The Science of Firescapes: Achieving Fire-Resilient Communities

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Wildland fire management has reached a crossroads. Current perspectives are not capable of answering interdisciplinary adaptation and mitigation challenges posed by increases in wildfire risk to human populations and the need to reintegrate fire as a vital landscape process. Fire science has been, and continues to be, performed in isolated "silos," including institutions (e.g., agencies versus universities), organizational structures (e.g., federal agency mandates versus local and state procedures for responding to fire), and research foci (e.g., physical science, natural science, and social science). These silos tend to promote research, management, and policy that focus only on targeted aspects of the "wicked" wildfire problem. In this article, we provide guiding principles to bridge diverse fire science efforts to advance an integrated agenda of wildfire research that can help overcome disciplinary silos and provide insight on how to build fire-resilient communities.

Keywords: wildland, fire, adaptation, mitigation, resilience

Wildland fires are a societal and ecological issue of global concern (Bowman et al. 2009). Within the United States, considerable resources are allocated annually to suppress wildfires and to protect people and property. However, the economic impact is staggering, with federal spending in the United States averaging $2.9 billion per year since 2000 to conduct fire suppression and limit direct fire impacts (Holmes et al. 2007); with countless billions of dollars spent globally to remediate the indirect, extended, and often unintended impacts on human health, property damage, loss of tourism, and the restoration of crucial ecosystem goods and services (Bowman et al. 2009). The economic costs of wildfires are expected to rise given the projected increases in fire activity under climate change, the growth of communities into the wildland urban interface, and stress on water resources (Westerling et al. 2011, Moritz et al. 2012, 2014, Barbero et al. 2015). Arguably, wildland fire management in the United States and elsewhere is not sustainable in its current form (Pyne 1997). Underlying the economic challenges of wildfire is a complex and interconnected web of social, physical, and political factors that are stymied by educational, organizational, and research "silos." Attempts to improve wildland fire management that focus on only one, or a few, of the contributors and impacts of fire can lead to unintended consequences that cascade to affect other ecosystem goods and services (Abatzoglou et al. 2014). In short, wildland fire management is a "wicked problem" for which there is no all-encompassing solution (Carroll et al. 2007, Chapin et al. 2008).

It has long been recognized that human populations, having coevolved with fire (Pyne 1997), need to acknowledge and respond to the role that wildfire plays in the landscapes they choose to be a part of (Bowman et al. 2009, Moritz et al. 2014). However, the coevolution of human populations with wildfire can look dramatically different across cultures and landscapes. Perspectives surrounding the risks and benefits of wildfire are in a state of constant flux and influenced by a diverse set of drivers ranging from interpersonal relationships to views about the environment. Accordingly, the risk to human populations that helps drive what many call the "wicked problem" must be understood as a complicated merger of two distinct components: (1) the shared human population values affected by wildfire (Champ et al. 2012, Breakwell 2014) and (2) the biophysical

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risk that is often measured by the probabilities of occurrence and the severity of impacts (Calkin et al. 2014). Many segments of traditional wildfire science focus on only one of these distinctions; what are needed are better mechanisms for integrating them. Addressing these challenges requires the collective definition of and concrete strategies for achieving fire-management goals across diverse human communities and fire-affected landscapes.

In acknowledging these challenges, the US government has identified three key priorities for advancing wildland fire management that are translated globally: (1) restoring and maintaining fire-adapted landscapes; (2) facilitating fire-adapted communities (FACs) that coexist with wildland fires; and (3) promoting collaborative, informed, safe, and effective wildland fire responses (WFEC 2014). The broad vision of the US strategy is summarized as, "To safely and effectively extinguish fire when needed; use fire where allowable; manage our natural resources; *and as a nation, to live with wildland fire*" (WFEC 2014). This mindset is reflected in fire-management and planning efforts globally (boxes 1–4). Governmental land-management agencies are not well positioned to coordinate the integrated partnerships necessary to achieve these goals, because they are often restricted by jurisdictional boundaries and institutional mandates. Furthermore, creating fire-adapted communities requires making the general public partners in initiatives to manage wildfire risk and protected lands. It necessitates human communities who make decisions that reduce professional firefighting burdens and allow wildfire to play a role in natural landscapes. This includes a need to better articulate what makes populations fire adapted and how we designate "community" as a unit of study (Flint and Luloff 2005). Although a few programs exist for communities to proactively prepare for wildfires, such as the Firewise USA Communities Program or the United Kingdom Forestry Commission planning program (box 2), the success of such initiatives is variable and fragmented across geographic space and over time. There is no established industry equipped to handle the issues of living with wildfires. There are limited standards for building in fire-prone areas, and disconnects are apparent between the results of wildfire science research and the specific adaptation strategies and mitigation actions that communities can readily adopt. This leads to an opportunity for the scientific community to engage communities and professionals in the identification of research and best practices that can improve wildland fire management, education, and policies, leading to the design of resilient fire communities and landscapes (Enright et al. 2015). Key to those efforts will be the tailored design of wildfire research and mitigation programs that reflect the unique communities, countries, and cultures that are each negotiating what it means to "live with fire." The outcomes of such efforts are likely to increase the chances that new knowledge is integrated into local action (Steelman and McCaffrey 2013).

In this article, we introduce a risk-to-resilience framework that can help stimulate collective discussion about the wicked wildfire problem and define new relationships between people and wildfire. Central to that framework is an expansion of firescape concepts (Wood et al. 2011) to couple biophysical landscapes with cultural overlays of human systems. We use this framework to elucidate potential pathways and define strategies for communities and landscapes to coexist with prescribed and unplanned wildland fires across varied spatial and temporal scales. Advancing those pathways first requires a better understanding of human populations' variable relationships to wildfire and the landscapes that sustain them, including perceptions of wildfire risk (Champ et al. 2013). Designing better relationships between people and wildfire will require participatory approaches and feedback mechanisms that allow citizens, land managers, and scientists to collectively define outcomes for wildfire management (Jakes and Sturtevant 2013, McCaffrey 2015).

Our framework addresses knowledge gaps influencing the future ability of communities to predict, adapt, and mitigate the immediate and cascading impacts of wildland fires on crucial ecosystem goods and services (Abatzoglou et al. 2014, Smith et al. 2014). It also recognizes that science designed to address knowledge gaps must be iteratively developed in ways that consider, support, and help achieve human populations' desired system states. We close by outlining grand challenges that are important for achieving resilient firescapes. Given the global nature of these challenges (Bowman et al. 2009a, 2009b, 2011), the framework outlined here has broad applicability.

Fire as a crucial Earth-system process

Fire is essential for human life and civilization and is a significant component of the Earth system that regulates the provision of key ecosystem goods and services (figure 1; Bowman et al. 2009, 2011, 2013). It recycles and redistributes nutrients locally and globally, initiates the regeneration of vegetation, and is necessary to the life cycle of countless species (Goetz et al. 2005, Duguy et al. 2012). Fire also has historical and ongoing importance to human civilization, whether as a source of light, warmth, and energy or in the documented use of prescribed fire by many cultures for land-management purposes (Pyne 1997). More recently, wildfire has re-emerged as a significant risk to human property, life, and other values. Addressing these risks is difficult from a policy perspective because fire exerts cascading and largely unacknowledged effects on key processes controlling food, water, and energy production (Abatzoglou et al. 2014). Cascading fire effects, such as accelerated sediment and water flows that predispose landscapes to secondary landslide and flood hazards (Abatzoglou et al. 2014), can compound economic costs, leading to decreased human resources and increased ecosystem vulnerabilities (Duguy et al. 2012).

The temporal variability, geographic extent, and magnitude of fire must be fully considered to estimate the impacts on coupled human and natural systems (Van der Werf et al. 2006); this is a challenge given that the occurrence, frequency, and intensity of wildfires will rise across many parts

Box 1. Firescape risk-to-resilience case study.

Yosemite National Park (United States)

Risk. High fire frequency, the diverse mixture of fire regimes across steep elevational gradients, high public use and sense of ownership, an extensive urban interface (including adjacent rural communities), and relatively proximal urban populations within affected water- and airsheds.

Adaptation. Science-driven, holistic fire-management strategies that embrace prescribed burning and multiple responses to wildfires, and intentionally integrated into broader park-management ethos.

Mitigation. Opportunistic fire re-introduction activities, extensive public education campaigns, applying principles of defensible space to both historic resources and natural treasures, and the re-allocation of human infrastructure to facilitate natural ecological processes.

Resilience. By promoting policies at the forefront of national policy but counter to public opinion, Yosemite National Park has, in the face of global change, shifted the social acceptance of fire leading to firescape resilience.

Top: ***Prescribed burn in Wawona to protect historic structures in an area where a lightning fire was being managed for resource benefit.*** **Bottom:** ***2001 Hoover fire that burned over several previous burns in the Illilouette Creek basin. The front left burned in the 1991 Ill Fire, and the lower right is montane chaparral that burned in the 1974 Starr King Fire. Photographs: US National Park Service.***

of the planet in response to anthropogenic climate change (Moritz et al. 2012, IPCC 2014). The impacts of increasing fire activity are heightened in the ever-expanding wildland–urban interface, in which human settlement is embedded within flammable wildland vegetation (Moritz et al. 2014, Paveglio et al. 2015a, 2015b). Further complicating the situation, considerable evidence has demonstrated that climate change has altered the mosaic of vegetative fuels (Chmura

Box 2. Firescape risk-to-resilience case study.

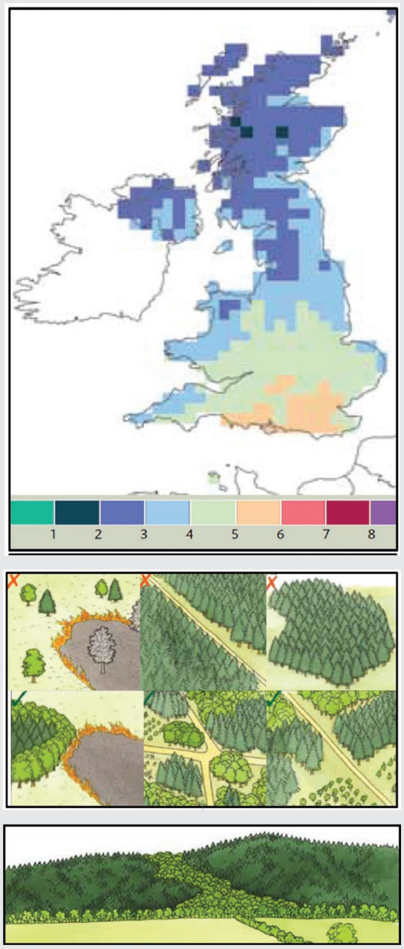
United Kingdom

Risk. The British Isles has a long history of human-set landscape fires to maintain open habitats such as “heathlands” and to remove crop residues. However, destructive wildfires are emerging as a threat because of changes in land-use patterns combined with more and severe droughts caused by climate change. Of particular importance are uncontrolled fires in forests, grasslands, arable crops, and upland peats. Wildfire can cause substantial socioeconomic disruptions, damage culturally significant landscape and structures, cause harm to biodiversity, and degrade ecosystem services. Severe wildfire hazard has also been defined in these systems (NRRCE 2015).

Adaptation. Evaluating the risk of forest fire formed part of the 2012 *UK Climate Change Risk Assessment* (DEFRA 2012). The increased recognition of the role of fire in the environment of the British Isles is stimulating regular meetings and conferences among scientists and practitioners.

Mitigation. New guidelines and tools are being developed to manage firescapes in the United Kingdom, including the UK Forestry Commission’s *Building Wildfire Resilience into Forest Management Planning* (UKFC 2014), designed to facilitate preparation for forest fires, and the UK Met Office fire weather danger tool, designed to identify areas where access to the countryside is closed because of immediate fire risk.

Resilience. To increase firescape resilience, attention is shifting to collaboratively produce geographically detailed contingency plans developed by landowners, NGOs, multiple government sectors (emergency, fire and rescue, forestry, countryside and cultural heritage). This includes risk assessment, the formulation of prevention measures, and incident0response preparation. Interventions include (a) landscape design principles and adaptive management changing the fuel continuity and vulnerability of economically, culturally, and biologically important assets using silvicultural management, planned burning, and grazing; (b) the reduction of accidental ignitions through the control of access and education programs; and (c) the establishment of firefighting infrastructure.



Top: ***Projected UK forest fire danger from 2070–2100 (UKMO, 2015). Values (risk: 1–100): 1 = no fires, 5–12 = ‘moderate’ 50 = serious, 75 = extreme, and 100 = catastrophic.*** **Middle:** ***Principles followed by the UK Forestry Commission to promote wildfire resilience into forest design.*** **Bottom:** ***Broadleaved trees planted in the cleared fire break to improve wildfire resilience while creating aesthetics of a hedge. Images reproduced as part of the Open Government License (UKNA, 2015).***

Box 3. Firescape risk-to-resilience case study.

Southern Australia

Risk. Southern Australia is a high fire-prone environment because of extensive flammable eucalypt forests, the dominance of interannual droughts cycles due to the El Niño climate mode, and the disruption of an ancient tradition of Aboriginal fire management. Urban sprawl into flammable environments and climate change compound the situation.

Adaptation. Australia has a long history of applied fire research that has developed methods to evaluate bushfire risk and reduce fuel loads by planned burning. The nation also pioneered community-based and individual-based firefighting strategies. However, these approaches are increasingly being tested by the growing incidence of severe fire events on the outskirts of all major Australian cities. This has led to major inquiries into bushfire risk such as the Victoria Bushfire Royal Commission (VBRC 2010) and the Tasmanian Bushfire Fire Inquiry (TBIR 2013).

Mitigation. In response to recent unprecedented fire events, a new "catastrophic" fire danger classification has been implemented, and new approaches to individual and community risks are being developed. Particularly the shift from the "stay or go" policy to one of "watch, act, and survive" that recommends everyone leaves fire-prone areas under catastrophic fire conditions (VBRC 2010). A greater emphasis is placed on improved building codes to make structures more likely to survive fire and improving power-line infrastructure to reduce accidental ignitions. Planned burning to reduce fuel loads has increased through mandated targets in Victoria and Tasmania. Current policy is a risk-based approach that targets specific treatable areas on public and private land.

Resilience. These firescapes remain hazardous despite significant investment and planning. Achieving sustainable fire management is a thorny issue demanding trade-offs in relation to reduction in fire hazard versus degrading amenity values, increased smoke pollution, negative biodiversity impacts, and the cost of retrofitting older housing stock to reach current building codes. Shrinking safe burning windows for planned burning due to climate change, concern about the health impacts of smoke pollution, and recognition that planned burning has limited benefit to protect the urban interface have, in some settings, stimulated consideration of the mechanical treatments of fuels and thinning vegetation to increase defensible spaces around homes (Grindlay 2015).

<u>Strategic Objectives and National Goals</u>

Effectively Managing the Land with Fire
- Maintain Appropriate Fire Regimes in Australia's Forests and Rangelands.
- Balance the Environmental Impacts of Fire.
- Promote Indigenous Australians' Use of Fire.

Involved and Capable Communities
- Community Engagement.
- Public Awareness and Education.

Strong Land, Fire, and Emergency Partnerships and Capability
- Integrated and Coordinated Decision Making and Management.
- Employment, Workforce Education, and Training.
- Bushfire Risk Mitigation.
- Bushfire Response.
- Safety in Fire Operations.
- Bushfire Recovery.
- International Responsibilities.

Actively and Adaptively Managing Risk
- Risk Management.
- Investing in and Managing Knowledge.

Top left and top right: ***Wildland urban interface of Hobart, Australia. Photographs: David Bowman.*** **Bottom:** ***Strategic objectives and national goals from the National Bushfire Management Policy Statement for Forests and Rangelands (FFMG, 2014).***

Box 4. Firescape risk-to-resilience case study.

Canadian Boreal Forests

Risk. The boreal forests of northern Canada rely on frequent high-intensity, stand-replacing crown fires for ecosystem health and maintenance. Boreal fire occurrence and severity are increasing and are expected to continue increasing because of climate change–induced extreme fire-weather and fire-danger conditions.

Adaptation. Modern but expensive fire-management programs have been effective to date, protecting much of the boreal zone for resource extraction and recreational use. A policy of aggressive fire suppression has been practiced for decades, most recently including resource sharing across Canada and with other countries. However, the recent Canadian Wildland Fire Strategy (CWFS) acknowledged that current fire-management practices have reached a point of diminishing returns, both economically and physically. Currently, 50% of the area burned in Canada occurs in remote northern boreal regions, where fires are monitored but not actively suppressed unless threatening property. An opportunity exists to adopt this policy more widely in heavily protected areas, assessing each fire in terms of potential values at risk, suppressing unwanted fires, and permitting more to burn naturally.

Mitigation. Canadian fire-management agencies are expanding public education and prevention programs and restricting public access to wildland areas during high-risk periods. This can reduce human-caused fire numbers, but lightning fires cannot be prevented and are forecast to increase under a changing climate as a result of greater atmospheric convective activity. The improved detection of lightning and fire occurrence prediction models may help. The further adoption of fuels and hazard mitigation practices to protect communities and high-value resources will be essential.

Resilience. Further public and political education and awareness around emerging fire-management issues and options are urgently required. Inhabitants of areas with forest ecosystems must recognize there will be more fire on the landscape in both the short and longer terms, with significant impacts including air quality, human health, and transportation. Evacuations of communities will increase, particularly in aboriginal communities.

Bottom line

Although natural fire has been deliberately promoted in more remote regions of the Canadian boreal zone, increasing fire activity will dictate a management strategy that monitors but allows more fire on the landscape, including increased fire in areas that were once under intensive protection.

Top: ***Crown fire in the Northwest Territories. Photograph: Dennis Quintilio.*** **Middle:** ***Smoke in Whati, Northwest Territories. Photograph: Dennis Quintilio.*** **Bottom:** ***Fire polygons 1980–2014.***

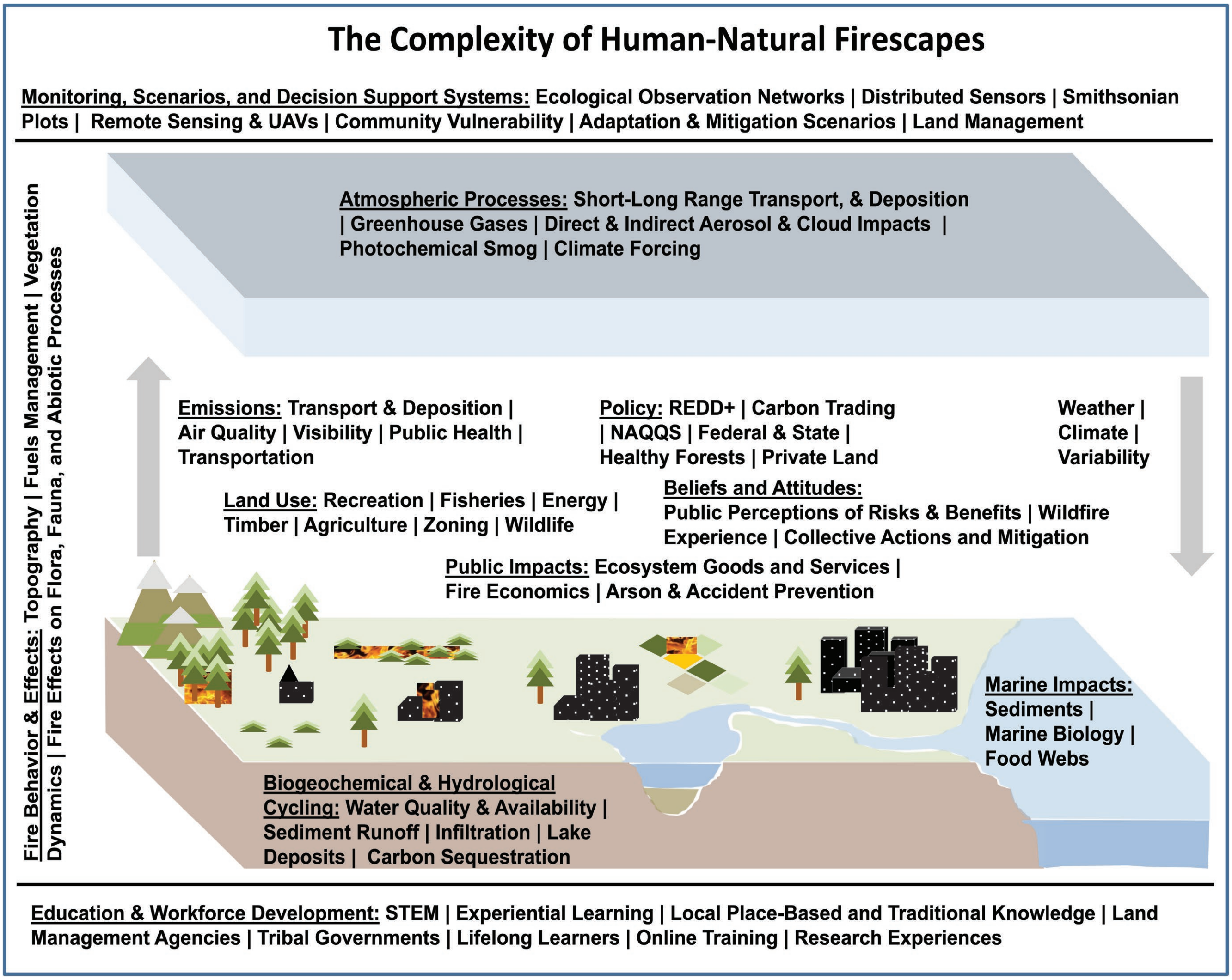


Figure 1. Research focusing on the design of wildland fire adapted firescape components will have to consider the complex cascading consequences of fires within human–natural firescapes. (color online only)

et al. 2011, Laurance et al. 2011). Many ecosystems have been pushed beyond their historic range of variability, leading to unfamiliar scenarios that will require new research to evaluate system vulnerabilities, as well as adaptation and mitigation options (Smith et al. 2014).

There is a historic tendency to focus on the biophysical drivers of wildfire while framing it as a hazard with unidirectional impacts to human populations. Other segments of the wildfire literature have long argued that social dynamics, politics, and the historical legacy of human institutions are significant contributors to the wildfire problem (Flint and Luloff 2005, Paveglio et al. 2015b). For instance, historic policies of wildfire suppression in the United States have had a significant influence on the buildup of fuels in many fire-prone regions (Carroll et al. 2007). Expanding residential development, changing perspectives toward wildland management, and the shift of human populations away from resource extraction industries can each alter the local human capacity to manage wildfire starts and further alter the feedbacks that moderate vegetative dynamics in a region (Abrams et al. 2015). Finally, public pressure or preferences can lead politicians to prioritize short-term goals of quick suppression rather than addressing other systemic influences on wildfire risk (e.g., land-use planning, climate change, and active resource management; Steelman and McCaffrey 2011). Any pathways for addressing the wicked wildfire problem cannot exist in isolation of existing wildfire social science that explores these topics and addresses wildfire as a function of people interacting with the environment.

Additional barriers to addressing the impacts of fire on coupled human and natural systems include a limited understanding of the interrelationships among fuels, fire behavior, and fire effects (Kremens et al. 2010); uncertainty in identifying regime shift early warning signals (Scheffer and Carpenter 2003, Carpenter et al. 2011); and the unknown social and economic consequences of these regime shifts

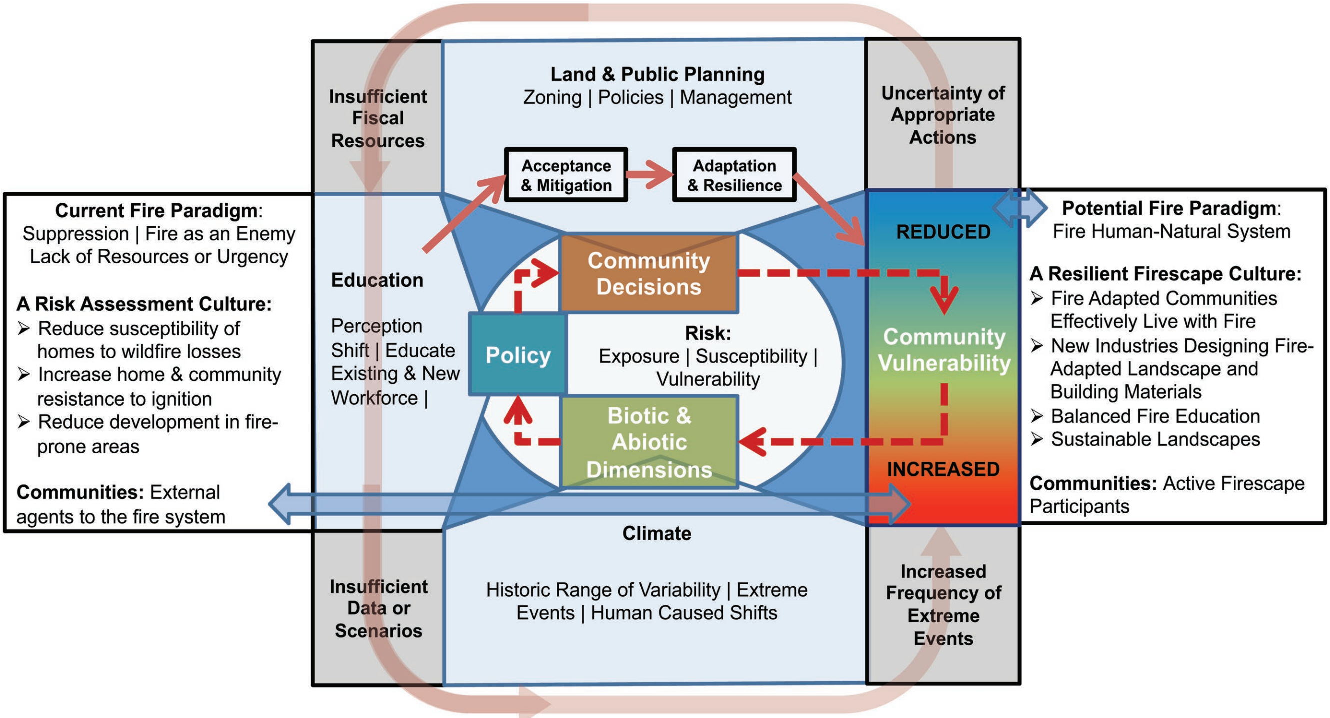


Figure 2. A paradigm shift is needed from a system where communities are predominately passively affected by fires to one where they actively work hand in hand with land management planners, architects, and agencies to coexist with wildland fires. Enhancements in education can lead to improved planning and informed adaptation and mitigation scenarios, leading to reduced community vulnerability. A lack of education, resources, or data to make informed decisions can act to increase community vulnerability. (color)

(Bowman et al. 2009, 2011, 2013). The degree to which these three barriers affect fire in coupled human and natural systems is poorly understood (Moritz et al. 2014, Paveglio et al. 2015a, 2015b).

Urgently needed are early-warning indicators to develop quantitative predictions of community and landscape vulnerability to fire (Scheffer and Carpenter 2003, Carpenter et al. 2011). Although wildfire risk is a widely used concept (Calkin et al. 2011, 2014), a typology of what fire vulnerability is and how to both quantify and describe different degrees of vulnerability to immediate and cascading consequences of wildfires is crucially needed. Research is also needed to evaluate coupled human and natural system responses to fire variability and extremes—particularly through the evaluation and cross-comparison of adaptation strategies and mitigation actions to lessen the loss of important ecosystem goods and services (figure 2; Jakes and Sturtevant 2013, Smith et al. 2014). Achieving landscape-to-regional predictions of various land-use and land cover–change scenarios in response to future fire activity will require improved mechanistic modeling of fire-relevant ecosystem components (Kloster et al. 2010) and enhanced scenario platforms that explore both the direct impacts and the cascading consequences of fire (Abatzoglou et al. 2014). Dynamically changing systems may lead to novel conditions across diverse regions, but those “new-to-them” conditions may be similar to existing or historic conditions from other regions (figure 3).

Firescapes: Fire integrated within human–natural systems

Human adaptation to wildfires is more than simply accepting that fires will occur. Rather, it is a complex set of interacting factors, including fire impacts on local values, local ability to organize in response to disturbance, personal experience with wildfire, perceptions of responsibility for fire management, and stakeholder understanding of the role of fire as a landscape process (Jakes et al. 2007, Fischer et al. 2014, Paveglio et al. 2015a, 2015b). Many of these lessons now need to be reintegrated into the scientific and public lexicon because of a historic focus on eliminating and suppressing wildfire. Since the early twentieth century, education and workforce development around wildland fire in the United States have focused on the control of fires through suppression strategies and tactics. The negative aspects of wildland fire were historically reinforced through media and film (e.g., Bambi or Smokey Bear). This culture has been driven by the need to protect human populations and resources from fire impacts, and it has created a professional culture focused on “fighting” fire as an adversary (Pyne 1997, Calkin et al. 2011, Moritz et al. 2014).

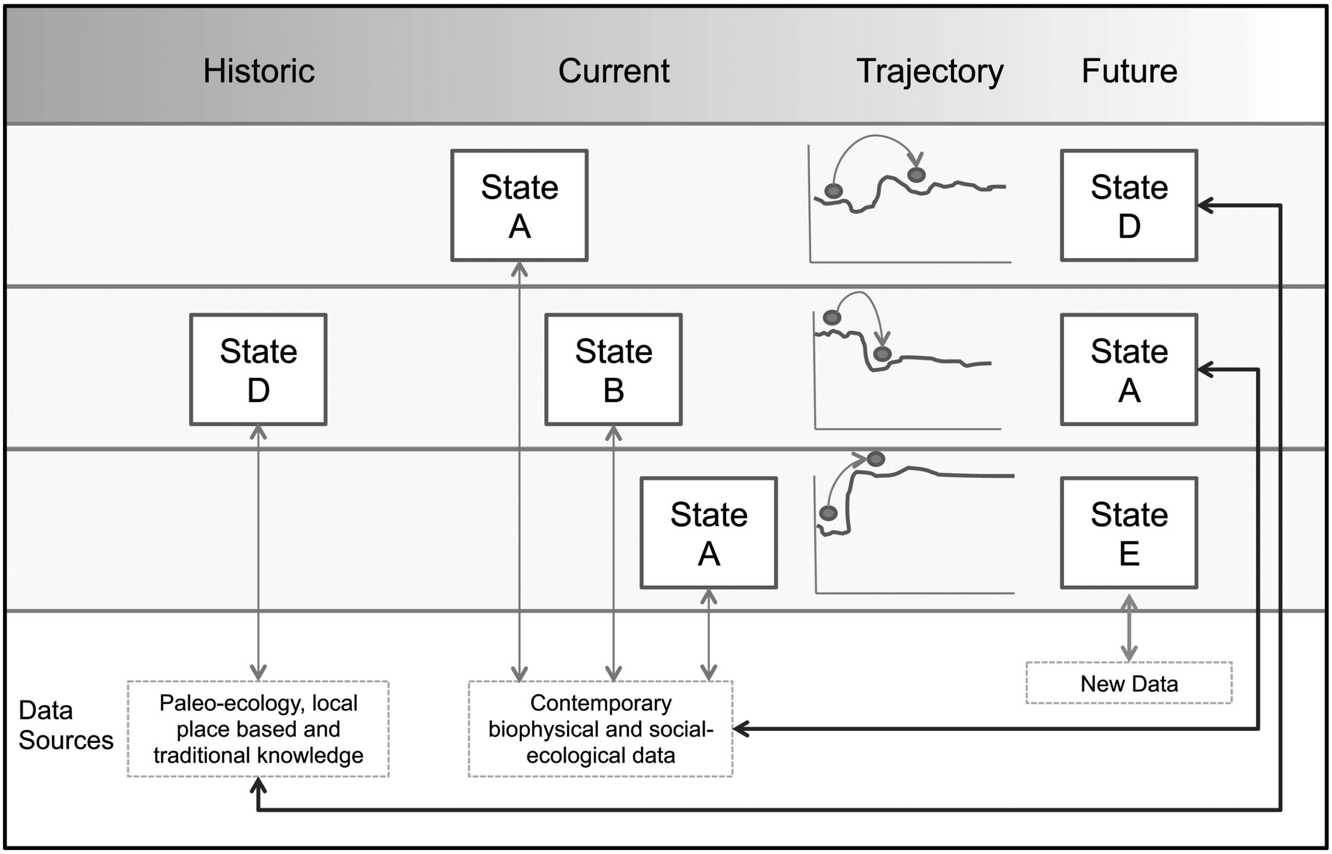


Figure 3. Dynamically changing systems may shift outside their historical range of variability, leading to novel conditions across diverse regions, but those "new-to-them" conditions may be analogous to contemporary or historic conditions elsewhere, where existing data are already available. Such data could include local place-based and traditional knowledge, paleoecology cores, distributed sensor networks (such as long-term ecological research sites), etc.

A significant body of social science has revolved around efforts to better understand public views about wildfire, associated wildland management, and the promotion of renewed ideas about its inevitability (McCaffrey 2015). Public acceptance of fire as a beneficial ecosystem process is increasing, but there remains a perception of fire as a largely preventable hazard that negatively affects property or other human values (Toman et al. 2013). For instance, the public is more accepting of wildland fire in backcountry settings and away from human settlements, which is not wholly congruent with the goals of coexisting or "living with" wildfire (Moritz et al. 2014). Overcoming such paradoxes are significant and variable challenges that may be unique to certain firescapes depending on historic and ongoing cultural and demographic changes in the region. In response, one focus of wildfire social science has concerned the development and variable adoption of mitigation activities that communities and individuals can perform to reduce wildfire risk to private values (e.g., reducing fuels around homes, building with fire-resistant materials, and evacuation planning; McFarlane et al. 2011, Champ et al. 2013). Although efforts have been made to identify the factors that influence the adoption and perpetuation of these strategies, researchers have yet to identify one consistent strategy for promoting wildfire adaptation. This is not surprising given the acknowledgment that risk is variable among populations and dependent on local dynamics. We also lack comprehensive mechanisms or methodologies for documenting adaptation across locations.

Framing the complex problems facing fire science and management requires us to characterize fire as an integrated, cascading, and cumulative phenomenon within coupled human and natural systems. Only by considering the ongoing and holistic processes of how fires interact within past, current, and future human–natural systems will communities be able to achieve the resilience sufficient to coexist with fire. Prior attempts to address parts of this typology challenge include the concepts of firescape ecology (Wood et al. 2011), which couples landscape topographic features and vegetation with landscape-scale imagery of fire-affected areas, and firesheds (Ager et al. 2006), which are large, homogenous fire-management landscapes delineated by areas that are likely to exhibit similar fire-behavior properties and similar fire-management response strategies, where the boundaries dynamically shift depending on management changes within the human–natural system. However, these concepts do not integrate social vulnerability, instead focusing on exposure analysis within a geospatial framework. Studies have also sought to incorporate various degrees of societal context, such as the concept of anthropogenic fire regimes (Bowman et al. 2011), which focus on how the human use of fire throughout the Holocene in North America and the Quaternary in Australia and Africa have modified landscapes. However, achieving resilience to wildfires at the spatial and temporal scales that communities operate over (i.e., individual homesteads to water catchments and airsheds of large metropolitan areas, over days to decades) requires integrating human-use data not only at Quaternary scales but also over the Anthropocene. Projected future trends in communities, population demographics, as well as adaptation and mitigation resources or limitations associated with local, regional, and national geopolitical realities are all needed to sustain resilience to fire into the future.

Our concept of firescapes applies the idea of anthropogenic fire regimes to the existing canvas of firescape ecology (including the Anthropocene), considers the diverse social context that can influence wildfire management, and includes projected future dynamics (figure 1). We argue that firescapes provide a more holistic view of human–natural systems and their influence on wildfire processes. Firescapes couple physical properties and dynamics with the cultural overlay of human values, perceptions, and processes. They are a product of both natural (e.g., lightning) and anthropogenic sources of fire. Firescapes implicitly acknowledge that fire interacts with a wide variety of both ecosystem and community processes; these processes will exhibit coupled feedbacks resulting in both immediate and cascading consequences. Firescapes include past, present, and projected future human–fire interactions.

The discipline of pyrogeography operates squarely within this context; pyrogeography seeks to develop holistic understandings of landscape-scale fire activity in time and space (Bowman et al. 2015). Pyrogeography is to firescapes as the discipline of geography is to landscapes. Firescapes are therefore elemental components that form the pyrogeography of a region. Applying pyrogeography to understand firescapes could allow fire science to explore fundamental multiscale and multidisciplinary challenges that span a diversity of spatial and temporal scales. Management approaches can be applied and leveraged across the firescape—residents can reduce ignition risks around their homes, agencies can sustain ecosystem goods and services through controlled fire application, and governments can implement policies to incentivize wildfire preparedness and responses.

The holistic development, testing, and validation of wildfire adaptation strategies and mitigation actions in response to changing firescape and large-scale processes such as urbanization, deforestation, or climate change will not be trivial. Furthermore, new public–private partnerships will also be needed to focus on (a) characterizing the historic and future dynamics of unique firescapes, (b) identifying and overcoming barriers that diverse communities face in becoming fire adapted, (c) collaboratively developing and initiating a cultural paradigm shift in wildland fire education and in the resultant workforce, and (d) promoting integration with emerging and innovative industry sectors to restore and maintain resilient firescapes. Finally, there is a crucial need for social-science research that can identify the scientific outputs most likely to promote policy development and individual action that address wildfire management among a diverse set of stakeholders (e.g., politicians, land-management professionals, and private citizens). This includes testing stakeholder trust in the outputs and assumptions that underlie wildfire science or simulation, the funding mechanisms most likely to support adoption of planning recommendations, and the messages that carry collaboratively designed initiatives.

The barriers to understanding firescapes and reducing community vulnerability to wildfires include insufficient knowledge of how best to tailor programs to local people or respond to specific scenarios, limited fiscal resources for trained responders or equipment, lack of models or projection of the cascading consequences of decisions, and limited community resources to deal with increasing fire occurrence (figure 2). Confounding this complex system are dynamic changes in land use and public planning (e.g., zoning and development codes), climate variability, and shifts in the availability and education of the workforce that would manage and apply the adaptation strategies and mitigation tactics. Overall, fire is inevitable, not only in "wildlands" but also in many populated regions.

Risk-to-resilience continuum

We contend that addressing these diverse needs would be best served by focusing on four points of a risk-to-resilience continuum for reducing community vulnerability and improving the resilience of firescapes: (1) risk, (2) adaptation, (3) mitigation, and (4) resilience (table 1). Central to achieving and maintaining resilient firescapes is the recognition that research, education, and workforce development are tightly connected. For example, the two dominant and often divergent fire-education belief systems that coexist in the United States are focused either on fire suppression or natural-resource sciences. The fire suppression system is characterized by vocational training, on-the-job experience, and land-management agency certification. The historical development of that system is intertwined with a paradigm that wildfires are a detrimental force that need to be fought in order to facilitate human use of firescapes. In contrast, the natural-resource science system is characterized by academic degrees in ecology, natural-resource stewardship, restoration, and natural-resource management that may include indigenous ecological knowledge (Worrell and Appleby 2000). This system recognizes that allowing fires to burn (when they don't risk human property, lives, or other values) and incorporating prescribed fires can help promote ecological resilience, because fires are a naturally occurring phenomenon with a long history of human engagement. This system struggles

Table 1. The risk to resilience spectrum.

	Risk	Adaptation	Mitigation	Resilience
Guiding principles	Incorporate immediate local impacts and longer-term cascading consequences to improve quantification and characterization of firescape vulnerability.	Improve classification typologies developed from collaborative in-depth community-level data to more effectively predict commonalities in firescape adaptation pathways.	Increase adoption of the tailored actions most likely to achieve fire adapted communities and landscapes through integrative and cooperative partnerships.	Co-develop adaptable decision support tools to increase resiliency and reduce community vulnerability through simulation of end-to-end data-enabled scenarios.
Priorities to advance guiding principles	(1) Characterize firescape vulnerability in the context of global change; (2) Identify and evaluate cascading consequences of wildfires across broad spatiotemporal scales using natural, physical, and social sciences; and (3) Evaluate bottom-up and top-down approaches to predict firescape trajectories and potential impacts on ecosystem goods and services.	(1) Synthesize factors and drivers that perpetuate the fire suppression paradigm; (2) Identify the common factors most likely to facilitate human adaptation to wildfire. (3) Codevelop alternative adaptation strategies to reduce community vulnerability given place-based knowledge, experience, and local culture.	(1) Coproduce “blueprints” for community and landscape mitigative activities that reduce wildfire vulnerability. (2) Codevelop fire-resilient materials through collaborative partnerships with production, application, and risk assessment industries. (3) Co-apply science-based knowledge in partnership with wildland fire mitigation organizations.	(1) Codevelop fire-related modules for ecosystem models that predict crucial thresholds and tipping points for important ecosystem goods and services. (2) Coproduce transparent, spatially explicit and accessible platforms that couple natural, physical, and social systems models. (3) Co-apply firescape adaptation scenarios to fire planning, adoption of mitigation actions, and collaboration across jurisdictions.

to integrate the best available fire science within land-management practices.

We posit a series of guiding principles and goals to begin overcoming these divides. Central to this is the collaborative development of what firescapes are, how we monitor firescape vulnerability, and how we assess future firescape dynamics (figure 2). In the following sections, we organize these guiding principles along the four points of the risk-to-resilience continuum. Each of these components is additionally highlighted through a series of firescape case studies (boxes 1–4), including Yosemite National Park in the United States (box 1), the United Kingdom (box 2), Southern Australia (box 3), and the Canadian Boreal region (box 4).

Risk

Risk most commonly includes the potential negative impact to property, persons, or ecosystem goods and services (Calkin et al. 2011, 2014). Although definitions vary, we here define *risk* through the terms *exposure*, *susceptibility*, and *vulnerability* (figure 2; Hinkel et al. 2011, Calkin et al. 2014, Smith et al. 2014). However, risks can span a broad array of characteristics and must reflect the collective agreement of firescape inhabitants about the values that might be affected by wildfire (Breakwell 2014). Potential impacts can be monetary, perceived disruptions to well-being, the loss of infrastructure supporting community function, or the breakdown of collaborative relationships (Paveglio et al. 2015a, 2015b).

The risk of exposure to wildfire is determined by a complex array of environmental and human factors, with climate as a dominant driver. Climate shapes the biogeographic distribution of vegetation that becomes fuel for wildfire: More mesic biomes provide abundant fuel but are flammability limited, whereas more semiarid biomes are highly flammable but fuel limited (Littell et al. 2009). Interannual climate variability and fine-resolution weather ultimately determine ignition probability and fire behavior at a given moment. Anthropogenic climate change is projected to alter the frequency and extent of wildfire primarily through fire potential, such as in temperate and boreal regions as a result of increased flammability during the dry season (Flannigan et al. 2009). The projected magnitude of change in wildfire activity varies substantially across the globe and across modeling efforts, making it difficult to accurately project future exposure risk. Furthermore, a changing climate will also fundamentally alter the underlying energy and moisture that facilitate vegetation assemblages that may lead to increased ecosystem vulnerability (Smith et al. 2014), altering contemporary climate–fire relationships (Flannigan et al. 2009, Littell et al. 2009).

The scope of cascading wildland fire impacts on natural, physical, and social systems is recognized but poorly understood (Abatzoglou et al. 2014). Identifying and quantifying interconnections and feedbacks across these systems require detailed environmental and social monitoring across a range of scales. The advancement of distributed sensor and imagery data, social–ecological data, and large-scale field and manipulation experiments will improve the quantification of interconnected systems. A crucial data need vital to understanding historical and Anthropocene fire use can be achieved through interacting with local place-based and traditional knowledge, such as tribes (or Aboriginal peoples) and multigeneration post–European settlement families. It is essential that researchers both openly share data and develop consistent standards, methods, and terminologies to make fire science truly global (figure 3).

Early-warning signals (see Carpenter et al. 2011 and Smith et al. 2014 for descriptions) are needed to identify tipping points for crucial ecosystem goods and services, perceptions of wildfire risk, and optimal planning actions for populations at risk from wildfire. Example early-warning signals are arguably already in use when considering public-health advisories associated with unhealthy and hazardous particular matter concentrations from wildfire smoke (Yao et al. 2013). New potential metrics should pay special attention to alternate stable states that may arise from ecosystem regime changes and diverse social and political climates that differentiate firescapes, such as the different ways communities may conceive of wildfire in their locality. Likewise, the dynamism inherent in firescapes can be integrated by building on existing typologies of communities within the wildland urban interface and by identifying consistent, empirical metrics to build a firescape typology (Paveglio et al. 2015a).

Adaptation

Adaptation research in firescapes requires a scalable methodology to better characterize the spatiotemporal dynamics of sensitivity, exposure, and adaptation to fire across the continuum of firescapes. Such characterization must draw from and synthesize the extensive literature that documents how local and regional social dynamics influence strategies developed to live with wildfire risk (Paveglio et al. 2015a). Existing adaptations to living with wildfire include community wildfire protection plans, the relationships people may have evolved in reacting to fire risk in their locality, and governmental strategies and policies supporting local ability to adapt to changing firescapes (Brenkert-Smith et al. 2012, Williams et al. 2012, Abrams et al. 2015).

A need exists to better assess the direct and indirect impacts (negative and positive) of wildfires on social systems and ecosystem goods and services (Stephenson et al. 2013). Adaptation scenarios should differ across firescapes and be designed to build on social system strengths (e.g., local wood-products market for fuels reduction and local collaborative groups) and overcome existing policy or social barriers specific to the firescape or its subelements (e.g., the lack of acceptance for prescribed fire or deficiency of resources). This means developing better tools for quickly assessing social context that influences wildfire adaptation, documenting and fostering organic efforts designed in response to site-specific wildfire risk in a given system, and engaging diverse human populations about the programs, incentives, and strategies that will enable them to maintain or change their local relationships with wildfire risk (Jakes et al. 2007, Jakes and Sturtevant 2013, Paveglio et al. 2015a). This includes the feasibility and flexible adoption of mitigations such as those described in the next section.

Future studies should incorporate indigenous or local, place-based, and traditional knowledge to develop transferrable toolkits to foster adaptation. There also is a need to test new approaches for coupling socioeconomic and biophysical responses to fire in order to parameterize ecosystem models and inform future decisionmaking processes (Spies et al. 2014). This includes the development and evaluation of outreach and workforce development solutions to increase active participation of vulnerable communities.

Mitigation

Mitigation is a multifaceted challenge that bridges basic and applied sciences, technologies, and workforce development. Meeting this challenge requires innovative codevelopment of resilient firescape components that are economically viable, socially acceptable, and congruent with other hazard mitigation standards (e.g., earthquake building codes) and that can enable the retrofitting of existing vulnerable firescapes. Some components of resilient firescapes have been proposed in the fire-science and -management literature at localized scales focusing on individual structures or forested stands. However, to effectively mitigate the full spectrum of wildfire risk, these components must be integrated and scaled to recognize that structural and wildland fire elements interact as dynamic components within a coupled human and natural system in which risk reduction, adaptation strategies, and mitigation actions are tightly coupled.

Two common strategies to reduce wildfire risk are landscape vegetation treatments and home ignition resistance (Mell et al. 2011), in which the focus is on limiting spread and reducing ignitions respectively. Specific tactics to reduce landscape fire spread through the alteration of fire behavior includes the mastication of tree limbs and small-diameter trees to lower the occurrence of crown-fire hazard (Kreye et al. 2014); promoting discontinuous fuels (firebreaks, nonflammable surfaces, etc.); different patterns of fuelbreaks (Finney 2001); and the placement of fuel breaks adjacent to structures (Massada et al. 2011). Specific tactics to reduce structural ignitions include using fire-resistant materials (e.g., metal roofs, fire-resistant windows and sidings, and homeowner-based retardant sprays) and removing fuels around structures to decrease ignitions from embers or surface fires, respectively (Massada et al. 2011, Mell et al. 2011, Gill et al. 2013).

Mitigations are only useful in achieving firescape resilience if they are enacted or enforced by residents at risk from wildfire. Likewise, mitigations need to be maintained and perpetuated across time and changes in property ownership. For that reason, there is a need to codify and draw crosscutting lessons from the body of wildfire social science identifying the variable incentives, codes, or regulations that promote wildfire mitigation actions (Brenkert-Smith et al. 2012, Fischer et al. 2014). It is also necessary to explore how new mitigation ideas overlap in response to two important components: (1) variable resident values for what is at risk (e.g., forested setting, timber stand, home) and most likely to increase adoption and (2) optimal reductions in the need for professional wildfire response, including the associated danger to firefighter safety and wildfire-suppression expenditures.

Advancing mitigation options also will require innovative combinations of wildland and structural fire science. For example, although flammability testing is a well-documented practice in structural fires and methods have been developed for Wildland Urban Interface structures, these methods are not standardized across wildland fire science (Mell et al. 2011). Further research is needed to explore the spatial arrangement and interactions of water features, vegetation assemblages, nonflammable surfaces, and proximity to households or community neighborhoods that are not similarly adapted. Examples of resilient firescape components in populated areas could include the selection of yard landscape components (e.g., concrete, pavers, gravel, and water features) and yard plants that inhibit fire spread. The latter would require additional flammability research, a task that would vary by locality and depend on individuals' aesthetic preferences for potential plants. Other examples could include the development of building components such as drip-line systems in roofs or homeowner-based fire retardant systems.

To overcome these challenges, interdisciplinary teams focused on mitigation-related research would be needed. For example, collaborations between architects, material scientists, and community planners could investigate the ignition and combustion characteristics of architectural elements and yard components across scales (individual structures, the Wildland Urban Interface, and rural landscapes). Such research also could use biomimicry to develop fire-resilient materials and designs while testing and validating wildfire-related mitigation recommendations. These mitigation tactics would be discrete actions that feed into and interact with larger adaptation strategies. Characterization of the ignition and combustion properties of firescape flora and features could provide essential knowledge to existing efforts that seek to promote fire adapted communities.

Investment in mitigating the cascading consequences of wildfires (e.g., via prescribed fires, fuel treatments, and material design) could result in long-term benefits, such as reducing the annual costs of wildland fire suppression and rehabilitation.

Resilience

Identifying wildfire risks and development of adaptation and mitigation frameworks can facilitate resilient firescapes. However, maintaining resilience requires adaptive management through the use of and testing surrounding user-accessible decision-support platforms. Many changing ecosystems will require the continual evaluation of system vulnerabilities and the iterative development of adaptation and mitigation options (figure 3). Equally, ecosystem regime shifts may result in states that are new or have not been observed for millennia in a given region but resemble contemporary or past states from other locations where data have been collected. International sharing networks including biophysical, paleo, and traditional knowledge data could help facilitate identification of those analog scenarios (figure 3).

Resilience will also be aided by firescape early-warning and information systems, which provide crucial data prior to a potential hazard. These early-warning and information systems will allow decisionmakers to make informed actions to avoid, pre-emptively mitigate, or prepare for effective and timely responses to any undesirable impacts (Yao et al. 2013, Smith et al. 2014). Firescape early-warning systems should include an integrated set of "early-warning signals" that are each focused on a defined ecosystem good or service potentially affected by fires. For instance, such decision-support systems for wildfire could predict coupled human and natural systems tipping points through the integration of early-warning signals (Scheffer and Carpenter 2003) related to a variety of human values (e.g., home loss, infrastructure damage, and loss of access), ecosystem goods and services (e.g., air quality, watershed health, food, and fiber), or underlying social conditions (e.g., land-use development and alternative incentive policies). In addition, the further development of these early warning signals could improve parameterization of ecosystem models. For natural resource management, knowledge of ecosystem transitions decades in advance may be sufficiently "early" for decisionmakers to act proactively (Smith et al. 2014), whereas evacuation warnings would be optimal at a timescale of days to hours (Paveglio et al. 2015b).

An important end product of firescape early-warning and information systems are visualizations (ideally science-based and visually realistic) that could aid the real-time assessment of how management, community, or individual decisions may affect the immediate or cascading consequences of fires (figure 4). Such virtual worlds and science-based visualization tools have been widely used to aid landscape and urban planning (Bishop et al. 2008) and could help facilitate resilient firescapes by providing centrally based platforms for fire science researchers to share model results and data, for land management personnel to evaluate different strategies, and for communities and land planners to view what such projections may mean for their locality. Social-science methods can be used to assess the utility of such visualizations and can help further refine and test their usefulness as a decision tool.

Conclusions

In the following sections, we highlight key challenges and barriers to achieving fire-resilient communities.

Characterizing firescape vulnerability. An urgent need exists to identify firescapes most vulnerable to ecosystem shifts (vegetation, human population, habitats, etc.) and reductions or losses of significant ecosystem goods and services (e.g., food, fiber, water, and energy) in response to future projected fire activity. Equally, interactions of climate, droughts, insects, water availability, and urbanization also need to be considered in projected firescape vulnerability. Such assessments could follow the methodology outlined in Laurance and colleagues (2011) but expand the focus to include communities and the complex interactions that influence cascading consequences associated with fires. The identification of

Figure 4. A scientific visualization of a virtual house and yard components that is navigable in 3D and interactive. Prior to the introduction of fire, the users can swap out yard and house features that all exhibit different ignition probabilities. Users could then directly view in real time modeled fire spread through this virtual world and see how their choices affect fire spread and the ignition of their property. (color)

ecosystems vulnerable to state shifts due to climate change is a vital initial step, but also understanding which systems require fire-related trigger events or which systems will shift because of interactions across multiple stressors and disturbances is also important. Integrating with private citizens and land managers to proactively identify what initial ecosystem conditions exist, what current and future ecosystem goods and services are desirable, and what adaptation and mitigation actions are feasible will enable science-based models to be grounded in reality. These data are needed across firescapes globally to identify potential pyrogeographic patterns, trends, and hot spots. This data then could be used to improve Earth-system models to provide early-warning indicators of where and when to apply targeted (and likely limited) adaptation and mitigation resources to promote resilient communities and landscapes in the face of future wildfires.

Diverse firescapes are defined by a variety of social and ecological characteristics that produce dynamic vulnerabilities across a spectrum of spatial, temporal, and political scales. There is a need to integrate and further develop firescapes typologies that specify the relationships between the evolving natural, physical, and social conditions that lead to firescape vulnerability. For example, the US typologies of fire regime and fuel classifications (e.g., LANDFIRE) could be coupled with social-science typologies of at-risk human populations to better quantify the characteristics that drive community vulnerability and facilitate optimal adaptation and mitigation approaches. Firescape characterizations will provide baseline metrics that can be used to assess progress toward fire resilience.

Identifying cascading fire consequences. The majority of fire research narrowly focuses on first-order direct fire impacts on discrete areas, human communities, or institutions. It therefore fails to recognize second-order, indirect impacts and the cascading consequences of fire on human–natural systems. There is recognition that erosion is a related hazard following wildfire events, and there are considerable efforts to both mitigate erosion and promote watershed health by Burned Area Emergency Response teams on public lands. Equally, smoke from wildfires can significantly affect communities that are hundreds to thousands of kilometers from the fires, and the impacts can persist for days to weeks. We need to better understand the extent to which human communities plan for such cascading consequences and how to adapt policies or management that incorporates these larger dynamics. These processes and potential impacts on ecosystem services are not fully integrated into pre-fire vulnerability assessments.

Identifying early warning signals of firescape vulnerability. Firescape typologies must identify multiple early-warning signals and predict when human values, including crucial ecosystem goods and services, become vulnerable, require mitigative interventions to recover function, and no longer contribute positively to a given human–natural system. However, these signals and associated thresholds must be relevant and appropriate for the human–natural system containing the unique firescape in question. Coupling these signals and thresholds will provide the basis for integrated early-warning systems for firescape resilience assessments.

Promoting standards and preparing for shifted ecosystem states. Consistent data standards are essential to quantify and compare firescapes globally. This could be facilitated through repositories of fire-relevant data as future ecosystem states may resemble other sites where data are archived, enabling the development of mitigation and adaptation plans with less new data. Likewise, fire scientists need to better engage professionals and private citizens to determine the research and data outputs that will be most effective in facilitating adaptation planning. Studies have also highlighted the crucial need to standardized fire science terminology and units of measurements to facilitate collaboration and global intercomparisons (Keeley 2009).

Addressing barriers and achieving firescape resilience. There is a need to more fully understand and potentially reframe the legacies that surround fire, including recognition that achieving resilience is a shared responsibility among all individuals and stakeholders within a firescape. Embedded challenges include the educational legacies surrounding wildfire and the need to couple divergent perspectives, especially gender and culture (Eriksen 2013). We need to better understand why and how these legacies impede the development of resilient firescapes, even when actors accept that fire is a necessary ecosystem function. Perhaps more importantly, we need to understand how the existing perceptions, abilities, and capacities of local people can be leveraged to design unique strategies for living with wildfire. This includes testing the circumstances, messages, and incentives that will facilitate or inhibit mitigation to achieve resilient firescapes. Not all firescapes will develop the same strategies to live with fire. For example, a firescape may focus primarily on developing materials and infrastructure, analogous to how the Dutch live with water, by potentially allowing low-intensity fires to pass through the Wildland Urban Interface. Alternatively, a firescape that includes important cultural sites that could be damaged by fires may opt for more aggressive fire suppression in those crucial areas.

The risk-to-resilience framework presented here provides a set of priorities and guidelines for achieving resilient firescapes that can be adapted globally. The firescape concept allows for flexibility in characterizing the diversity of social and biophysical systems, and the risk-to-resilience framework provides concepts and initial steps for achieving resilience in those firescapes.

Wildland fire management has reached a crossroads. Fire is projected to increase in frequency and extent in many regions under anthropogenic climate change. Unsustainable wildfire suppression efforts will continue to spiral out of control unless fire management considers options such as the risk-to-resilience framework. The framework and priorities outlined in this article provide a means for focusing the diverse threads of wildland fire science. Failing to choose an alternative pathway such as the one we have provided will perpetuate the wicked problem of wildfire.

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References cited

Abatzoglou JT, Kolden CA, DiMento JFC, Doughman P, Nespor S. 2014. Climate-change effects, adaptation, and mitigation. Pages 53–104 in Dimento JFC, P Doughman, eds. Climate Change: What It Means for Us, Our Children, and Our Grandchildren. MIT Press.

Abrams J, Nielsen-Pincus M, Paveglio T, Moseley C. 2015. Community wildfire protection planning in the American West: Homogeneity within diversity? Environmental Planning and Management 28: 1–22.

Ager AA, Bahro BB, Finney MA. 2006. Automating fireshed assessments and analyzing wildfire risk with ArcObjects and ArcGIS. Forest Ecology and Management 234: S215.

Barbero R, Abatzoglou JT, Larkin NK, Kolden CA, Stocks BJ. 2015. Climate change presents increased potential for very large fire in the contiguous United States. International Journal of Wildland Fire 24: 892–899.

Bishop ID, Stock C, Williams KJ. 2008. Using virtual environments and agent models in multi-criteria decision-making. Land Use Policy 26: 87–94.

Bowman DMJS. 2015. What is the relevance of pyrogeography to the Anthropocene? The Anthropocene Review 2: 73–76.

Bowman DMJS, et al. 2009a. Fire in the Earth system. Science 324: 481–484.

Bowman DMJS, Murphy BP, Boer MM, Bradstock RA, Cary GJ, Cochrane MA, Fensham RJ, Krawchuk MA, Price OF, Williams RJ. 2009b. Forest fire management, climate change, and the risk of catastrophic carbon losses. Frontiers in Ecology and Environment 11: 66–67.

Bowman DMJS, et al. 2011. The human dimension of fire regimes on Earth. Journal of Biogeography 38: 2223–2236.

Breakwell GM. 2014. The Psychology of Risk. Cambridge University Press.

Brenkert-Smith H, Champ P, Flores N. 2012. Trying not to get burned: Understanding Homeowners' Wildfire Risk Mitigation Behaviors. Environmental Management 50: 1139–1151.

Calkin DC, Finney MA, Ager A, Thompson MP, Gebert KM. 2011. Progress towards and barriers to implementation of a risk framework for US federal wildland fire policy and decision making. Forest Policy and Economics 13: 378–389.

Calkin DC, Cohen JD, Finney MA, Thompson M. 2014. How risk management can prevent future disasters in the wildland–urban interface. Proceedings of the National Academy of Sciences 111: 746–751.

Carpenter SR, et al. 2011. Early warning of regime shifts: A whole-ecosystem experiment. Science 332: 1079–1082.

Carroll MS, Blatner KA, Cohn PJ, Keegan CE, Morgan T. 2007. Managing fire danger in the forests of the US inland northwest: A classic "wicked problem" in public land policy. Journal of Forestry 105: 239–244.

Champ JG, Brooks JJ, Williams DR. 2012. Stakeholder understandings of wildfire mitigation: A case of shared and contested meanings. Environmental Management 50: 581–597.

Champ PA, Donovan GH, Barth CM. 2013. Living in a tinderbox: Wildfire risk perceptions and mitigating behaviors. International Journal of Wildland Fire 22: 832–840.

Chapin FS, et al. 2008. Increasing wildfire in Alaska's boreal forest: Pathways to potential solutions of a wicked problem. BioScience 58: 531–540.

Chmura DJ, Anderson PD, Howe GT, Harrington CA, Halofsky JE, Peterson DL, Shaw DC, St. Clair JB. 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. Forest Ecology and Management 261: 1121–1142.

[DEFRA] Department for Environment, Food, and Rural Affairs. 2012. UK Climate Change Risk Assessment: Government Report. The Stationery Office. (1 November 2015; *www.gov.uk/government/uploads/system/uploads/attachment_data/file/69487/pb13698-climate-risk-assessment.pdf*).

Duguy B, Alloza JA, Baeza MJ, De la Riva J, Echevveria M, Ibarra P, Llovet J, Cabello FP, Rovira P, Vallejo RV. 2012. Modelling the ecological vulnerability to forest fires in Mediterranean ecosystems using geographic information technologies. Environmental Management 50: 1012–1026.

Enright NJ, Fontaine JB, Bowman DMJS, Bradstock RA, Williams RJ. 2015. Interval squeeze: Altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. Frontiers in Ecology and the Environment 13: 265–272.

Eriksen C. 2013. Gender and Wildfire: Landscapes of Uncertainty. Routledge.

[FFMG] Forest Fire Management Group for The Council of Australian Governments. 2014. National Bushfire Management: Policy Statement for Forests and Rangelands. (1 November 2015; *www.sfmc.tas.gov.au/sites/sfmc.tas.gov.au/files/NationalBushfireManagementPolicy_2014.pdf*).

Finney MA. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47: 219–228.

Fischer AP, Kline JD, Ager AA, Charnley S, Olsen KA. 2014. Objective and perceived wildfire risk and its influence on private forest landowners' fuel reduction activities in Oregon's (USA) ponderosa pine ecoregion. International Journal of Wildland Fire 23: 143–153.

Flannigan M, Stocks B, Turetsky M, Wotton M. 2009. Impacts of climate change on fire activity and fire management in the cicumboreal forest. Global Change Biology 15: 549–560.

Gill AM, Stephens SL, Cary GJ. 2013. The worldwide "wildfire" problem. Ecological Applications 23: 438–454.

Goetz SJ, Bunn AG, Fiske GJ, Houghton RA. 2005. Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. Proceedings of the National Academies of Sciences 102: 13521–13525.

Grindlay D. 2015. Mechanical removal of trees to reduce bushfire risk; could America's $400 million program work in Australia? (1 November 2015; *www.abc.net.au/news/2015-04-10/bushfire-trials-prevention-clearing-forestry-fire/6383854*).

Hinkel J. 2011. Indicators of vulnerability and adaptive capacity: Towards a clarification of the science–policy interface. Global Environmental Change 21: 198–208.

Holmes TP, Abt KL, Huggert R Jr, Prestermon JP. 2007. Efficient and equitable design of wildfire mitigation programs. Pages 143–156 in Daniel TC, Carroll MS, Mosley C, Raish C, eds. People, Fire, and Forests: A Synthesis of Wildfire Social Science. Oregon State University.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Climate Change 2014: The Physical Science Basis. Cambridge University Press.

Jakes PJ, Kruger L, Monroe M, Nelson KC, Sturtevant VE. 2007. Improving wildfire preparedness: Lessons from communities across the US. Human Ecology Review 14: 188–197.

Jakes PJ, Strutevant V. 2013. Trial by fire: Community wildfire protection plans put to the test. International Journal of Wildland Fire 22: 1134–1143.

Keeley JE. 2009. Fire intensity, fire severity, and burn severity: A brief review and suggested usage. International Journal of Wildland Fire 18: 116–126.

Kloster S, Mahowald MN, Randerson JT, Thornton PE, Hoffman FM, Levis S, Lawrence PJ, Feddema JJ, Oleson KW, Lawrence HM. 2010. Fire dynamics during the twentieth century simulating by the Community Land Model. Biogeosciences 7: 1877–1902.

Kremens R, Smith AMS. Dickinson M. 2010. Fire metrology: Current and future directions in physics-based measurements. Fire Ecology 6: 13–35.

Kreye JK, Brewer NW, Morgan P, Varner JM, Smith AMS, Hoffman CH, Ottmar RD. 2014. Fire behavior in masticated fuels: A review. Forest Ecology and Management 314: 193–207.

Laurance WF, et al. 2011. The 10 Australian ecosystems most vulnerable to tipping points. Biological Conversation 144: 1472–1480.

Linder M, et al. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259: 698–709.

Littell JS, McKenzie D, Peterson DL, Westerling AL. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecological Applications 19: 1003–1021.

Massada AB, Radeloff VC, Stewart SI. 2011. Allocating fuel breaks to optimally protect structures in the wildland–urban interface. International Journal of Wildland Fire 20: 59–68.

McCaffrey S. 2015. Community wildfire preparedness: A global state-of-the-knowledge summary of social science research. Current Forestry Reports 1: 81–90.

McFarlane BL, McGee TK, Faulkner H. 2011. Complexity of homeowner wildfire risk mitigation: An integration of hazard theories. International Journal of Wildland Fire 20: 921–931.

Mell WE, Manzello SL, Maranghides A, Butry D, Rehm RG. 2011. The wildland–urban interface fire problem: Current approaches and research needs. International Journal of Wildland Fire 19: 238–251.

Moritz MA, Parisienm M-A, Batllori E, Krawchuk MA, Van Dorn J, Ganz DJ, Hayhoe K. 2012. Climate change and disruptions to global fire activity. Ecosphere 3: 1–22.

Moritz MA, et al. 2014. Learning to coexist with wildfire. Nature 515: 58–66.

[NRRCE] UK National Risk Register for Civil Emergencies. 2015. (1 November 2015; *www.gov.uk/government/publications/national-risk-register-for-civil-emergencies-2015-edition*).

Paveglio TB, Moseley C, Carroll MS, Williams DR, Davis EJ, Paige FA. 2015a. Categorizing the social context of the Wildland Urban Interface: Adaptive capacity for wildfire and community "archetypes." Forest Science 61: 298–310.

Paveglio TB, Brenkert-Smith H, Hall TE, Smith AMS. 2015b. Understanding social impact from wildfires: Advancing means for assessment. International Journal of Wildland Fire 24: 212–224.

Pyne SJ. 1997. Fire in America: A Cultural History of Wildland and Rural Fire. University of Washington Press.

Scheffer M, Carpenter SR. 2003. Catastrophic regime shifts in ecosystems: Linking theory to observation. Trends in Ecology and Evolution 18: 648–656.

Smith AMS, et al. 2014. Remote sensing the vulnerability of vegetation in natural terrestrial ecosystems. Remote Sensing of Environment 154: 322–337.

Spies TA, et al. 2014. Examining fire-prone forest landscapes as coupled human and natural systems. Ecology and Society 19 (art. 9).

Stephenson, C, Handmer J, Betts R. 2013. Estimating the economic, social, and environmental impacts of wildfires in Australia. Environmental Hazards 12: 93–111.

Steelman TA, McCaffrey S. 2013. Best practices in risk and crisis communication: Implications for natural hazards management. Natural Hazards 65: 683–705.

Steelman TA, McCaffrey S. 2011. What is limiting more flexible fire management—public or agency pressure? Journal of Forestry 109: 454–461.

[TBIR] Tasmanian Bushfires Inquiry. 2013. (1 November 2015; *www.dpac.tas.gov.au/divisions/osem/2013_tasmanian_bushfires_inquiry_report/2013_tasmanian_bushfires_inquiry_report*).

Toman E, Melanie S, McCaffrey S, Shindler B. 2013. Social Science at the Wildland–Urban Interface: A Compendium of Research Results to Create Fire-Adapted Communities. General Technical Report no. NRS-GTR-111. US Department of Agriculture Forest Service.

[UKFC] United Kingdom Forestry Commission.. 2014. Building wildfire resilience into forest management planning. Forestry Commission Practical Guide. Forestry Commission. (1 November 2015; *www.forestry.gov.uk/pdf/FCPG022.pdf/$FILE/FCPG022.pdf*).

[UKMO] United Kingdom Met Office. 2015. Fire Severity Index. (1 November 2015; *http://www.metoffice.gov.uk/public/weather/fire-severity-index/#?tab=map*).

[UKNA] United Kingdom National Archives. 2015. (1 November 2015; *www.nationalarchives.gov.uk/doc/open-government-licence/version/3*).

Van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano AF Jr. 2006. Inter-annual variability in global biomass burning emissions from 1997 to 2004. Atmospheric Chemistry and Physics 6: 3423–3441.

[VBRC] Victorian Bushfires Royal Commission. 2010. The 2009 Victorian Bushfires Royal Commission Final Report. (1 November 2015; *www.royalcommission.vic.gov.au/Commission-Reports/Final-Report.html*).

Westerling AL, Bruant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shresta SR. 2011. Climate change and growth scenarios for California wildfire. Climatic Change 109: S445–463.

[WFEC] Wildland Fire Executive Council. 2014. The National Strategy: The Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy. WFEC.

Williams DR, Jakes PJ, Burns A, Cheng AS, Nelson KC, Sturtevant V, Brummel RF, Staychock E, Souter SG. 2012. Community wildfire protection planning: The importance of framing, scale, and building sustainable capacity. Journal of Forestry 110: 415–420.

Wood SW, Murphy BP, Bowman DMJS. 2011. Firescape ecology: How topography determines the contrasting distribution of fire and rain forest in the south-west of the Tasmanian Wilderness World Heritage Area. Journal of Biogeography 38: 1807–1820.

Worrell R, Appleby MC. 2000. Stewardship of natural resources: Definition, ethical and practical aspects. Journal of Agricultural and Environmental Ethics 12: 263–277.

Yao J, Brauer M, Henderson SB. 2013. Evaluation of a wildfire smoke forecasting system as a tool for public health protection. Environmental Health Perspectives 121: 1142–1147.

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