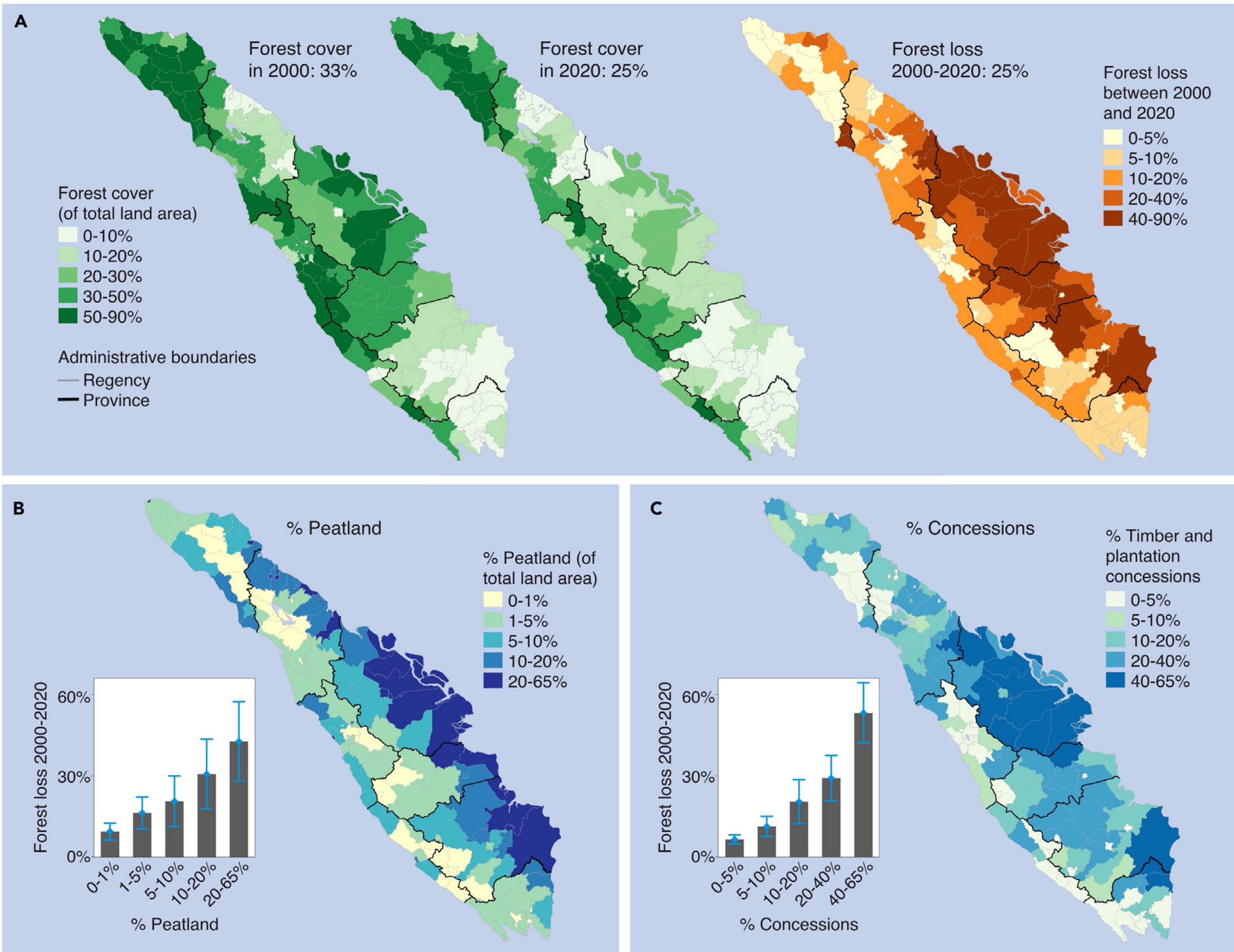

Figure 2. Forest cover and the rates of forest loss

(A) Forest cover across regencies in Sumatra in 2000 and 2020, and the rates of forest loss between the two time periods.

(B) Percentage of regency's land area located on peatland, and the rates of forest loss between 2000 and 2020 by peatland percentage (with 95% CI error bars).

(C) Percentage of regency's land area allocated to timber and plantation concessions, and the rates of forest loss between 2000 and 2020 by percentage of concessions (with 95% CI error bars).

The annual trends in $PM_{2.5}$ concentration (Figure 3B) show similar patterns to the trends in fire occurrences (Figure 3A). During dry years, $PM_{2.5}$ concentration in peatland had increased by 0.78 $\mu g\ m^{-3}$ per year ($p < 0.001$) (Figure 3B; Table S6) following the decline in rainfall (Figure 1C). Conversely, in lands on mineral soil, $PM_{2.5}$ concentration had increased only marginally by 0.18 $\mu g\ m^{-3}$ per year (Figure 3B). During wet years, $PM_{2.5}$ concentration both in lands on peat soil and mineral soil had also increased marginally (Figure 3B; Table S6). The heightening of anthropogenic activities through time, such as increased emissions from industries and vehicles, may be partly responsible for the overall increase in $PM_{2.5}$ for all soil types and climate regimes.

Respiratory cases and environmental change

The prevalence of respiratory illnesses between 2001 and 2018 across Sumatran regencies was estimated to be 12.2% (CI 11.7%–12.7%) or 122 cases per 1,000 people on average per year, almost twice the prevalence at a global level.[2] On a whole, the prevalence appears to have increased marginally over the last two decades (Figure 4A). However, the trend for dry years and wet years differed. During dry years, the prevalence of respiratory illnesses became more prominent; it increased from 118 to 128 cases per 1,000 people between 2001 and 2018 ($p = 0.048$). In contrast, during wet years, the prevalence declined; it decreased from 123 to 114 cases per 1,000 people over the same period ($p = 0.041$) (Figure 4A; Table S7). This pattern is correlated with the change in rainfall patterns across Sumatra over the last two decades (Figure 1B), during which time the local climate became increasingly dry during the drought years but wetter during wet years.

Despite a marginal increase in the overall prevalence between 2001 and 2018, the annual respiratory cases per regency increased markedly by 19.6% (from approximately 38,000 to 47,000 cases, on average) (Figure 4B), linked to growth in the human population.[45] As the number of people populating regencies with considerable extents of peatland (more than 10% of the

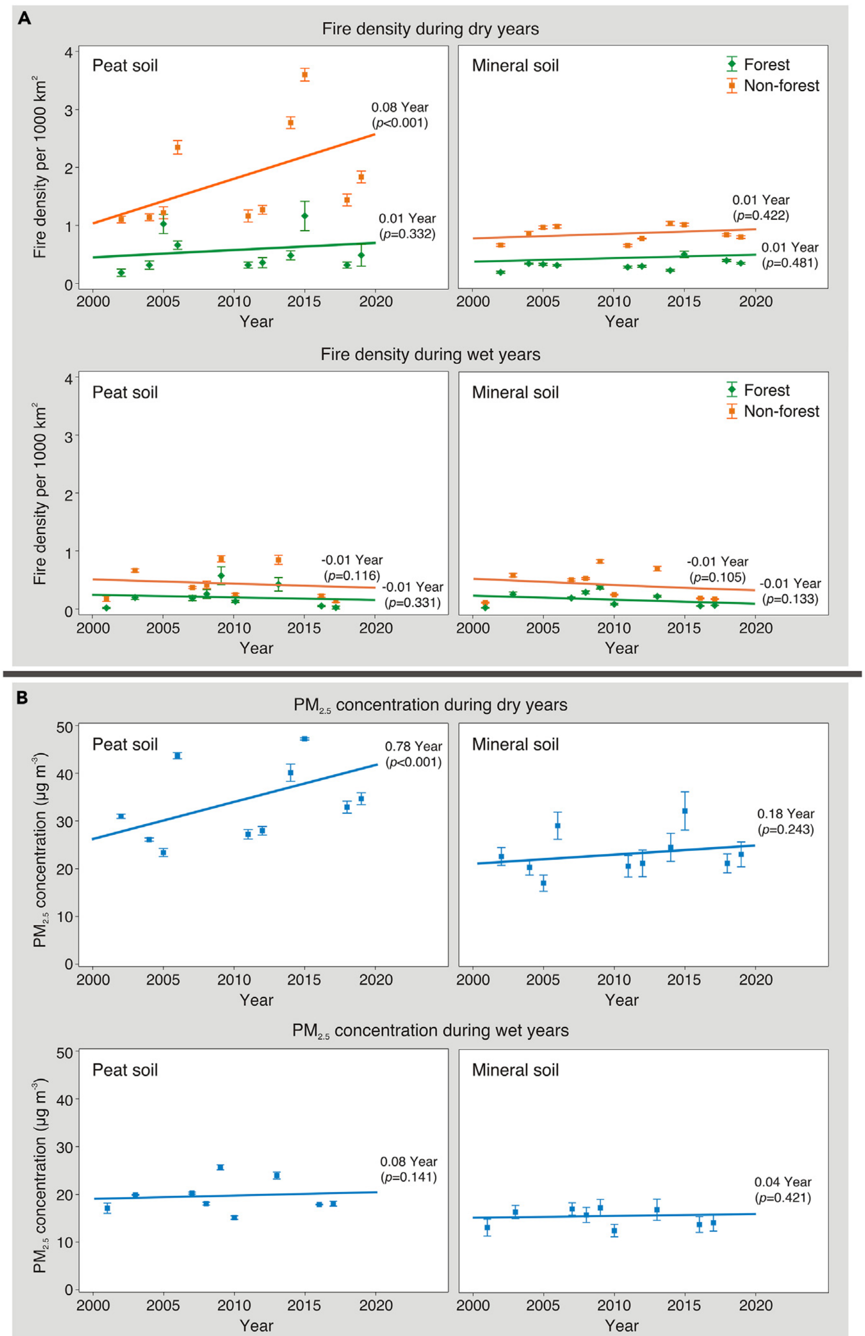

Figure 3. Trends in fire density and $PM_{2.5}$ concentration

(A) Trends in mean annual density of fire across regencies in Sumatra between 2000 and 2019, broken down by rainfall condition (i.e., dry years when the annual rainfall is below 235 mm per month and wet years when the annual rainfall is above 235 mm per month), soil type (i.e., peat and mineral soil), and deforestation status. Error bars represent 95% CIs.

(B) Trends in mean annual $PM_{2.5}$ concentration between 2000 and 2019, broken down by rainfall condition (i.e., dry years and wet years) and soil type (i.e., peat and mineral soil). Error bars are 95% CIs.

total land area on peatland; 37 regencies mostly in the coastland lowlands) is 34% higher than in regencies composed mostly of mineral soil (that is, more than 90% of the total land area located on mineral soil; 94 regencies), the number of respiratory cases in hospitals is also higher in regencies located on peatland. For these peat-dominated regencies, 54,748 people (95% CI, 48,903–60,592) were estimated to be affected by respiratory illnesses annually on average between 2001 and 2018 (Figure 4B). Comparatively, for those regencies mostly on mineral soils, the annual respiratory incidence over the same period was 38,133 people on average (95% CI, 35,865–40,401) (Figure 4B).

We fitted the regency annual respiratory illnesses data (Figure S2) with generalized boosted regression models (GBMs)[46] to explore the link between variation in environmental and socioeconomic factors and respiratory prevalence among regencies. Considering that drivers of respiratory prevalence are likely different between peat and mineral soil, we conducted separate analyses for each soil type. Our findings show that, in regencies with mineral soil, higher prevalence of respiratory diseases was largely associated with reduced poverty (explaining 24.4% of the total variation in respiratory prevalence), increased human population density (21.6%), reduced mean monthly rainfall (19.7%), and reduced forest cover (16.1%), whereas the contributions of urban areas, density of fires, and $PM_{2.5}$ were marginal (<8%) (Figure 5A). On the other hand, in regencies on peat soil, high respiratory disease prevalence was largely associated with reduced forest cover (explaining 20.1% of the total variation in respiratory prevalence), increased fire occurrence (18.3%), reduced mean monthly rainfall (17%), increased $PM_{2.5}$ (16.8%), and increased poverty (13%), whereas the contributions of urban areas and population density were marginal (<8%) (Figure 5B). This implies that respiratory ailments in areas of mineral soil are likely to be directly attributed to higher anthropogenic activities and development following deforestation, such as factories in productive and in developed areas where poverty rates are comparatively low. On the other hand, in areas on peat soil, respiratory illnesses were associated largely with multiple anthropogenic land-use change and environmental effects, such as air pollution from fires due to peatland deforestation and draining in areas where poverty rates are high.

The GBM models allow us to reconstruct the predicted spatiotemporal changes in the prevalence of respiratory illnesses between 2001 and 2018 across all 131 Sumatran regencies

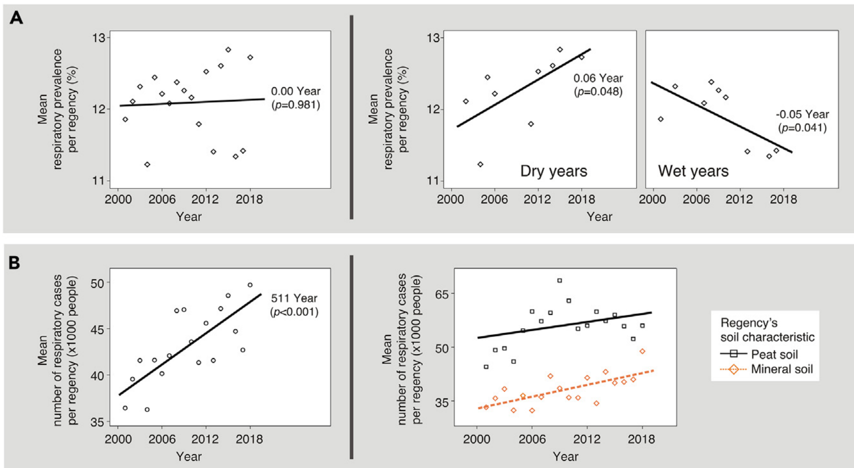

Figure 4. Trends in respiratory illnesses

(A) Trends in the average prevalence of respiratory illnesses across regencies in Sumatra between 2001 and 2018, and the trends broken down by dry years and wet years.

(B) Trends in the mean number of respiratory cases across regencies between 2001 and 2018, and the trends broken down by peat soil regencies and mineral soil regencies.

(Figure S11) and the interannual number of respiratory cases (Figure 6). The models predict the respiratory prevalence data with 98.2% accuracy. Between 2001 and 2009, we estimated 5.15 million (95% CI, 4.83–5.47 million) cases of respiratory illnesses were experienced annually over Sumatra, on average, and this was similar between dry and wet years (Figure 6). However, between 2010 and 2018, the annual respiratory cases increased to 6.15 million (95% CI, 5.74–6.56 million) during the dry years, while the number of cases during the wet years was 5.40 million (95% CI, 5.24–5.56 million).

DISCUSSION

There has been a significant body of literature on the impacts of ambient pollution on respiratory health globally, but contributions from developing countries are underrepresented.[47] Moreover, studies from Southeast Asia are mostly focused on relatively developed countries such as Singapore and Malaysia[32–34] (Table S2). These studies often utilize hospital records in urban areas and concentrate primarily on the physiology and demography of diseases to inform local public health intervention.[48–52] Studies investigating the epidemiology and environmental health of pollution-induced illnesses over broad areas are lacking, and, in the absence of healthcare facility data, have needed to rely on coarse pollution indices or aerosol emission information to estimate the relative risk to health.[35,36] Our study evaluates the large-scale spatiotemporal change in respiratory cases in Southeast Asia, which utilizes time-series hospital and healthcare facility records. This approach allowed for the reconstruction of the annual prevalence of respiratory illness across regencies over the last two decades and revealed how respiratory cases develop in relation to local patterns in climate, land-use, and socioeconomic changes.

We found that the absolute number of respiratory cases over Sumatra increased over the last two decades, and this differed markedly between wet years (associated with the La Niña episodes) and dry years (associated with the El Niño episodes when the risk of fires is high). During wet years, cases increased by 5% (from 5.14 million cases per year over the entire island in 2001–2009 to 5.40 million cases per year in 2010–2018) (Figure 6). However, during dry years, the number increased markedly by 19% (from 5.16 million cases per year in 2001–2009 to 6.15 million cases per year in 2010–2018) (Figure 6). Thus, in recent years, the number of hospital attendances due to respiratory complaints during dry years was 14% higher (or 756,180 cases higher for the whole of Sumatra) on average than during the wet years. Our findings corroborate earlier results from other Southeast Asian cities on the significant increase in hospital outpatient attendance and admissions for respiratory illnesses in the fire and associated haze season (during the dry years) compared with the non-haze season (during the wet years).[48–52] For example, the fire and haze season in the region has been found to be associated with increased lung cancer diagnosis in non-smoking adults[49] and a marked reduction in lung functioning among adolescents.[48]

Ambient air pollution is known to have significant negative repercussions on lung development during the prenatal period (fetal development) and childhood, predisposing children to chronic respiratory illness.[6,7,53] Recent studies have further highlighted the impact of air pollution on the impairment of brain structure and cognitive development in infants and children.[54,55] We did not have detailed data on the age of patients attending and admitted to hospital to be able to estimate the number of children affected by respiratory illnesses. However, data from the National Board for Disaster Management of Indonesia (BNPB) and provincial health agencies that were most affected by haze (captured from various reports; Table S8) indicate that infants and children under the age of 5 years comprised approximately 42% of the total hospital attendance for respiratory illnesses, mainly ARI. Based on this proportion, we estimate that the number of children under the age of 5 years with respiratory health problems during the dry years between 2010 and 2018 across Sumatra is approximately 2.59 million per year, a surge of 314,293 cases during the dry years compared with the wet years. This surge could represent a critical intergenerational loss and the societal long-term costs associated with fire and haze. Poor families with inadequate dwelling conditions and access to sufficient healthcare are likely to bear most of this burden, potentially leading to a poverty trap across generations.[56] It is worth noting that our estimates are based on the year-long hospital attendance on various respiratory complaints, including patients diagnosed with ARI, pneumonia, bronchitis, asthma, COPD, nasopharyngitis, and influenza. Our estimates are therefore greater than those captured by the BNPB or provincial health agency reports, which are often based solely on the incidence of ARI aggregated to provinces with the highest prevalence of fires (Table S8).

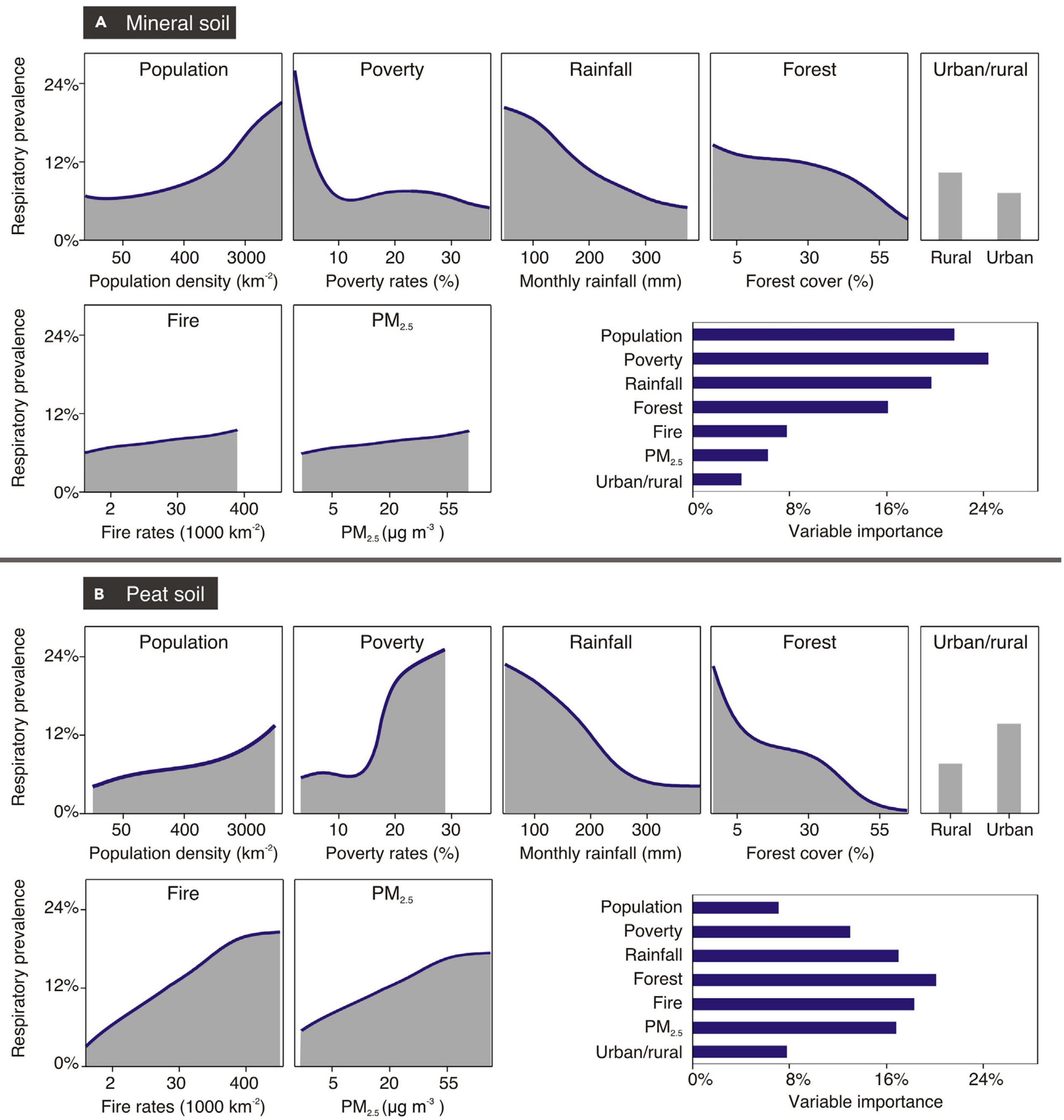

Figure 5. Drivers of respiratory illnesses across regencies by dominant soil type

(A and B) The effects and importance of population density, poverty rates, mean monthly rainfall, forest cover, fire density, $PM_{2.5}$ concentration, and rural-urban area on the prevalence of respiratory illnesses in Sumatra in a given year, for (A) mineral soil regencies (i.e., more than 90% of the total land area is located on mineral soil), and (B) peat soil regencies (i.e., more than 10% of the total land area is on peatland).

Our study provides evidence of the complex interlinkages between the shifts in local climate patterns, land-use and land-cover change, fine particulate matter emission from fire, and respiratory diseases. We found that climate patterns in Sumatra changed over the last decades, with drought becoming more pronounced during the El Niño phase and conversely the intensity of heavy rains increasing during the La Niña phase. Several studies have examined the change in rainfall patterns over Southeast Asia and the Indonesian archipelago, but none have focused specifically on Sumatra, where land fires are most prominent (Table S2). We found that rapid deforestation and land degradation in Sumatra, especially on peatland, increased the vulnerability of soil to extreme drought brought by the El Niño season, and consequently inflated the risk of fire, and the concomitant air pollution and respiratory illnesses in people. Our results corroborate findings from past studies (see analysis scope 2–3

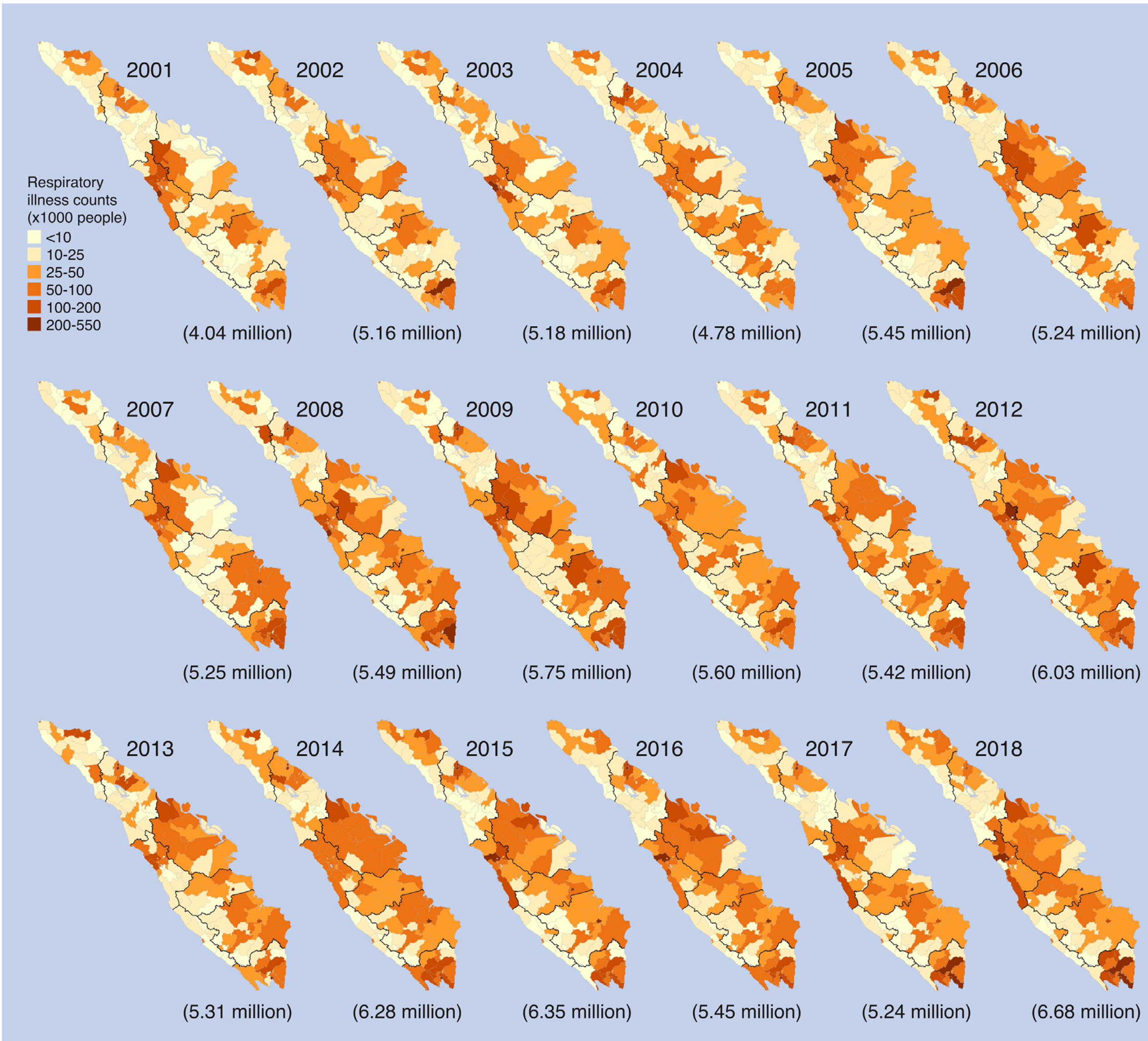

Figure 6. Number of respiratory cases across regencies between 2001 and 2018

These numbers were estimated by the generalized boosted regression models (GBMs). The number inside the parentheses below each map represents the total respiratory cases (as captured from healthcare attendance data) in the corresponding year.

in Table S2 and Figure S3). Existing research has, however, mainly focused on the relationship between climate variability, land-use change, and fire occurrence or air pollution patterns over broad areas using remote sensing and environmental science.[26,57,58] Another body of research has focused on the relationship between ambient air pollution and respiratory illnesses, usually in large cities where hospital data are readily available.[48–52] Bridging these two lines of enquiry, we comprehensively analyzed the path from change in climate and land cover to respiratory health outcomes in an interdisciplinary way.

The rising incidence of respiratory illnesses in Sumatra in the past two decades associated with the complex linkages of deforestation, soil degradation, climatic change, and fire-related air pollution is a significant public health concern. Although public hospitals and healthcare centers across Indonesia have substantially increased in numbers over the same period as this study, this is not commensurate with the rise in the human population, and many of these institutions still lack medical facilities, equipment (e.g., ventilators), and personnel. In Sumatra, four physicians are currently serving 10,000 people, on average[38] (Figure 7A). Although this number meets the national requirement of doctor-population ratio of 1:2,500 (Regulation of the Minister of Law and Human Rights of the Republic of Indonesia No. 34/2016), there are substantial geographical disparities, especially between urban and rural regencies. Our analysis of the public health data[38] shows that 70% of Sumatra's rural regencies are falling below the national requirement (Figure 7B). Indonesia is also behind other Southeast Asian countries in the number of medical doctors

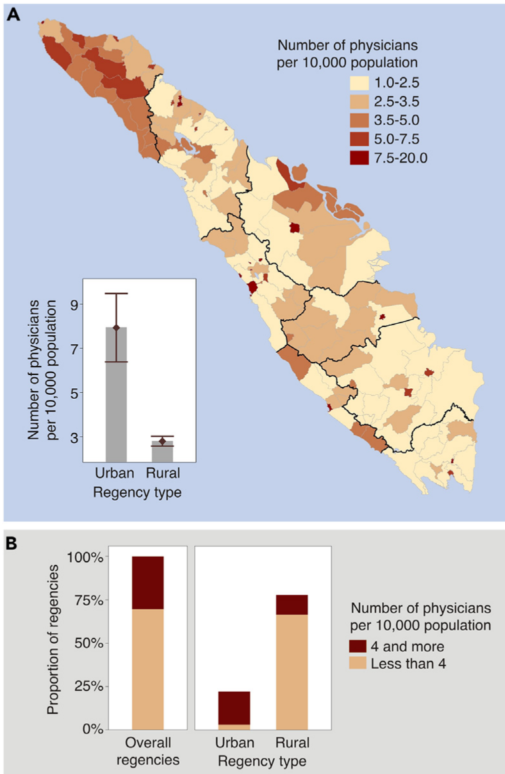

Figure 7. Physician-population ratio

(A) Number of physicians per 10,000 population across regencies in Sumatra, and the average physician-population ratio by urban and rural regencies (with 95% CI error bars).

(B) The proportion of regencies with physician-population ratio below the national standard of four doctors per 10,000 population, and the proportion broken down by urban and rural regencies.

overall, for example compared with Singapore and Malaysia (with 23 and 15 physicians per 10,000 people, respectively),[59] despite experiencing greater problems from land fires, smoke, and haze. As fire and smoke haze are known to have detrimental impacts not only on respiratory health but also on other illnesses such as cardiovascular diseases,[60–62] skin diseases[63–65] and rheumatoid arthritis,[66–68] hospital attendance will likely rise significantly for multiple illnesses during the haze season. Consequently, this will further stretch the local healthcare system (Figure S12), especially in rural areas where extensive fire and smoke occur in disputed lands between local communities and agro-industries.[69,70] Hence, substantial public health investment, particularly during the haze season, will be required.

Almost every year in recent decades, the Southeast Asia region is blanketed with smoke and haze. Smoke and haze from land fires in Sumatra pose significant environmental health threats to residents. Respiratory illnesses may increase as drought becomes more intense in the future due to heightening of the El Niño event.[41] Mitigation measures that can reduce forest and landscape fire are important pre-emptive strategies to mitigate problems related to haze-induced respiratory diseases, and these include (1) moratorium on conversion of natural forest and peatland, especially for development of industrial-scale agricultural or paper/pulp plantations; (2) zero-burning policies on peatland; (3) pre-emptive hotspot surveillance and resource deployment of fire mitigation in fire-sensitive areas during dry years; and (4) restoration of degraded (i.e., deforested, canalized, drained, and converted) peatland ecosystems. The large-scale exploitation of land that occurred in Sumatra over the last decades has resulted in significant environmental damage, with the social and health impacts particularly felt by rural or poorer households. Reducing this societal burden will require active involvement of major land actors and concession holders to adopt fire mitigation measures and ecological restoration and to incorporate the health costs of environmental damage into public health interventions.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Truly Santika (T.Santika@greenwich.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data used in this paper are derived from the cited references or databases. Data and code supporting the findings of this study are deposited at https://doi.org/10.5281/zenodo.7652710 and publicly available as of the date of publication. Any additional information required for reanalyzing the data reported in this paper is available from the lead contact upon request.

Study area and data

We used regency administration boundary and year as the spatial and temporal unit of analysis, respectively. There are 131 regencies across Sumatra over the last 18 years (from 2001 to 2018). We included both urban and rural regencies in the evaluation. The size of urban regencies is substantially smaller than that of the rural regencies (414 km^2 compared with 4,210 km^2, on average), and the population density in urban regencies is also markedly higher (2,738 compared with 135 people per km^2, on average, in 2018).

Yearly hospital and healthcare attendances for respiratory illnesses between 2001 and 2018 were obtained from local health agencies across Sumatra as part of annual censuses conducted by the Bureau of Statistics of Indonesia.[71] We converted the attendance counts to prevalence (per 100 populations). The number of regencies reporting healthcare attendances increased from 13–43 regencies in the period of 2001–2006 to 55–85 regencies in 2013–2018 (Figure S2).

We included biophysical variables rainfall (Figure S4), land-cover change (Figure S5), soil type, fire occurrences (Figure S6), and total $PM_{2.5}$from all sources (Figure S7). Year-on-year mean monthly rainfall figures were obtained from CHIRPS,[40] which combines rainfall precipitation surfaces captured from satellites and precipitation records from rainfall weather stations. Annual land-cover change was estimated by combining data on the extent of primary and secondary forest in Sumatra in 2000[72] and forest loss from the Global Forest Change (GFC) database.[73] Soil type, describing the extent of peat and mineral soil, was obtained from the Peatland Hydrological Map.[74] Monthly fire occurrences were obtained from the MODIS MCD14ML,[75] and monthly $PM_{2.5}$ concentrations were obtained from the Surface PM2.5 database (V5.GL.02).[76] Both the MODIS MCD14ML and the Surface PM2.5 datasets have a spatial resolution of 1 km. Socioeconomic variables, including poverty rates and human population density (Figure S8), were derived from government censuses between 2001 and 2018.[71]

Analytical framework

We performed three stages of analysis corresponding to the three most important nodes within the climate (rainfall), fire, air pollution, and respiratory disease pathways (Figure S3), namely (1) examining the spatiotemporal change in rainfall patterns over the last two decades; (2) evaluating the response of fire and $PM_{2.5}$ to change in forest cover, land degradation, and rainfall variability; and (3) evaluating the response of respiratory illnesses to change in climate, environment, and socioeconomic conditions. The analysis process is outlined below.

Change in rainfall patterns

Several studies have assessed the change in rainfall patterns across Indonesia and the Southeast Asia region, but those focusing on Sumatra are lacking (Table S2). Broad analyses over the region demonstrate that the overall monthly rainfall decreased[77] but variability increased,[78] with rainfall becoming more intense, especially during the wet season (typically between December and March).[79] Informed by these broad-scale studies, we examined the interannual change in monthly rainfall between 2000 and 2019 (derived from the CHIRPS dataset). Given that El Niño and La Niña episodes play important roles in regulating rainfall intensities across the tropics, we further evaluated how rainfall patterns change during the dry and wet years (brought by the El Niño and La Niña phases, respectively). We investigated the shift in rainfall over all months and in different seasons; i.e., dry months (May to October) and wet months (November to April). To verify the trends in rainfall (RAIN) over time (YEAR) in each Sumatran regency i for rainfall regime $r \in$ {dry years, wet years} and season $k \in$ {all months, dry months, wet months}, we fitted the ordinary linear regression models:

$$\text{RAIN}_{irk} = \alpha_{0rk} + \alpha_{1rk}\text{YEAR}_{irk} \quad \text{(Equation 1)}$$

$$\text{for } r \in \{\text{dry years, wet years}\} \text{ and } k \in \{\text{all months, dry months, wet months}\}$$

where α_{0rk} and α_{1rk} are the parameters to be estimated.

Fire and air pollution response to change in land cover and rainfall patterns

Numerous studies have evaluated fire patterns in Indonesia and Malaysia in relation to rainfall variability, soil type, and land-cover change (Table S2). We analyzed data from Sumatra to validate the patterns found in previous studies. For each year and regency, we intersected area defined as forest and non-forest (overlaid data of primary and secondary forest in 2000 and forest loss from the GFC database) with area defined as peat and mineral soil (derived from the Peatland Hydrological Map). These intersected areas formed our unit of analysis. We then calculated the density of fires (derived from the MODIS MCD14ML datasets) in each of these combinations of land cover and soil type (i.e., peat forest, non-forest land on peatland, forest on mineral soil, and non-forest land on mineral soil) each year. Density of fire was then grouped by rainfall regime of dry and wet years (derived from the CHIRPS data). The trends in the density of fire (FIRE) over time (YEAR) in each regency i in rainfall regime $r \in$ {dry years, wet years} and land cover and soil type $l \in$ {1 = peat forest, 2 = non-forest land on peatland, 3 = forest on mineral soil, 4 = non-forest land on mineral soil} were then verified by fitting the ordinary linear regression models:

$$\text{FIRE}_{irl} = \beta_{0rl} + \beta_{1rl}\text{YEAR}_{irl} \quad \text{(Equation 2)}$$

$$\text{for } r \in \{\text{dry years, wet years}\} \text{ and } l \in \{1,2,3,4\}$$

where β_{0rl} and β_{1rl} the parameters to be estimated.

The link between fire occurrence (FIRE) and air pollution level as indicated by the $PM_{2.5}$ (PM25) in each regency i in land cover and soil type $l \in$ {1 = peat forest, 2 = non-forest land on peatland, 3 = forest on mineral soil, 4 = non-forest land on mineral soil} was estimated by fitting the ordinary linear regression models:

$$\text{PM25}_{il} = \gamma_{0l} + \gamma_{1l}\text{FIRE}_{il} \text{ for } l \in \{1,2,3,4\} \quad \text{(Equation 3)}$$

where γ_{0l} and γ_{1l} are the parameters to be estimated. The trends in the concentration of $PM_{2.5}$ (PM25) over time (YEAR) in each regency i in rainfall regime $r \in$ {dry years, wet years} and soil type $s \in$ {peat soil, mineral soil} were further assessed by fitting the ordinary linear regression models:

$$\text{PM25}_{irs} = \delta_{0rs} + \delta_{1rs}\mathit{YEAR}_{irs}$$

$$\text{for } r \in \{\text{dry years, wet years}\} \text{ and } s \in \{\text{peat, mineral}\} \quad \text{(Equation 4)}$$

where δ_{0rs} and δ_{1rs} are the parameters to be estimated.

Respiratory response to changes in land cover, rainfall, fire, air pollution, and socioeconomic factors

Our literature review from studies in Southeast Asia (Table S2) suggests that ambient air pollution affects respiratory health mainly through three types of pollutants: (A) gas and smoke emissions generated from vegetation fire; (B) sand and dust pollutants and gas emissions from smoldering degraded peat (without fire being necessarily detected or observed on the surface); and (C) emissions from solid-fuel households, vehicles, and factories. These three types of pollutants can be driven by the same biophysical and socioeconomic factors, although some factors are likely to be more prominent than others (Figure S3).

Gas and smoke emissions from vegetation fire are thought to be driven by a complex interrelation between atmospheric factors (such as rainfall variability induced by the El Niño episodes), terrestrial factors (such as soil type and land degradation, with drained and degraded peatland being significantly more prone to fire than other land types), and socioeconomic factors (such as poverty, livelihoods, the presence of industrial concessions that are associated with land pressure).[20,80] Atmospheric and terrestrial biophysical factors play significant roles in determining the interannual and regional variability in fire occurrence, whereas the socioeconomic factors may be less critical at the regional level but can be a significant driver at the local level.[20,56] Sand and dust pollutants can be more prevalent during drought, especially in dry lands that had become increasingly arid due to land degradation.[81,82] Drought can also exacerbate the rates of gas emissions from smoldering degraded peat.[16] Unlike pollutant type A (gas and smoke emissions from fire) and type B (sand and dust pollutants, and gas emissions from smoldering peat), which are both significantly driven by biophysical factors such as interannual climate conditions,[16,20,81,82] the intensity of pollutant type C (emissions from solid-fuel households, vehicles, and factories) is likely to be largely attributed to socioeconomic factors and anthropogenic activities that may fluctuate less on an annual basis.[8,83]

We first analyzed the annual trends in respiratory prevalence across Sumatran regencies, overall and broken down by dry and wet years. Ordinary linear regression models were fitted to the relationship between the mean annual respiratory prevalence (RESP) and the year (YEAR) at regency l:

$$\text{RESP}_{ir} = \zeta_{0r} + \zeta_{1r}\mathit{YEAR}_{ir} \text{ for } r \in \{\text{dry years, wet years}\} \quad \text{(Equation 5)}$$

where ζ_{0r} and ζ_{1r} are the parameters to be estimated.

We then evaluated the relationship between biophysical factors, socioeconomic factors, and respiratory prevalence. The biophysical factors include the mean monthly rainfall (RAIN), forest cover (FOREST), fire density (FIRE), and $PM_{2.5}$ concentration (PM25). The socioeconomic factors include population density (POPDENS), poverty rates (POVERTY), and rural-urban categories (URBAN). Considering that the process of fire and the resulting $PM_{2.5}$ emissions differ between peatlands and lands on mineral soil, we fitted a separate model to regencies based on these soil characteristics. We defined peat soil regency as regency with more than 10% of the total land area located on peatland, which comprised 37 regencies mainly located in Sumatra's lowlands. The remaining regencies are then defined as mineral soil regency, which comprised 94 regencies. The 10% threshold was based on the median proportion of peatland area across regencies with peat soil. We fitted a GBM[34] to the respiratory variable (RESP) at regency i and year t:

$$\begin{aligned}\text{RESP}_{it} = {} & f_1(\text{RAIN}_{it}) + f_2(\text{FOREST}_{it}) + f_3(\text{FIRE}_{it}) + f_4(\text{PM25}_{it}) + f_5(\text{URBAN}_i) \\ & + f_6(\text{POPDENS}_{it}) + f_7(\text{POVERTY}_{it})\end{aligned} \quad \text{(Equation 6)}$$

The maximum absolute correlation among predictor variables is 0.456 for mineral soil regencies and 0.519 for peat soil regencies (Figure S13); therefore, we included all these variables in the assessment.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.02.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.S., S.M., S.B., and B.H.; methodology and writing – original draft, T.S., J.Y.T.P., and M.J.S.; data curation, software, formal analysis, and visualization, T.S.; investigation and writing – review & editing, T.S., S.M., S.B., B.H., F.A., K.A.W., M.J.S., and J.Y.T.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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