SPECIAL REPORT

Wildfires, Global Climate Change, and Human Health

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The world has already observed many devastating effects of human-induced climate change.[1] A vivid manifestation is the several large wildfires that have occurred recently — in some cases, fires of unprecedented scale and duration — including wildfires in Australia in 2019 to 2020, the Amazon rainforest in Brazil in 2019 and 2020, the western United States in 2018 and 2020, and British Columbia, Canada, in 2017 and 2018. Since August of this year, record-breaking wildfires have burned 2.7 million hectares (as of September 18, 2020) along the West Coast of the United States, killing more than 30 people and leaving tens of thousands homeless.[2] Robust projections indicate that the risk of wildfires will continue to increase in most areas of the world as climate change worsens[3-6] and that the fires will increase excess mortality and morbidity from burns, wildfire smoke, and mental health effects.[7-9]

Substantial greenhouse-gas emissions and forest loss from wildfires are likely to accelerate climate change further and possibly lead to a reinforcing feedback loop.[3] This report summarizes the status of wildfires under climate change, current knowledge and gaps about the health risks of wildfires, and challenges of developing and implementing strategies for reducing associated health risks.

CLIMATE CHANGE AND WILDFIRES

For a wildfire to start, three essential conditions (known as the fire triangle) are needed: fuel, oxygen, and an ignition source.[10] Climate change can increase the chances that each of these will be present.

Climate change–related rainfall anomalies can intensify drought in tropical and subtropical areas.[1] Rainfall is becoming more concentrated in winter, making other seasons, especially summer, hotter and drier.[1,3,11] An increase in the evaporation of moisture in soil during dry periods leads to an increase in flammable vegetation that can fuel wildfires, under the assumption that forest management is unchanged.

The global surface wind speed has increased substantially since 2010, after three decades of decrease. This shift is driven mainly by ocean–atmosphere oscillations, such as El Niño events, which might be related to climate change.[12,13] Climate change is projected to enhance differences in temperature between the land and the sea, resulting in greater land–sea differences in air pressure, which boost wind power in tropical and southern subtropical areas.[14] Strong winds provide more oxygen for wildfires and encourage their spread, potentially outstripping firefighting capability.[10]

Increases in the frequency and intensity of heat waves under climate change provide more ignition sources for wildfires.[6,10] Climate change also affects lightning strikes, another important ignition source.[3,15] A study of cloud ice fluxes — changes in the mass of ice particles in clouds over time, which are positively correlated with lightning strikes — projected an overall decrease in lightning strikes, especially in tropical regions, but a likely increase over North America and Siberia.[15]

Furthermore, the wildfire season is starting much earlier and ending later because of a warming climate.[3,6] Consequently, there is a wider window in which wildfires can occur and a narrower window for prescribed burning — deliberate burning of available vegetation during cooler seasons, which is an essential strategy to reduce the risk of wildfires.[3]

Fire suppression and the conversion of tropical savannas and grasslands to agricultural lands have resulted in a decline of approximately 30% in the overall global area of land burned by wild-

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fires since 1930, but the area of land burned in dense forests has increased.[16] Deliberate setting of fires to convert tropical forest to open lands (e.g., agricultural lands, cattle ranches, and lands for real-estate speculation) contributes to climate change and to the associated disease burden through large emissions of greenhouse gases and air pollutants.[1,3,16] Although wildfires and climate change could reduce the availability and growth of vegetation, the risk and severity of wildfires in forests (often alongside human activities) and the area of land burned are expected to increase in the future.[3-6]

The interplay between climate change and wildfires could be reinforcing and synergistic (Fig. 1). From 1997 to 2016, the global mean carbon dioxide emissions from wildfires equated to approximately 22% of the carbon emissions from burning fossil fuels.[3] Forest loss in tropical areas due to wildfires damages the Earth's ability to absorb carbon dioxide and to cool the climate.[18] Wildfires in the Arctic and boreal forest ecosystem could melt the permafrost in that region directly and lead to the release of previously frozen carbon and methane, which is a stronger greenhouse gas than carbon dioxide.[3]

HEALTH RISKS ASSOCIATED WITH WILDFIRES

The health risks associated with wildfires include direct risks from exposure to fires or involvement in wildfire events, as well as risks from wildfire smoke (Fig. S1 in the Supplementary Appendix, available with the full text of this article at NEJM.org).

DIRECT HEALTH RISKS FROM WILDFIRE EVENTS

For firefighters and people living near wildfires, direct health effects include burns, injuries,

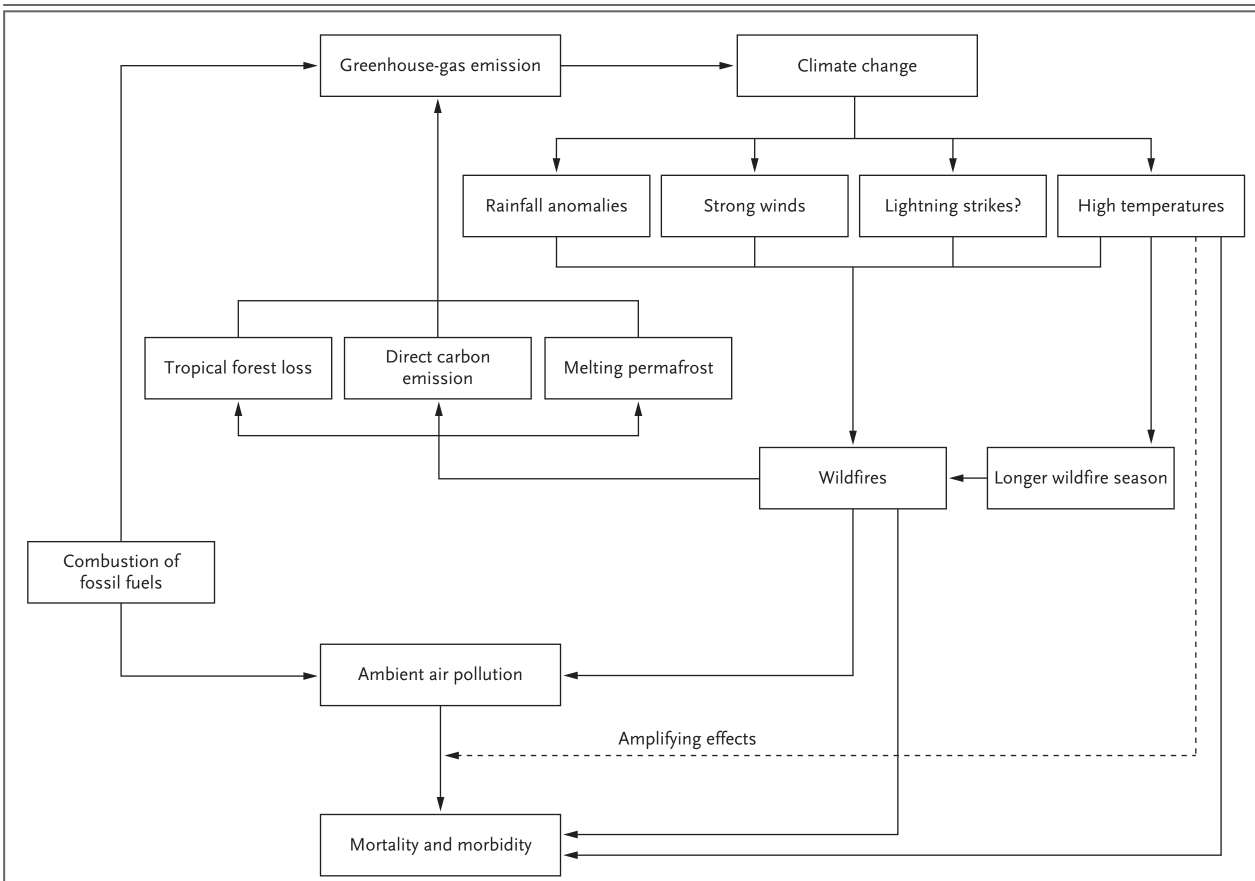

Figure 1. Potential Reinforcing Feedback Loop of Climate Change, Wildfires, and Health Risks.

The dashed line indicates that high temperatures could amplify, or enhance, the effects of ambient air pollution on mortality and morbidity.[17]

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mental health effects, and death due to exposure to flames or radiant heat.[7] For example, the 2009 "Black Saturday" wildfires in Australia killed 173 people directly; in the first 72 hours, 146 patients with burns and 64 with physical trauma presented to local emergency departments.[19] In addition, firefighters are at high risk for heat-related illnesses ranging from dehydration-induced heat cramps to life-threatening heat stroke.[20]

Owing to traumatic experiences, property loss, and displacement, residents in areas affected by wildfires are at an increased risk for mental illness, including post-traumatic stress disorder, depression, and insomnia.[21] The psychological consequences of wildfire events can persist for years,[22] and children and adolescents are particularly vulnerable.[23] A 20-year follow-up study showed that exposure to wildfires in childhood was associated with an increased likelihood of mental illness in adulthood.[24] Furthermore, wildfire events have been associated with a subsequent decrease in academic performance in children.[25]

HEALTH RISKS FROM WILDFIRE SMOKE

In areas surrounding a wildfire, heavy smoke can cause eye irritation and corneal abrasions and can substantially reduce visibility, increasing the risk of traffic accidents.[7] As far as 1000 km away, wildfire smoke can increase ambient air pollution,[26] along with associated risks of illness and death.

Air Pollutants from Wildfire Smoke

The primary air pollutants from wildfire smoke are particulate matter; carbon monoxide; nitrogen oxides, including nitrogen dioxide and nitric oxide; and volatile organic compounds.[27,28] A photochemical reaction between volatile organic compounds and nitrogen oxides under sunlight generates a secondary pollutant, ground-level ozone.[27] Peat fires, such as those that occurred in Indonesia during the 2015 El Niño event, may extend up to 20 m underground and result in an extraordinarily high level of air pollution, including high emissions of carbon dioxide and many potentially toxic compounds, such as formaldehyde and hydrogen cyanide.[29]

The major pollutants of public health concern during wildfire events are carbon monoxide, ozone, and particulate matter.[10] Increases in carbon monoxide are usually restricted to the areas that are directly affected by the fire, but ozone and particulate matter spread much farther.[28] Wildfire smoke is an increasingly important source of ambient air pollution in the United States, where industrial emissions of air pollutants are declining.[30] In the United States between 1997 and 2016, wildfires were a contributing factor on approximately 10% of the days that the surface ozone level exceeded the 8-hour standard (70 parts per billion).[28] Most studies evaluating the health effects of wildfire smoke have focused on the health risks associated with wildfire particulate matter with a diameter of 10 μm or less (PM_{10}) (Table 1). PM_{10} includes fine particles (diameter, ≤2.5 μm [$PM_{2.5}$]), submicronic particles (diameter, ≤1 μm [PM_1]), and ultrafine particles (diameter, ≤0.1 μm [$PM_{0.1}$]); smaller particle size is correlated with a greater toxic effect.[35] Although it is clear that urban background $PM_{2.5}$ has major effects on human health, the evidence specifically for wildfire $PM_{2.5}$ is more limited.

Short-Term Health Effects of Wildfire Smoke

Studies suggest a consistent association between the level of particulate matter during wildfire events and the risk of death from any cause or nonaccidental death, but the association between the level of wildfire particulate matter and the risk of death from specific causes (e.g., respiratory or cardiovascular causes) remains uncertain, possibly because of limited sample sizes (details are provided in Table S1).[8,9,36] In the vicinity of the 2020 California wildfires, the daily mean $PM_{2.5}$ level has often reached 350 to 500 μg per cubic meter, far exceeding the 24-hour standard in the United States (35 μg per cubic meter); as far as 1000 km away from the fires, the daily mean $PM_{2.5}$ level has reached 35 to 150 μg per cubic meter.[2] During wildfire events, each increase of 10 μg per cubic meter in the daily $PM_{2.5}$ level and in the daily PM_{10} level has been associated with an increase of 0.8 to 2.4% and 0.8 to 3.5%, respectively, in the risk of death from any cause or nonaccidental death for up to 4 days after the exposure.[8,9,36] In comparison, in a recent global study, the same change in the daily $PM_{2.5}$ level and the daily PM_{10} level (regardless of the source, with mainly urban sources) was associated with an increase of 0.68% and 0.44%, respectively, in the daily risk of death from any cause.[37] Although this comparison does not account for location-specific modifying factors (e.g., socioeconomic and climatic factors),[37] it suggests that wildfire particulate

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Table 1. Characteristics and Health Risks of Wildfire Particulate Matter.*

Feature	Description
Source	Wildfire particulate matter results from combustion of biomass.[27,28]
Particle size	The particles are smaller than those in particulate matter from urban sources (i.e., with a higher proportion of $PM_{2.5}$ and PM_1 in PM_{10}).[31]
Contribution to ambient particulate matter	In the continental United States in 2000 to 2016, wildfires were a contributing factor on 20% of the days that the daily $PM_{2.5}$ level exceeded the 24-hour standard (35 μg per cubic meter).[30] During the 2019–2020 Australian wildfire, the daily $PM_{2.5}$ level reached 600 μg per cubic meter in Sydney.[32]
Components and toxic effects	As compared with urban background particulate matter, wildfire particulate matter that reaches urban areas may contain more oxidative components (e.g., oxygenated PAHs and quinones) and proinflammatory components (e.g., aldehydes and oxides of nitrogen) and may have greater oxidative potential.[33] As wildfire smoke ages, the oxidative potential can more than double.[34] When wildfire particulate matter reaches urban areas, toxic effects on macrophage cells could be 5 times as intense as effects with the same dose of urban particulate matter, but the effects may vary according to combustion conditions and type of burned vegetation.[35]
Short-term health effects	
Mortality	There is consistent evidence of an increased risk of death from any cause but uncertain evidence of an increased risk of death from specific causes.[8,9,36] Wildfire particulate matter may have a stronger effect on mortality than urban particulate matter,[8,9,36,37] owing to the smaller particle size,[31] more abundant oxidative and proinflammatory components,[33] and amplifying effects of high temperature[17] and ozone.[38]
Morbidity	There is consistent evidence of an increased risk of respiratory events, including hospitalizations and emergency department visits due to asthma, chronic obstructive pulmonary disease, and respiratory infection.[8,9,36,39] Wildfire particulate matter has a stronger effect on the risk of asthma-related events than urban particulate matter.[33,40,41] Data are inconsistent regarding the risk of cardiovascular events,[8,9,36] but the effect may be similar to that of urban particulate matter.[41]
Risk of other health effects	Risks of low birth weight and preterm birth are increased.[8,9] Rates of influenza are increased.[42] Ambulance dispatches among people with diabetes are increased.[43]
Long-term health effects	Effects are largely unknown; wildfire particulate matter might impair lung capacity, self-reported general health, and physical functioning several years later.[44]
Vulnerable populations	Older adults, children, and pregnant women are more susceptible. People with preexisting cardiac or respiratory conditions (or both) have increased risks. People living in low-income areas have increased risks. Outdoor workers have increased exposure.

* Details regarding the short-term health effects of wildfire particulate matter are provided in Table S1 in the Supplementary Appendix, available at NEJM.org. Particulate matter with a diameter of 10 μm or less (PM_{10}) includes fine particles (diameter, ≤2.5 μm [$PM_{2.5}$]), submicronic particles (diameter, ≤1 μm [PM_1]), and ultrafine particles (diameter, ≤0.1 μm [$PM_{0.1}$]). PAH denotes polycyclic aromatic hydrocarbon.

matter could be more lethal than urban particulate matter.

As compared with urban background particulate matter, which results mainly from the combustion of fossil fuels, wildfire particulate matter tends to have a smaller particle size[31] and to contain more oxidative components (e.g., oxygenated polycyclic aromatic hydrocarbons and quinones) and proinflammatory components (e.g., aldehydes and oxides of nitrogen),[33] features that potentially lead to stronger toxic effects.[35] In addition, the high temperatures that often accompany wildfires and the oxidant gases from wildfires (ozone and nitrogen dioxide) can amplify the health risks of wildfire particulate matter.[17,38]

Exposure to wildfire particulate matter is associated with an increased risk of respiratory events, including impaired lung function and hospitalizations, emergency department visits, physician visits, and medication use for asthma, chronic obstructive pulmonary disease, and respiratory infection (Table S1).[8,9,36,39] The associa-

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tion with the risk of asthma-related events has been the strongest and most consistent.[39] Studies also suggest that exposure to wildfire particulate matter might have a stronger effect on the risk of asthma-related events than exposure to urban particulate matter, probably because of the more abundant oxidative and proinflammatory components in wildfire particulate matter.[33,40,41]

There is an inconsistent association between wildfire particulate matter and cardiovascular events (Table S1). Observational studies showed that the association was often not significant, but in many of the studies, power was limited by a relatively small number of cardiovascular events during wildfire periods.[8,9,36] In a large study that analyzed 2.5 million hospitalizations for cardiovascular diseases among Medicare recipients (≥65 years of age) in the United States who were living within 200 km of large wildfires, increases in cardiovascular risk associated with wildfire particulate matter were similar to those associated with urban particulate matter.[41] A small randomized, double-blind, crossover trial showed adverse effects of acute (3-hour) exposure to woodsmoke on central arterial stiffness and heart-rate variability.[45]

Limited data support associations between wildfire particulate matter and adverse pregnancy outcomes (e.g., low birth weight and preterm birth; Table S1),[8,9] increased rates of influenza,[42] and increased ambulance dispatches for patients with diabetes mellitus.[43] Other short-term health effects of exposure to wildfire particulate matter remain largely unexplored.

Few studies have evaluated the health effects of gaseous air pollutants from wildfire smoke other than particulate matter, mainly ozone and carbon monoxide.[8,9,36,39,46] Carbon monoxide poisoning is a potential concern for residents and firefighters during wildfire events.[28,47] The secondary pollutant ozone can travel much farther[28] and should be considered when evaluating the health risks of wildfire smoke.[46]

Long-Term Health Effects of Wildfire Smoke

Data are lacking to quantify the long-term health risks of wildfire smoke. In one study with follow-up data obtained 10 years after the 1997 Indonesian forest fires,[44] people who had been exposed to wildfire smoke had poorer results for lung capacity, self-reported general health, and physical functioning than those who had not been exposed.[44]

Vulnerable Populations Affected by Wildfire Smoke

Populations that are particularly vulnerable to adverse effects of wildfire smoke include people 65 years of age or older, who have an increased risk of short-term respiratory events[40,48]; people with preexisting cardiac or respiratory conditions (or both) and people living in low-income areas, who have an increased risk of short-term cardiopulmonary events[48-50]; and pregnant women, who have a risk of adverse pregnancy outcomes.[8,9] Outdoor workers are also a high-risk group, owing to their increased exposure to wildfire smoke. It is hypothesized that children are more susceptible to harm from wildfire smoke than adults because they have less mature respiratory and immune systems, have a higher breathing rate relative to body size, and spend more time outdoors.[51] Priority should be given to these vulnerable populations when implementing strategies to reduce the health risks of wildfire smoke (e.g., staying indoors or using air cleaners).

PROTECTING HEALTH AGAINST WILDFIRES

It is important for residents in areas affected by wildfires to keep track of reliable information and community evacuation plans during the wildfire season and to gather emergency supplies (e.g., food, water, medication, and N95 or P100 face masks) before wildfires occur.[10] When evacuation is required, it is important to drive with caution in conditions of low visibility.[7] People who present with eye irritation should be screened for corneal abrasions, if possible.[7] Careful triage and planning for each patient before hospitalization can improve the ability of surrounding hospitals to manage increased patient loads.[19]

Personal protective equipment, rest periods, adequate hydration, and health awareness are vital for preventing heat-related illnesses in firefighters.[7,20] Psychological support services are important for addressing mental health effects during and after wildfires, especially in children and the most affected communities.[7,21-24] Wildfire ash, which contains polycyclic aromatic hydrocarbons and heavy metals, can heavily pollute the water and land in affected communities, and these areas must be cleaned after the event, in accordance with guidelines.[7,10] During and after wildfire events, residents in affected areas should avoid drinking from water supplies that could be contaminated by wildfire ash, fire retardant, dead

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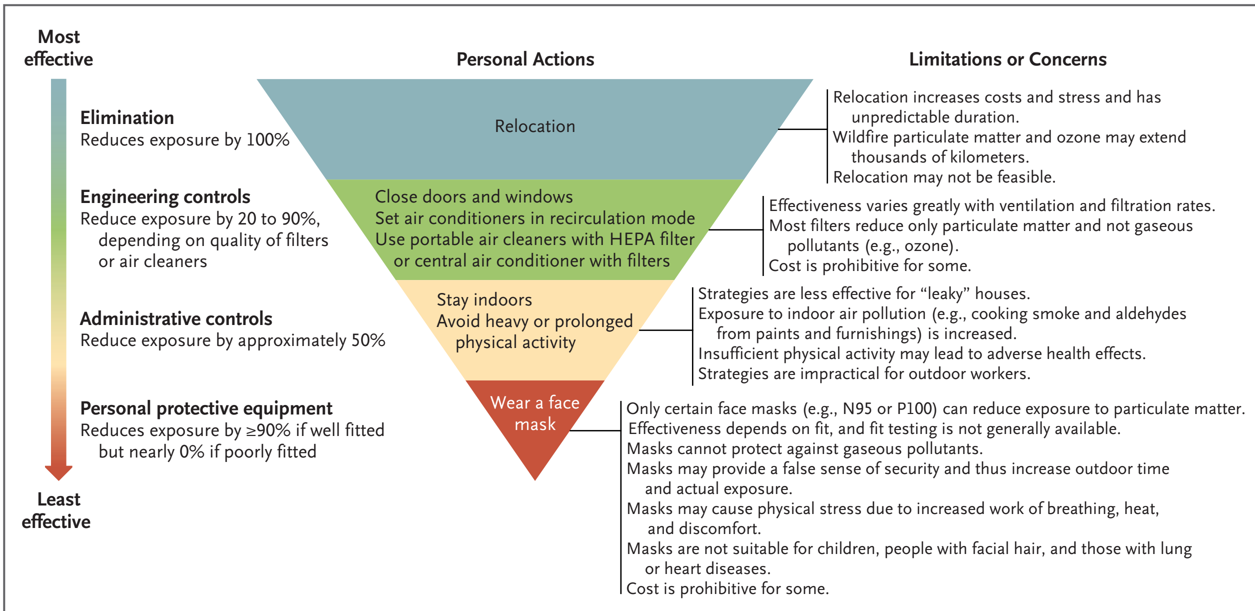

Figure 2. Main Actions That Individual People Can Take to Reduce Exposure to Wildfire Smoke and Its Health Risks.

Data are adapted from the Centers for Disease Control and Prevention,[10] Vardoulakis et al.,[32] and Laumbach.[53] The strategies are organized according to the hierarchy of controls proposed by the National Institute for Occupational Safety and Health (NIOSH).[53] The use of N95 or P100 face masks certified by the NIOSH or their potential equivalents (e.g., KN95 or P95 masks) is recommended. Recommendations regarding the use of face masks, air conditioning, and air cleaners are provided in the Supplementary Appendix, available at NEJM.org. HEPA denotes high-efficiency particulate air.

animals, or damaged water pipes, until testing confirms that the water is safe to drink.[52]

Public agencies are responsible for releasing accurate and clear information regarding air quality and advice regarding health protection against wildfire smoke.[10,32] Residents should keep track of the air quality and adjust their behavior accordingly.[10] When air-quality data are not available, residents should "trust their senses" — that is, use risk-reduction strategies when smoke can be smelled or seen or when visibility is substantially reduced, even when a wildfire is at a distance.[32] Key strategies that individual people can use to minimize health risks associated with wildfire smoke are summarized in Figure 2.[10,32,53]

However, all these strategies have limitations. For example, wearing an N95 or P100 face mask can cause physical stress from increased work of breathing, heat, and discomfort, particularly in the hot weather that is common during wildfire events.[53] Both central air conditioners with high-efficiency filters and portable air cleaners with high-efficiency particulate air (HEPA) filters can reduce indoor levels of $PM_{2.5}$ efficiently, but neither can remove gaseous pollutants, and some electronic air cleaners (e.g., some electrostatic precipitators and ionizers) could even generate ozone.[10] Air cleaners or filters that are designed for removing gaseous pollutants remain limited. The most widely used activated carbon filters can clean volatile organic compounds and odors but not ozone (details are provided in the Supplementary Appendix). Cost is also a concern, especially in the low-income population, given that air cleaners that cost less than $200 are often ineffective in removing air pollutants.[10]

It has been proposed that the use of rescue medications might decrease the respiratory effects of wildfire smoke among children with asthma.[54] However, data are lacking to inform the effectiveness of such medications in this population or in other people with chronic conditions (e.g., asthma, chronic obstructive pulmonary disease, or heart diseases) after exposure to wildfire smoke.

MITIGATING WILDFIRE RISKS BY LIMITING GLOBAL TEMPERATURE INCREASE

Projections indicate that, in a scenario of high greenhouse-gas emissions, the frequency of wild-

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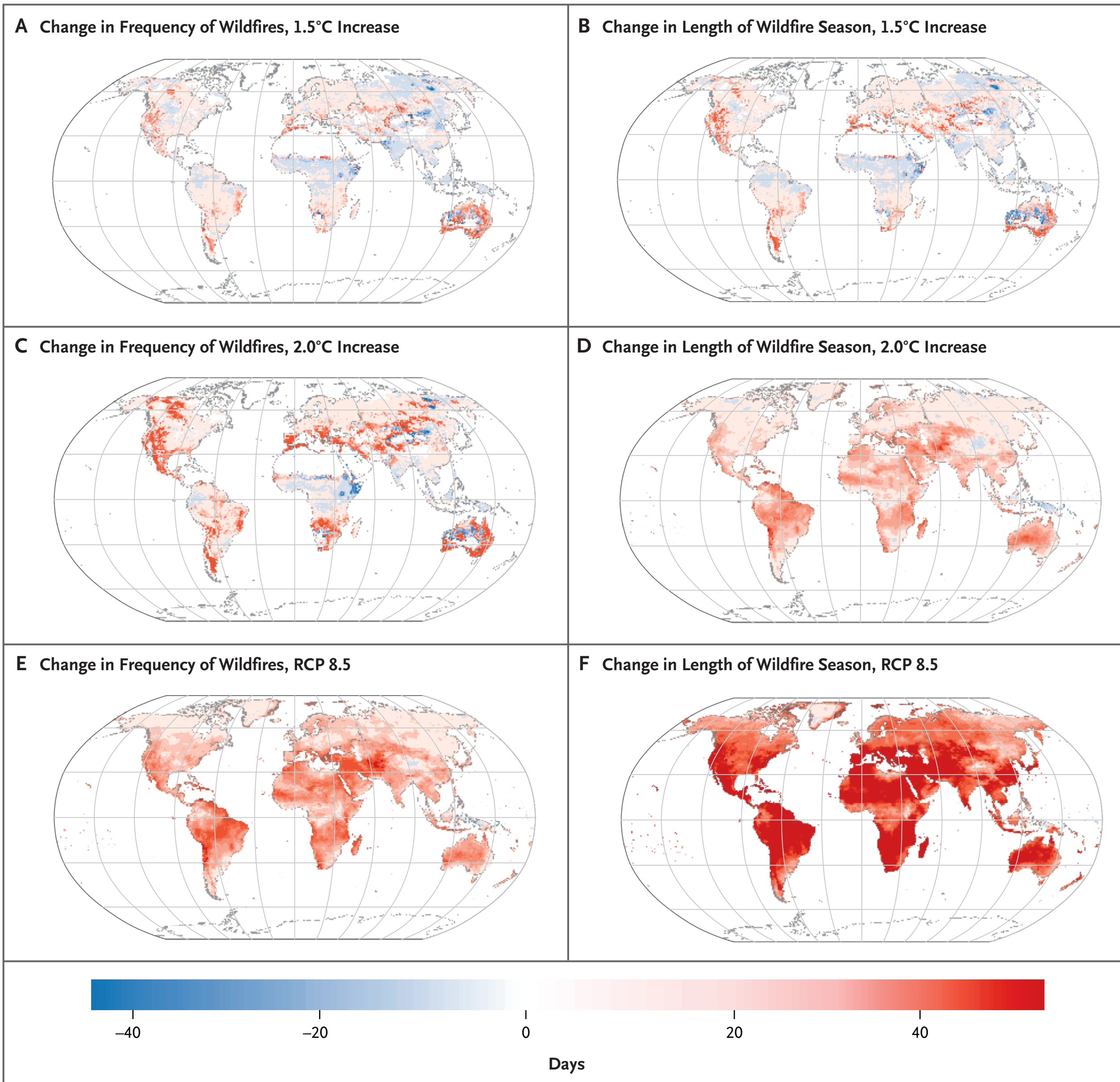

Figure 3. Projected Change from 1981–2000 to 2080–2099 in Frequency of Wildfires and Length of Wildfire Season, According to Global Mean Surface-Temperature Increase.

Adapted from Sun et al.[6] Shown is the projected change from 1981–2000 to 2080–2099 in the frequency of wildfires (days with wildfire events per year) and the length of the wildfire season (days with a normalized daily fire danger index value above a threshold of 50 per year) with an increase in the global mean surface temperature of 1.5°C (Panels A and B, respectively) and with an increase of 2.0°C (Panels C and D, respectively) relative to the preindustrial level. Also shown is the projected change under the conditions of representative concentration pathway (RCP) 8.5 (Panels E and F, respectively), which is a future scenario of high greenhouse-gas emissions and no climate change–mitigation policy, with an increase in the global mean surface temperature of 3.2°C to 5.4°C relative to the preindustrial level (corresponding to an increase of 2.2°C to 4.4°C relative to the 2019 level). Details are provided in the Supplementary Appendix.

fires will substantially increase over 74% of the global land mass by the end of this century.[6] However, if immediate climate change–mitigation steps are taken to limit the global mean temperature increase to 2.0°C or 1.5°C above the preindustrial level, then 60% or 80%, respectively, of the increase in wildfire exposure could be avoided (Fig. 3).[6] Reaching the 1.5°C target

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would require reducing global net anthropogenic carbon dioxide emissions from 2010 levels by approximately 45% by 2030 and reaching “net zero” by around 2050.[1] The 1.5°C target remains achievable if carbon dioxide emissions decline by 7.6% per year from 2020 to 2030.[55]

Cutting carbon emissions may appear to be difficult and costly, but its near-term benefits outweigh its costs in many areas.[56] Even only accounting for the improved air quality due to the reduction in burning fossil fuels, the cost savings associated with reduced mortality and morbidity from exposure to $PM_{2.5}$ and ozone is estimated to be 1.40 to 2.45 times as high as the cost of reducing carbon emissions, albeit with considerable regional variation.[57] The long-term benefits of avoiding health and other risks of climate change, including those associated with wildfires, are additional motivations for urgent climate actions.

As a trusted source, health professionals are responsible for educating the public about the health risks of wildfires and risk-reduction strategies. They can also focus on reducing the carbon intensity of health care systems and advocate for lifestyles, actions, and policies with low environmental impact, such as the rapid transition to renewable energy.[56]

CONCLUSIONS

Wildfires are associated with increased morbidity and mortality, but there are many gaps in knowledge regarding their health effects. At the individual level, people can do little to reduce the adverse health consequences of exposure to wildfires. Societal action is requisite. Without immediate actions to limit the global temperature increase, the interplay between wildfires and climate change is likely to form a reinforcing feedback loop, making wildfires and their health consequences increasingly severe.

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1. Masson-Delmotte V, Zhai P, Pörtner H-O, et al. Global warming of 1.5°C: special report. Geneva: Intergovernmental Panel on Climate Change, 2018.

2. California and Oregon 2020 wildfires in maps, graphics and images. BBC News. September 18, 2020 (https://www.bbc.com/news/world-us-canada-54180049).

3. Bowman DMJS, Kolden CA, Abatzoglou JT, Johnston FH, van der Werf GR, Flannigan M. Vegetation fires in the Anthropocene. Nat Rev Earth Environ 2020;1:500-15.

4. Hurteau MD, Liang S, Westerling AL, Wiedinmyer C. Vegetation-fire feedback reduces projected area burned under climate change. Sci Rep 2019;9:2838.

5. Turco M, Rosa-Cánovas JJ, Bedia J, et al. Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. Nat Commun 2018;9:3821.

6. Sun Q, Miao C, Hanel M, et al. Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. Environ Int 2019;128:125-36.

7. Finlay SE, Moffat A, Gazzard R, Baker D, Murray V. Health impacts of wildfires. PLoS Curr 2012;4:e4f959951cce2c.

8. Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, Elliott CT. Critical review of health impacts of wildfire smoke exposure. Environ Health Perspect 2016;124:1334-43.

9. Black C, Tesfaigzi Y, Bassein JA, Miller LA. Wildfire smoke exposure and human health: significant gaps in research for a growing public health issue. Environ Toxicol Pharmacol 2017;55:186-95.

10. Centers for Disease Control and Prevention. Wildfire Smoke: a guide for public health officials: revised 2019. 2019 (https://www.cdc.gov/air/wildfire-smoke/default.htm).

11. Swain DL, Langenbrunner B, Neelin JD, Hall A. Increasing precipitation volatility in twenty-first-century California. Nat Clim Chang 2018;8:427-33.

12. Wang B, Luo X, Yang YM, et al. Historical change of El Niño properties sheds light on future changes of extreme El Niño. Proc Natl Acad Sci U S A 2019;116:22512-7.

13. Zeng Z, Ziegler AD, Searchinger T, et al. A reversal in global terrestrial stilling and its implications for wind energy production. Nat Clim Chang 2019;9:979-85.

14. Karnauskas KB, Lundquist JK, Zhang L. Southward shift of the global wind energy resource under high carbon dioxide emissions. Nat Geosci 2018;11:38-43.

15. Finney DL, Doherty RM, Wild O, Stevenson DS, MacKenzie IA, Blyth AM. A projected decrease in lightning under climate change. Nat Clim Chang 2018;8:210-3.

16. Arora VK, Melton JR. Reduction in global area burned and

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wildfire emissions since 1930s enhances carbon uptake by land. Nat Commun 2018;9:1326.
17. Shaposhnikov D, Revich B, Bellander T, et al. Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. Epidemiology 2014;25:359-64.
18. Brando PM, Soares-Filho B, Rodrigues L, et al. The gathering firestorm in southern Amazonia. Sci Adv 2020;6(2):eaay1632.
19. Cameron PA, Mitra B, Fitzgerald M, et al. Black Saturday: the immediate impact of the February 2009 bushfires in Victoria, Australia. Med J Aust 2009;191:11-6.
20. Domitrovich J, Sharkey BJ. Heat illness basics for wildland firefighters. Washington, DC: Department of Agriculture, Forest Service, Technology & Development Program, June 2010.
21. Belleville G, Ouellet M-C, Morin CM. Post-traumatic stress among evacuees from the 2016 Fort McMurray wildfires: exploration of psychological and sleep symptoms three months after the evacuation. Int J Environ Res Public Health 2019;16:1604.
22. Bryant RA, Gibbs L, Gallagher HC, et al. Longitudinal study of changing psychological outcomes following the Victorian Black Saturday bushfires. Aust N Z J Psychiatry 2018;52:542-51.
23. Brown MRG, Agyapong V, Greenshaw AJ, et al. After the Fort McMurray wildfire there are significant increases in mental health symptoms in grade 7-12 students compared to controls. BMC Psychiatry 2019;19:18.
24. McFarlane AC, Van Hooff M. Impact of childhood exposure to a natural disaster on adult mental health: 20-year longitudinal follow-up study. Br J Psychiatry 2009;195:142-8.
25. Gibbs L, Nursey J, Cook J, et al. Delayed disaster impacts on academic performance of primary school children. Child Dev 2019;90:1402-12.
26. Kollanus V, Tiittanen P, Niemi JV, Lanki T. Effects of long-range transported air pollution from vegetation fires on daily mortality and hospital admissions in the Helsinki metropolitan area, Finland. Environ Res 2016;151:351-8.
27. Urbanski SP, Hao WM, Baker S. Chemical composition of wildland fire emissions. Dev Environ Sci 2009;8:79-108.
28. Tao Z, He H, Sun C, Tong D, Liang X-Z. Impact of fire emissions on U.S. air quality from 1997 to 2016 — a modeling study in the satellite era. Remote Sens 2020;12:913.
29. Stockwell CE, Jayarathne T, Cochrane MA, et al. Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. Atmos Chem Phys 2016;16:11711-32.
30. Kaulfus AS, Nair U, Jaffe D, Christopher SA, Goodrick S. Biomass burning smoke climatology of the United States: implications for particulate matter air quality. Environ Sci Technol 2017;51:11731-41.
31. Makkonen U, Hellén H, Anttila P, Ferm M. Size distribution and chemical composition of airborne particles in south-eastern Finland during different seasons and wildfire episodes in 2006. Sci Total Environ 2010;408:644-51.
32. Vardoulakis S, Jalaludin BB, Morgan GG, Hanigan IC, Johnston FH. Bushfire smoke: urgent need for a national health protection strategy. Med J Aust 2020;212(8):349.e1-353.e1.
33. Verma V, Polidori A, Schauer JJ, Shafer MM, Cassee FR, Sioutas C. Physicochemical and toxicological profiles of particulate matter in Los Angeles during the October 2007 southern California wildfires. Environ Sci Technol 2009;43:954-60.
34. Wong JPS, Tsagkaraki M, Tsiodra I, et al. Effects of atmospheric processing on the oxidative potential of biomass burning organic aerosols. Environ Sci Technol 2019;53:6747-56.
35. Dong TTT, Hinwood AL, Callan AC, Zosky G, Stock WD. In vitro assessment of the toxicity of bushfire emissions: a review. Sci Total Environ 2017;603-604:268-78.
36. Cascio WE. Wildland fire smoke and human health. Sci Total Environ 2018;624:586-95.
37. Liu C, Chen R, Sera F, et al. Ambient particulate air pollution and daily mortality in 652 cities. N Engl J Med 2019;381:705-15.
38. Lavigne E, Burnett RT, Weichenthal S. Association of short-term exposure to fine particulate air pollution and mortality: effect modification by oxidant gases. Sci Rep 2018;8:16097.
39. Reid CE, Maestas MM. Wildfire smoke exposure under climate change: impact on respiratory health of affected communities. Curr Opin Pulm Med 2019;25:179-87.
40. Borchers Arriagada N, Horsley JA, Palmer AJ, Morgan GG, Tham R, Johnston FH. Association between fire smoke fine particulate matter and asthma-related outcomes: systematic review and meta-analysis. Environ Res 2019;179:108777.
41. DeFlorio-Barker S, Crooks J, Reyes J, Rappold AG. Cardiopulmonary effects of fine particulate matter exposure among older adults, during wildfire and non-wildfire periods, in the United States 2008-2010. Environ Health Perspect 2019;127:37006.
42. Landguth EL, Holden ZA, Graham J, et al. The delayed effect of wildfire season particulate matter on subsequent influenza season in a mountain west region of the USA. Environ Int 2020;139:105668.
43. Yao J, Brauer M, Wei J, McGrail KM, Johnston FH, Henderson SB. Sub-daily exposure to fine particulate matter and ambulance dispatches during wildfire seasons: a case-crossover study in British Columbia, Canada. Environ Health Perspect 2020;128:67006.
44. Kim Y, Knowles S, Manley J, Radoias V. Long-run health consequences of air pollution: evidence from Indonesia's forest fires of 1997. Econ Hum Biol 2017;26:186-98.
45. Unosson J, Blomberg A, Sandström T, et al. Exposure to wood smoke increases arterial stiffness and decreases heart rate variability in humans. Part Fibre Toxicol 2013;10:20.
46. Reid CE, Considine EM, Watson GL, Telesca D, Pfister GG, Jerrett M. Associations between respiratory health and ozone and fine particulate matter during a wildfire event. Environ Int 2019;129:291-8.
47. Santos LR, Alves-Correia M, Câmara M, et al. Multiple victims of carbon monoxide poisoning in the aftermath of a wildfire: a case series. Acta Med Port 2018;31:146-51.
48. Kondo MC, De Roos AJ, White LS, et al. Meta-analysis of heterogeneity in the effects of wildfire smoke exposure on respiratory health in North America. Int J Environ Res Public Health 2019;16:960.
49. Jones CG, Rappold AG, Vargo J, et al. Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015-2017 California wildfires. J Am Heart Assoc 2020;9(8):e014125.
50. Mott JA, Mannino DM, Alverson CJ, et al. Cardiorespiratory hospitalizations associated with smoke exposure during the 1997, Southeast Asian forest fires. Int J Hyg Environ Health 2005;208:75-85.
51. Vanos JK. Children's health and vulnerability in outdoor microclimates: a comprehensive review. Environ Int 2015;76:1-15.
52. Proctor CR, Lee J, Yu D, Shah AD, Whelton AJ. Wildfire caused widespread drinking water distribution network contamination. AWWA Water Sci 2020;2(4):e1183.
53. Laumbach RJ. Clearing the air on personal interventions to reduce exposure to wildfire smoke. Ann Am Thorac Soc 2019;16:815-8.
54. Lipner EM, O'Dell K, Brey SJ, et al. The associations between clinical respiratory outcomes and ambient wildfire smoke exposure among pediatric asthma patients at National Jewish Health, 2012–2015. Geohealth 2019;3:146-59.
55. Emissions gap report 2019. Nairobi, Kenya: United Nations Environment Programme, November 26, 2019.
56. Haines A, Ebi K. The imperative for climate action to protect health. N Engl J Med 2019;380:263-73.
57. Markandya A, Sampedro J, Smith SJ, et al. Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. Lancet Planet Health 2018;2(3):e126-e133.

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