GEOGRAPHY

Increasing global human exposure to wildland fires despite declining burned area

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Although half of Earth's population resides in the wildland-urban interface, human exposure to wildland fires remains unquantified. We show that the population directly exposed to wildland fires increased 40% globally from 2002 to 2021 despite a 26% decline in burned area. Increased exposure was mainly driven by enhanced colocation of wildland fires and human settlements, doubling the exposure per unit burned area. We show that population dynamics accounted for 25% of the 440 million human exposures to wildland fires. Although wildfire disasters in North America, Europe, and Oceania have garnered the most attention, 85% of global exposures occurred in Africa. The top 0.01% of fires by intensity accounted for 0.6 and 5% of global exposures and burned area, respectively, warranting enhanced efforts to increase fire resilience in disaster-prone regions.

Wildland fires, defined here as fires in vegetated land excluding commercial agriculture areas, have increasingly affected social and environmental systems in various regions across the globe in recent years (*1*, *2*), directly accounting for at least 2500 human deaths and 10,500 injuries from 1990 to 2021 (*3*). Indirect impacts of wildland fires are several times larger and extend for years after the burn (*4*). For example, an annual 1.53 million deaths around the globe are attributable to landscape-fire–induced air pollution (*5*). Fire activity is directly linked with climate and weather (*6*), and climate change has increased the number of days conducive to extreme fire behavior over many fire-prone regions, culminating in a >54% increase in extreme fire weather from 1979 to 2022 globally (*3*), longer fire-weather seasons (*7*), and increased nighttime flammability (*8*).

Human activities can compound or confound the climate change impacts on fire activity (*3*, *9*, *10*). Human ignitions, both intentional and accidental, account for 84% of all wildfires in the contiguous United States (*11*) and for >90% in Mediterranean Europe (*12*). Although lightning ignitions can dominate in more remote regions (*13*, *14*), human activity strongly modifies the timing and locations of fires (*11*, *15*), as well as the vegetation type, structure, density, and continuity, which in turn change regional fire regimes (*16*). For example, the introduction of invasive species in deserts of North America resulted in more frequent and larger wildfires (*17*), whereas agriculturally induced land fragmentation in African savannas reduced burned areas (*18*). Outside of the tropics, humans commonly seek to limit burned area by suppressing fire, but as settlement expands into previously wildland areas, causing the wildland-urban interface (WUI) to grow (*19*), human exposure to fire also grows (*20*). Although the WUI covers only 4.7% of the global land surface, nearly half of Earth's population resides in WUI areas (*21*), and regional and global WUIs have been expanding (*22*, *23*).

The confluence of changing social and environmental controls of fires resulted in a 26% decline in global burned area in the past two decades driven by trends in African savannas (*24*) despite the increased fire extent in temperate and boreal forests (*25*) and the increased occurrence of intense fire events (*26*). Here, we examine the global and regional patterns and trends of human exposure to wildland fires. We further probe the characteristics of wildland fires that affect humans and investigate the role of population dynamics in the overall exposure patterns and trends. Additionally, we investigate patterns, trends, and drivers of population exposure to intense fire events because exposure to such fires has been tied to fire disasters (*2*). We used 18.6 million individual fire records from 2002 to 2021 from the MODIS-based Global Fire Atlas (*18*, *27*) and gridded population data from WorldPop (*28*). We also used MODIS-based land cover and use data (*29*), active fire records (*30*), and vegetation indices (*31*) to exclude nonwildland fires in the Global Fire Atlas (*27*). Our approach does not exclude deforestation and other vegetation-clearing fires, so it does not differentiate between intentional fire use and wildfires. We define human exposure to wildland fire as the number of persons who resided within the burned perimeters, noting that (i) burned perimeters include unburned patches, (ii) consequential human impacts from fires extend well beyond burn perimeters, and (iii) human and societal impacts of exposures to less frequent but more intense fires (e.g., in Western North America) are different from those in the case of frequent low intensity fires (e.g., in African savannas). Exposure to wildland fires can be harmful and devastating, resulting in loss of lives and damage to infrastructure, but not all instances of exposure lead to negative outcomes.

Patterns of global exposure to wildland fire

A total of 440.2 million persons were directly exposed to wildland fires globally from 2002 to 2021 (Fig. 1A), and 85.6% of these exposures occurred in Africa. Although major wildfire disasters occurred in Oceania, Europe, and North America in recent years, these three continents cumulatively accounted for <2.5% of global exposures (Fig. 1B). Cumulative burned area in these wildland fires from 2002 to 2021 was 49.2 million km^2 (Fig. 1C), of which Africa accounted for 64.3% (Fig. 1D). Europe had the highest human exposure per unit burned area, hereafter referred to as exposure density (17.7 persons/km^2), followed by Africa (11.9 persons/km^2). The global exposure density was 8.9 persons/km^2 (fig. S1B).

Spatial patterns of cumulative human exposure to wildland fire, cumulative burned area, and per capita human exposure illustrate the variability in human relationships to fire across latitudes and continents (Fig. 1, A, C, and E). The highest levels of per capita exposure to wildland fire occurred in the tropical savannas of Africa (Fig. 1E and figs. S2 and S3), areas characterized by frequent human- and lightning-started low-intensity fires where populations regularly use fire for land management and agricultural purposes (*16*). From 2002 to 2021, 1.8% of Africa's population was exposed to wildland fire, more than an order of magnitude larger than the per capita exposure on any other continent. Similarly, cumulative exposure to fire was highest in regions such as tropical Africa (*16*), with five tropical African countries accounting for half of the global exposures (Fig. 1A). The high cumulative burned area in tropical Australia and Brazil (Fig. 1C) reflects both naturally started fires and widespread intentional use of fire for regenerative and deforestation practices in sparsely populated to unpopulated areas, whereas moderate cumulative

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burned area in sparsely populated regions of northern Russia and North America reflects increasing wildfire area burned associated with climate change.

Top-quintile events in terms of size, perimeter, duration, speed, and spread rate accounted for the largest fraction of wildland fire exposures (see the supplementary materials, section S1, and figs. S4 to S9).

Trends of global exposure to wildland fire

Global annual exposure to wildland fire increased by 7.7 million persons (+39.6%) from 2002 to 2021 (382,700 persons/year; $P < 10^{-5}$; fig. S1A). Africa accounted for nearly all of the increase (373,000 persons/year; $P < 10^{-7}$; +46.3%). South America (+33.8%), North America (+15.7%), and Asia (+2.8%) experienced nonsignificant increases in exposure to wildland fire from 2002 to 2021, whereas Oceania (–47.3%) and Europe (–17.3%) observed nonsignificant declines (fig. S1A). Interannual variability of exposure to wildland fire and age distribution of the exposed populations are discussed in the supplementary materials, sections S2 and S3 (fig. S10), respectively.

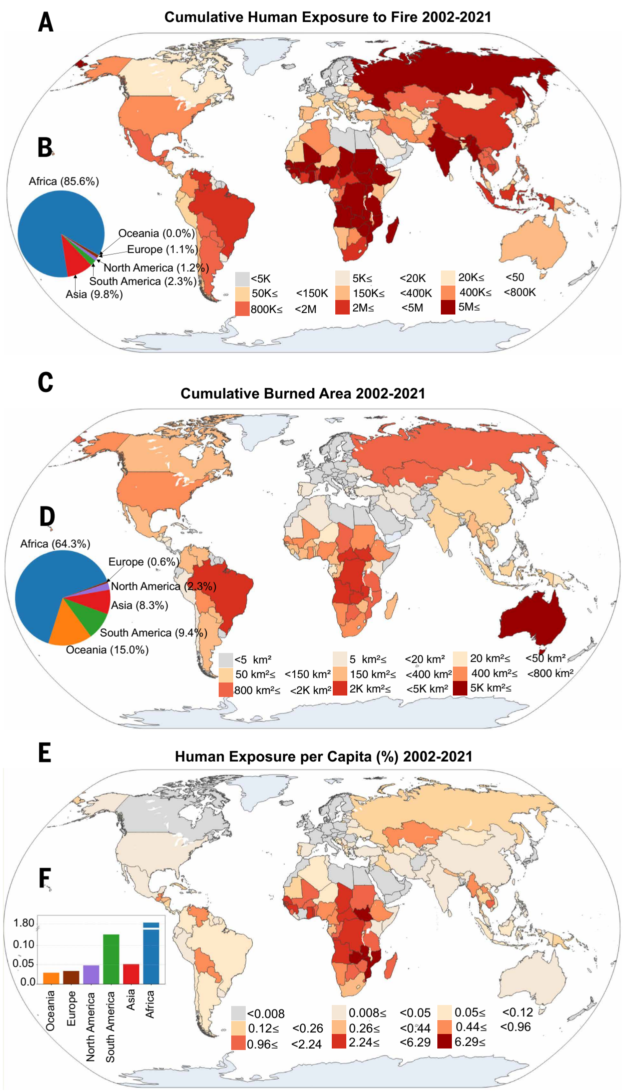

Fig. 1. Human exposure to wildland fires from 2002 to 2021. (**A** and **C**) Cumulative human exposure to wildland fires (A) and cumulative burned area (C) from 2002 to 2021 at the country level. (**B** and **D**) Share of continents in wildland fire exposure (B) and burned areas (D). (**E** and **F**) Percentage of population exposed to wildland fire from 2002 to 2021 in each country (E) and continent (F). K, one thousand; M, one million.

Exposure density also increased globally from 2002 to 2021, exposing an additional 6.2 (+93.4%) persons/km^2 of burned area in these two decades ($P < 10^{-6}$; fig. S1B). All continents experienced rising exposure density, with Africa and Europe showing the largest increases, exposing an additional 7.9 (+90.4%) and 6.8 (+42.3%) persons/km^2 of burned area, respectively, in two decades ($P < 10^{-7}$ and $P = 0.2$, respectively; fig. S1B).

Role of population dynamics in exposure to wildland fire

By applying fixed 2002 population patterns, we developed a counterfactual model to account for the role of population dynamics versus fire dynamics in driving the observed exposure trends. Population dynamics, i.e., population growth and migration, from 2002 to 2021 accounted for 111.3 million exposures to wildland fire in the past two decades globally (25.3% of all global exposures; Fig. 2A). Without the effects of population dynamics, cumulative exposure to wildland fire from 2002 to 2021 would have been between 10.0 and 27.9% lower in Africa, Asia, North America, and South America but 5.0 and 2.3% higher in Europe and Oceania, respectively (Fig. 2). Counterfactual trends in Europe and Oceania were driven by the marginal shrinking of the fire and human settlement overlap from 2002 to 2021 due to a variety of factors, including migration from rural to urban areas.

In the absence of population dynamics, the global exposure to wildland fire would have decreased at a rate of 278,000 persons/year ($P < 10^{-4}$; 27.7% decline in two decades), commensurate with the decline in burned area (Fig. 2A), with counterfactual trends primarily driven by

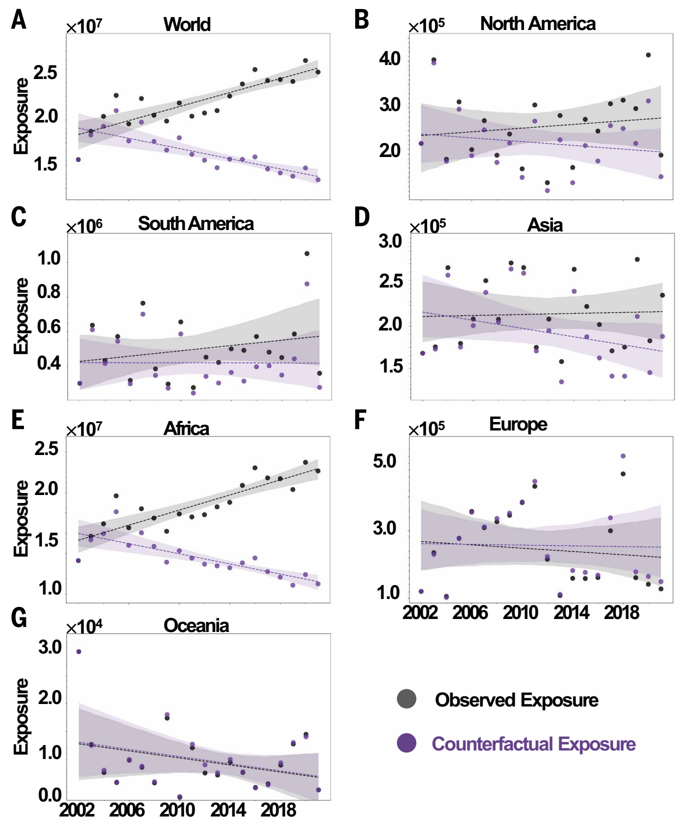

Fig. 2. Contribution of population dynamics to wildland fire exposure. (**A** to **G**) Observed (black) and counterfactual constant-population scenario (purple) exposures to wildland fire from 2002 to 2021 across the globe (A) and in each continent [(B) to (G)]. In observed exposures, both population and burned area data are dynamic, whereas in counterfactual exposures, population is fixed at year 2002 but the burned area is dynamic.

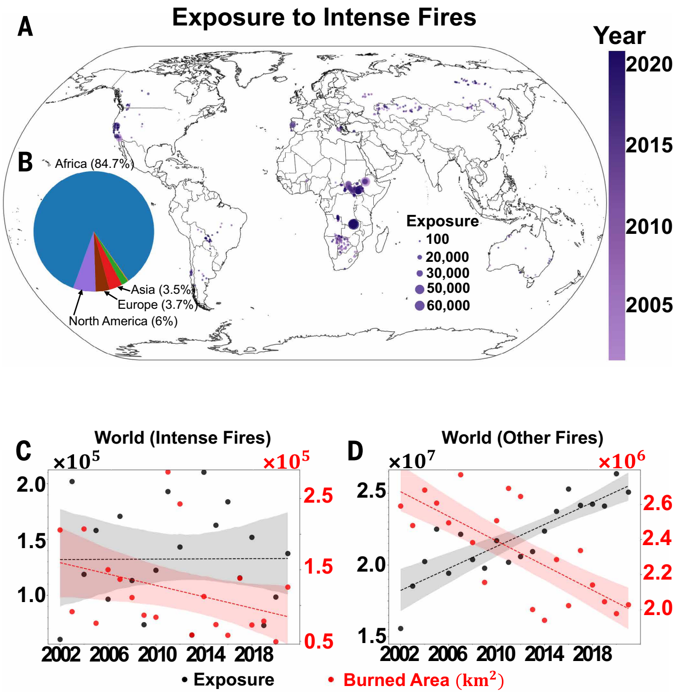

Fig. 3. Population exposure to intense wildland fires. (**A** and **B**) Location, occurrence year, and exposure to individual intense fires that exposed >100 persons from 2002 to 2021 (A) and share of continents in global population exposure to intense fires (B). (**C** and **D**) Trends in annual exposure to and burned area by intense fires globally.

declines in Africa of –250,000 persons/year ($P < 10^{-4}$; –29.8% decline in two decades; Fig. 2E).

Without the population changes since 2002, exposure per unit burned area would have been rather stable globally (1.8% decline in two decades; –0.006 persons/km^2/year; $P = 0.83$), indicating that human influences, including population increase in and migration to fire-prone areas, were the main driver of increasing exposures to wildland fires in the past two decades.

Population exposure to intense wildland fires

Following Cunningham *et al.* (*26*), we define "intense" fires as events with cumulative fire radiative power exceeding the 99.99th percentile of all wildland fires globally (Fig. 3A). Intense fires had a disproportionately large impact, representing just 0.01% of all wildland fires yet accounting for 0.6% of total population exposures (2.7 million persons) and 5.0% of the cumulative burned area (2.4 million km^2) globally. Similar to all wildland fires, 84.7% of global exposures to intense wildland fires occurred in Africa, whereas a significantly higher proportion was observed in North America (6.0% for intense fires compared with 1.2% for all wildland fires). Regional impacts of intense fires were pronounced in North America, Oceania, and Europe, accounting for 3.1% (14.1%), 2.7% (15.2%), and 2.0% (4.1%) of all population exposures to wildland fire (burned area) in each continent, respectively (fig. S11). See fig. S12 for the contribution of population dynamics to exposure to intense fires.

Population exposure to intense fires remained stable globally from 2002 to 2021 (Fig. 3B), with mixed nonsignificant trends in different continents (fig. S11). Global burned area declined both for intense fires (–47.2%; $P = 0.12$) and other fires (–24.9%, $P < 0.01$) (Fig. 3, B and C) in the past two decades. Regional trends, however, showed nuanced differences; for example, burned area by intense fires increased significantly in North America and South America from 2002 to 2021 (fig. S11).

In the wildfire disaster–prone regions (*2*) of Western North America, the Mediterranean, and Southern Australia, where loss of life and property to wildfires has occurred several times, 253,400 persons were exposed to intense fires from 2002 to 2021, accounting for 32.0, 4.1, and 2.8% of all exposures to wildland fire in each region, respectively (fig. S13), far in excess of the 0.6% of global exposures to intense fires. Population exposure to intense fires showed nonsignificant increases in Western North America and Southern Australia from 2002 to 2021 (fig. S13).

Discussion

Fires are complex social-ecological phenomena, and using burned area alone, often a common indicator of fire activity, fails to capture their full impact (*20*). The contrasting trends of burned area and exposure to wildland fire indicate multidimensional relationships among fire, humans, and landscapes (*9*, *10*, *25*, *32*, *33*). Specifically, land fragmentation (*24*) induced by increasing human presence and expanding commercial agriculture in Africa reduced regional burned area but colocated more humans with wildland fires, including intentional fires, and increased their exposure (*3*). Increasing human exposure to wildland fire in North America is due to both expansion of the WUI (*19*) and increasing burned area (*14*), and declining exposures in Europe are due to depopulation of rural areas (*34*), although climatic trends promoted more extreme potential fire behavior in both regions (*35*–*37*). In South America and Asia, population dynamics increased human exposure to wildland fire despite a decline in burned areas from 2002 to 2021.

We found an increasing colocation of wildland fire and human settlements globally and in every continent. Global exposure density roughly doubled in the past two decades, mostly driven by trends in Africa. These trends are consistent with the expansion of the global WUI (*22*, *23*). WUI expansion not only places humans at a higher risk for the negative effects of fire (*19*), it also increases the number of anthropogenic ignitions of fire (*38*).

Effects of intense fires were particularly significant in North America, Oceania, and Europe, coinciding with global hotspots in fire disasters (*2*). Various wildfire mitigation strategies can be implemented in disaster-prone regions to reduce human impacts from fire exposure (*39*), as well as to limit human-caused fires (*40*). In wildfire-prone WUI areas, home hardening, i.e., incorporating structural and landscaping modifications to enhance fire resistance, is essential. There is also a need for increased intentional fire use as a vegetation management tool to mitigate wildfire disasters (*41*–*43*).

Our wildland fire exposure estimates focus solely on direct human exposure and do not account for indirect impacts such as exposure to smoke and postfire debris flow and flood (*44*). As a result, these figures are conservative, and the total number of persons affected by wildland fires directly or indirectly is likely much higher. Extreme fire weather and fire behavior are expected to intensify in a warming climate (*45*), and fires are projected to increasingly affect humans, especially given the population increases and WUI expansions (*23*).

Finally, our analysis indicates that the geography of wildfire disasters is distinctly different from the geography of major human exposures to wildland fires globally (*2*). Most wildfire disasters with the highest fatalities and societal losses have occurred in areas with Mediterranean climates in Australia, Southern Europe, South Africa, Western North America, and the west coast of South America (*2*, *26*, *46*). These wildfire disaster regions are not global hotspots in human exposure to wildland fire. By contrast, our analysis found the highest cumulative area burned and the highest human exposure to wildland fire, both cumulative exposure and exposure density, in regions that have had relatively few wildfire disasters, such as tropical Africa (*2*).

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Supplementary Text; Figs. S1 to S20; Table S1; References (*48*–*61*)

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