ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Fires that matter: reconceptualizing fire risk to include interactions between humans and the natural environment

To cite this article: Virginia Iglesias *et al* 2022 *Environ. Res. Lett.* **17** 045014

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
31 December 2021

REVISED
23 February 2022

ACCEPTED FOR PUBLICATION
9 March 2022

PUBLISHED
24 March 2022

LETTER

Fires that matter: reconceptualizing fire risk to include interactions between humans and the natural environment

Virginia Iglesias[1,8,*], Natasha Stavros[1,8], Jennifer K Balch[1,8], Kimiko Barrett[2], Jeanette Cobian-Iñiguez[3], Cyrus Hester[4], Crystal A Kolden[5], Stefan Leyk[6], R Chelsea Nagy[1], Colleen E Reid[6], Christine Wiedinmyer[7], Elizabeth Woolner[1] and William R Travis[1]

[1] Earth Lab (Cooperative Institute for Research in Environmental Sciences), University of Colorado Boulder, Boulder, CO, United States of America
[2] Headwaters Economics, Bozeman, MT, United States of America
[3] Mechanical Engineering Department, University of California Merced, Merced, CA, United States of America
[4] Institute of Behavioral Science, University of Colorado Boulder, Boulder, CO, United States of America
[5] Department of Management of Complex Systems, University of California Merced, Merced, CA, United States of America
[6] Department of Geography, University of Colorado Boulder, Boulder, CO, United States of America
[7] Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, United States of America
[8] These authors contributed equally to this work.
[*] Author to whom any correspondence should be addressed.

E-mail: virginia.iglesias@colorado.edu

Keywords: firescape, hazard, exposure, vulnerability, social-environmental-technological system

Supplementary material for this article is available online

Abstract

Increasing fire impacts across North America are associated with climate and vegetation change, greater exposure through development expansion, and less-well studied but salient social vulnerabilities. We are at a critical moment in the contemporary human-fire relationship, with an urgent need to transition from emergency response to proactive measures that build sustainable communities, protect human health, and restore the use of fire necessary for maintaining ecosystem processes. We propose an integrated risk factor that includes fire and smoke hazard, exposure, and vulnerability as a method to identify 'fires that matter', that is, fires that have potentially devastating impacts on our communities. This approach enables pathways to delineate and prioritise science-informed planning strategies most likely to increase community resilience to fires.

1. The fire crisis

The world has experienced some of the most destructive and deadly wildfires in a century during the past decade. In the US alone, tens of thousands of homes have been destroyed [1], over 200 people have lost their lives in blazes, and an order of magnitude more have died due to health impacts from smoke exposure [2], with many more requiring hospitalisation for respiratory or cardiovascular disease [3]. The US spends over USD 2B a year fighting wildfires; the accrued direct and indirect impacts of wildfires on infrastructure, buildings and communities could be 30 times that amount [4]; and there is no clear end to these mounting costs in sight.

The last few years suggest that we are reaching a critical point beyond which mass wildfire destruction will be the norm, rather than the exception. We struggle with devastating events because we have failed to develop and implement a holistic, sustainable regional system approach for co-existing with fire. Rather than conceptualising fire as an extrinsic phenomenon that threatens communities, we need a framework that places social, environmental, and technological factors as interrelated and interacting components [5, 6]. The 2018 Camp Fire in Paradise, California, ignited by a faulty powerline, exemplifies the necessity for this paradigm shift, as its unprecedented impacts resulted from rapid fire progression facilitated by natural and urban fuels [7], limited evacuation routes, and inherent social vulnerabilities [8]. Similarly, the 2017 Thomas Fire in California and the 2021 Marshall Fire in Colorado burned through both natural and developed landscapes, destroying thousands of homes. These fire disasters suggest that not only do we have a wildland fire problem, but also an urban fire problem.

The majority of the world population already lives in urban areas [9–11]. In the US, an anticipated 87.6 million people will live in cities by 2050 [12], creating an expanding development fringe that increasingly intersects with wildlands [13]. Urban expansion and densification along the rural–urban continuum grow the fire risk, as we introduce ignitions [14], building materials that are often more flammable than the surrounding vegetation [15], and communities with a range of social vulnerabilities into fire-prone areas [16]. For this reason, there is a pressing need to reframe firescapes as social-environmental-technological systems (SETS) [17]. Such a multi-component fire risk framework is critical for identifying resilience pathways and precipitating a shift from emergency response to proactive sustainable planning.

More integrated risk management framings of the fire problem are already emerging [18–23]. Dunn *et al* for example, provide such an assessment focused on wildfire management at the site to landscape scale, including decision support for allocation of fire suppression assets, pre-fire planning and prefiguring of resources, and evaluating risk to firefighters and to priority land resources [24]. Here, we propose an approach for analysing relationships between humans and fire as part of a SETS and conduct a quantitative, census-tract-level risk assessment across the western US that encompasses direct and indirect fire hazard from flame and smoke, population exposure, and social vulnerability. We then use this framework to provide community-specific recommendations for resilience pathways that could reduce the likelihood of the most destructive and disruptive events, i.e. the 'fires that matter'.

2. Fire risk is an emergent property of SETS

The fire crisis is partly due to the higher probability of fire and expansion of urban development into wildlands observed in recent years. Anthropogenic contributions to climate change have also effectively doubled the amount of western forests that have burned since 1984 [25], and created a fire season that is up to three months longer than in previous decades [26, 27]. Although social, economic, and technological factors are known to exacerbate fire effects and increase the likelihood of disasters [28], implementation of a fully-integrated SETS fire risk model remains challenging [18, 23, 29, 30].

For millennia, people have started and managed fires [31], and fire regimes have co-evolved with societies as their economies shifted toward hunting-gathering, pastoralism, farming, and industrialization [24, 32, 33]. Today, settlement patterns significantly alter the number of homes in harm's way [34], increase fire ignitions [14], and sustain combustion [15, 35]. Firescapes are thus a palimpsest of ecological and historical processes, shaped by waves of land use and urban expansion. In this context, fire risk, defined as the likelihood of substantial alterations in the normal functions of a community [36], emerges from the combined effects of fire hazard (section 2.1), the presence of people, livelihoods, infrastructure, and assets in places that are exposed to fire and smoke (hereafter, 'exposure'; section 2.2), and socio-economic, health, and built-environment vulnerability (section 2.3) (figure 1).

2.1. Hazard: the potential for fire and smoke

The fire regime, i.e. the characteristic seasonality, return interval, size, spatial complexity, intensity, and severity of fire in an ecosystem [37], is a function of the interplay between climate, vegetation, and ignitions [38]. The influence of climate on fire is relatively well understood: in ecosystems with sufficient fuels to carry fire, drier conditions lead to increased burning as long as the probability of ignition remains unchanged [39]. In these areas, hotter, drier future climates will increase the likelihood of fire [40]. Burning also depends on the abundance of fuel. Thus, semiarid areas like the Great Basin experience some of the largest wildfires in the US [41] when wetter conditions in the months preceding the fire season allow the growth of abundant grasses and shrubs [42, 43]. Finally, ignitions occur from lightning or human causes including prescribed burning, sparks produced through powerline or equipment failure, cigarette butts, campfires, and arson. Studies investigating the role of lightning- vs human-related ignitions suggest that while the former are the main cause of burning in remote regions [44], human-started fires account for 84% of all wildfires in the US and are especially significant in areas where dry convective storms are rare [45].

The behaviour of a particular fire depends on cross-scale interactions among climate/weather, topography, and fuel [27]. For example, fast fires that outpace suppression efforts ($\sim$0.4 km production line*hr^{-1} [46]) are driven by ambient and fire-induced winds, and can be exacerbated by fuel accumulation and drought, especially in steep terrain [47]. Fuel load, type (e.g. grasses vs shrubs), condition (e.g. dead vs alive), and horizontal connectivity, in turn, are a function of ecological processes and the legacy of past land use and management. The long-lasting effects of management are evidenced by decades of fire suppression in several regions with resulting fuel build-up conducive to more destructive fires [48]. Exceptional accumulation of fuel can also occur due to high tree mortality, such as that observed in the Sierra Nevada of California due to bark beetle outbreaks [49]. There, the unusual abundance of large

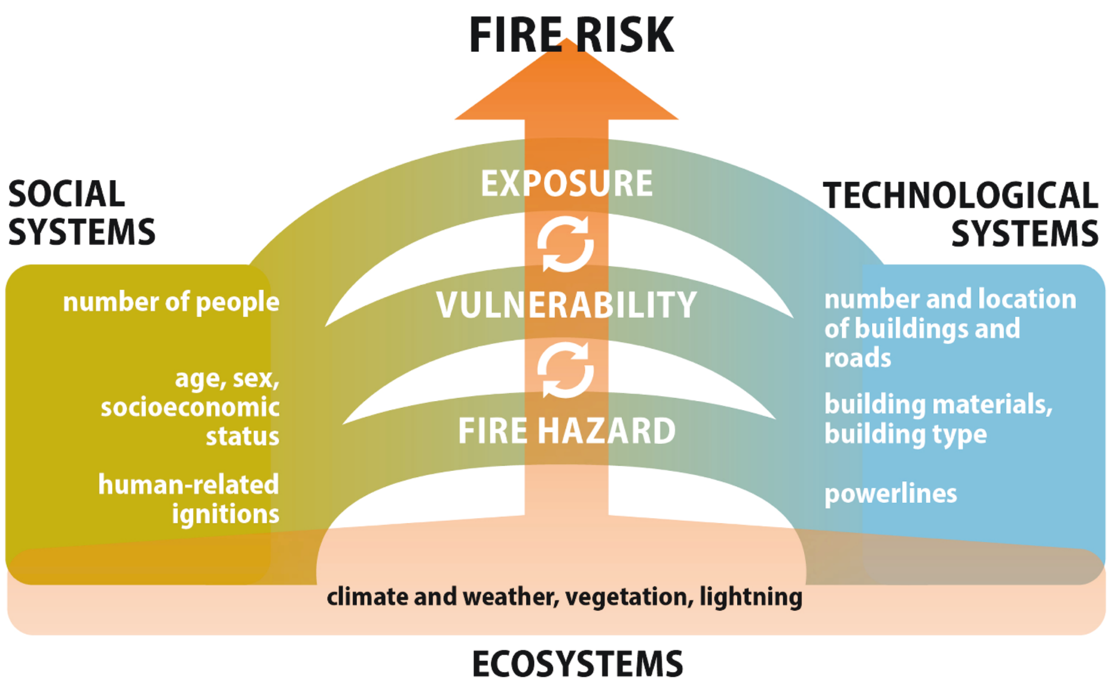

Figure 1. Fire risk is an emergent property of social-ecological-technological systems that results from interactions between fire hazard, exposure of people and assets, and their vulnerability.

surface fuels may increase the potential for smouldering fire [50] that alters local fire spread dynamics.

2.2. Fire exposure: direct and indirect

Fire exposure refers to the 'presence of people, livelihoods, services, resources, infrastructure, or economic, social, or cultural assets in settings that could be adversely affected' by fire [36]. Within the context of SETS, we identify two types of fire exposure: direct exposure of people and buildings to flames, and indirect exposure due to smoke. Both direct and indirect threats can potentially impact people's psychological, physical and financial wellbeing.

Firescapes include areas of varying levels of development, from wildlands to rural, suburban, and even densely-populated urban systems. Communities adjacent to, intermingled with, or surrounded by wildland (Wildland-Urban Interface; WUI) constitute hotspots where high fire potential meets the built environment. In the US, ∼60 million structures were less than 1 km from the boundaries of wildfires between 1992 and 2015 [14]. The extent of the WUI is projected to double by 2030 [51], suggesting that millions of new homes will be exposed to elevated fire hazard in years to come [52–54]. Due to the growing number of buildings in these transitional zones, there is an urgent need to understand how spatial patterns in housing development influence risk, both through changing exposure and by altering the continuity, abundance, and flammability of fuels across the landscape.

Although the WUI is of special interest to direct exposure mitigation, it is important to recognize that it is part of the wildland–rural–urban gradient. Wildfires anywhere along this gradient affect people who live, work, or recreate downwind due to smoke exposure [55, 56]. However, smoke exposure is often neglected in fire risk assessment. It is estimated with a blend of statistical models with *in situ* monitoring data, satellite observations, and chemical transport models [57–60]. These data are also used to judge the effects of a key wildfire mitigation strategy: prescribed burning, which has different and sometimes reduced air-pollutant emissions compared to wildfires [61, 62]. Although this difference could have large implications for smoke management, key questions related to air-pollutant composition, concentrations, locations and timing still remain. Furthermore, despite calls for more prescribed burning for fuel and ecosystem management [63], existing policy implementations of the National Ambient Air Quality Standards (NAAQS) limit how much burning can actually be done [64].

2.3. Vulnerability: social and built environment

Vulnerability is defined as the 'degree of loss to each element should a hazard of a given severity occur' [36]. When assessing vulnerability to fire, the 'elements' that could be adversely affected include people and buildings, and therefore at least two types of vulnerability need to be considered: social and built-environment. Social vulnerability depends on the characteristics of an individual or community that influence their ability to anticipate, respond to, and cope with disasters [65]. Key elements of social vulnerability such as age, sex, race, income, and other demographics related to the ability to interpret information and access resources [66], interact with natural hazards making communities more or less likely to suffer damages and long-lasting disruptions. For example, lower income communities may have fewer resources to mitigate against fire (e.g. installation of ignition-resistant roofing [67]) and smoke exposure (e.g. use of air conditioning or air purifiers [68]), as well as resources for socio-economic recovery (e.g. insurance).

Built-environment vulnerability to fire is defined by the properties of buildings in flammable landscapes, and has to be understood separately from, although interrelated with, social vulnerability. Homes are ignitable and combustible, representing a complex fuel element located in the WUI, yet current fuel classifications do not account for their presence. Higher rates of structure loss have been related to intermediate structure densities located within more flammable herbaceous fuels, as higher building densities may protect subdivisions from direct flame impingement but constitute a source of heat and embers when burned [35, 69]. Moreover, construction material and design can increase the ignitability, and subsequently the vulnerability of a home [15, 70, 71]. It is noteworthy that, while federal land agencies have spent billions of dollars on vegetation-fuel assessment and treatment (e.g. USD 2.7B between 2001 and 2006 to treat millions of hectares [72]), research has only begun to focus on the importance of defensible space, and little attention has been given to the influence of building density and arrangement on fire spread and intensity [73, 74].

Social vulnerability assessments need to incorporate both direct (flames) and indirect (smoke) threats from fires. The WUI, which is directly threatened by fire, is predominantly developed and occupied by White and economically secure populations [68, 75, 76], leading many to equate threat of wildfire with low social vulnerability. However, the same studies highlight that these estimates are averages, and at least a third of the Americans living in areas of high fire hazard are Hispanic, Black, Native American, over the age of 65, have disabilities, or live in poverty [16], with an unknown greater number of socially-vulnerable people affected by smoke in neighbouring urban and rural areas.

The impacts of smoke are also magnified by underlying social and health disparities. A recent meta-analysis showed growing evidence that, when exposed to wildfire smoke, women are more likely to experience asthma exacerbations than men, adults are more affected than children [77], and elderly African American people are more vulnerable than elderly White people [78]. Of special concern are people who work long shifts outdoors, such as farmworkers [79]. In many cases, low income, limited access to information, healthcare, and immigration status increase the vulnerability of these populations to smoke exposure and other hazards [80].

3. Investigating hazard, exposure, and vulnerability to mitigate fire and smoke risk

Effective mitigation strategies need to target the underlying drivers of fire and smoke risk. As a proof of concept, we evaluated the relative contribution of hazard, exposure, and social vulnerability to fire risk in the western US, at the census-tract level. We calculated direct fire hazard as the median annual probability of fire in each census tract using the fire probability layer of the Wildfire Hazard Potential data product [81] (figure 2(a)). To estimate the probability of unhealthy air conditions due to smoke (indirect fire hazard), we employed daily fine-particulate-matter concentrations ($PM_{2.5}$) generated by Reid *et al* for 2008–2018 [82]. Although smoke is not the only source of $PM_{2.5}$, it is the main contributor during the summer months in fire-prone areas such as the western US [83, 84] and has been associated with adverse health effects including lung cancer [85], cardiorespiratory morbidity [86], and mortality [87]. For this reason, we calculated the probability of at least one summer day per year with unhealthy $PM_{2.5}$ concentrations ($PM_{2.5} > 55$ [88]) (figure 2(b)). Lastly, we obtained population estimates and the social vulnerability index (SVI) from the Center for Disease Control to quantify exposure and the capacity of local populations to cope with and recover from direct and indirect impacts [89], respectively.

Following the IPCC [36, 90], we calculated risk as (1):

$$\mathrm{Risk}_{(\mathrm{CT})} = \mathrm{Hazard}_{(\mathrm{CT})} \times \mathrm{Exposure}_{(\mathrm{CT})} \times \mathrm{Vulnerability}_{(\mathrm{CT})}, \quad (1)$$

where $\mathrm{hazard}_{(\mathrm{CT})}$ is the probability of fire (figure 2(c)) or smoke in census tract CT (figure 2(d)) and has lower and upper boundaries of 0 and 1; $\mathrm{exposure}_{(\mathrm{CT})}$ is the total population in census tract CT arithmetically scaled so that the minimum value registered in the western US corresponds to 0 and the highest to 1; and $\mathrm{vulnerability}_{(\mathrm{CT})}$ is the SVI in census tract CT. By design, the SVI is unitless and ranges between 0 and 1 [89]. The multiplicative nature of the equation allows estimation of the likelihood of a person being affected by fire or smoke given their social vulnerability and the probability of hazard, which is consistent with the definition of risk that we adopted.

Analyses that incorporate hazard, exposure, and vulnerability illustrate the complexity of fire risk (figure 3) and point to different mitigation opportunities across geographies (figure 4). On average, high fire risk in the western US (top 5% census tracts) does not result from exceptional hazard or exposure, but from high vulnerability (figures 3(a)–(c)). However,

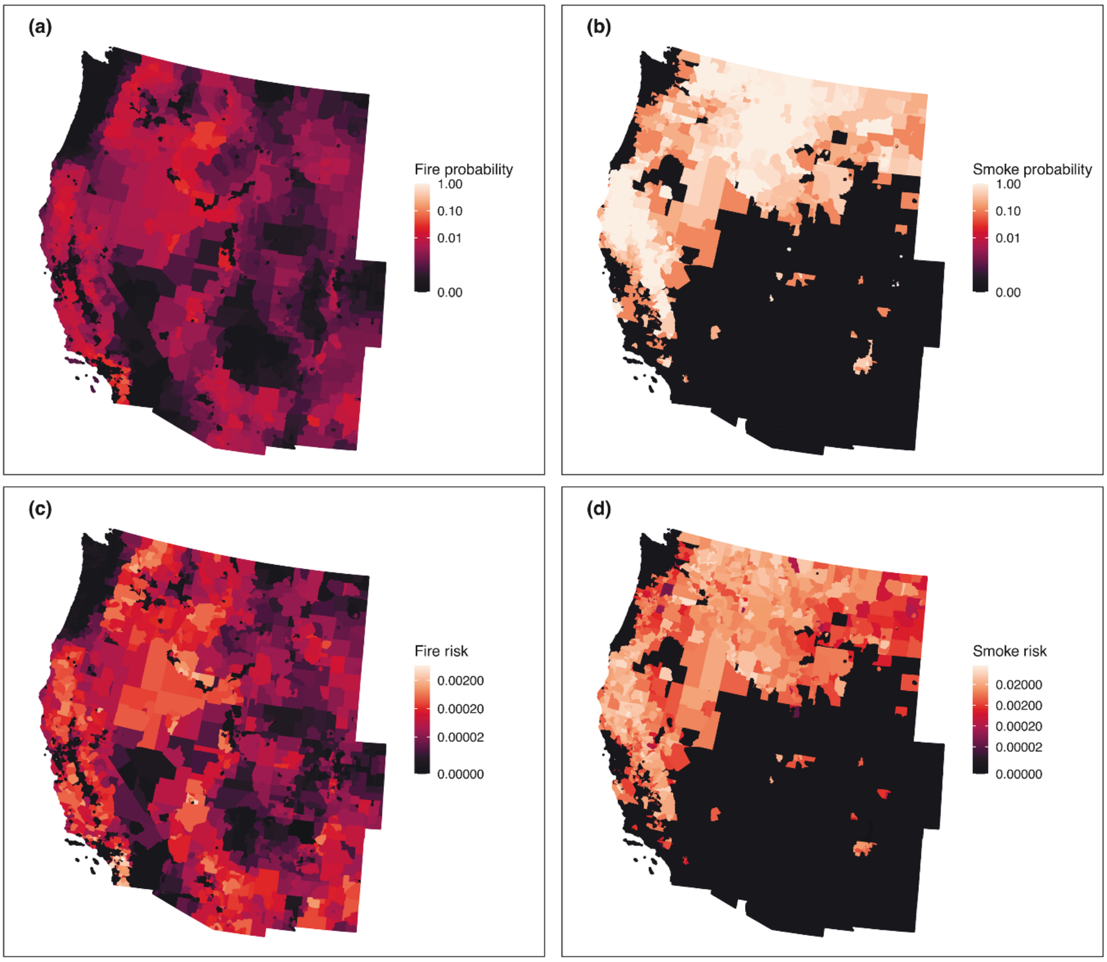

Figure 2. Annual probability of (a) fire and (b) unhealthy air quality due to smoke ($PM_{2.5} > 55\ \mu g^{*} m^{-3}$) in the western US. Risk of (c) fire and of (d) unhealthy air quality due to smoke ($PM_{2.5} > 55\ \mu g^{*} m^{-3}$). Note that the colour scales are logarithmic.

census tracts in California, Idaho and Nevada show that the relative influence of exposure, vulnerability and hazard is community-dependent and variable. Thus, more discerning risk assessment can point to tailored mitigation strategies. Situations of high fire hazard and low exposure (figure 2(a)) call for actions to reduce fire ignitions and spread (sections 4.1 and 4.2). Places marked by low/ moderate fire probability and vulnerability (figure 2(b)) but elevated exposure require an emphasis on building better (section 4.3). Risk in other communities may chiefly arise from high social vulnerability (figure 3(c)), placing the mitigation emphasis on reducing socioeconomic disparities and serving environmental justice (section 4.4).

In terms of smoke, the average high-risk census tract (top 5%) has a very high probability of unhealthy concentrations of $PM_{2.5}$, high social vulnerability, and moderate smoke exposure (figures 3(d)–(f)). Similar to fire risk, the relative importance of these factors changes as we shift from the regional scale to individual census tracts. However, a difference emerges: while high direct fire risk is associated with variable levels of fire hazard, high smoke risk always reflects very high probability of unhealthy $PM_{2.5}$ concentrations. Strategies aimed at minimising the probability of ignition (section 4.1) and fire spread (sections 4.2) would thus be particularly effective at reducing risk. Implementation of these strategies may prove challenging, as smoke crosses geopolitical and administrative boundaries, and the communities affected by smoke are not necessarily the same ones directly impacted by wildfires (figure 2). The impacts of smoke thus raise issues of morally permissible risk imposition and highlight the necessity for a systems approach that crosses geopolitical boundaries to holistically incorporate fire and smoke in fire risk mitigation towards a more resilient future.

4. Identifying resilience pathways

At present, the siloed approach to mapping fire risk as purely direct or indirect constrains implementation of policies (e.g. Fire Hazard Reduction, Endangered Species Act, and National Ambient Air Quality Standards), such that managers have limited pathways to build resilience [64]. Meanwhile, our market-driven system of settlement and development, subsidised

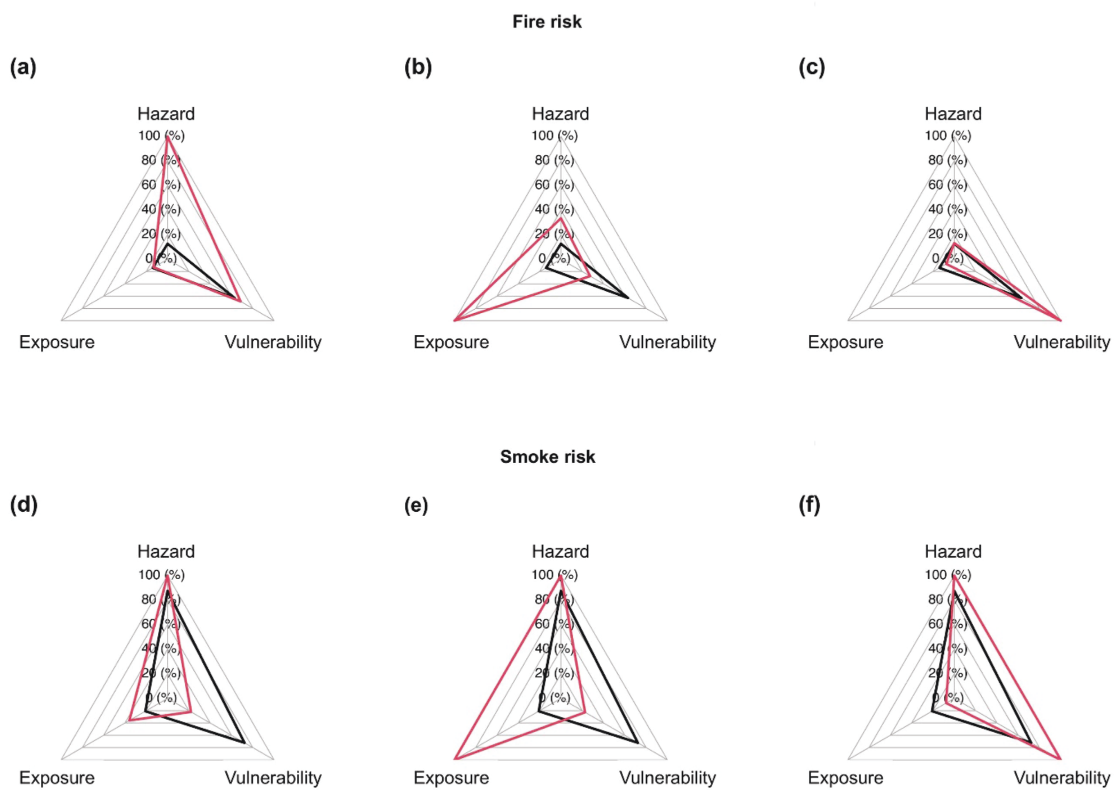

Figure 3. Spiderplots of fire (a)–(c) and smoke (d)–(f) risk showing the interplay among hazard, exposure, and vulnerability. In all cases, the axes are scaled so that the minimum values of each parameter registered in the western US correspond to 0% and the highest ones to 100%. Median values for the top 5% riskiest census tracts in the western US (supplementary tables 1 and 2 available online at stacks.iop.org/ERL/17/045014/mmedia) are depicted in black. Red triangles show census tracts with the highest hazard ((a) Elko County, Nevada, and (d) Ada County, Idaho)); exposure ((b) San Diego County, California, and (e) Ada County, Idaho); and vulnerability ((c) Riverside County, California, and (f) Jackson County, Oregon).

with public infrastructure investments, is exceedingly robust and thereby able to maintain behaviours (maladaptive or otherwise) despite repeated shocks and growing uncertainty [91, 92]. As a result, low-density and leapfrog development, income stratification, and environmental injustice are persistent features absent systemic reform [93–95]. A systems approach that quantifies fire risk across the wildland-rural-urban gradient as a function of fire and smoke hazard, exposure, and vulnerability (section 3) paves the way to more discerning, sustainable mitigation. By adopting this perspective, we can recognize the mismatch of proposed mitigation invested primarily in control and emergency management. Adapting to modern fire regimes requires us to instead invest in a system of 'social-ecological resilience' that promotes sustainability, adaptive capacity, learning, and innovation [91]. In this spirit and guided by our risk assessment, we present four pathways toward resilience that reduce human-related ignitions (section 4.1), implement prescribed burns (section 4.2), build better (section 4.3), and serve environmental justice (section 4.4) (figure 4).

4.1. Reduce human-related ignitions

Increased settlements and WUI expansion mean increased human-caused ignitions, which are responsible for 97% of all wildfires in the western US WUI [14]. These fires consume about a third of fire-fighting costs [96], and result in billions in damages [1]. Although not all ignitions are avertable, some can be prevented. Faulty power lines, for example, have started 10 of the 20 most destructive fires in California [97], costing PG&E more than USD 6B, and ultimately resulting in them filing what some have called the first climate change bankruptcy [98]. Direct incentives that could reduce the probability of ignition by power lines include infrastructure improvements (e.g. wires, poles, transformers), targeted inspections/remediations (e.g. grid hardening and vegetation removal), public-safety power shutoffs, and moves to decentralised power (e.g. microgrids) thereby reducing energy transport. Many of these mitigations can be costly, and power companies, which often serve a regional community, need to prioritise investments, making high-resolution analyses of risk essential.

4.2. Implement prescribed burns to reduce fire hazard and promote better smoke management

Restoring fire to fire-adapted SETS is one of the primary paths to sustainability in the western US. The suppression of wildfire and exclusion of Indigenous cultural fire over the 20th century is widely recognized

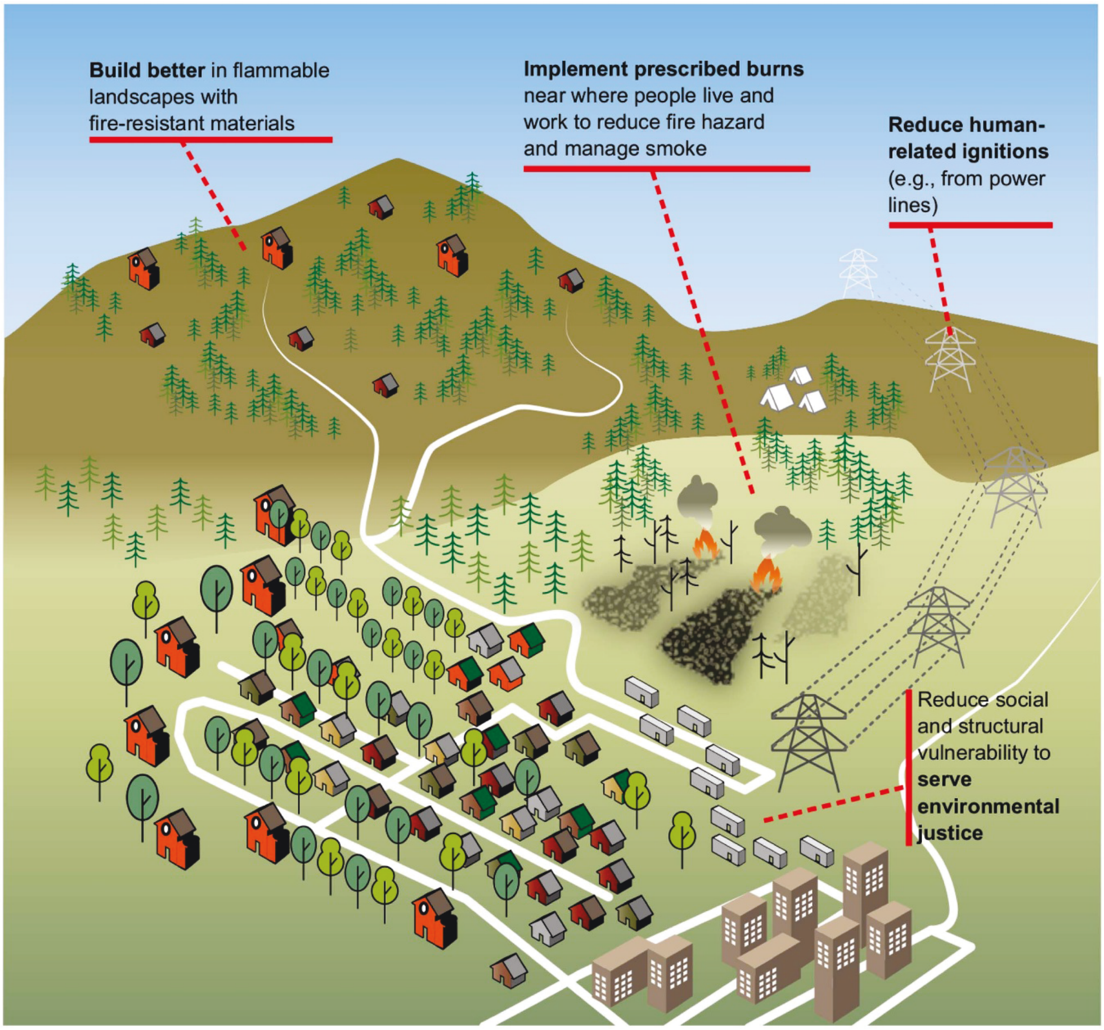

Figure 4. Resilience pathways for a fire-prone, interconnected social-ecological-technological system along the human-wildland gradient.

as a key driver of contemporary large and fast-moving fires [99]. This recognition, however, has not translated into increased prescribed fire due to a host of policy, fiscal, and social barriers [63, 100]. There is concern that attempts to restore fire in contemporary novel SETS that developed under similarly novel climates may yield equally disastrous results from continued exclusion [101, 102]. Given the barriers to increasing intentional fire use, we need to ask whether application below some minimum desired threshold will sufficiently offset the negative impacts so as to be justified.

Because we can control location and timing, prescribed burning could yield lesser smoke impacts on the atmosphere and populations downwind than wildland fires [61, 62]. For example, ozone concentrations, regulated by the Clean Air Act, can increase due to wildfire emissions, and are problematic in the summer when ozone formation conditions are optimal [103, 104]. Altering the timing of smoke emissions through the use of prescribed burning such that the emissions occur outside of the ozone season may reduce health impacts, while also mitigating direct impacts from wildfire. It is therefore critical to understand when, how much, and where prescribed fire is required to effectively mitigate direct and indirect fire risk without triggering undesired ecological transformations or introducing toxic levels of smoke beyond what wildfire would produce.

4.3. Build better

The 'fire-adapted community' movement has developed an integrated framework for mitigation that considers the nature of buildings, nearby vegetation treatments, vehicle access, and water sources. Recent events indicate the need to integrate larger infrastructure systems, especially the electricity grid, as well as consider how community design affects human-caused ignitions (section 4.2). An even more holistic approach would incorporate fire into all hazard and climate mitigation, as codified in the US Conference of Mayors Climate Protection Agreement, signed by more than 1000 cities.

A recent study demonstrated that building a new home with fire-resistant materials costs about the same as building a traditional home [71]. Furthermore, while massive urban conflagrations led to building codes to reduce flammability indoors and protect occupants (e.g. Chicago in 1871), today, similar measures extending from the skeleton of the structure out to the landscape are needed to create defensible space [73, 74]. Greater focus is needed on reducing dwelling susceptibility and treating nearby hazardous fuels through proactive planning efforts and implementation of neighbourhood zoning or county-level building codes that create ignition-resistant communities [18]. Guided by comprehensive risk assessments that include built-environment exposure and vulnerability, such efforts could eventually aggregate to reduced fire risk at the regional scale despite increased fire hazard due to expanding development and a warmer and drier climate. Efforts to develop datasets on the built environment necessary to conduct such risk assessment and mitigation would be valuable to help identify efficient pathways to improved fire resilience.

4.4. Serve environmental justice

The interaction of environmental and socioeconomic change is reshaping our experience with fire in the American West, similar to other cases of 'double exposure' (e.g. [105, 106]). Research suggests that land managers are poorly equipped to integrate procedural and distributional justice concerns into fire risk mitigation, while vulnerable communities often lack the capacity to engage in collaborations to increase resilience [76, 107]. The metrics of fire risk that we incorporate, namely human exposure, social vulnerability, and fire and smoke hazard (equation (1); figures 1 and 3) could facilitate federal compliance with US Executive Order 12 898 [108], which requires that agencies address disproportionate risks (as well as lack of benefits) to the health and environment of low income and minority populations. The limited research available regarding US Forest Service compliance with this Executive Order indicates that environmental justice concerns are currently not a priority in hazardous fuel reduction efforts [107], resulting in an array of outcomes based on local context. Therefore, an increased focus on the social aspects of wildfire vulnerability may not only improve compliance but also produce more universally beneficial outcomes which are less dependent on local factors. Specific actions to serve environmental justice include: considering differential impact when managing fuels [107]; recognizing cultural, language, and perception differences during both planning periods and emergencies [109–112]; and incentivizing and increasing access to other risk mitigation efforts (e.g. batteries for decentralised renewable energy, insurance, and assistance with grant applications).

5. Conclusions: out of the ashes comes an opportunity for change

Our national fire problem results from more homes spread over fire-prone places, compounded with social vulnerability, people providing ignitions, and a changing landscape with urban fuels, all against a backdrop of a warming climate. This requires urgent, resilient solutions. In recent years, hazards research has highlighted the need to both enhance the robustness of infrastructure and institutions, and improve the capacity of communities to respond to and recover from extreme events [113]. Resilience capacity is constrained by social and economic disparities, which are often a by-product of the demographic processes underpinning the mosaic of land uses delineating cities and their hinterlands [114–120]. Thus, we expect that the design of fire-resilient and sustainable regional systems must also attend to a diversity of adaptive capacities and vulnerabilities, including the social-environmental processes that shape them.

Increasing fire resilience requires us to complement the advances made in fire and smoke hazard modeling with an understanding of the social processes incentivizing development and increasing exposure, as well as the causes of uneven vulnerabilities across communities [121–123]—the interrelated components of a SETS. By extension, we propose three broad principles for any resilient fire governance strategy: (a) appreciating that vulnerable communities are often simultaneously exposed to economic hardship, political marginalisation, and climate-induced risks [105, 106]; (b) respecting and integrating local knowledge into planning and implementation strategies while empowering communities to identify vulnerabilities, leverage situational expertise, build adaptive capacity, and carry out localised resilience strategies [118]; and (c) anticipating that adaptation is a socio-political process [123] wherein cultural norms and interests compete to shape outcomes often excluding vulnerable communities [107].

Redefining 'the fires that matter' as fires with negative social impact in a SETS that spans the wildland–rural–urban gradient, and conceptualising fire risk as the convergence of hazard, exposure, and social and built-environment vulnerability enables pathways to planning and funding initiatives for more fire resilient communities. In this context, the effects of fire on ecosystem processes and services, including biodiversity and water supply, need to be factored into the risk equation alongside smoke and other indirect hazards. Now is the time to build a holistic view of equitable SETS that enables data-driven science to inform decision making. A systems lens, convergent interdisciplinary research that honours traditional ecological knowledge [124, 125], and fine-resolution data that enable a refined, dynamic assessment of risk are critical for understanding, identifying and implementing effective fire resilience pathways across wildland-urban-rural gradients before the cost of inaction is too great.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

Conceptualization: V I (risk framework), N S (cross-disciplinary and systems thinking), J K B (fire theory, cross-disciplinary thinking, and resilience pathways), K B (built-environment vulnerability), J C-I (fire behavior), C H (social vulnerability), C A K (fire theory, resilience pathways), S L (built environment exposure and vulnerability), R C N (fire theory, cross-disciplinary thinking), C E R (smoke exposure and vulnerability and health impacts), C W (smoke exposure and vulnerability), E W (environmental justice), W R T (risk framework); Data analysis: V I; Visualizations: K A Bogan (figures 1 and 4), V I (figures 2 and 3); Writing and editing: All authors; Funding: J K B; Supervision: N S, J K B, W R T.

Conflict of interests

Authors declare no competing interests.

Funding

Funding for this work was provided by Earth Lab through the University of Colorado Boulder's Grand Challenge Initiative.

ORCID iDs

Virginia Iglesias https://orcid.org/0000-0001-5732-3714
Colleen E Reid https://orcid.org/0000-0001-8572-1162
Christine Wiedinmyer https://orcid.org/0000-0001-9738-6592

References

[1] Headwaters Economics 2020 Wildfires destroy thousands of structures each year (available at: https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/)
[2] Wang D *et al* 2021 Economic footprint of California wildfires in 2018 *Nat. Sustain.* **4** 252–60
[3] Fann N *et al* 2018 The health impacts and economic value of wildland fire episodes in the US: 2008–2012 *Sci. Total Environ.* **610–1** 802–9
[4] Schoennagel T *et al* 2016 Insights from wildfire science: a resource for fire policy discussions [White paper] *Headwaters Econ.* 1–9 (available at: https://headwaterseconomics.org/wp-content/uploads/wildfire-insights-paper.pdf)
[5] Pickett S T A and Cadenasso M L 2009 Altered resources, disturbance, and heterogeneity: a framework for comparing urban and non-urban soils *Urban Ecosyst.* **12** 23–44
[6] Pataki D E 2015 Grand challenges in urban ecology *Front. Ecol. Evol.* **3** 57
[7] Krishnakumar P and Schleuss J 2018 More than 18,000 buildings burned in Northern California. Here's what that looks like from above *Los Angeles Times* (available at: www.latimes.com/projects/la-me-camp-fire-building-destruction-map/)
[8] Maranghides A *et al* 2021 A case study of the camp fire—fire progression timeline (Gaithersburg, MD: National Institute of Standards and Technology) (Accessed 20 December 2021) p NIST TN 2135 (available at: https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2135.pdf)
[9] Bettencourt L and West G 2010 A unified theory of urban living *Nature* **467** 912–3
[10] Wigginton N S, Fahrenkamp-Uppenbrink J, Wible B and Malakoff D 2016 Cities are the future *Science* **352** 904–5
[11] Seto K C, Golden J S, Alberti M and Turner B L 2017 Sustainability in an urbanizing planet *Proc. Natl Acad. Sci. USA* **114** 8935–8
[12] United Nations, Department of Economic and Social Affairs, Population Division 2015 World urbanization prospects: the 2014 revision *ST/ESA/SER.A/366* p 493 (available at: https://population.un.org/wup/Publications/Files/WUP2014-Report.pdf)
[13] Burke M, Driscoll A, Heft-Neal S, Xue J, Burney J and Wara M 2021 The changing risk and burden of wildfire in the United States *Proc. Natl Acad. Sci. USA* **118** e2011048118
[14] Mietkiewicz N, Balch J, Schoennagel T, Leyk S, St Denis L and Bradley B 2020 In the line of fire: consequences of human-ignited wildfires to homes in the US (1992–2015) *Fire* **3** 50
[15] Cohen J 2010 The wildland-urban interface fire problem *J. For. Hist.* **38** 20–26
[16] Headwaters Economics 2021 The unequal impacts of fire (Bozeman) (available at: https://headwaterseconomics.org/natural-hazards/unequal-impacts-of-wildfire/)
[17] Markolf S A *et al* 2018 Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience *Earth's Future* **6** 1638–59
[18] Ager A A, Kline J D and Fischer A P 2015 Coupling the biophysical and social dimensions of wildfire risk to improve wildfire mitigation planning: coupling the biophysical and social dimensions of wildfire risk *Risk Anal.* **35** 1393–406
[19] Fischer A P *et al* 2016 Wildfire risk as a socioecological pathology *Front. Ecol. Environ.* **14** 276–84
[20] Steelman T 2016 US wildfire governance as social-ecological problem *Ecol. Soc.* **21** art3
[21] Schoennagel T *et al* 2017 Adapt to more wildfire in western North American forests as climate changes *Proc. Natl Acad. Sci. USA* **114** 4582–90
[22] Oliveira S, Rocha J and Sá A 2021 Wildfire risk modeling *Curr. Opin. Environ. Sci. Health* **23** 100274
[23] Essen M, McCaffrey S, Abrams J and Paveglio T 2022 Improving wildfire management outcomes: shifting the paradigm of wildfire from simple to complex risk *J. Environ. Plann. Manage.* 1–19 [in press]
[24] Pyne S J 2001 *Fire: A Brief History* (Seattle, WA: University of Washington Press) p 204
[25] Abatzoglou J T and Williams A P 2016 Impact of anthropogenic climate change on wildfire across western US forests *Proc. Natl Acad. Sci. USA* **113** 11770–5
[26] Westerling A L, Hidalgo H G, Cayan D R and Swetnam T W 2006 Warming and earlier spring increase western US forest wildfire activity *Science* **313** 940–3

[27] Westerling A L 2017 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring *Phil. Trans. R. Soc.* B **371** 20150178

[28] McCaffrey S 2015 Community wildfire preparedness: a global state-of-the-knowledge summary of social science research *Curr. For. Rep.* **1** 81–90

[29] McCaffrey S, Toman E, Stidham M and Shindler B 2013 Social science research related to wildfire management: an overview of recent findings and future research needs *Int. J. Wildland Fire* **22** 15

[30] Toman E, Stidham M, McCaffrey S and Schindler B 2013 Social science at the wildland-urban interface: a compendium of research results to create fire-adapted communities (Newtown Square: US Department of Agriculture, Forest Service, Northern Research Station) p NRS-GTR-111

[31] Marlon J R *et al* 2012 Long-term perspective on wildfires in the western USA *Proc. Natl Acad. Sci.* **109** E535–43

[32] Iglesias V, Vannière B and Jouffroy-Bapicot I 2019 Emergence and evolution of anthropogenic landscapes in the Western Mediterranean and adjacent Atlantic regions *Fire* **2** 53

[33] Pyne S J 2020 From pleistocene to pyrocene: fire replaces ice *Earth's Future* **8** e2020EF001722

[34] Iglesias V *et al* 2021 Risky development: increasing exposure to natural hazards in the United States *Earth's Future* **9** e2020EF001795

[35] Knapp E E, Valachovic Y S, Quarles S L and Johnson N G 2021 Housing arrangement and vegetation factors associated with single-family home survival in the 2018 camp fire, California *Fire Ecol.* **17** 25

[36] IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) p 582

[37] Sugihara N G, van Wagtendonk J W and Fites-Kaufman J 2006 Fire as an ecological process *Fire in California's Ecosystems* ed N Sugihara (Berkeley, CA: University of California Press) pp 58–74

[38] Moritz M A, Morais M E, Summerell L A, Carlson J M and Doyle J 2005 Wildfires, complexity, and highly optimized tolerance *Proc. Natl Acad. Sci.* **102** 17912–7

[39] Whitlock C, Higuera P E, McWethy D B and Briles C E 2010 Paleoecological perspectives on fire ecology: revisiting the fire-regime concept *Open Ecol. J.* **3** 6–23

[40] Joseph M B *et al* 2019 Spatiotemporal prediction of wildfire size extremes with Bayesian finite sample maxima *Ecol. Appl.* **29** e01898

[41] Nagy R C, Fusco E, Bradley B, Abatzoglou J T and Balch J K 2018 Human-related ignitions increase the number of large wildfires across US ecoregions *Fire* **1** 4

[42] Stavros E N, Abatzoglou J, Larkin N K, McKenzie D and Steel E A 2014 Climate and very large wildland fires in the contiguous western USA *Int. J. Wildland Fire* **23** 899

[43] Balch J *et al* 2018 Switching on the big burn of 2017 *Fire* **1** 17

[44] Rorig M L and Ferguson S A 1999 Characteristics of lightning and wildland fire ignition in the Pacific Northwest *J. Appl. Meteorol.* **38** 1565–75

[45] Balch J K, Bradley B A, Abatzoglou J T, Nagy R C, Fusco E J and Mahood A L 2011 Human-started wildfires expand the fire niche across the United States *Proc. Natl Acad. Sci. USA* **114** 2946–51

[46] Broyles G 2011 Fireline production rates *USDA Forest Service* p 19 (available at: www.fs.fed.us/eng/pubs/pdf/11511805.pdf)

[47] Coen J L, Cameron M, Michalakes J, Patton E G, Riggan P J and Yedinak K M 2013 WRF-fire: coupled weather–wildland fire modeling with the weather research and forecasting model *J. Appl. Meteorol. Climatol.* **52** 16–38

[48] Collins B M, Das A J, Battles J J, Fry D L, Krasnow K D and Stephens S L 2014 Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival *Ecol. Appl.* **24** 1879–86

[49] Stephens S L *et al* 2018 Drought, tree mortality, and wildfire in forests adapted to frequent fire *BioScience* **68** 77–88

[50] Cobian-Iniguez J *et al* 2022 Wind effects on smoldering behavior of simulated wildland fuels *Combust. Sci. Technol.* 1–18 [in press]

[51] Theobald D M and Romme W H 2007 Expansion of the US wildland–urban interface *Landscape Urban Plan.* **83** 340–54

[52] Mann M L *et al* 2014 Modeling residential development in California from 2000 to 2050: integrating wildfire risk, wildland and agricultural encroachment *Land Use Policy* **41** 438–52

[53] Radeloff V C *et al* 2018 Rapid growth of the US wildland-urban interface raises wildfire risk *Proc. Natl Acad. Sci. USA* **115** 3314–9

[54] Strader S M 2018 Spatiotemporal changes in conterminous US wildfire exposure from 1940 to 2010 *Nat. Hazards* **92** 543–65

[55] Wu Y, Arapi A, Huang J, Gross B and Moshary F 2018 Intra-continental wildfire smoke transport and impact on local air quality observed by ground-based and satellite remote sensing in New York City *Atmos. Environ.* **187** 266–81

[56] Johnson M S, Strawbridge K, Knowland K E, Keller C and Travis M 2021 Long-range transport of Siberian biomass burning emissions to North America during FIREX-AQ *Atmos. Environ.* **252** 118241

[57] Reid C E *et al* 2015 Spatiotemporal prediction of fine particulate matter during the 2008 northern California wildfires using machine learning *Environ. Sci. Technol.* **49** 3887–96

[58] Crippa P *et al* 2016 Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia *Sci. Rep.* **6** 37074

[59] Lassman W *et al* 2017 Spatial and temporal estimates of population exposure to wildfire smoke during the Washington state 2012 wildfire season using blended model, satellite, and *in situ* data: multimethod estimates of smoke exposure *GeoHealth* **1** 106–21

[60] Watson G L, Telesca D, Reid C E, Pfister G G and Jerrett M 2019 Machine learning models accurately predict ozone exposure during wildfire events *Environ. Pollut.* **254** 112792

[61] Wiedinmyer C and Hurteau M D 2010 Prescribed fire as a means of reducing forest carbon emissions in the western United States *Environ. Sci. Technol.* **44** 1926–32

[62] Liu X *et al* 2017 Airborne measurements of western US wildfire emissions: comparison with prescribed burning and air quality implications *J. Geophys. Res. Atmos.* **122** 6108–29

[63] Kolden C 2019 We're not doing enough prescribed fire in the western United States to mitigate wildfire risk *Fire* **2** 30

[64] Clark S, Miller A and Hankins D 2021 Good fire: current barriers to the expansion of cultural burning and prescribed burning in California and recommended solutions *Karul Tribe* (available at: https://karuktribeclimatechangeprojects.com/good-fire/)

[65] Blaikie P, Cannon T, Davis I and Wisner B 2005 *At Risk* (Routledge) (available at: www.taylorfrancis.com/books/9781134887088)

[66] van Zandt S, Peacock W G, Henry D W, Grover H, Highfield W E and Brody S D 2012 Mapping social vulnerability to enhance housing and neighborhood resilience *Hous. Policy Debate* **22** 29–55

[67] Collins T W and Bolin B 2009 Situating hazard vulnerability: people's negotiations with wildfire environments in the US southwest *Environ. Manage.* **44** 441–55

[68] Shrestha P M *et al* 2019 Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons *Int. J. Environ. Res. Public Health* **16** 3535
[69] Syphard A D, Keeley J E, Massada A B, Brennan T J and Radeloff V C 2012 Housing arrangement and location determine the likelihood of housing loss due to wildfire *PLoS One* **7** e33954
[70] Cohen J 2000 Preventing disaster: home ignitability in the wildland-urban interface *J. For.* **98** 15–21
[71] Quarles S and Pohl K 2018 *Building a Wildfire-Resistant Home: Codes and Costs* 49 Headwaters Economics
[72] Schoennagel T, Nelson C R, Theobald D M, Carnwath G C and Chapman T B 2006 Implementation of national fire plan treatments near the wildland-urban interface in the western United States *Proc. Natl Acad. Sci.* **106** 10706–11
[73] Syphard A D, Brennan T J and Keeley J E 2014 The role of defensible space for residential structure protection during wildfires *Int. J. Wildland Fire* **23** 1165
[74] Braziunas K H, Seidl R, Rammer W and Turner M G 2021 Can we manage a future with more fire? Effectiveness of defensible space treatment depends on housing amount and configuration *Landscape Ecol.* **36** 309–30
[75] Wigtil G *et al* 2016 Places where wildfire potential and social vulnerability coincide in the coterminous United States *Int. J. Wildland Fire* **25** 896
[76] Davies I P, Haugo R D, Robertson J C and Levin P S 2018 The unequal vulnerability of communities of color to wildfire *PLoS One* **13** e0205825
[77] Kondo M *et al* 2019 Meta-analysis of heterogeneity in the effects of wildfire smoke exposure on respiratory health in North America *Int. J. Environ. Res. Public Health* **16** 960
[78] Liu J C *et al* 2017 Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *Am. J. Epidemiol.* **186** 730–5
[79] Mendez M, Flores-Haro G and Zucker L 2020 The (in)visible victims of disaster: understanding the vulnerability of undocumented Latino/a and indigenous immigrants *Geoforum* **116** 50–62
[80] Austin E, Kasner E, Seto E and Spector J 2021 Combined burden of heat and particulate matter air quality in WA agriculture *J. Agromed.* **26** 18–27
[81] Dillon G K 2018 Wildfire hazard potential (WHP) for the conterminous United States (270-m GRID) (Accessed 21 April 2020) (available at: www.fs.usda.gov/rds/archive/Product/RDS-2015-0047-2)
[82] Reid C E, Considine E M, Maestas M M and Li G 2021 Daily PM2.5 concentration estimates by county, ZIP code, and census tract in 11 western states 2008–2018 *Sci. Data* **8** 112
[83] McClure C D and Jaffe D A 2018 US particulate matter air quality improves except in wildfire-prone areas *Proc. Natl Acad. Sci. USA* **115** 7901–6
[84] O'Dell K, Ford B, Fischer E V and Pierce J R 2019 Contribution of wildland-fire ssmoke to US PM 2.5 and its influence on recent trends *Environ. Sci. Technol.* **53** 1797–804
[85] Hamra G B *et al* 2014 Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis *Environ. Health Perspect.* **122** 906–11
[86] Rajagopalan S, Al-Kindi S G and Brook R D 2018 Air pollution and cardiovascular disease *J. Am. Coll. Cardiol.* **72** 2054–70
[87] Achilleos S, Kioumourtzoglou M-A, Wu C-D, Schwartz J D, Koutrakis P and Papatheodorou S I 2017 Acute effects of fine particulate matter constituents on mortality: a systematic review and meta-regression analysis *Environ. Int.* **109** 89–100
[88] US EPA 2012 Revised air quality standards for particle pollution and updates to the air quality index (AQI) (available at: www.epa.gov/sites/default/files/2016-04/documents/2012_aqi_factsheet.pdf)
[89] Centers for Disease Control and Prevention/ Agency for Toxic Substances and Disease Registry/ Geospatial Research, Analysis, and Services Program 2020 CDC/ATSDR Social vulnerability index (available at: www.atsdr.cdc.gov/placeandhealth/svi/data_documentation_download.html)
[90] Reisinger A *et al* 2020 *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-working Group Discussions* (Geneva: Intergovernmental Panel on Climate Change) p 15
[91] Folke C 2006 Resilience: the emergence of a perspective for social–ecological systems analyses *Glob. Environ. Change* **16** 253–67
[92] Anderies J, Janssen M and Ostrom E 2004 A framework to analyze the robustness of social- ecological systems from an institutional perspective *Ecol. Soc.* **9** 18
[93] Glaeser E, Gyourko J and Saks R 2005 *Urban Growth and Housing Supply* (Cambridge: National Bureau of Economic Research) p w11097
[94] Waddell P *et al* 2008 Forecasting demand for urban land *Urban Ecology* ed J M Marzluff, E Shulenberger, W Endlicher, M Alberti, G Bradley and C Ryan (Boston, MA: Springer US) pp 493–518
[95] Banzhaf S, Ma L and Timmins C 2019 Environmental justice: the economics of race, place, and pollution *J. Econ. Perspect.* **33** 185–208
[96] St Denis L, Mietkiewicz N P, Short K C, Buckland M and Balch J 2020 ICS-209-PLUS—An all-hazards dataset mined from the US National incident management system 1999–2014 *Nat. Sci. Data* **7** 64 [in review]
[97] CAL FIRE 2020 Top 20 most destructive California wildfires (available at: www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf)
[98] MacWilliams J, La Monaca S and Kobus J 2019 *PG&E: Market and Policy Perspectives on the First Climate Change Bankruptcy* (New York: Center on Global Energy Policy, Columbia University) p 42
[99] Stephens S L *et al* 2014 Temperate and boreal forest mega-fires: characteristics and challenges *Front. Ecol. Environ.* **12** 115–22
[100] Schultz C A, McCaffrey S M and Huber-Stearns H R 2019 Policy barriers and opportunities for prescribed fire application in the western United States *Int. J. Wildland Fire* **28** 874
[101] Stephens S L *et al* 2013 Managing forests and fire in changing climates *Science* **342** 41–42
[102] Flatley W T and Fulé P Z 2016 Are historical fire regimes compatible with future climate? Implications for forest restoration *Ecosphere* **7** e01471
[103] Pfister G G, Wiedinmyer C and Emmons L K 2008 Impacts of the fall 2007 California wildfires on surface ozone: integrating local observations with global model simulations *Geophys. Res. Lett.* **35** L19814
[104] Brey S J and Fischer E V 2016 Smoke in the city: how often and where does smoke impact summertime ozone in the United States? *Environ. Sci. Technol.* **50** 1288–94
[105] Bolin B, Barreto J D, Hegmon M, Meierotto L and York A 2013 Double exposure in the sunbelt: the sociospatial distribution of vulnerability in Phoenix, Arizona *Urbanization and Sustainability* ed C G Boone and M Fragkias (Dordrecht: Springer) p 159–78
[106] O'Brien K L and Leichenko R M 2000 Double exposure: assessing the impacts of climate change within the context of economic globalization *Glob. Environ. Change* **10** 221–32
[107] Adams M D O and Charnley S 2020 The environmental justice implications of managing hazardous fuels on federal forest lands *Ann. Am. Assoc. Geogr.* **110** 1907–35
[108] EO 12898 1994 Federal actions to address environmental justice in minority populations and low-income populations 94–3685 pp 7629–33 (available at: www.govinfo.gov/content/pkg/FR-1994-02-16/html/94-3685.htm)
[109] Bowker J, Lim S, Cordell H, Green G, Rideout-Hanzak S and Johnson C 2008 Wildland fire, risk, and recovery:

results of a national survey with regional and racial perspectives *J. For.* **106** 268–76
[110] Ojerio R, Moseley C, Lynn K and Bania N 2011 Limited involvement of socially vulnerable populations in federal programs to mitigate wildfire risk in Arizona *Nat. Hazards Rev.* **12** 28–36
[111] Axelrod J 2017 California fires spark issues of bilingual emergency communications American City and Country (available at: www.americancityandcounty.com/2017/12/13/california-wildfires-spark-issues-of-bilingual-emergency-communications/)
[112] Nagler E 2017 Filling the gaps: inequitable emergency preparedness and disaster relief policies serving immigrant and refugee communities *Int. Undergraduate J. Serv. Learn. Leadersh. Soc. Change* **6** 10–22
[113] Bettencourt L M A and Kaur J 2011 Evolution and structure of sustainability science *Proc. Natl Acad. Sci.* **108** 19540–5
[114] Holling C and Goldberg M 1971 Ecology and planning *J. Am. Inst. Plann.* **37** 221–30
[115] Cronon W 1992 *Nature's Metropolis: Chicago and the Great West* (New York: Norton) p 53
[116] Scoones I 1998 Sustainable rural livelihoods: a framework for analysis *IDS Report No.: 72*
[117] Alberti M, Marzluff J M, Shulenberger E, Bradley G, Ryan C and Zumbrunnen C 2003 Integrating humans into ecology: opportunities and challenges for studying urban ecosystems *BioScience* **53** 1169
[118] Smit B and Wandel J 2006 Adaptation, adaptive capacity and vulnerability *Glob. Environ. Change* **16** 282–92
[119] Eakin H and Luers A L 2006 Assessing the vulnerability of social-environmental systems *Annu. Rev. Environ. Resour.* **31** 365–94
[120] McPhearson T *et al* 2016 Advancing urban ecology toward a science of cities *BioScience* **66** 198–212
[121] Schlosberg D 2007 Defining environmental justice (Oxford University Press) (Accessed 3 February 2022) (available at: https://oxford.universitypressscholarship.com/view/10.1093/acprof:oso/9780199286294.001.0001/acprof-9780199286294)
[122] Eriksen S *et al* 2011 When not every response to climate change is a good one: identifying principles for sustainable adaptation *Clim. Dev.* **3** 7–20
[123] Eriksen S H, Nightingale A J and Eakin H 2015 Reframing adaptation: the political nature of climate change adaptation *Glob. Environ. Change* **35** 523–33
[124] Kimmerer R and Lake F 2001 The role of indigenous burning in land management *J. For.* **99** 36–41
[125] Lake F K, Wright V, Morgan P, McFadzen M, McWethy D and Stevens-Rumann C 2017 Returning fire to the land: celebrating traditional knowledge and fire *J. For.* **115** 343–53