

Continuous wildfires threaten public and ecosystem health under climate change across continents

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HIGHLIGHTS

- Wildfire and emission patterns vary globally, intensifying at high latitudes.
- Climate change-driven warming and drought are key in wildfire patterns.
- Wildfires impact health, especially in high-emission areas, lack management.

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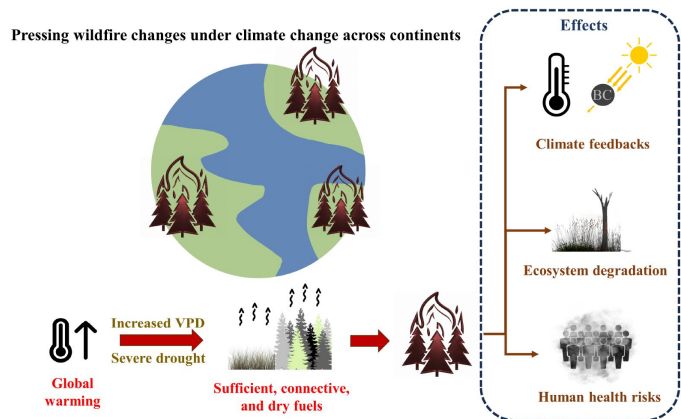
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ABSTRACT

Wildfires burn approximately 3%–4% of the global land area annually, resulting in massive emissions of greenhouse gases and air pollutants. Over the past two decades, there has been a declining trend in both global burned area and wildfire emissions. This trend is largely attributed to a decrease in wildfire activity in Africa, which accounts for a substantial portion of the total burned area and emissions. However, the northern high-latitude regions of Asia and North America have witnessed substantial interannual variability in wildfire activity, with several severe events occurring in recent years. Climate plays a pivotal role in influencing wildfire activity and has led to more wildfires in high-latitude regions. These wildfires pose significant threats to climate, ecosystems, and human health. Given recent changes in wildfire patterns and their impacts, it is critical to understand the contributors of wildfires, focus on deteriorating high-latitude areas, and address health risks in poorly managed areas to mitigate wildfire effects.

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1 Introduction

In the summer of 2023, Canada experienced significant wildfire activities that scorched over 13 million hectares as of July 31, according to the Canadian Interagency Forest Fire Center. This event was estimated to have released over one billion tons of carbon dioxide (CO₂) (Wang et al., 2023). Globally, wildfires contribute approximately 2 petagrams (Pg C) of direct carbon emissions to the atmosphere annually, with widespread impacts on the global carbon cycle (van der Werf et al., 2017; Arora and Melton, 2018; Zheng et al., 2021). Wildfires act as a source of CO₂ on a short-term timescale, as they can exceed the recovery capabilities of vegetation and soil (Zheng et al., 2021). Moreover, epidemiological studies have indicated that smoke from wildfires results in approximately 339,000 deaths (interquartile range [IQR], 260,000–600,000) each year (Johnston et al., 2012). Therefore, wildfires have emerged as a pressing global environmental concern.

Wildfires represent a global environmental challenge, with significant impacts on emissions. Globally, a substantial expansion of regions succumbs to wildfires annually, constituting a significant source of CO₂, black carbon (BC), and fine particulate matter (PM_{2.5}) emissions. Although there has been a general decrease in global wildfire burned area (BA), their emissions were not reduced proportionally and trends vary significantly across continents (Doerr and Santín, 2016; Graham et al., 2021; Tang et al., 2021; Zheng et al., 2021); however, the trends and drivers of wildfires, particularly in the context of climate change, remain insufficiently explored (Holden et al., 2018). In particular, continent-based studies, which could offer unique insights owing to more similar natural and societal conditions within a continent than across continents, are relatively scarce in global-scale research (Song et al., 2024). Our study presents a continent-based perspective on global wildfires from 2003 to 2022, detailing BA, CO₂, BC, and PM_{2.5}, utilizing data from the Emissions Database for Global Atmospheric Research

(EDGAR) and the Copernicus Atmosphere Monitoring Service Global Fire Assimilation System (GFAS). In our paper, we discuss the drivers of these changes, including climate, fuel, and ignition factors, and discuss the repercussions of wildfires on the climate, ecosystems, and human health. Our study underscores the need for heightened research on global wildfire trends in the context of climate change.

2 Trends in burned area and emissions

Vegetation, climate, and policies differ significantly across continents, as do wildfires (Table 1). An average of 3%–4% of the global land area is burned annually by wildfires (Doerr and Santín, 2016; Tang et al., 2021). Despite strong interannual variability, the global burned area shows a declining trend from 2003 to 2022 at approximately 1.5% (95% confidence interval [CI], 1.1%–2.0%) per year. Previous studies have reported that annual carbon emissions from wildfires are approximately 2 Pg C/a, and most of these carbon emissions are in the form of carbon dioxide (Hong et al., 2023). BC, a significant radiative forcing agent, contributes 1.9 Mt (95% CI, 1.7–2.0) annually to the atmosphere as soot from global wildfires, with interannual variability detected across continents (Figs. 1(a) and S1). PM_{2.5}, a crucial pollutant released by wildfires, poses substantial health risks and influences the radiative processes. Wildfires annually release 25.2 Mt (95% CI, 23.1–27.4) PM_{2.5}, especially in days with large nearby wildfires. For example, between October 2019 and February 2020, Australian wildfire emissions of PM_{2.5} exceeded five years of fully anthropogenic emissions, with concentration surpassing 70 µg/m³ generally and 300 µg/m³ in some cities (Graham et al., 2021).

2.1 Asia

Approximately 10.0% of the total BA (95% CI, 9.3%–

Table 1 Profiles of vegetation, climate, policies, and wildfires by continent

Continent	Vegetation	Climate	Policy	Wildfire
Asia	Boreal, tropical forests, peatlands	Cold and wet in high-latitude forest; high temperature and abundant rainfall in tropical	Less management in remote boreal forest and lack of management for tropical agricultural activities	Severe in boreal and likely to worsen; South-east Asia affected by El Niño
North America	Boreal forests, grasslands	Cold and wet in high-latitude forest; hot and dry in western summers	Limited prescribed fires and active fire suppression	Severe in boreal and likely to worsen
Europe	Temperate forests	Hot and dry in Mediterranean summer	Shift from strict fire suppression to prescribed fires	Generally small scale except in occasional years
South America	Tropical forests	High temperature and rainfall in Amazon	Diminished management in Amazon	Severe in Amazon
Africa	Savannas, grasslands	High rainfall in wet season and low in dry season in semi-arid areas	Little and late management	Large scale but decreasing trend
Oceania	Grasslands, forests	High rainfall in wet season and low in dry season in semi-arid areas; moderate rainfall in temperate Southeast	Fire suppression and prescribed fires	Mostly in grassland except 2019–2020

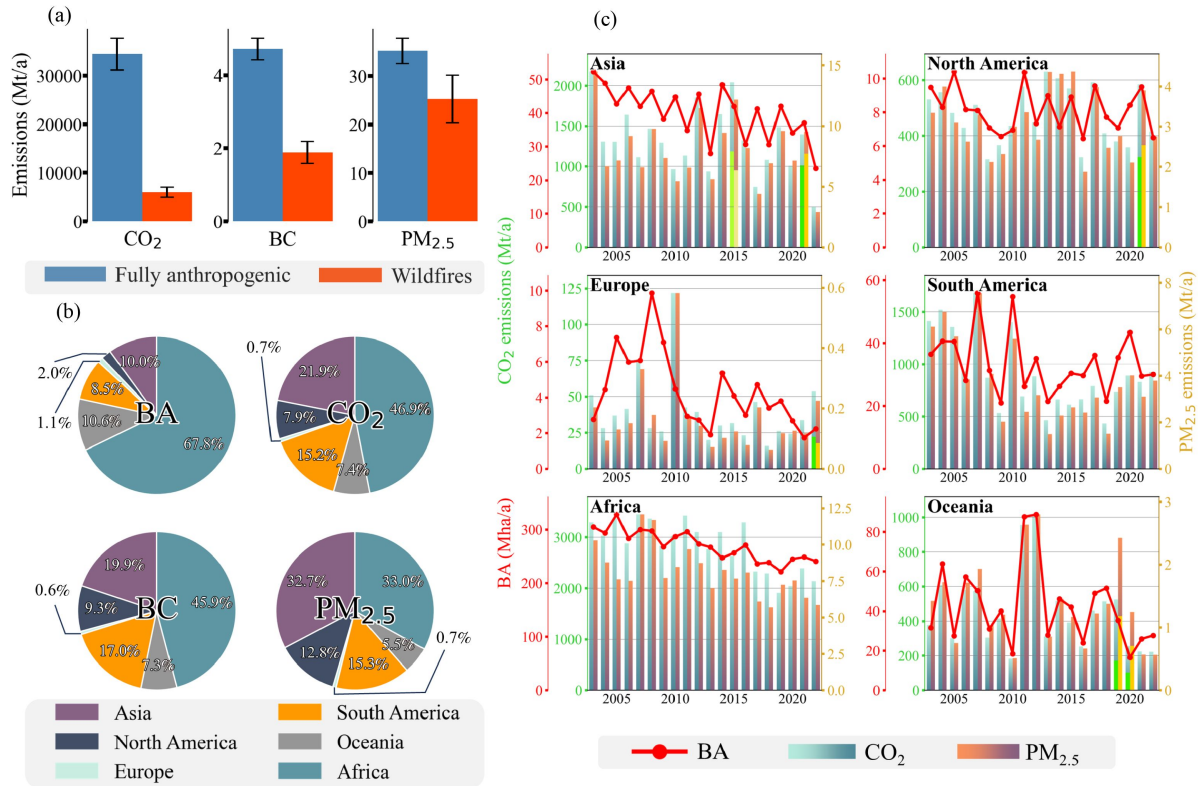


Fig. 1 Recent global wildfire burned area and emissions (2003–2022). (a) Average emissions of CO₂, BC (2003–2018), and PM_{2.5} (2003–2018) from fully anthropogenic (blue) and wildfire (red) sources, with 95% CI error bars. Data from Emissions Database for Global Atmospheric Research (EDGAR) and Copernicus Atmosphere Monitoring Service Global Fire Assimilation System (GFAS). (b) Continental contributions to global cumulative BA and emissions of CO₂, BC, and PM_{2.5}. Data from Moderate Resolution Imaging Spectroradiometer burn product (MCD64A1) and GFAS. (c) Annual continental BA and emissions of CO₂ and PM_{2.5}. Bright bars represent the contributions of 2015 Indonesia, 2021 Siberia and North America, 2022 Mediterranean and 2019–2020 South-east Australia, respectively.

10.7%) and quite considerable emissions occurs in Asia, mainly due to high emission intensity of forest fires (Figs. 1(b) and 1(c)). Asia's vast expanse features significant variations in climate, vegetation, and policies across its regions. Yet, the boreal high-latitude areas and tropical regions are the most affected by wildfires (Fig. S2).

In Siberia, while Russian federal and regional governments oversee most regions, remote areas suffer from ineffective management due to limited financial and monitoring support, leaving wildfires largely influenced by climatic factors (Canosa et al., 2023). Siberia witnessed a surge in fire frequency and the extent of the area burned in 2019, coinciding with unusually high temperature (AMAP, 2021; Kharuk et al., 2021). As the climate warms, the northern and Arctic ecosystems are increasingly susceptible to fires (AMAP, 2021). In 2021, boreal fires contributed ~23% (480 Mt of carbon) of global fire CO₂ emissions, the highest since 2000, with boreal forest (including Siberia and North America, Fig. 1(c)) growing wildfires being a major contributor (Zheng et al., 2023). Some research raised concerns about carbon neutrality in boreal forest due to frequent disturbances in boreal landscapes under climate change,

which is likely to suppress carbon resequstration during growing seasons (Bowman et al., 2009; Veraverbeke et al., 2017; Bowman et al., 2021; Zheng et al., 2023).

In South-east Asia, wildfires are influenced not only by climate, but by conventional slash-and-burn agriculture due to lack of awareness, infrastructure, and policy (Wang et al., 2021). South-east Asia frequently experiences peat fires, largely due to ignition from agricultural activities and land clearing practices (Nechita-Banda et al., 2018). These wildfires are particularly prevalent during El Niño-affected years and can result in extreme fire events. For instance, the 2015 Indonesian fires culminated in an estimated total carbon release of 0.35–0.60 Pg C to the atmosphere (Figs. 1(c) and S2), 5 to 20 times more than in non-El Niño-affected years (van der Werf et al., 2017; Nechita-Banda et al., 2018). Together with an increase in fire susceptibility related to climate change, future agricultural development may pose a significant fire risk.

2.2 North America

In North America, while the burned area constitutes only

2.1% (95% CI, 1.9%–2.2%) of the global total, the emissions are considerable (Figs. 1(b) and 1(c)). Human intervention and management of wildfires in the USA and Canada are substantial. Traditionally, laws aimed to suppress all fires, including indigenous custom fires that help manage the landscape (Nikolakis and Roberts, 2022). However, managers have recently realized that serious fire suppression heightens destructive wildfire risks and started limited hazardous-fuels removal (Kolden, 2019). The proportion of wildfires occurring in western North America has increased in recent decades, and wildfires in non-forest areas show an upward trend, driven by a combination of climate change and human activities (Westerling, 2016; Mueller et al., 2020; Brown et al., 2021; Hessburg et al., 2021; Koshkin et al., 2022). This shift has implications for emissions: while most parts of the USA have seen significant reductions in surface PM_{2.5}, these declining trends have stagnated and even reversed in the western USA, which is largely attributed to wildfires (McClure and Jaffe, 2018; Burke et al., 2022; Wilmot et al., 2022).

2.3 Europe

In Europe, both burned area and emissions are minimal except for a few years influenced by the European part of Russia, with a declining trend in wildfire activities (Figs. 1(b) and 1(c)). This trend was largely attributed to serious suppression policies post-1980s. Although these policies have yielded short-term reductions in wildfire numbers and burned area, they amplify fuel loads and connectivity, increasing the risk of larger fires (Doerr and Santín, 2016; Curt and Frejaville, 2018; Trucchia et al., 2022). In 2022, prolonged fuel accumulation and persistent drought and heatwaves led to severe wildfires in South-west Europe (Fig. 1(c)), with some areas burning at rates 50 times their 2001–2021 median, causing significant economic and ecological damage (Rodrigues et al., 2023). Although policies have incorporated some preventive measures within suppression-oriented actions, there is a lack of management in the hinterland and rural areas, with limited community involvement and inadequate investment in prevention (Chas-Amil et al., 2015; Curt and Frejaville, 2018; Alló and Loureiro, 2020).

2.4 South America

In South America, both burned area (8.4% of total BA; 95% CI, 7.5%–9.4%) and emissions are relatively high, exhibiting a pattern of initially decreasing and then increasing over the past two decades (Figs. 1(b) and 1(c)). During severe drought episodes, such as 2005, 2007, and 2010, fire emissions increased 1.5 to 2.8 fold compared with non-drought years (Fig. 1(c)) (Ye et al., 2022). In Amazon, wildfire activities decreased from 2005 to 2013 due to strict policies related to deforestation, then rose following policy reversals (Zheng et al., 2021).

2.5 Africa

Africa contributes the most burned area (68.0% of total BA; 95% CI, 66.2%–69.8%) and emissions (Figs. 1(b) and 1(c)), mainly because of broad fire-prone savanna and insufficient management. Wildfire management in these regions is often inadequate and delayed due to resource constraints and remote distances. While human-induced fires occur in slash-and-burn agricultural regions, more burning takes place in protected areas and remote landscapes that are outside the scope of management, thus making African wildfires largely influenced by climate (Cassidy et al., 2022). Over the past two decades, both the BA and emissions in Africa have shown a downward trend (–1.4%; 95% CI, –1.7% to –1.0%) (Fig. 1(c)), a change largely due to agricultural expansion and reduced precipitation in savannas, which results in decreased fuel loads (Andela and Van Der Werf, 2014; Wei et al., 2020).

2.6 Oceania

Oceania also contributes relatively large burned area (10.6% of total BA; 95% CI, 8.5%–12.3%) and emissions (Figs. 1(b) and 1(c)). Australia has implemented preventative and risk-based wildfire management policies (Gonzalez-Mathiesen et al., 2021), but it has witnessed an infrequent extreme wildfire in recent years. During 2019–2020 “black summer” in South-east Australia, just a few months of intense wildfires released 179–715 M tons of CO₂ and over 1 M tons of PM_{2.5} (Fig. 1(c)) (Li et al., 2021; van der Velde et al., 2021). Unlike regular savanna fires in northern and central Australia (e.g., 2011 and 2012), infrequent extreme eucalyptus forest fires in South-east Australia likely create a relative CO₂ imbalance, as the slow-growing forest may not sequester carbon in short-term to offset the emissions (Bowman et al., 2021; van der Velde et al., 2021).

3 Factors influencing wildfires

Wildfires occur when the combined influence of meteorological conditions, fuel availability, and ignition factors reaches a critical threshold (Williams et al., 2019; Pausas and Keeley, 2021). However, under the important influence of global climate change, significant changes have occurred in these factors, particularly in meteorological conditions, leading to variations in the wildfire patterns. Meteorological conditions serve as the direct catalyst for wildfires. Extreme fire weather conditions, characterized by drought and high temperature, facilitate the rapid spread and challenge of containment efforts. With climate change, many regions are expected to experience an increase in such extreme fire weather events in the future (Jain et al., 2022).

The alteration of meteorological conditions driven by

global climate change is a primary factor contributing to changes in wildfire patterns (Fig. 2). Increased vapor pressure deficit (VPD) is an important manifestation of this, which increases evaporation demand and then exacerbates wildfires (Holden et al., 2018; Williams et al., 2019; Mueller et al., 2020). Over 50% of the increased BA in the western USA since 1985 is linked to anthropogenic climate change, characterized by rising temperatures, increased droughts, longer fire seasons, and earlier snowmelt (Abatzoglou and Williams, 2016; Schoennagel et al., 2017), with further increased BA expected by mid-century (Yue et al., 2013; 2015). Precipitation affects fuel loads and moisture, enhancing vegetation growth in wet season and modulating dryness and VPD in fire season (Holden et al., 2018; Jain et al., 2022). Furthermore, persistent reductions in precipitation coupled with rising temperatures could intensify wind-driven fires by increasing oxygen supply and evapotranspiration (Ruffault et al., 2018; Pausas and Keeley, 2021).

Fuel availability is the key factor in wildfires. In low-productivity savannas, limited biomass and fuels restrict fire spread, making rainfall's role in vegetation growth more crucial than its impact on moisture deficits (Williams et al., 2019; Richardson et al., 2022); consequently, reduced rainfall may result in smaller BA in Africa (Andela and Van Der Werf, 2014). In tropical South America, the expansion of forest-savanna transitions potentially increases fire risks due to more flammable grasses (Hirota et al., 2010; Abades et al., 2014). In high-latitude regions, permafrost thawing can release flammable old carbon yet kill above-ground vegetation, while boreal areas lower fire risks by replacing coniferous

forests with deciduous ones (AMAP, 2021). Additionally, changes in insect populations and forest diseases can cause tree mortality without promoting fire-resistant species and can increase drier and more flammable surface fuels (Stephens et al., 2018; Fettig et al., 2022). Human activities impact wildfires differently: aggressive fire suppression, like in the Mediterranean, reduced incidents but led to fuel accumulation (Pausas and Keeley, 2021; Rodrigues et al., 2023), while in select regions of North America and Australia, prescribed fires—which consume a portion of accumulated fuels under acceptable weather conditions and fuel loads—can decrease fuel loads and moderate wildfire severity, though quantification remains elusive (Fernandes and Botelho, 2003; Kolden, 2019).

Lightning and human activities are the primary ignition factors for wildfires. Lightning, accounting for half of recorded ignitions, often strikes remote locations and is projected to increase with global warming (Read et al., 2018; Tymstra et al., 2020; Pérez-Invernón et al., 2023; Tian et al., 2023), potentially causing larger affected areas (Veraverbeke et al., 2017; Coogan et al., 2019; Hessilt et al., 2022). Human activities are responsible for the other half, particularly in populated regions. Despite rapid response fire suppression in these areas, there are more ignition sources, such as cultural practices, agricultural activities, and powerline failures (Williams et al., 2019; Fang et al., 2021; Pausas and Keeley, 2021; Ying et al., 2021). Urbanization and the expansion of wildland-urban interface (WUI) result in more ignitions, affecting wildfire dynamics (Pechony and Shindell, 2010; Radeloff et al., 2018).

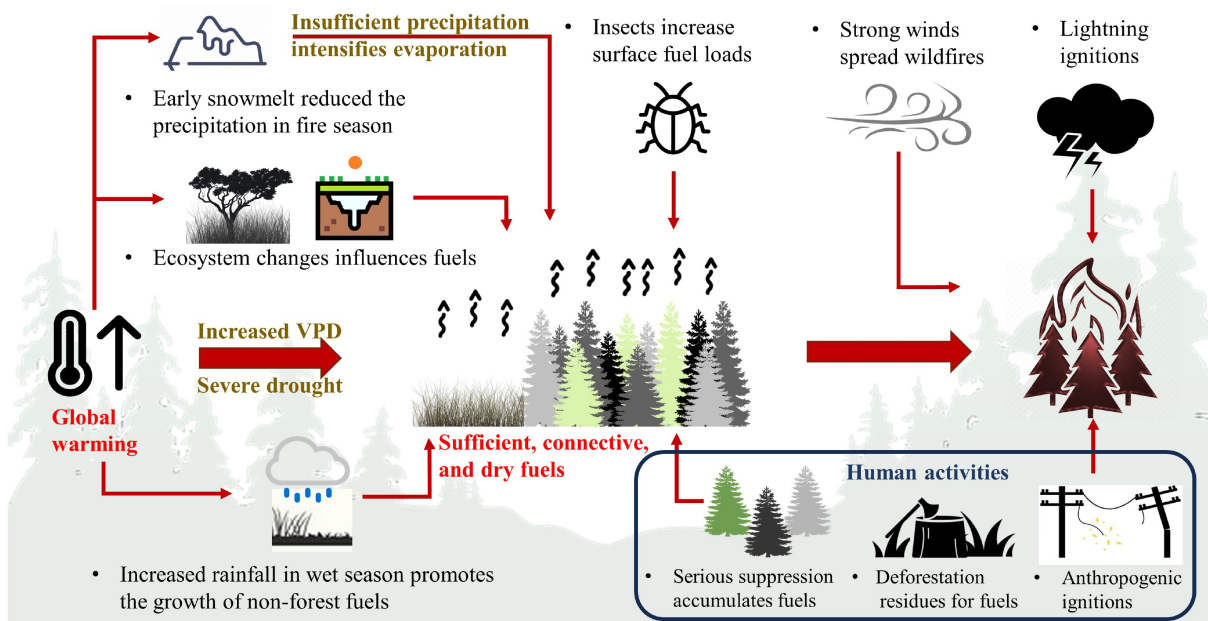


Fig. 2 Factors influencing wildfires. VPD: vapor pressure deficit.

4 Effects of wildfires on climate, ecosystem, and human health

4.1 Effects on climate

Wildfire disturbances can profoundly influence biophysical processes and the Earth's radiative budget, subsequently affecting climate. Forest fires can raise surface temperature for one to five years post-burn by reducing evapotranspiration (Liu et al., 2019), while charred debris from fires reduces albedo depositing on nearby snowpacks, increasing radiation absorption and hastening melt, potentially affecting local precipitation (Fig. 3) (Aubry-Wake et al., 2022; Koshkin et al., 2022). Moreover, large towering pyro-cumulonimbus plumes from wildfires can affect stratosphere (Pausas and Keeley, 2021; Bernath et al., 2022). For example, the 2019–2020 Australian wildfires injected approximately 0.9 Mt of smoke containing 2.5% black carbon by mass into the stratosphere, significantly warming lower stratospheric and depleting ozone over high southern latitudes (Yu et al., 2021; Ohneiser et al., 2022).

4.2 Effects on ecosystem degradation

The aftermath of wildfires invariably affects local ecosystems and can precipitate environmental calamities (Fig. 3). Severe wildfires may overwhelm ecosystem resilience due to factors like the absence of seed sources, warmer and drier post-fire climate, and short-interval reburning, leading to shifts in species composition and the potential conversion of forests to other vegetation types (Steel et al., 2018; Whitman et al., 2019; Coop et al., 2020; Rodrigues et al., 2023). Over large scales, fire-induced forest loss may result in long-term land

degradation, counteracting the increasing trend in forest areas (Rodrigues et al., 2023). Additionally, wildfires can also affect permafrost terrain by altering surface temperature (Holloway et al., 2020). The thawing of permafrost in the boreal zone can cause a transition from initially wet soils to a state of desiccation, eventually increasing dry ground fuels and fire risks (AMAP, 2021).

4.3 Effects on human health

Wildfire smoke, a complex mixture of particulate matter (PM) and gases, is linked with adverse health effects. It releases carbon monoxide (CO), nitrogen oxide, and volatile and semi-volatile organic compounds, which act as precursors of harmful ozone (O₃) and secondary aerosols (Chen et al., 2021b). Wildfire PM_{2.5} is a major seasonal health burden, and it is estimated that wildfire PM_{2.5} emissions approach or exceed anthropogenic PM_{2.5} emissions in large parts of sub-Saharan Africa, Latin America, South East Asia, and Australia, particularly in areas with intermediate population density (10 to 100 people/km²) (Knorr et al., 2017). Consistent epidemiological evidence indicates significant associations between wildfire smoke exposure and respiratory morbidity (e.g., asthma, chronic obstructive pulmonary disease (COPD), and respiratory infections), with widespread global impacts (Reid et al., 2016). Numerous studies also indicate the potential adverse effect of wildfire smoke exposure on cardiovascular morbidity and mortality (Chen et al., 2021a; 2021b; Ye et al., 2022). Chen et al. estimated that 0.64% (95% CI, 0.50%–0.78%) of respiratory deaths and 0.55% (95% CI, 0.43%–0.67%) of cardiovascular deaths annually were attributable to wildfire-related PM_{2.5} exposure (Chen et al., 2021a). Additionally, some research suggests the possible effects

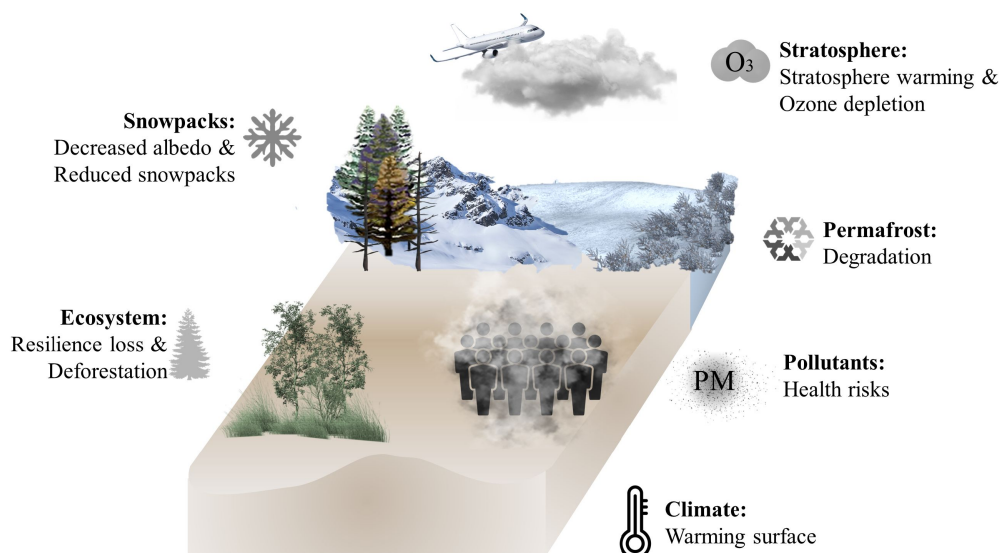


Fig. 3 Effects posed by wildfires.

of wildfire smoke on preterm birth and low birthweight at term (Abdo et al., 2019; Zhang et al., 2023). It is believed that annual deaths caused by wildfire-related PM_{2.5} can lead to substantial economic losses. For example, the annual health burden from wildfire PM_{2.5} in Brazil can be equivalent to approximately 0.1% to 0.2% of GDP (Wu et al., 2023). Under high-emission scenarios, wildfire-related PM_{2.5} mortality and morbidity are projected to increase (Neumann et al., 2021). Regarding O₃, wildfires emit precursors that raise global annual mean O₃ levels (Lei et al., 2021), but the overall impact of wildfires on surface O₃ remains uncertain due to various non-fire factors such as anthropogenic emissions and meteorological conditions related to sunlight (Xu et al., 2023).

5 Perspectives for future research

Our study reveals research gaps in the study of global wildfires, particularly regarding the spatial heterogeneity of wildfire trends, their driving factors, and impacts on the environment and humans across different regions due to distinct climate, vegetation, and fire management practices. We highlight the varying trends in wildfire activity and emissions across continents, revealing distinct drivers. More research is needed in various regions due to different climate backgrounds, vegetation cover, and human intervention.

While there is a wealth of research analyzing the historical trends of wildfires, considerable uncertainty remains in projecting wildfire activities, partly due to uncertainty in projections of climate and meteorological conditions. Although temperature projections exhibit relative consistency, projections for precipitation, relative humidity, and wind events under climate scenarios remain highly uncertain (IPCC, 2021; Tian et al., 2023), increasing the uncertainty in projected BA and emissions. Additionally, ecosystem changes, such as the likely shift from evergreen conifers to deciduous broadleaf trees in boreal zones (Mekonnen et al., 2019), and the underexplored effects of insects and forest diseases, require further investigation due to their impacts on fuel availability and wildfire dynamics.

Research on the implications, particularly in quantifying emissions, remains inadequate due to large uncertainties in both bottom-up approaches using emissions inventories and chemical transport models (Xu et al., 2023), and top-down estimates with satellite data and machine learning (Childs et al., 2022). Future studies should integrate satellite and observational data, along with higher-resolution and more detailed inventories and models to better assess wildfire emissions and their complex interactions with climate and vegetation, as well as to incorporate these emissions into global carbon cycle accounting (Coogan et al., 2019). Research on human health effects of wildfire-related PM_{2.5} is also essential,

requiring differentiation from all sources. However, a more significant challenge arises from the substantial uncertainties associated with the exposure-response functions in epidemiological studies, which exceed those found in geophysical research (Shindell et al., 2024). Focusing on and improving the uncertainties stemming from climate and health effects are essential. Given the frequency of wildfires, the intensity of emissions, and notably significant warming in boreal regions, high-latitude forests are crucial areas for wildfire regime research. However, densely populated area with insufficient wildfire management, where wildfire pollutants significantly threaten human health, such as in sub-Saharan Africa, South-east Asia, and Latin America, also warrant more attention to mitigate the effects of wildfires on human health.

Effective wildfire management is crucial, particularly through the implementation of prescribed fires. In contrast to adverse wildfires, prescribed fires can increase ecosystem resilience to wildfires and minimize smoke impacts (Dombeck et al., 2004; Liu et al., 2017). However, the utilization of prescribed fires remains inadequate in regions prone to frequent and large-scale wildfires (Kolden, 2019). The threat of wildfires under climate change and increased human activity continues to escalate, underscoring the need for effective measures by governments, societies, and scientific researchers to mitigate losses, adapt to wildfires, and coexist with them.

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