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Learning to coexist with wildfire

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The impacts of escalating wildfire in many regions — the lives and homes lost, the expense of suppression and the damage to ecosystem services — necessitate a more sustainable coexistence with wildfire. Climate change and continued development on fire-prone landscapes will only compound current problems. Emerging strategies for managing ecosystems and mitigating risks to human communities provide some hope, although greater recognition of their inherent variation and links is crucial. Without a more integrated framework, fire will never operate as a natural ecosystem process, and the impact on society will continue to grow. A more coordinated approach to risk management and land-use planning in these coupled systems is needed.

Fire is unique among the natural hazards that affect human communities and the ecosystems on which we depend[1]. Although humans sometimes intentionally ignite and manage fires, our main focus is on fighting them. For other natural hazards, such as earthquakes, hurricanes and floods, there is much more emphasis on identifying vulnerabilities and adaptations. The 'command and control' approach[2] typically used in fire management neglects the fundamental role that fire regimes have in sustaining biodiversity and key ecosystem services[3–6]. Unless people view and plan for fire as an inevitable and natural process, it will continue to have serious consequences for both social and ecological systems.

Over the past two decades, wildfires around the world have increasingly affected human values (for example, lives, views or sacred environments) and assets (for example, damage to homes or public infrastructure) and ecosystem services (for example, air quality and long-term carbon storage). The growing list of negative outcomes and their financial effects have complex causes and consequences[7]. The natural range of fire sizes and resultant frequencies, timings and intensities — the 'fire regime' — varies greatly among ecosystems, as do the ways in which human activities have altered them (for example, through timber harvesting, fire suppression, urban or agricultural encroachment, novel ignition patterns and invasive species). Not surprisingly, policy strategies to address wildfires often emphasize fuel reduction[8,9]. However, even where strategies recognize interacting cultural, environmental and economic dimensions of wildfire[10–12], few tackle the difficult land-use issue of where and how humans choose to build their communities in the first place. The prospect of widely increasing fire activity with climate change[13] intensifies the need for a new path forward.

Viewing fire-related problems in the context of coupled socioecological systems (SESs)[14], which explicitly recognize links between humans and their natural environments, provides insights into achieving a more sustainable coexistence with wildfire. We have learned a great deal about fire as an essential ecosystem process and the human dimensions of living on fire-prone landscapes. Synthesis of this knowledge through a coupled systems approach can highlight specific vulnerabilities and trade-offs, and facilitate adaptation strategies across widely varying public and private landscapes (Fig. 1). In this Review, we summarize research on fire-prone ecosystems and fire effects on human communities through the lens of SESs, identify links in these coupled systems, and discuss recommendations for greater resilience. We emphasize insights from three regions (Fig. 2) where major fire-related losses have occurred in recent decades: the Mediterranean basin, the western United States and Australia.

Socioecological systems and fire

Sustainable solutions to most environmental problems will be impossible if the links and interdependencies between humans and ecosystems are ignored[14]. In the context of wildfire, the most well-developed SES research that incorporates this coupling concerns climate-change effects on Alaskan boreal forest ecosystems and rural indigenous communities[15,16]. Case studies in rural communities of New Zealand[17] and California[18] also exist. Remarkably, a coupled wildfire SES framework has yet to be adopted for the more densely developed wildland–urban interface (WUI; area in which communities intermix with or abut natural vegetation), where most of the human fatalities, home losses and fire-suppression expenditures occur.

The complexity of how wildfire operates in different ecosystems and how humans interact with it indicates that place-based hazards and risks should be addressed as a coupled SES[16,19]. Reframing the problem to minimize harmful effects as the climate changes and humans increasingly inhabit fire-prone landscapes identifies an integrated set of coupled SES linkages (Fig. 1). Importantly, this allows us to recognize how the geographic context of the coupling itself contributes to impacts and losses of assets throughout the wildfire SES. Local characteristics of the WUI, and the components on either side of it, will largely determine the degree to which fire may be accommodated and how communities will be affected. The spatial scale of the coupling may also be broad in some cases, such as when fires compromise recreation values (for example, trail access, camping facilities or fishing habitat) and water supplies of distant urbanized areas, or when concerns over human exposure to drifting smoke influence management decisions about fires that are burning relatively far away. Although this framing does not intrinsically address connections between fire and global-scale climate change mitigation[13,15,20], it helps to

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reveal geographically relevant solutions for decreasing harmful effects and increasing the positive benefits of fire on the landscape. The institutional complexity that underlies many aspects of this coupled SES framework — agency mandates, property rights, building ordinances, indigenous governance, economic subsidies and political pressures — will also feed into a particular set of solutions, often creating challenging constraints.

Sustainable coexistence with wildfire is both a process and a long-term goal, such that policy, planning and management are adapted and refined through time (Fig. 1). Responsibility must be shared between governments and the people at risk, and the approach integrates building, planning, fuel management, suppression capability, and knowledge of fire and ecosystem dynamics at different scales. Coexistence with wildfire should ultimately allow ecologically appropriate fire regimes to operate on landscapes near and far from the WUI, with relatively low risks to people, property and resources, while also allowing us to enjoy ecosystem services enhanced by fire (for example, habitat maintenance, potential hazard reduction, natural hydrologic functioning, and carbon and nutrient cycling). This outcome should also reduce the costs of fire suppression and the need to put firefighters at risk.

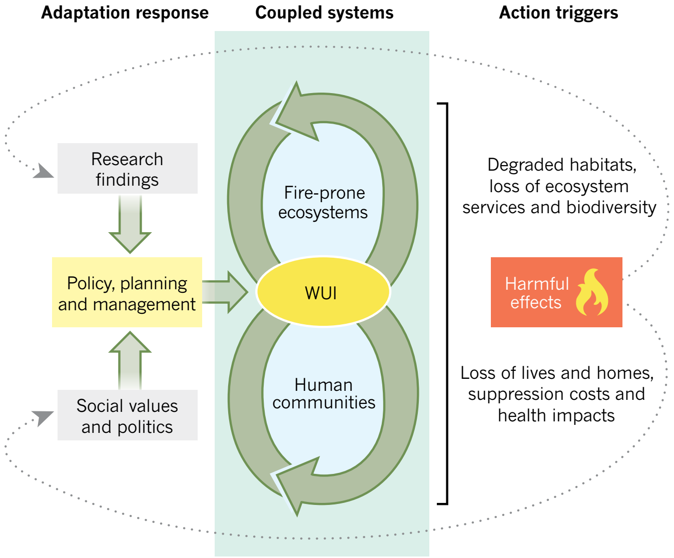


Figure 1 | Links and pathways to resilience in coupled socioecological systems affected by fire. Coexistence with wildfire is strongly influenced by the type of natural fire regimes that operate on a given landscape, and the degree to which communities can reduce exposure and vulnerabilities there. The wildland–urban interface (WUI) is the spatial manifestation of the coupling, and the most proximate scale of exposure and risk mitigation. To learn from and minimize the harmful effects of fire in both the ecosystem and the community, links between systems and scales of interactions must be recognized. Doing so will trigger, through research and in response to changing social values and political context, further adaptation and change in policy, planning and management.

Fire and ecosystems

The role of fire in different ecosystems varies by the degree of current landscape modification, relative to natural or historical patterns and processes. Some regions have large expanses of semi-wilderness where maintenance or restoration of certain fire regimes is crucial to ongoing habitat characteristics or ecosystem services (for example, the western United States and Australia). Here the links between fire characteristics and ensuing ecological effects, or fire 'severity', are often emphasized. Other regions have been so completely altered for various human needs that what is 'natural' is no longer a clear consideration (for example, the Mediterranean basin). Furthermore, climatic controls on fire regimes (for example, frequency of droughts or high-wind events, or length of fire season) tend to dominate in some ecosystems, whereas local controls (for example, topography, fuel loads and ignitions) strongly influence others. Fire resilience is thus context-dependent, varying with the biophysical environment and desired future conditions. Accordingly, our capacity to avoid ecosystem degradation and catastrophic shifts[21] (Fig. 1) depends on the ecosystem in question and how climate change will manifest there.

Mediterranean basin

Mediterranean landscapes are mosaics of various shrublands and oak- and pine-dominated woodlands intermixed with extensive pastures, cultivated lands and abandoned agricultural fields[22]. Despite fire's ecological influence there[4], no reference conditions exist for fire management or restoration, and traditional use of fire for rangeland and game management has strongly influenced historical landscape dynamics[23]. Pronounced biophysical and land-use gradients have recently resulted in contrasting fire and vegetation dynamics. The southern and eastern regions are subject to land over-exploitation and reduction in vegetation cover that increases the risk of desertification and loss of ecosystem services. By contrast, socioeconomic drivers are increasing fire hazards and losses over Mediterranean Europe (northern region) owing to rural depopulation, increased WUI exposure and land-cover changes that are sometimes promoted through afforestation policies[24]. Most shrublands and woodlands in the northern region are becoming dense enough to support climate-driven high-intensity 'crown' fires[22,25].

Wildfire in European Union countries is addressed in national and regional forest policy plans, but consensus on fire and ecosystem management is lacking. In spite of large expenditures, increased preparedness and greater firefighting abilities, extreme fire-weather conditions have caused devastating fires in several Mediterranean countries[26]. A new framework to regulate and promote traditional fire practices, accommodating diverse territorial contexts and operational use of fire, has thus been advocated[27]. Currently limited to local management, prescribed burning is increasing across Europe as a tool that aims to reduce fuel loads and diminish the risk of high-intensity fires[28]. Modest changes to regional and national wildfire policies have therefore included long-term preventive actions, but fire management is still primarily centred on short-term fuel- and suppression-oriented measures[8]. There are concerns over the ecological consequences of recent fire patterns[29], but human-centred fire exclusion generally prevails on most Mediterranean-basin landscapes.

Western United States

Fire management in many western US ecosystems is informed by research on the historical role of fire[30], especially through dendrochronology[31] and landscape reconstructions[32]. Before modern management, different types of fire occurred among vegetation types and maintained important natural structures and functions, with great variation geographically[5,32–35].

In western US forests, high-severity fires that kill overstory trees are typical of cool, high-elevation, subalpine environments[36,37]. Although severe fires may seem catastrophic from a human perspective, in these forests they stimulate vegetation regeneration, promote landscape diversity in terms of vegetation types, provide habitat for many species and sustain other ecosystem services[5]. The many organisms and propagules that may survive the fire, combined with heterogeneity in age, structure and species composition across landscapes, confer resilience against shifts to non-forest types. High-severity fires predominate across about 30% of western US forests, naturally mixing with low-severity fires through time and space across another ~45%[36]. Key regional controls of high-severity fire regimes are extreme drought and high winds[37], and local (for example, topographic) influences on severity patterns can emerge during less dry conditions[38]. Fuels tend to be naturally abundant in these ecosystems, so modern fire suppression may have decreased historical levels of landscape fragmentation, but it has not increased fuel loads[5,39].

By contrast, many dry and mesic, low-elevation and mid-montane forests historically experienced more frequent low-severity fires that maintained relatively open forest structures of fire-resistant

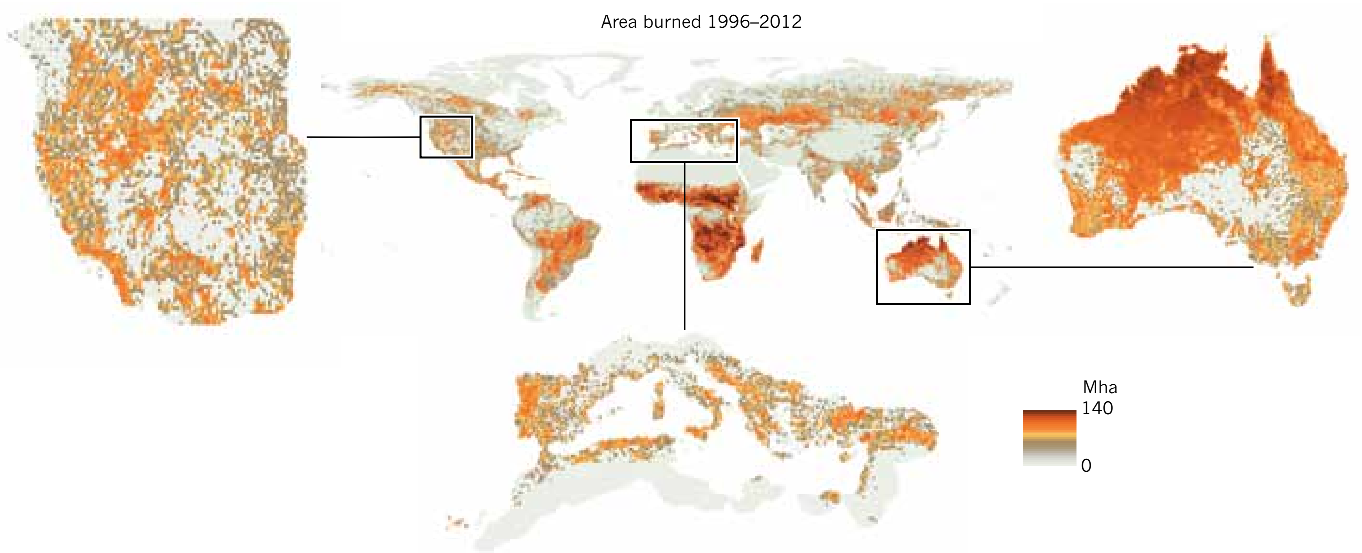


Figure 2 | Area burned patterns and locations of fire-prone regions. The cumulative area burned between 1996 and 2012 in millions of hectares (Mha) per mapped cell. The western US region consists of the 11 western states in the conterminous United States (left), the Mediterranean basin (middle) contains the Mediterranean-climate biomes and the Australian region (right) encompasses the entire continent (see Supplementary Information).

trees[33,34,40], across about 25% of western US forests[36]. Ignition patterns, vegetation structure and fuel amount exert a strong control on regimes of frequent low-severity fire, making them more sensitive to modern human perturbations and also more amenable to fuel-management techniques[33,39–41]. Unlike high-severity fire regimes, timber harvesting and decades of fire suppression in drier forests have lengthened intervals, increased densities of smaller trees and shifted regimes of mostly low-severity fires to include more high-severity, stand-replacing fires. The extent to which this has happened is a topic of debate, raising questions about how widespread 'mixed severity' fire regimes were prehistorically[32,35,42]. Regardless, reducing accumulated fuels in these forests is often a high management priority. Only where such departures from natural fire regimes have led to denser, multilayered, fire-intolerant forests, however, may fuel-reduction treatments restore more characteristic forest structure and function (Box 1).

There is a general consensus regarding the importance of fire, including the need for prescribed burning, to maintain native grasslands and open woodlands. Woody plant encroachment in many ecosystems with sparse tree cover, driven by a lack of fire and replacement of native herbivores, has reduced plant biodiversity, altered vegetation structure and threatened the fauna that depend on those habitats[43,44]. Fire also plays a crucial part in regeneration for some of the vast shrublands of the western United States, especially California's densely urbanized chaparral ecosystems. Similar to high-elevation forests, fire in chaparral is stand-replacing and under strong climatic control (patterns of drought and extreme fire weather)[45], meaning that fuel-reduction efforts have limited effect except in strategic locations[46,47]. Increased fire frequencies, due to abundant human ignitions and non-native grasses that support rapid reburning, threaten to convert many native shrublands to degraded habitats[48]. Invasive grasses also cause very frequent and often large fires across parts of the Great Basin in the western United States[34,49], driven by the 'grass-fire cycle' positive feedback[50] and bringing serious management challenges even to fire-sensitive desert ecosystems[51].

Australia

Fire is ubiquitous in Australian ecosystems, including deserts and tropical forests, and a wide range of fire regimes have been mapped using remote sensing[52]. Annual pulses of relatively intense fire dominate the extensive savannahs of northern Australia, with less frequent, massive fires in the arid zone occurring after above-average rainfall[53]. By contrast, large fires in the temperate forests of the south, although intense, are less extensive and also less regular (decadal occurrence). Biophysical models of fire-regime controls[54] and analysis of trade-offs in fuel characteristics and fire types[52] confirm the primary role of climate, especially the gradient in summer monsoonal precipitation. Thus, fire frequencies tend to vary with latitude, decreasing towards the south and especially the arid interior. Most fire activity on the Australian continent is in grass fuels and of relatively low intensity.

Although palaeo-charcoal deposits document fire's very long history in Australia[55], fine-scale understanding of fire-regime variability through dendrochronology is generally lacking, hindering detailed perspectives on long-term variations in fire regimes. Comprehensive fire management initiatives focus on key environmental objectives, such as biodiversity conservation[20] and emissions reduction[56], as a function of local context. Maintenance of contemporary fire regimes for biodiversity conservation is a priority in most regions, as opposed to the emphasis on restoration that dominates western US approaches.

Australia's productive eucalyptus forests, which can burn at very high intensities and low–moderate frequencies, are largely restricted to southern and eastern edges of the continent. Although these forests are characteristically Australian, their proximity to urbanized areas has probably fed the continent's reputation for high-intensity fire events (see 'Where do people live?'). Debates over the degree to which fuel reduction, whether by mechanical or prescribed fire treatment, can alter the probabilities of high-intensity events[57,58] are similar to those that occur for western US forests.

Prescribed burning in Australia is extensive, but controversial. Fuel reduction burning can partially reduce risk to human life and economic assets, although trade-offs with risks to environmental assets such as biodiversity and ecosystem services are not well understood[3,59]. However, functional responses of species to fire frequencies, sizes, timings and intensities provide a measurable basis for predicting how ecological diversity will respond to management and climate change[60,61].

Resilience and climate change

Ecosystem managers in the three regions covered here (Fig. 2) may have limited ability to alter the numbers, sizes and characteristics of fires occurring in different ecosystems[5,34,39,59]. As already discussed, this is because coarse-scale climatic influences tend to control fire regimes in many ecosystems, especially those that are naturally prone to large and high-severity fires. Except under the most extreme conditions, fire regimes typically constrained by more local-scale controls, such as ignition frequencies and biomass accumulation rates, may respond more strongly to prescribed fire and mechanical fuel reductions. This characterization of two opposing types of fire regimes is, however, a vast over-simplification — idealized end points along a spectrum of variation within and between fire-prone ecosystems[62] — and management prescriptions need to somehow accommodate such complexity. Furthermore, fire-related sensitivities and responses vary among plant and animal species, so fire management for the persistence of one important group of organisms may not favour that of the others.

The potential for climate change to cause 'novel' or 'no analogue' environmental conditions in some ecosystems presents new challenges for management, policy and planning. An obvious goal is to have ongoing fire regimes that minimize the risk of biodiversity loss[59]. Yet, what adaptation responses are appropriate (Fig. 1) if we do not know how future climates and related biophysical processes will differ from the recent past? These uncertainties have resulted in somewhat similar recommendations about fire and ecosystem resilience[63–65]. Heterogeneity in vegetation types, stand structures and successional age classes at all spatial scales and environmental settings is emerging as a strategy for enhancing ecosystem resilience to climate change. This essentially facilitates diverse initial conditions for multiple future ecological trajectories, the most likely and successful of which will not be known for decades. The role of diverse topography in creating microclimate refugia, or 'holdouts'[66], as well as in influencing fire sizes and severity characteristics within large fires[38,67], comprises the physical template for resilience in more mountainous regions. In ecosystems with a recent paucity of burning, fire management that fosters burning under diverse conditions may be useful for achieving this desired heterogeneity and reducing fuel accumulations[41]. Not all fire-generated heterogeneity is ecologically significant, however, so understanding the effects of specific types of 'pyrodiversity' is important[68].

Where do people live?

The WUI is the most proximate spatial manifestation of the coupling in a wildfire SES (Fig. 1). Understanding and addressing vulnerabilities related to the WUI in fire-prone areas is therefore crucial to long-term solutions. As distances between urbanized areas and those protected from development decrease globally[69], a growing WUI will expand the scope of coupling in wildfire SESs worldwide. Negative fire effects that were once due to 'distant' fires (for example, the impacts of smoke on human health) will be increasingly common, making coexistence with wildfire much more challenging.

The current WUI of the western United States is relatively well characterized, with over 60% expansion since 1970 (ref. 70) and about 70% in private ownership[71]. The WUI in this region also predominantly occurs where fire severities are high[70]. Only 14% of private land in the western US WUI is developed, so substantial increases in human exposure to fire may occur as the remaining portions become populated[72]. Although less well characterized, there is growing awareness of expanding WUI in Mediterranean Europe[24,73,74] and Australia[19,75].

Global systematic analyses of human settlement in fire-prone environments is important, but lacking[76]. Coarse-scale characterization of how population densities relate to various fire-prone environments (Fig. 3) provides some insight. Although often characterized as a 'forest fire' problem, western US patterns indicate that highly fire-prone locations with large numbers of people tend to be associated with sparse or no tree cover (for example, the chaparral shrublands of southern California); locations with both high population densities and denser forests exhibit the least area burned (Fig. 3, left). Australia exhibits greater area burned over a broader range of environments, with intermediate population densities being more fire-prone regardless of the amount of forest cover (Fig. 3, middle). The Mediterranean basin is unique because the greatest area burned coincides with the highest population densities (Fig. 3, right), although this too occurs in locations with relatively low forest cover (for example, abandoned agricultural lands[26]).

Acknowledging the diversity of the fire-prone environments and vegetation types where people live is important, because it has implications for the types of fuel treatments that may or may not work to mitigate fire hazards within or near the WUI, and it could help to guide future resource allocation decisions (for example, among vegetation removal, evacuation planning and home vulnerability retrofits)[77]. Awareness of the institutional and social diversity of different human communities is also important, as we discuss in the next section, because it influences their capacity for preparation and mitigation of hazards such as wildfires[18].

Fire and human communities

This section reviews research on how fires affect human communities and is organized by the scale of coupling in a wildfire SES (Fig. 1), ranging from individuals to landscapes. Social science research on wildfire, primarily undertaken in Australia and the United States,

BOX 1

What can 'thinning' of fuels achieve?

There is intense pressure on land-management agencies to reduce fire hazards (for example, rates of spread or flame lengths if a fire occurs). Treatments should be prioritized, however, where they may help to protect communities or reduce fuel loads in the areas that are most likely to experience uncharacteristically severe burns[36,71]. Mechanical fuel-reduction treatments are most suited to certain dry and fire-prone mesic forests[34,39–41,77], where thinning the density of smaller understory trees and removing surface fuel residues (non-merchantable tree tops and limbs) created by these treatments can reduce fire intensities and rates of spread[40]. Not treating the additional surface-fuel by-products can actually increase fire intensity and severity when a wildfire does occur[41].

Some of the most basic trade-offs that limit the widespread use of mechanical fuel reductions involve their economic viability. Often, larger commercial trees will be harvested to help offset operational costs, but this typically generates more surface-fuel residues. Moreover, opening up the overstory canopy and increasing sunlight penetration can increase growth of highly flammable understory vegetation. Controlling this growth response is an ongoing endeavour, the economic feasibility of which is unknown.

Uncertainty about when and where treatments might actually perform as desired must also be considered. Although there are many examples of fuel treatments reducing fire behaviour when conditions are not extreme, recently treated forests can experience a stand-replacing crown fire when wind speeds exceed 30 km h^{-1} and when fuel moisture is low[102]. When the probability of fire occurring in a particular area is relatively low, the odds of a fuel treatment influencing the behaviour of a wildfire there, within the time frame that treatments are effective, is also low[103]. The degree of protection provided by a particular mechanical treatment may thus depend on uncertain parameters (for example, ignition patterns and extreme wind frequencies).

In many areas, ecological restoration and fuel-management goals may be best balanced and accomplished through fire[4,41], which creates natural heterogeneity and provides for fire-dependent species.

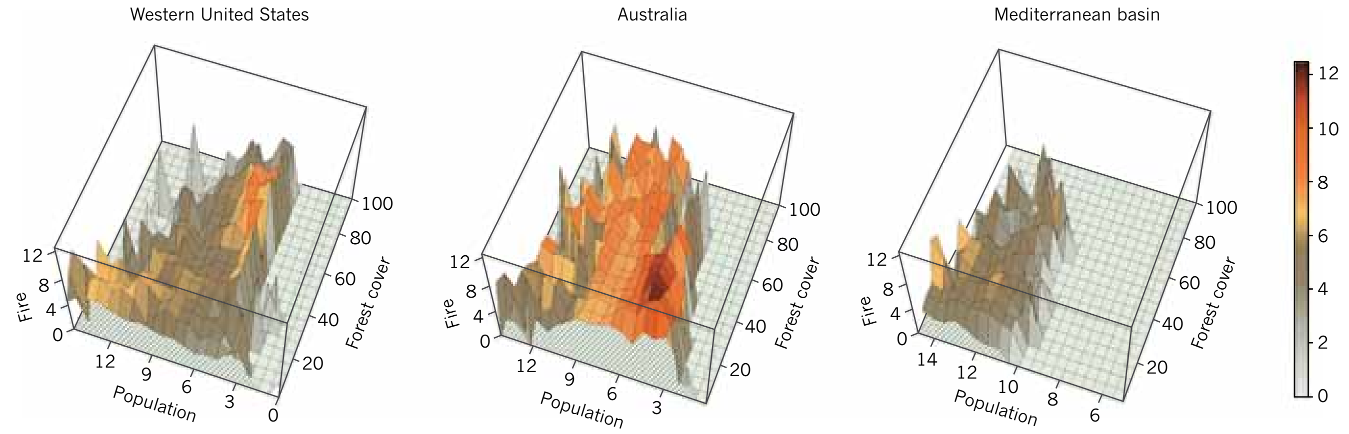


Figure 3 | Relationship between forest cover, population density and area burned in fire-prone regions. Locations with both higher human populations and greater amounts of burning tend not to be consistently characterized by high forest cover. Patterns vary greatly among regions, reflecting the different contexts in which each side of the wildfire socioecological system have intersected. (Data were aggregated from original sources (see Supplementary Information) to 0.25° resolution cells and plotted as density surfaces.) Forest cover is the percentage area covered by trees (>5 m height) per cell in 2000; population is number of people per cell (log transformed) in 2000; and fire is total area burned in hectares per cell (log transformed) between 1996 and 2012. The colour scale for fire is to help differentiate higher peaks in area burned.

is relatively sparse and not easily generalized. Work in the United States emphasizes social acceptance of techniques to mitigate fire risk (for example, fuel reduction on public and private lands) and, more recently, public response during and after fires[78]. In Australia, where many people do not evacuate during fires, risk perception, homeowner preparedness and response during fires, and community safety[79] are key areas of research. We also include studies outside the social sciences that have examined the role of vegetation and fuel treatments linked with losses and the built environment itself.

Risk perception and public response

Public response to wildfire is shaped by numerous factors, such as local context and individual personality and experience, so simple explanations for action or inaction do not exist. For instance, many researchers and managers assume that individuals do not understand fire risk. But US studies show that most people living in high-fire-risk areas understand their exposure, but there is a tenuous link between understanding risk and taking action to mitigate it; whereas recognizing risk might be necessary to consider mitigation, perceived efficacy of mitigation and resource constraints can be more influential[80]. Similarly, whereas around 80% of people in the fire risk areas of Victoria, Australia, know they are in a hazardous area[81], this does not necessarily translate to safer actions. After the devastating 2009 Black Saturday fires in Victoria, most people in high-fire-risk areas were aware of what new fire warnings meant and how to ensure their safety, but few acted on the knowledge when the highest-level warning was issued[81]. A deeper understanding of the influences on preparedness, evacuation decisions and support for hazard mitigation is needed.

Specific cultural and institutional systems affect public response to wildfire, as do psychological and social dynamics. For example, institutional structures in the United States and Australia are quite different, but key social dynamics have many similarities. In both countries, trust is a key factor shaping public support for agencies, whether they provide information or engage in fire-management activities[82]. US studies of public acceptance of prescribed fire reveal that trust in the personnel implementing the burn, along with familiarity with the practice, are associated with higher acceptance levels[83]. In terms of the US public response during fires, evacuating has long been the norm, often with mandatory evacuation orders; until Black Saturday, Australians were urged to either prepare to stay and protect their properties, or to leave early, on the basis that either option was safer than leaving late[79]. Despite this difference, the range of public behaviours in both countries is similar, with some residents leaving early, some staying to defend and a substantial number waiting to see how the situation develops. Furthermore, individual actions do not necessarily reflect a consistent response, as some household members may leave and some stay, while others go back and forth to check on property, animals or those who stay[84]. Although historically 'stay or go' seems to have worked reasonably well in Australia[79], the approach was questioned after the Black Saturday fires, as it was widely seen to have contributed to many of the 173 deaths. However, roughly half the people (around 3,000 households) in the burnt areas seemed to have stayed and defended their properties successfully and about half left, almost as the fire front was approaching. Most were satisfied with their decision and said they would do the same thing again[84]. Most also stated that they would like to be better prepared. The post-fire effort naturally concentrated on fatalities, with official advice after Black Saturday inquiries shifting to leaving early.

When the public response is to evacuate, key elements to success include environmental conditions (especially fire-weather severity), patterns of roads, neighbourhoods and topography. In Australia, public warnings have been based on a fire-weather danger scale, which was revised after Black Saturday to capture the most extreme conditions, along with altered warning messages and advice for these extremes. There is some public understanding of the reclassification, but little evidence of altered behaviour[81] or understanding that weather conditions well below the extreme level are still dangerous. Analogous fire-weather warnings are issued regularly in other parts of the world, but are not standardized and rarely trigger evacuation orders. Similar to many regions, fatalities during evacuations in the Mediterranean basin tend to occur during the most severe weather conditions, when fires have already begun and people choose to evacuate too late[85]; in addition, such extreme events seem to be on the rise[26]. A growing public safety challenge associated with evacuating people from fire-prone communities in mountainous terrain is limited road access. For example, housing densities are increasing in many WUI regions of the western United States without commensurate increases in the road network to support their evacuation[86]. Emergency planning, including preparation of structures and training for those who choose to stay or simply cannot evacuate safely[87], is thus increasingly important to the resilience of many communities in the regions reviewed here.

Structures and surrounding vegetation

To mitigate the risk of structure losses during wildfires, there is increasing evidence from many regions that it is best to focus on the house first and move outward from there[77]. Most structure losses are due to ember attack[88,89], when flaming or smoldering plant material is lofted by winds and blown inside or against the building or adjacent elements, often long before the flaming front arrives. Embers can cause structure ignition by entering through gaps as small as

2 mm[90] or accumulating outside against flammable building (or surrounding) features. Once ember ignition is addressed through structural design or retrofitting, less prevalent modes of structure loss are important, such as radiant heat and flame exposure. To address these, both building design and surrounding vegetation management are normally considered in unison[19], with the balance of these treatments being site specific. Similar to evacuation success, an understanding of the local fire-weather conditions and expected types of fires is required[91]. Hence, the building design strategy is to either consider all possible extremes and the weakest link in the system[88] or to pick a threshold level beyond which the structure may not survive. By relating these to a corresponding fire-weather severity, the occupant has the information for deciding when it is necessary to leave early. As a contingency, egress paths from the building interior to another building or area of minimal fuel could improve safety, but preparation for such a fallback is needed long before a wildfire arrives.

Vegetation reduction is most effective immediately adjacent to structures[88,92–94], as it can eliminate the most immediate sources of combustible material. Vegetation overhanging the structure[91] and ornamental plants[95] have been strongly associated with structure loss. Vegetation clearances more than about 30 m away, however, seem to provide no significant additional benefit in shrubland environments of southern California, even on steep slopes[94], reflecting an important trade-off between hazard reduction and habitat values (for organisms dependent on the vegetation removed). Although these findings may only apply to similar shrubland environments, a similar distance to heavily vegetated areas has also been identified for some forested environments, based on radiant heat exposure to structures[77,96]. In Australia, however, a distance from forest edges of more than 30 m was found to influence home losses[93], indicating that this buffer distance may vary substantially (for example, with fuels, weather and construction types). Another key reason to reduce vegetation near the home is to provide a relatively safe place to engage in structure protection, in case home owners or firefighters are present. It is notable, however, that some species of well-maintained trees (litter removed and high foliar moisture) near the home can actually provide protection, screening embers[19] and acting as a heat sink[96] for an approaching wildfire.

Landscape-scale patterns

Although fuel treatments seem to provide the greatest protection when located near human communities[19,88,93,94,97], landscape-scale characteristics of the WUI itself are important. For this reason, a long-term

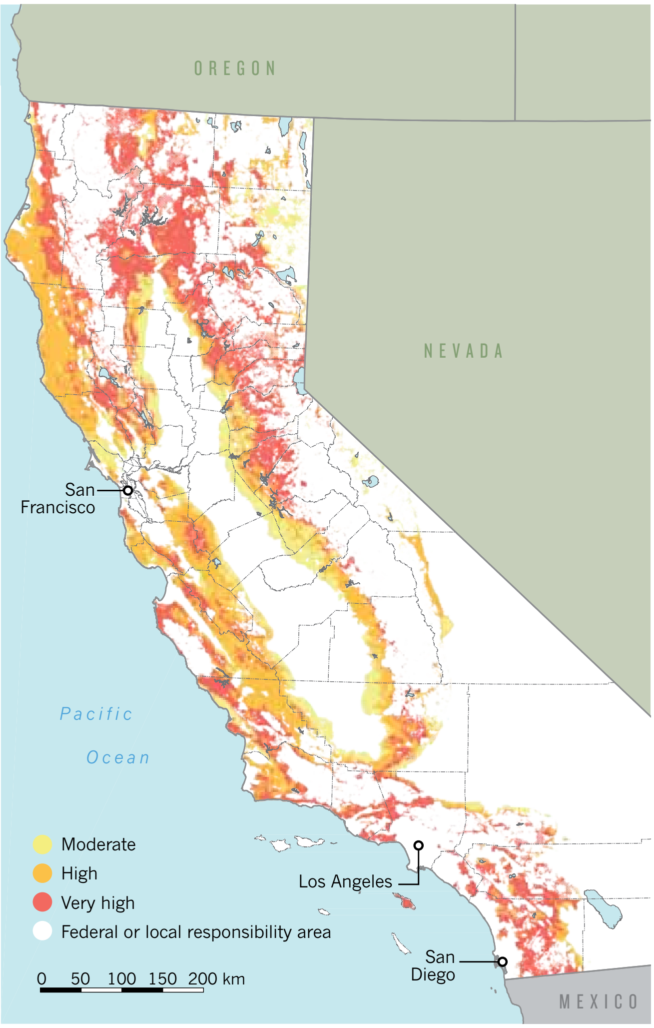
BOX 2

Adaptation measures and fire-hazard mapping

Regardless of the surrounding ecosystem conditions, all communities can better coexist with fire by taking several steps: retrofitting homes against ember attack, effectively managing fuels around homes, developing household and community plans for evacuation compared with stay-and-defend decisions, and participating in risk awareness continuing education. For existing high-hazard wildland–urban interface (WUI) areas, landowners may need to take primary responsibility for pursuing the optimal combination of adaptation measures, based on their local vulnerabilities and wildfire exposure. For development of new communities in high-hazard WUI areas, governments need to take a leadership role in planning. Regardless of responsibility, however, all of these efforts will be guided by better mapping of the fire hazard itself.

The fire hazard severity zone (FHSZ) maps (Box Fig.) of California are an official product of the state Department of Forestry and Fire Protection based on a consistent statewide methodology for estimating potential fire behaviour under a set of relatively dry and high wind conditions. Variables that affect modelled fire behaviour include local topography and potential fuel loads, although weather conditions in the current iteration of maps are not tailored to local extremes. Future updates to the FHSZ methodology will incorporate locally varying wind patterns, better reflecting conditions that cause the worst fire-related losses of lives and homes[45,98].

Fire-resistant residential construction standards are determined by the FHSZ rating of the location in question. In addition, FHSZ classifications must be disclosed at the time of home sales; although this may not deter a sale, it can affect the cost of insuring the home against fire losses. FHSZ maps are thus an incremental but important step towards treating fire like other natural hazards (for example, land-use restrictions associated with flood-plain and earthquake fault maps). Similar mapping methods and codes are produced in Victoria, Australia. Such maps do not explicitly restrict development from occurring — a constraint that should be considered in extremely hazardous locations. Comprehensive approaches should, however, help to better design communities within a complex matrix of both risk and resilience that such maps could reflect spatially. (See Supplementary Information).



approach involving land-use planning offers great potential for reducing wildfire impacts in human communities. A greater understanding is needed concerning building configuration in the WUI and how it relates to risk of losses and fatalities in various environments[73,74]. In some shrubland-dominated landscapes, the arrangement and location of homes have been the most important factors for explaining structure loss: landscape factors such as low housing density, isolated clusters of residential development and long distances to major roads are better predictors of house loss than local factors such as defensible space, fuel or terrain[94,98]. Whether these findings apply to fire-prone landscapes in general or whether there are variations between development patterns and fire regimes needs further research. Although isolated clusters of development and low housing density mean that homes are embedded within, and more exposed to, a matrix of wildland vegetation[19], ignition-prone homes that are closely spaced in neighbourhoods can also facilitate the spread of house-to-house fire, especially during extreme fire weather.

Achieving a sustainable coexistence with wildfire

A coupled SES view of wildfire highlights the variation in each half of the SES, as well as how they come together at the WUI, to create many permutations of hazards and vulnerabilities for both human and natural systems. As such, there will be different thresholds for how harmful effects trigger action before, during and after wildfires, and competing societal pressures will influence the degree to which scientific findings are able to guide adaptive responses (Fig. 1). Despite such complexity, some priorities for future work emerge from the extensive research reviewed here.

Context-specific and place-based approaches will be needed to address many existing and future coupled wildfire SES problems. This is because certain fire regimes are inherently more amenable to management activities than others, and also due to the institutional and social diversity that influences human capacity for mitigating risks to individuals and their communities. It is possible, however, that the permutations mentioned above collapse into characteristic typologies that could inform more systematic analyses. If so, are there mutually resilient combinations that are well matched or somehow compatible? Some fire regimes might dictate the degree to which evacuations should be mandatory or how resources might be allocated (for example, training homeowners to protect homes compared with fuel reduction or structure retrofits). A deeper understanding of the variation, links and scales of causes and effects in coupled wildfire SESs is therefore vital.

Governments have a primary responsibility in the long-term evolution of the WUI and the degree to which it limits or amplifies trans-boundary threats in coupled wildfire SESs, so much greater attention to land-use planning is warranted. Land-use regulations to guide fire-related building codes (Box 2) or restrict development in the most fire-prone locations[2,26,99,100] are clearly important steps that government agencies could take to manage the coupling in a wildfire SES. Agencies have a deeper role, however, in the growth of these trans-boundary threats. For example, the ‘safe development paradox’ applied to flood and hurricane protection demonstrates that making hazardous areas safer for human habitation in the short term actually increases the potential for severe losses over longer time scales[101]. Given that government agencies around the world have focused on reducing fire hazards (for example, through subsidized fire suppression and/or fuel reduction), much less attention has been paid to the ways in which vulnerable WUI development might have been designed from the start. As further development occurs and the WUI expands, so does the need for increased hazard reduction. A perverse consequence of the typical human reaction to fire — to fight it instead of accommodate it — thus contributes to a deepening of coupled wildfire SES problems.

Strategically addressing threats at the WUI maximizes the potential for both effective risk mitigation within developments and management for sustainable fire regimes over the broader sweep of landscapes. Ultimately, trade-offs and sacrifices must be made to balance these competing demands, but concentration of management effort for risk mitigation in the WUI minimizes the area where adverse effects on environmental assets are likely. Better maps of fire hazards, ecosystem services and climate change effects are thus important for assessing these and other related trade-offs. Addressing all social, economic and environmental assets at risk will necessarily focus on separating those that require exclusion of fire from those where fires of some sort are desirable or inevitable. However, it is unlikely that any planning or management regime will completely exclude fires from vulnerable developments on many landscapes (considerable residual risk to people and property will endure). The capacity for communities to cope with the inevitability of fire, as well as its effects at multiple scales, will therefore be essential.

There is a great deal of research to support better policy, planning and management in all aspects of the coupled wildfire SES problem. Viewing fire as a natural and inevitable hazard should be central to most solutions, so we can anticipate its important positive and negative effects on both human and natural systems. Given that combustion is one of the most basic and ongoing natural processes on Earth, we must continue to learn from our experiences to achieve a sustainable coexistence with wildfire. ■

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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