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Pathways framework identifies wildfire impacts on agriculture

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Wildfires are a growing concern to society and the environment in many parts of the world. Within the United States, the land area burned by wildfires has steadily increased over the past 40 years. Agricultural land management is widely understood as a force that alters fire regimes, but less is known about how wildfires, in turn, impact the agriculture sector. Based on an extensive literature review, we identify three pathways of impact—direct, downwind and downstream—through which wildfires influence agricultural resources (soil, water, air and photosynthetically active radiation), labour (agricultural workers) and products (crops and livestock). Through our pathways framework, we highlight the complexity of wildfire–agriculture interactions and the need for collaborative, systems-oriented research to better quantify the magnitude of wildfire impacts and inform the adaptation of agricultural systems to an increasingly fire-prone future.

Fire is an integral feature of the Earth system, affecting biological, social and geophysical processes[1,2]. Humanity shares a long history with fire, with rich legacies of Indigenous fire stewardship seen in cultures across the world[2–4]. Fire has been used over time for a variety of local domestic purposes and to modify nearby habitats, and the advent of agricultural fire can be estimated to date back at least 10,000 years[1]. Within fire-prone ecosystems, Indigenous and tribal relations with land reflect a coexistence with fire and an understanding of humans and fire as a coupled socio-ecological system[3,5]. The historic and ongoing structure of settler colonialism[4,6] has suppressed and denied Indigenous fire stewardship and cultural burning in many regions, contributing to changes in fire regimes over the past 500 years and in the present day[3,4]. Contemporary land management in the United States influences fire regimes by altering the number and timing of ignitions, and the structure and availability of fuels[1,4].

In the United States, land management and climate change-driven increases in fuel aridity have lengthened the frequency, extent and severity of large wildfires[7–11] (where wildfires are defined as free-burning, uncontrolled vegetation fires[2,12]). Contrary to global burned area trends (Fig. 1a), the wildfire burned area in the United States has steadily increased over the past four decades, reaching nearly 41,000 km^2 in 2020, the second largest burned area on record[13] (Fig. 1b). Between 1989 and 2022, an average of 29.6 km^2 of cropland was lost to fire annually, with roughly 45% of losses occurring in western states[14]. Out of the 11 years where western states accounted for 50% or more of the total burned area, eight of these occurred in the past 10 years (ref. 14).

Wildfire frequency and burned area are expected to increase in western states (Fig. 2), where agricultural sales are some of the highest in the United States and 16% of the nation's 3.4 million agricultural producers operate[12,15–18]. According to the *2017 Census of Agriculture*, over 2.4 million agricultural workers were hired in the United States across 513,137 farms and 36.5% of these workers were hired in western states[16]. California and Washington hired the most agricultural workers in the country, with 377,593 and 228,588 workers hired, respectively[16]. California also ranked as the country's top producer of agricultural products (crops and livestock), comprising 12% of agriculture sales across the United States in 2012 and 2017 (ref. 16).

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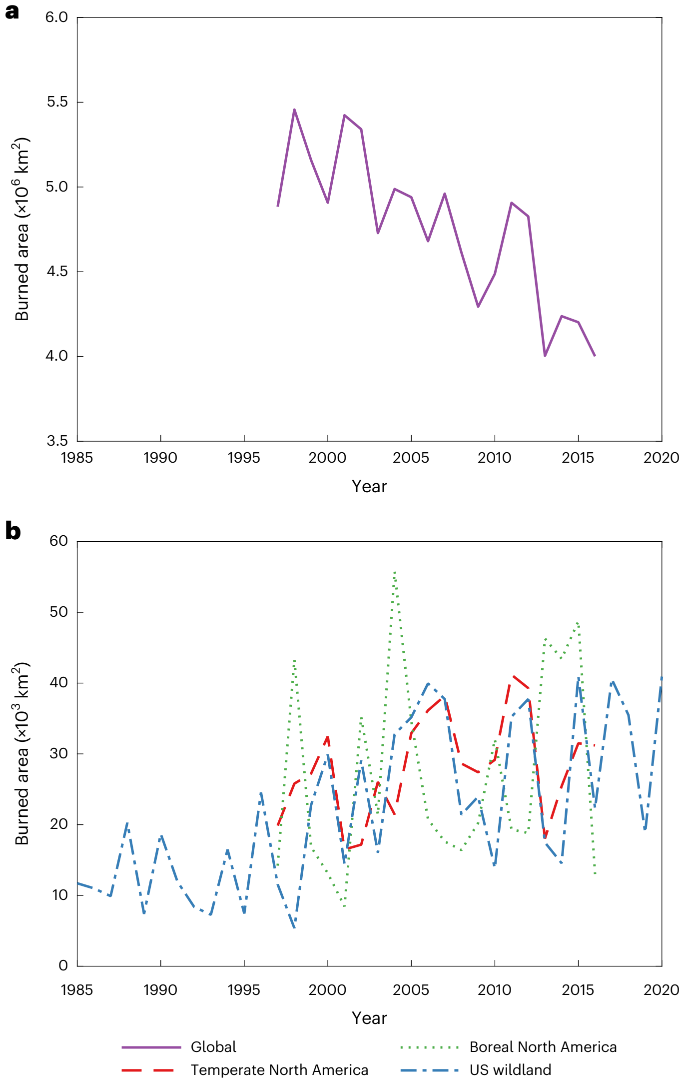

Fig. 1 | Trends in burned area. a, Global burned area from the Global Fire Emissions Database (GFED, version 4.1 s)[116], calculated as the sum of all regions using the Analysis Tool at www.globalfiredata.org. **b**, Burned area for the GFED Temperate North America region, the GFED Boreal North America region and the National Interagency Coordination Center (NICC) US wildland fires[13,116]. GFED data are shown for 1997–2016, and NICC data are shown for 1985–2020.

As wildfire frequency and burned area are expected to increase in western states in the twenty-first century, wildfires pose a substantial threat to agricultural production in the United States[12,15,19]. Natural hazards can leave multilayered and lasting impacts on agricultural landscapes, and wildfires are no exception[17,18]; yet wildfire–agriculture interactions remain understudied. Our Review proposes three pathways of impact—direct, downwind and downstream—that highlight how wildfires affect agricultural resources (soil, water, air, photosynthetically active radiation (PAR)), labour (agricultural workers) and products (crops and livestock) (Fig. 3). While wildfires impact agriculture across the globe, we focus on the impacts of wildfires in the western United States, and survey the current state of research concerning our three pathways, identifying knowledge gaps and areas for continued research.

Direct pathway

The presence of wildfire in the agricultural landscape can directly damage livestock, agricultural property, crops and soil, thus impacting the productivity and profitability of agricultural resources and products in both the short and long term.

Livestock and grazing lands

Livestock are both victims and indirect agents of wildfire spread. When wildfires come into direct contact with cattle, the impacts range from cattle that appear unharmed, cattle that sustain injuries affecting their production capacity (burned feet, udders, eyes and severely singed hair) and cattle that lose their lives[20]. Eligible ranchers and farmers that lose cattle and other livestock to wildfire can seek compensation from the United States Department of Agriculture (USDA) Farm Service Agency Livestock Indemnity Program[21].

The risks to livestock from fire can be exacerbated or suppressed by management practices. In the US Southwest, the addition of Buffelgrass (*Pennisetum ciliare*) for cattle production and grazing has contributed to more frequent fires. This exotic perennial grass serves as fire fuel by filling the spaces between typically sparse desert vegetation such as shrubs and cactus[22]. Fire, in turn, promotes the spread of Buffelgrass, causing larger and more frequent desert fires[23]. On the other hand, targeted cattle grazing efforts can help to suppress fires by removing fine fuels (for example, cheatgrass), creating fuel breaks and preparing seed beds through grazing hoof action[24–27]. Studies show the potential for targeted grazing to reduce fuel loads, occurrences of fires smaller than 1 ha and rates of burned area spread[24–26]. The potential for livestock activities to both spread and suppress wildfire highlights the need for fire-informed livestock and land-management practices that prioritize adaptation to increasingly flammable landscapes.

Agricultural property

Farmers can face major challenges in obtaining financial assistance for fire-induced damages to agricultural property. The California Farm Bureau Federation reports that since 2017 farmers in Sonoma County have submitted approximately 1,500 applications for help with damages; meanwhile, some agricultural policyholders have experienced fourfold increases in insurance premiums, while others have lost complete coverage[28]. Before July 2021, agricultural properties in California were excluded from the basic property insurance provided by the state's Fair Access to Insurance Requirements Plan, the 'insurer of last resort' that many Californians turn to when coverage is denied on the open market[29]. For both homeowners and farmers, securing and maintaining property insurance in wildfire-prone areas is difficult and makes acquiring loans to pay for damaged and lost property even harder[30,31]. California Senate Bill 11, approved by California's governor in July 2021, revised the Fair Access to Insurance Requirements Plan to include commercial farms and ranches in the definition of 'basic property insurance'[30].

Crop losses

As fires become more prevalent in the United States, western states are experiencing the greatest physical and financial losses. The USDA Cause of Loss dataset shows that in 2020 western states accounted for over 96% of US cropland area lost to fire, with California (180.4 km^2), Washington (13.7 km^2), and Oregon (8.3 km^2) reporting the highest net-determined crop acres lost to fire damage[14]. The indemnity amount for 2020, or the total amount lost to fire, was also highest in these states, at US$250 million for California, US$3 million for Washington and US$5.75 million for Oregon[14]. The 2017 fires in California's Napa and Sonoma Counties damaged about 200 ha of vineyards and prevented the harvest of about 800 ha of wine grapes, resulting in an estimated US$75 million in economic losses[28]; 39 wineries in Napa County were also damaged or destroyed by the 2020 Glass Fire[32,33].

The USDA provides emergency financial services to farmers affected by fire and highlights a model to account for the unequal vulnerability faced by historically under-represented farmers. The USDA Emergency Loan Program assists farmers in recovering from

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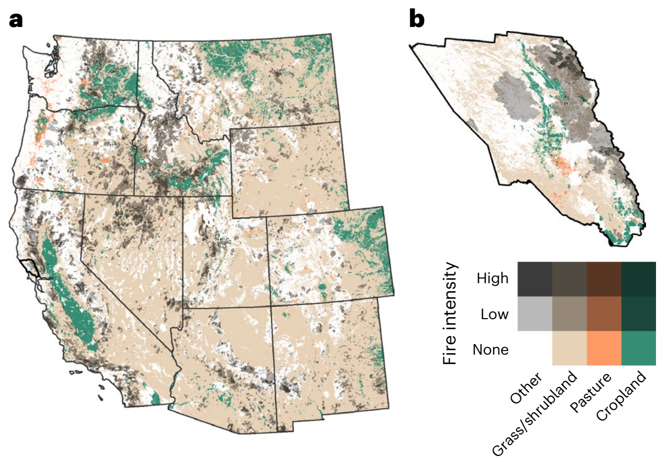

Fig. 2 | Land cover and fire intensity in the western United States and Sonoma County. a,**b**, Land-cover data for the western United States (**a**) and Sonoma County, California (**b**) were extracted from the National Land Cover Database 2019 survey; we only included land-cover classes that relate to agricultural or ranching activities[117]. Fire intensity data were derived from the Monitoring Trends in Burned Severity dataset, where fire intensity is rated from 1–4 (low–high) each year. We summed fire intensity data from 1985 to 2020 and classified 'low' fire intensity as areas where the summed values were equal to or less than 4 and 'high' fire intensity as areas with values greater than 4 (ref. 118). Credit: map in **a**, Esri, US DOC Census Bureau, US DOC, NOAA, NOS, NGS.

production and physical losses due to natural disasters and quarantine. The Noninsured Crop Disaster Assistance Program (NAP) provides financial aid to producers of non-insurable commercial agricultural crops[34], and aims to address some of the systemic challenges facing farmers of colour, women farmers, low-income farmers and beginning farmers. Applicants who qualify as socially disadvantaged, limited resource, or beginning are eligible for a waiver of the service fee and a 50% premium reduction. As demand for wildfire and disaster assistance increases, equity-focused models will be critical to aiding farmers of different backgrounds.

Soil health

Defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans"[35], soil health is integral to the productivity of agricultural lands and is differentially impacted by wildfire severity[36]. We outline soil processes that are commonly associated with wildfires below, and suggest how they can interact with agricultural systems.

Chemical properties. Low-severity fires can increase soil organic matter (SOM)[37] and total extractable cations, whereas high-severity fires can deplete SOM, alter patterns of nitrogen cycling and increase soil cations[36]. In the short term, the pH, electrical conductivity and available phosphorus in soils can increase[38] following wildfire, and agricultural soils can benefit from the addition of SOM in the form of burnt plant materials and ash. Owing to the loss of vegetative cover after fire, however, the potential for soil erosion and associated nutrient loss remain a threat to the long-term health of agricultural soils[39,40].

Physical properties. After fire, changes in soil hydraulic properties, hydrophobicity and ground cover can result in elevated rates of surface runoff and erosion[41–43]. High-severity fires that combust SOM can reduce aggregate stability, increase bulk density and develop surface seals, all of which can and reduce infiltration capacity[36,43]. Further decreases in infiltration capacity may be caused by soil-water repellency, which can result from high temperature fires that cause organic compounds in soils to vaporize and then condense on soil particles, making them hydrophobic[44]. Moreover, the loss of ground cover makes soils more susceptible to erosion, nutrient runoff and leaching, and organic matter loss[45–47].

Biological properties. Wildfires drive important changes to the soil microbiome, reducing belowground microbial biomass by up to 96% while also decreasing microbial richness, evenness and diversity[48]. Microbial communities that persist in burnt soils are frequently distinct from those in unburnt controls[49], and specific classes of 'fire-loving' pyrophilous soil bacteria and fungi can be enriched following wildfire[50,51]. Microbially driven nitrogen cycling is frequently altered post-wildfire, with reported decreases in the number of genes encoding denitrification in burnt forest soils[52]. However, highlighting the complexity and temporal dynamics of biogeochemical cycles post-wildfire, other studies have reported increasing denitrification rates in burned soils[53,54], probably stimulated by transient periods of high rates of nitrification[55,56]. Microbial symbioses with plant roots in the rhizosphere are also critical for plant health, and the loss of key microbial community members can disrupt these interactions[57]. In the western United States, the extent of pre-fire bark-beetle-driven tree mortality remains poorly understood in terms of its impacts on the resilience of the soil microbiome. Further research is needed on post-wildfire interactions between wildfire severity and the physical, chemical and biological properties and processes of soils to better understand how wildfires impact agricultural soils over time[58,59].

Downwind pathway

Agricultural resources, workers and products can be impacted by changes in air quality and PAR that stem from wildfire smoke—a complex mixture of particulate matter, including fine particulate matter measuring 2.5 μm or less in diameter ($PM_{2.5}$), and gases[60]. Smoke from wildfires routinely elevates the abundance of $PM_{2.5}$, hazardous air pollutants and ozone (O_3) across the United States, particularly in western states[60,61,62]. Smoke can impact agricultural worker and livestock health, as well as alter the light use efficiency and productivity of crops.

Agricultural worker health

Wildfire smoke is harmful to the health of agricultural workers and is associated with respiratory irritation and the exacerbation of underlying health conditions, including asthma and chronic obstructive pulmonary disease[60,63]. Despite these health risks and increasing trends of wildfire smoke exposure[61], the full national impacts of wildfire smoke remain poorly quantified for the 2.5–3 million agricultural workers in the United States[64,65].

Health risks for agricultural workers are magnified when smoke exposure occurs concurrently with high heat. For example, in the Pacific Northwest, high levels of $PM_{2.5}$ driven by wildfires typically occur on days when the heat index exceeds 29 °C (ref. 60). Excessive environmental and metabolic heat exposure can cause heat rashes, heat cramps, heat syncope, heat exhaustion and heat stroke[66,67], as well as an increased likelihood of traumatic injuries and acute kidney injury[68,69]. The combination of heat, dehydration and fatigue can also affect cognition and balance[66,68].

Frontline communities that face the most damaging effects of wildfire smoke largely comprise marginalized social and demographic groups, who are more likely to face barriers to accessing healthcare, economic aid and social services[70]. Of the participants surveyed in the US Department of Labor's 2015–2016 National Agricultural Workers Survey, 75% were born outside the United States, 83% self-identified as Hispanic and roughly half were unauthorized to work in the United States[65,71,72]. Half of all workers reported having no health insurance and named multiple barriers to receiving healthcare, including cost, language barriers, lack of transportation and poor treatment[72,73];

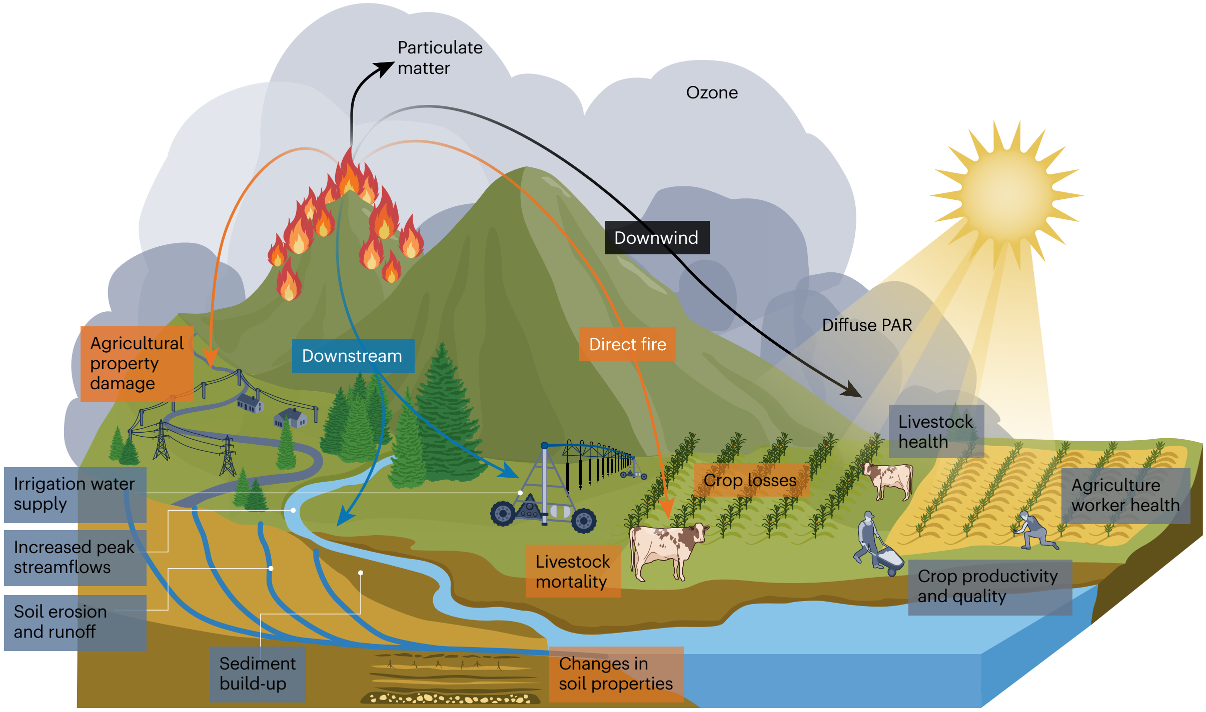

Fig. 3 | Pathways of wildfire impacts on agricultural systems. Wildfires influence agricultural landscapes through direct, downwind and downstream pathways, affecting agricultural resources, labour and products.

authorized workers were nearly three times as likely to have health insurance[72] than unauthorized workers. Similarly, a quantitative analysis of community characteristics found that census tracts with majorities of Black, Hispanic and Native American people are more vulnerable to wildfires than census tracts with majorities of white and Asian people[74].

Workplace policies that require outdoor air quality monitoring, communication of wildfire smoke risks and personal protective equipment—when the air quality index meets or exceeds 151 for $PM_{2.5}$—have gained attention at federal and state levels in recent years[61,75], but challenges remain in implementing adaptation solutions on farms[70]. The practice of piece-rate pay, where workers are paid by the amount they harvest, as well as the short harvest windows for some crops, are at odds with limiting exposure to wildfire smoke[76]. Workplace cultures, power dynamics, worker replaceability and attitudes of supervisors towards wildfire smoke remain barriers to implementing and enforcing education and safety practices[61,64,77].

Livestock health

Wildfire smoke is also damaging to the health and productivity of livestock, although the national scope of this issue remains poorly quantified. Smoke irritates the eyes and respiratory tracts of livestock and is associated with behavioural responses that include nervousness, panic, aggressive and resistant behaviour and attempts to escape. In this elevated state, flight syndrome can activate in livestock and lead to injury or death while trying to flee from wildfires into fences and other barriers[78].

Livestock are additionally affected by the $PM_{2.5}$ emitted from wildfire events and anthropogenic activity. In recent studies on dairy cows in Colorado and Idaho, increased $PM_{2.5}$ exposure was significantly associated with decreased milk yield, even when controlling for known health effects of temperature and humidity[78,79]. Air pollution episodes have also been linked directly to livestock mortality since the late nineteenth century[76,80,81], although modern scientific studies on air pollution-induced mortality (from wildfires or otherwise) are notably limited.

Crop productivity

The relationship between wildfire smoke and crop production is complex, with the potential for both harmful and beneficial impacts on productivity, depending on the nature of the exposure. Wildfire smoke contains thousands of gas- and particle-phase pollutants[82,83], including oxidizing gas species that are known to reduce crop yields, such as O_3, nitrogen oxides (NO_x) and acyl peroxyl nitrates. Smoke also contains particulate matter that can change the availability and characteristics of light reaching plants. Thus, as a smoke plume evolves downwind from wildfire and either envelops crops or travels overhead, it can add to pollutant exposure, decrease total radiation and alter the distribution of direct and diffuse radiation. Given current data, we focus our discussion here on the impacts of O_3 and particulate matter on crops.

The production of O_3 from wildfires depends on the smoke composition and age, plume concentration and dilution rates, time of day and meteorological conditions[82,84]. Mixing between smoke and urban air masses can enhance O_3 production[85], contributing to urban air pollution throughout the United States[86]. When O_3 enters plant leaves through the stomata, it damages plant tissues through the production of free radicals that hinder photosynthesis[87,88]. Yield reductions, increased susceptibility to disease and increased senescence are observed in annual and perennial crops exposed to O_3 (refs. 87,89). While studies have estimated the financial costs of O_3-induced declines in production—for example, losses of around US\$1 billion yr^{-1} for perennial crops in California alone—additional research is needed to link production losses directly to the O_3 attributable to wildfires[88,90].

Observational studies that quantify the impacts of wildfire PM on crops are limited; however, we know that plant productivity is sensitive to variations in total and diffuse PAR, and that smoke contributes to variability in both parameters across the United States. Although decreases in total PAR can reduce productivity, enhanced light use efficiency from a greater diffuse fraction can counteract losses[84]. Increases in plant light use efficiency are expected in environments with complex canopy architecture[84,91] where shade-adapted leaves can utilize diffuse PAR, leading to positive correlations between aerosol optical depth and gross primary productivity[91]. The photosynthetic pathway of plants may also play a role in determining the degree to which increased diffuse radiation impacts productivity. Compared with C_4 crops, C_3 crops exhibit greater light use efficiency when exposed to an elevated diffuse fraction of radiation[92–94].

In addition to wildfire O_3 and PM, wildfire-induced biogenic volatile organic compounds and smoke-related taint are impacting specialty crops such as wine grapes, and leading to reductions in quality, flavour and profitability[32,95].

To understand the impact of wildfire smoke on crops, information on smoke age, smoke thickness, smoke altitude, canopy structure and photosynthetic pathway are needed. As the numbers of wildfires and the sizes of burned areas continue to increase, understanding the diverse implications of wildfire smoke on crop production will become increasingly important.

Downstream pathway

Forests serve as headwaters for nearly 40% of watersheds in the western United States, making them a critical area that can threaten agricultural and drinking water when burnt[96,97]. As wildfires burn forests and human structures, water quantity and quality in streams, reservoirs and irrigation water supplies will be negatively impacted.

Water quantity

Wildfires impact the timing and magnitude of stream flows by decreasing transpiration and altering soil interception and infiltration[98]. When vegetative cover burns, canopy structure and albedo are altered, impacting snow accumulation and melt rates[99,100]. Reduced infiltration capacity on burnt, hydrophobic soils can also lead to overland flow, destructive floods and debris flows[101–103]. Although lower-severity wildfires have limited effects on streamflow, moderate- to high-severity wildfires can increase peak flows by 5–870 times[45]. The net effects of wildfire on streamflow are highly variable across different timescales, climates, types of disturbance, rates of regrowth and other factors[104]; however, any changes that decrease the availability and reliability of surface water supplies for irrigation can negatively impact agricultural systems.

Water quality

Soil sediments transported in storms after wildfire can impact irrigation water supplies by causing physical damage, reducing reservoir capacity and threatening water quality[105,106]. Following the 2002 Hayman Fire, the City of Denver (Colorado) spent US$30 million on a dredging project to remove roughly 480,000 m^3 of sediment from the Strontia Springs Reservoir[45]. Post-fire storms can also leave streams with large amounts of sediments, nutrients, heavy metals and contaminants, posing a threat to agricultural lands and water supplies[45,107].

As soil nutrients combust, they can remain in particulate form and enter water sources through erosion and leaching. While water quality responses vary over time and across watersheds, increases in certain nutrient, ion and metal concentrations and loadings have been observed 5 years after fire[108]. High levels of sediment and ash can also temporarily increase the pH of water and impact the availability of certain plant nutrients[109]. As wildfires increasingly burn at the wildland–urban interface (where human structures meet or mix with natural vegetation[110]), the combustion of plastics and other materials associated with human activity can generate cocktails of harmful products[111,112]. The quantities of such compounds in irrigation water and the implications for soil and crop health are unknown.

A wildfire–agriculture research agenda

Changes in climate and land management have increased the frequency and size of wildfires in the western United States today. Although the discussion around wildfire impacts on society and the environment is well recognized, the effects of wildfire on agriculture remain understudied. We identified three pathways of impact—direct, downwind and downstream—through which wildfires influence agricultural resources, labour and products. We find that wildfire impacts on the agricultural landscape can be highly disruptive and nuanced, cutting across fields of study, and influencing both human and natural systems.

We propose that future research seek to understand the magnitude and scope of wildfire impacts on agriculture within each pathway and how these impacts may change across time and environments. This research will inform our understanding of the relative importance of each pathway and how these impacts may differ from region to region, given the diversity of climates, wildfire regimes and agricultural systems across the world. Where possible, research should quantify the economic costs of wildfire impacts to enable comparison between pathways and highlight management priorities.

We encourage conversations involving agricultural communities, researchers, policymakers and Indigenous tribes (that is, cross-cultural fire stewardship[3,12]) to promote collaboration in developing adaptation strategies, management practices and future research, and acknowledge the paramount need to rebuild trust with tribal nations. Greater preparedness and stronger relationships among stakeholders will be necessary for effective post-fire responses and communication, especially considering the extent and severity of today's fires. Such efforts would be particularly timely given the infusion of funding for cross-boundary fuel reduction under the Infrastructure Investment and Jobs Act (Public Law 117-58; ref. 113) and subsequent Wildfire Crisis Strategy from the US Forest Service[19]; this would also build on other cross-boundary, collaborative approaches in forest management (for example, the Collaborative Forest Landscape Restoration Program[113]). Existing collaborative efforts and capacity to reduce fire hazards could be leveraged through: (1) rebuilding stronger consensual partnerships with tribal nations (see the White House Office of Science and Technology Policy (OSTP) and Council on Environmental Quality (CEQ) Memorandum[114], which emphasizes the need to integrate Indigenous knowledge and sovereignty into federal decisions); (2) integrating activities for all stages of fire management, including pre-, during- and post-fire responses; and (3) integrating downwind and downstream agricultural communities into collaborative fire management groups.

While our Review highlights the western United States, agriculture is a critical industry across the world that will continue to be influenced by changing wildfire regimes, making this a globally relevant topic of discussion[2,7,10,22,115]. Research on wildfire–agriculture interactions in many different contexts will be needed to understand the diversity of impacts and mitigate harms where possible. Re-examining our relationship with fire and understanding anthropogenic influences and cultural practices as being interconnected with ecological drivers of wildfire could provide a critical shift in how we think about and respond to fire, with the aim of better informing the future of policy, adaptation, management and research surrounding wildfire and agriculture interactions[3].

Methods

Sampling strategy

We reviewed scientific literature, reports and news articles that discussed wildfire and agriculture in the western United States and North America. No statistical methods were used; instead, keywords were used for sampling in Google Scholar and Web of Science: wildfire and agriculture, wildfire and crops, wildfire on soil, wildfire and livestock, wildfire impacts on agriculture, wildfire and farmworkers, wildfire smoke and crops, wildfire smoke on agriculture. References from relevant papers were also utilized in the sampling strategy.

Data availability

The annual burned area datasets used were open access and obtained from the Global Fire Emissions Database analysis tool (1997–2016)[116] and the National Interagency Fire Center (1983–2020)[13]. Burned

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areas were converted and reported in square kilometres per year. Land-cover data and fire intensity data in Fig. 2 were extracted from two open-access sites: land-cover data were derived from the National Land Cover Database (NLCD) 2019 (ref. 117) and fire intensity data were derived from the Monitoring Trends in Burned Severity (MTBS) dataset, where fire intensity is rated from 1–4 (low–high) each year[118].

References

1. Bowman, D. M. J. S. et al. The human dimension of fire regimes on Earth. *J. Biogeogr.* **38**, 2223–2236 (2011).
2. McLauchlan, K. K. et al. Fire as a fundamental ecological process: research advances and frontiers. *J. Ecol.* **108**, 2047–2069 (2020).
3. Lake, F. K. & Christianson, A. C. in *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires* 1–9 (Springer, Cham, 2020).
4. Vinyeta, K. Under the guise of science: how the US Forest Service deployed settler colonial and racist logics to advance an unsubstantiated fire suppression agenda. *Environ. Sociol.* **8**, 134–148 (2021).
5. Spies, T. A. et al. Examining fire-prone forest landscapes as coupled human and natural systems. *Ecol. Soc.* https://doi.org/10.5751/ES-06584-190309 (2014).
6. Glenn, E. N. Settler colonialism as structure: a framework for comparative studies of U.S. race and gender formation. *Sociol. Race Ethnic.* **1**, 52–72 (2015).
7. *Impacts, Risks, and Adaptations in the United States: Fourth National Climate Assessment* Vol. 2 (US Global Change Research Program, 2018).
8. *Climate Change Indicators: Wildfires* (US EPA, 2016); https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires
9. Wehner, M. F., Arnold, J. R., Knutson, T., Kunkel, K. E. & LeGrande, A. N. in *Climate Science Special Report: Fourth National Climate Assessment* Vol. 1 (eds Wuebbles, D. J. et al.) 231–256 (U.S. Global Change Research Program, 2017).
10. Andela, N. et al. A human-driven decline in global burned area. *Science* **356**, 1356–1362 (2017).
11. Abatzoglou, J. T. & Williams, A. P. Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl Acad. Sci. USA* **113**, 11770–11775 (2016).
12. *Spreading Like Wildfire: The Rising Threat of Extraordinary Landscape Fires* (United Nations Environment Programme, 2022).
13. *Wildfires and Acres: Total Wildland Fires and Acres (1983-2020)* (National Interagency Coordination Center, 2020); https://www.nifc.gov/fire-information/statistics/wildfires
14. *Cause of Loss* (United States Department of Agriculture Risk Management Agency, 2020); https://www.rma.usda.gov/SummaryOfBusiness/CauseOfLoss
15. Brey, S. J., Barnes, E. A., Pierce, J. R., Swann, A. L. S. & Fischer, E. V. Past variance and future projections of the environmental conditions driving western U.S. summertime wildfire burn area. *Earth Future* **9**, e2020EF001645 (2021).
16. *2017 Census of Agriculture* (USDA National Agricultural Statistics Service, 2019).
17. *The Impact of Natural Hazards and Disasters on Agriculture, Food Security and Nutrition* (FAO, 2015); http://www.fao.org/3/i5128e/i5128e.pdf
18. *The Impact of Disasters and Crises on Agriculture and Food Security* (FAO, 2017); http://www.fao.org/3/I8656EN/i8656en.pdf
19. *Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests* (USDA Forest Service, 2022); https://www.fs.usda.gov/managing-land/wildfire-crisis
20. Rethorst, D. N., Spare, R. K. & Kellenberger, J. L. Wildfire response in range cattle. *Vet. Clin. N. Am. Food Animal Pract.* **34**, 281–288 (2018).
21. *Disaster Assistance: Livestock Indemnity Program* (US Department of Agriculture Farm Service Agency, 2021); https://www.fsa.usda.gov/programs-and-services/disasterassistance-program/livestock-indemnity/index#:~:text=LIP%20provides%20benefits%20t%20livestock,market%20value%20of%20the%20livestock
22. Franklin, K. A. et al. Buffelgrass (*Pennisetum ciliare*) land conversion and productivity in the plains of Sonora, Mexico. *Biol. Conserv.* **127**, 62–71 (2006).
23. Butler, B. D. W. & Fairfax, R. J. Buffel grass and fire in a Gidgee and Brigalow woodland: a case study from central Queensland. *Ecol. Manage. Restor.* **4**, 120–125 (2003).
24. Davison, J. Livestock grazing in wildland fuel management programs. *Rangelands* **18**, 242–245 (1996).
25. Lasanta, T. et al. Clearing shrubland and extensive livestock farming: active prevention to control wildfires in the Mediterranean mountains. *J. Environ. Manage.* **227**, 256–266 (2018).
26. Davies, K. W., Boyd, C. S., Bates, J. D. & Hulet, A. Winter grazing can reduce wildfire size, intensity and behaviour in a shrub-grassland. *Int. J. Wildland Fire* **25**, 191–199 (2015).
27. Forrest, T. Use of livestock to mitigate risk of wildfire and for restoration. In *Restoring the West Conference 2015 - Restoration and Fire in the Interior West* (Utah State Univ., 2015); https://www.youtube.com/watch?v=y-D7NKC7R8M
28. *The Impact of Wildfires on California Agriculture Report* (California State Assembly Committee, 2020); https://agri.assembly.ca.gov/sites/agri.assembly.ca.gov/files/The%20Impact%20of%20Wildfires%20on%20California%20Agriculture%20Informational%20Hearing%20Report.pdf
29. Bittle, J. As wildfires worsen, more California farms are deemed too risky to insure. *Grist* (28 July 2021).
30. Rubio, S. *SB-11 The California FAIR Plan Association: Basic Property Insurance: Exclusions. California Insurance Code 10091-10094.5* (California State Senate, 2021).
31. Flavelle, C. Wildfires hasten another climate crisis: homeowners who can't get insurance. *The New York Times* (10 Sep 2020).
32. Flavelle, C. Scorched, parched and now uninsurable: climate change hits wine country. *The New York Times* (18 July 2021).
33. Martichoux, A., Feingold, L. & Behle, B. Glass Fire map shows wineries, landmarks destroyed in wine country. *ABC7 News* (14 October 2021); https://abc7news.com/glass-fire-map-napa-sonoma-wineries-damaged-in/6655733/
34. *Disaster Assistance: Noninsured Crop Disaster Assistance Program* (US Department of Agriculture Farm Service Agency, 2020); https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/noninsured_crop_disaster_assistance_program-nap-fact_sheet.pdf
35. *Soil Health* (United States Department of Agriculture Natural Resources Conservation Service, 2019); https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
36. Hrelja, I., Šestak, I. & Bogunović, I. Wildfire impacts on soil physical and chemical properties: a short review of recent studies. *Agricult. Conspect. Sci.* **85**, 293–301 (2020).
37. Pellegrini, A. F. A. et al. Low-intensity frequent fires in coniferous forests transform soil organic matter in ways that may offset ecosystem carbon losses. *Glob. Change Biol.* **27**, 3810–3823 (2021).
38. Muñoz-Rojas, M., Erickson, T. E., Martini, D., Dixon, K. W. & Merritt, D. J. Soil physicochemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems. *Ecol. Indic.* **63**, 14–22 (2016).
39. Jiménez-González, M. A. et al. Post-fire recovery of soil organic matter in a cambisol from typical Mediterranean forest in Southwestern Spain. *Sci. Total Environ.* **572**, 1414–1421 (2016).

40. Rhoades, C. C. et al. The legacy of a severe wildfire on stream nitrogen and carbon in headwater catchments. *Ecosystems* **22**, 643–657 (2019).
41. Doerr, S. H., Shakesby, R. A. & Walsh, R. P. D. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Sci. Rev.* **51**, 33–65 (2000).
42. Moody, J. A. et al. Relations between soil hydraulic properties and burn severity. *Int. J. Wildland Fire* **25**, 279 (2015).
43. Larsen, I. J. et al. Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing? *Soil Sci. Soc. Am.* **73**, 1393–1407 (2009).
44. Letey, J. Causes and consequences of fire-induced soil water repellency. *Hydrol. Process.* **15**, 2867–2875 (2001).
45. Bladon, K. D., Emelko, M. B., Silins, U. & Stone, M. Wildfire and the future of water supply. *Environ. Sci. Technol.* **48**, 8936–8943 (2014).
46. González-Pérez, J. A., González-Vila, F. J., Almendros, G. & Knicker, H. The effect of fire on soil organic matter—a review. *Environ. Int.* **30**, 855–870 (2004).
47. Moench, R. & Fusaro, J. *Soil Erosion Control after Wildfire 6.308* (Colorado State Univ., 2012); https://extension.colostate.edu/topic-areas/agriculture/soil-erosion-control-after-wildfire-6-308/
48. Stavi, I. et al. Fire impact on soil-water repellency and functioning of semi-arid croplands and rangelands: Implications for prescribed burnings and wildfires. *Geomorphology* **280**, 67–75 (2017).
49. Pressler, Y., Moore, J. C. & Cotrufo, F. Belowground community responses to fire: meta-analysis reveals contrasting responses of soil microorganisms and mesofauna. *Oikos* **128**, 309–327 (2018).
50. Whitman, T. et al. Soil bacterial and fungal response to wildfires in the Canadian boreal forest across a burn severity gradient. *Soil Biol. Biochem.* https://doi.org/10.1016/j.soilbio.2019.107571 (2019).
51. Glassman, S. I., Levine, C. R., DiRocco, A. M., Battles, J. J. & Bruns, T. D. Ectomycorrhizal fungal spore bank recovery after a severe forest fire: some like it hot. *ISME J.* **10**, 1228–1239 (2016).
52. Nelson, A. R. et al. Wildfire-dependent changes in soil microbiome diversity and function. *Nat. Microbiol.* **7**, 1419–1430 (2022).
53. Cobo-Díaz, J. F. et al. Metagenomic assessment of the potential microbial nitrogen pathways in the rhizosphere of a Mediterranean forest after a wildfire. *Microb. Ecol.* **69**, 895–904 (2015).
54. Niboyet, A. et al. Global change could amplify fire effects on soil greenhouse gas emissions. *PLoS ONE* https://doi.org/10.1371/journal.pone.0020105 (2011).
55. Liao, X., Inglett, P. W. & Inglett, K. S. Fire effects on nitrogen cycling in native and restored in calcareous wetlands. *Fire Ecol.* **9**, 6–20 (2013).
56. Dove, N. C., Safford, H. D., Bohlman, G. N., Estes, B. L. & Hart, S. C. High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. *Ecol. Adapt.* https://doi.org/10.1002/eap.2072 (2020).
57. Ball, P. N., Mackenzie, M. D., DeLuca, T. H. & Holben Montana, W. E. Wildfire and charcoal enhance nitrification and ammonium-oxidizing bacterial abundance in dry montane forest soils. *J. Environ. Qual.* https://doi.org/10.2134/jeq2009.0082 (2010).
58. Pulido-Chavez, M. F., Alvarado, E. C., DeLuca, T. H., Edmonds, R. L. & Glassman, S. I. High-severity wildfire reduces richness and alters composition of ectomycorrhizal fungi in low-severity adapted ponderosa pine forests. *For. Ecol. Manage.* https://doi.org/10.1016/j.foreco.2021.118923 (2021).
59. Dove, N. C., Safford, H. D., Bohlman, G. N., Estes, B. L. & Hart, S. C. High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. *Ecol. Appl.* **30**, e02072 (2020).
60. O'Dell, K. et al. Estimated mortality and morbidity attributable to smoke plumes in the United States: not just a western US problem. *Geohealth* **5**, e2021GH000457 (2021).
61. Prendergast-Miller, M. T. et al. Wildfire impact: natural experiment reveals differential short-term changes in soil microbial communities. *Soil Biol. Biochem.* **109**, 1–13 (2017).
62. Fenske, R. A. & Pinkerton, K. E. Climate change and the amplification of agricultural worker health risks. *J. Agromed.* **26**, 15–17 (2021).
63. Austin, E., Kasner, E., Seto, E. & Spector, J. Combined burden of heat and particulate matter air quality in WA agriculture. *J. Agromed.* **26**, 18–27 (2020).
64. Reid, C. E. et al. Critical review of health impacts of wildfire smoke exposure. *Environ. Health Perspect.* **124**, 1334–1343 (2016).
65. Riden, H. E. et al. Wildfire smoke exposure: awareness and safety responses in the agricultural workplace. *J. Agromed.* **25**, 330–338 (2020).
66. *Facts About Agricultural Workers* (National Center for Farmworker Health, Inc., 2020); http://www.ncfh.org/facts-about-agricultural-workers-fact-sheet.html
67. Spector, J. T. *Heat Stress and Safety Issues for Farmers and Farmworkers in the Context of Climate Change* (Climate Adaptation Research Center, 2020).
68. Jackson, L. L. & Rosenberg, H. R. Preventing heat-related illness among agricultural workers. *J. Agromed.* **15**, 200–215 (2010).
69. Spector, J. T. et al. A case-crossover study of heat exposure and injury risk in outdoor agricultural workers. *PLoS ONE* **11**, e0164498 (2016).
70. Layton, K. Proposed federal OSHA standards for wildfire smoke. *Seattle J. Technol. Environ. Innov. Law* **10**, 5 (2020).
71. Tigchelaar, M., Battisti, D. S. & Spector, J. T. Work adaptations insufficient to address growing heat risk for U.S. agricultural workers. *Environ. Res. Lett.* **15**, 94035 (2020).
72. Martin, P. US farm employment and farm workers. *Wilson Center* (24 June 2020); https://www.wilsoncenter.org/article/us-farm-employment-and-farm-workers
73. Hernandez, T. & Gabbard, S. *Findings from the National Agricultural Workers Survey (NAWS) 2015-2016: A Demographic and Employment Profile of United States Farmworkers* (US Department of Labor, 2018); https://www.dol.gov/sites/dolgov/files/ETA/naws/pdfs/NAWS_Research_Report_13.pdf
74. *Farmworkers' Health Fact Sheet: Data from the National Agricultural Workers Survey* (Farmworker Justice & The National Center for Farmworker Health, 2015); http://www.ncfh.org/uploads/3/8/6/8/38685499/fs-nawshealthfactsheet_jbs_approved.pdf
75. Davies, I. P., Haugo, R. D., Robertson, J. C. & Levin, P. S. The unequal vulnerability of communities of color to wildfire. *PLoS ONE* **13**, e0205825 (2018).
76. Anderson, A., Rezamand, P. & Skibiel, A. L. Effects of wildfire smoke exposure on innate immunity, metabolism, and milk production in lactating dairy cows. *J. Dairy Sci.* **105**, 7047–7060 (2022).
77. *Worker Protection from Wildfire Smoke* (California Department of Industrial Relations, 2021); https://www.dir.ca.gov/dosh/doshreg/Protection-from-Wildfire-Smoke/Wildfire-smoke-emergency-standard.html
78. Cotton, S. & Mcbride, T. *Caring for Livestock During Disaster - 1.815* (Colorado State Univ., 2010).
79. Beaupied, B. L. et al. Cows as canaries: the effects of ambient air pollution exposure on milk production and somatic cell count in dairy cows. *Environ. Res.* https://doi.org/10.1016/j.envres.2021.112197 (2021).
80. Cox, B. et al. Ambient air pollution-related mortality in dairy cattle: does it corroborate human findings? *Epidemiology* **27**, 779–786 (2016).

81. Bertyn, F. Le brouillard et le bétail. *Ann. Gembloux* **25**, 153–173 (1913).
82. Nemery, B., Hoet, P. H. & Nemmar, A. The Meuse Valley fog of 1930: an air pollution disaster. *Lancet* **357**, 704–708 (2001).
83. Jaffe, D. A. & Wigder, N. L. Ozone production from wildfires: a critical review. *Atmos. Environ.* **51**, 1–10 (2012).
84. Hemes, K. S., Verfaillie, J. & Baldocchi, D. D. Wildfire-smoke aerosols lead to increased light use efficiency among agricultural and restored wetland land uses in California's Central Valley. *J. Geophys. Res. Biogeosci.* https://doi.org/10.1029/2019JG005380 (2020).
85. Robinson, M. A. et al. Variability and time of day dependence of ozone photochemistry in western wildfire plumes. *Environ. Sci. Technol.* **55**, 10280–10290 (2021).
86. Ninneman, M. & Jaffe, D. A. The impact of wildfire smoke on ozone production in an urban area: insights from field observations and photochemical box modeling. *Atmos. Environ.* https://doi.org/10.1016/j.atmosenv.2021.118764 (2021).
87. Brey, S. J. & Fischer, E. V. Smoke in the city: how often and where does smoke impact summertime ozone in the United States? *Environ. Sci. Technol.* **50**, 1288–1294 (2016).
88. Hong, C. et al. Impacts of ozone and climate change on yields of perennial crops in California. *Nat. Food* **1**, 166–172 (2020).
89. McGrath, J. M. et al. An analysis of ozone damage to historical maize and soybean yields in the United States. *Proc. Natl Acad. Sci. USA* **112**, 14390–14395 (2015).
90. Mauzerall, D. L. & Wang, X. Protecting agricultural crops from the effects of tropospheric ozone exposure: reconciling science and standard setting in the United States, Europe, and Asia. *Annu. Rev. Energy Environ.* **26**, 237–268 (2001).
91. Zhang, J. et al. Effects of increasing aerosol optical depth on the gross primary productivity in China during 2000–2014. *Ecol. Indic.* **108**, 105761 (2020).
92. Greenwald, R. et al. The influence of aerosols on crop production: a study using the CERES crop model. *Agric. Syst.* **89**, 390–413 (2006).
93. Kanniah, K. D., Beringer, J., North, P. & Hutley, L. Control of atmospheric particles on diffuse radiation and terrestrial plant productivity: a review. *Progr. Phys. Geogr. Earth Environ.* **36**, 209–237 (2012).
94. Schiferl, L. D. & Heald, C. L. Particulate matter air pollution may offset ozone damage to global crop production. *Atmos. Chem. Phys.* **18**, 5953–5966 (2018).
95. Maleknia, S. D. & Adams, M. A. Impact of volatile organic compounds from wildfires on crop production and quality. *Asp. Appl. Biol.* **88**, 93–98 (2008).
96. Huber-Stearns, H. R. & Cheng, A. S. The evolving role of government in the adaptive governance of freshwater social-ecological systems in the western US. *Environ. Sci. Policy* **77**, 40–48 (2017).
97. Huber-Stearns, H. R., Schultz, C. & Cheng, A. S. A multiple streams analysis of institutional innovation in forest watershed governance. *Rev. Policy Res.* **36**, 781–804 (2019).
98. Nolan, R. H., Lane, P. N. J., Benyon, R. G., Bradstock, R. A. & Mitchell, P. J. Changes in evapotranspiration following wildfire in resprouting eucalypt forests. *Ecohydrology* **7**, 1363–1377 (2013).
99. Harpold, A. A. et al. Changes in snow accumulation and ablation following the Las Conchas forest fire, New Mexico, USA. *Ecohydrology* **7**, 440–452 (2013).
100. Maxwell, J. D., Call, A. & st. Clair, S. B. Wildfire and topography impacts on snow accumulation and retention in montane forests. *For. Ecol. Manage.* **432**, 256–263 (2019).
101. Brogan, D. J., Nelson, P. A. & MacDonald, L. H. Reconstructing extreme post-wildfire floods: a comparison of convective and mesoscale events. *Earth Surf. Process. Landf.* **42**, 2505–2522 (2017).
102. Cannon, S. H., Gartner, J. E., Parrett, C. & Parise, M. *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment* 71–82 (Millpress, 2003).
103. Moody, J. A. & Martin, R. G. Measurements of the initiation of post-wildfire runoff during rainstorms using in situ overland flow detectors. *Earth Surf. Process. Landf.* **40**, 1043–1056 (2015).
104. Goeking, S. A. & Tarboton, D. G. Forests and water yield: a synthesis of disturbance effects on streamflow and snowpack in western coniferous forests. *J. For.* **118**, 172–192 (2020).
105. Moody, J. A. & Martin, D. A. Wildfire impacts on reservoir sedimentation in the western United States. In *Proc. Ninth International Symposium on River Sedimentation* 1095–1102 (Tsinghua Univ. Press, 2004).
106. Wohl, E., McConnell, R., Skinner, J. & Stenzel, R. *Inheriting Our Past: River Sediment Sources and Sediment Hazards in Colorado* (Colorado Water Resources Research Institute, 1998); http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.529.955&rep=rep1&type=pdf
107. Moody, J. A., Shakesby, R. A., Robichaud, P. R., Cannon, S. H. & Martin, D. A. Current research issues related to post-wildfire runoff and erosion processes. *Earth Sci. Rev.* **122**, 10–37 (2013).
108. Rust, A. J., Hogue, T. S., Saxe, S. & McCray, J. Post-fire water-quality response in the western United States. *Int. J. Wildland Fire* **27**, 203–216 (2018).
109. Waskom, R., Kallenberger, J., Grotz, B. & Bauder, T. *Addressing the Impacts of Wildfire on Water Resources* Fact Sheet No. 6.706. (Colorado State Univ., 2013); https://ucanr.edu/sites/postfire/files/248231.pdf
110. Moritz, M. A. et al. Learning to coexist with wildfire. *Nature* **515**, 58–66 (2014).
111. Isaacson, K. P. et al. Drinking water contamination from the thermal degradation of plastics: implications for wildfire and structure fire response. *Environ. Sci.* **7**, 274–284 (2021).
112. Alexakis, D. E. Suburban areas in flames: dispersion of potentially toxic elements from burned vegetation and buildings. Estimation of the associated ecological and human health risk. *Environ. Res.* https://doi.org/10.1016/j.envres.2020.109153 (2020).
113. Schultz, C. A. et al. Policy design to support forest restoration: the value of focused investment and collaboration. *Forests* https://doi.org/10.3390/f9090512 (2018).
114. Lander, E. S. & Mallory, B. *Indigenous Traditional Ecological Knowledge and Federal Decision Making* (Executive Office of the United States President, Office of Science and Technology Policy, Council on Environmental Quality, 2021).
115. Duncan, Z. M. et al. Effects of prescribed fire timing on grazing performance of yearling beef cattle, forage biomass accumulation, and plant community characteristics on native tallgrass prairie in the Kansas Flint Hills. *Transl Anim. Sci.* **5**, txab077 (2021).
116. van der Werf, G. R. et al. Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data* **9**, 697–720 (2017).
117. Dewitz, J. & US Geological Survey. *National Land Cover Database (NLCD) 2019 Products (ver. 2.0)* (US Geological Survey, 2021).
118. *Monitoring Trends in Burn Severity (MTBS) Thematic Burn Severity* (USD Forest Service and US Geological Survey, 2022); http://mtbs.gov/direct-download

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Author contributions

L.K., L.L.S. and N.D.M. designed the study. E.V.F., S.K., S.M., C.S. and M.J.W. contributed content expertise regarding wildfire smoke, human and livestock health, federal fire policy and soil health. E.K. developed Fig. 2. L.K. led the literature review and writing with assistance from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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