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Synthesis

Resilience and fire management in the Anthropocene

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ABSTRACT. Fire management around the world is now undergoing extensive review, with a move toward fire management plans that maintain biodiversity and other ecosystems services, while at the same time mitigating the negative impacts to people and property. There is also increasing recognition of the historical and anthropogenic dimensions that underlie current fire regimes and the likelihood that projected future climate change will lead to more fires in most regions. Concurrently, resilience theory is playing an increasingly important role in understanding social-ecological systems, and new principles are emerging for building resilience in both human and natural components. Long-term fire data, provided by paleoecological and historical studies, provide a baseline of knowledge about the linkages between climate, vegetation, fire regimes, and humans across multiple temporal and spatial scales. This information reveals how processes interacting over multiple spatial and temporal scales shape the local fire conditions that influence human and ecological response. This multiscale perspective is an important addition to adaptive fire management strategies that seek to build resilience, incorporate stakeholder perspectives, and support polycentric decision making.

Key Words: *adaptive management; historical range of variability; prescribed burns: scale*

INTRODUCTION

Attempts to impose stability on inherently dynamic systems are widely recognized by the scientific and conservation communities as futile, given the rapid pace of current changes in climate and land use and the ubiquity of disturbance as an organizing force in ecosystem dynamics (Holling and Meffe 1996). The recognition that ecosystems are intrinsically unstable, however, often conflicts with prevailing land management strategies designed to preserve steady-state conditions and ensure reliable delivery of ecosystem goods and services to meet human needs (North et al. 2015). Ecosystem science points to a need for management and conservation strategies that can better accommodate change as well as novel conditions (Higgs et al. 2014, Johnstone et al. 2016, Falk 2017). Ecosystem-based management approaches based on a “flux of nature” paradigm have evolved to accommodate change while maintaining ecological resilience and adaptive capacity and at the same time meeting human needs. However, in many areas, a lack of information about past variability or future trajectories of change confounds long-range resource management planning (North and Keeton 2008, van Wilgen and Biggs 2011). Proactive strategies would include consideration of key ecological processes that have operated in the past and are likely to be important in the future, including critical thresholds of climate change, levels of natural and human-induced disturbance, the extent of land-cover change, and sensitivity of species to environmental change (Grumbine 1994, 1997, Biggs et al. 2015, Barnosky et al. 2017).

In recent decades, the importance of natural and human-induced disturbance in ecosystem dynamics, biodiversity, and nutrient and energy flows has been increasingly recognized, and it is widely understood that changes in fire regimes will serve as a catalyst of ecological change in the future (Turner et al. 2003, North and Keeton 2008, Penman et al. 2011). Global levels of biomass burning are now thought to exceed those of the last 22,000 years (Marlon et al. 2016), and the intensity and spatial extent of fire have increased in most boreal, temperate, semiarid, and tropical ecosystems in the last 40 years (Mouillot and Field 2005, Flannigan et al. 2009). Recent “megafire” events have been linked to global warming and past fire suppression, with more fires likely in the future (Abatzoglou and Williams 2016, Balch et al. 2018). Given the importance of fire in many ecosystems, understanding its causes and consequences over multiple temporal and spatial scales has become a priority for earth systems science, conservation strategies, and resource management (Bowman et al. 2009).

BUILDING ECOLOGICAL RESILIENCE INTO FIRE MANAGEMENT

Ecological resilience is defined as the capacity of a system to deal with change and continue to adapt (Berkes and Folke 1998). Until recently, building social-ecological resilience was a somewhat nebulous management objective, with unclear measures of success and poor identification of critical thresholds. However, resilience studies are in an exciting phase of transitioning from theory to practice. In restoration ecology, for example, there is a shift toward maintaining ecological processes that support resistance, recovery, and reorganization, rather than re-create prior reference conditions (Falk 2017). Biggs et al. (2015) outline seven principles for building resilience of ecosystem services (Table 1) providing a framework for ecosystem management in the face of changes in fire, climate, and land use. We apply the principles outlined in Biggs et al. (2015) to fire management and consider the use of paleoecological and historical information and diverse stakeholder engagement as critical components of establishing social and ecological resilience to fire in the future.

A brief review of the history of fire management

Fire has been part of the earth system for more than 40 million years, and it has been managed by people for at least 600,000 years (Bowman et al. 2011, O’Connor et al. 2011). Human use of fire has generally followed a common trajectory, tracking the course of cultural evolution. Initially, fire was used to procure game, promote valuable plants and products, facilitate travel, and provide protection. As populations increased in size and became more sedentary, levels of burning increased to clear forest and facilitate pastoral and agriculture activities. In many regions, fire

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Table 1. Seven principles for building resilience (modified from Biggs et al. 2015).

Principle	General Description	Relevance to Fire Management
Principle 1: maintain diversity and redundancy	Maintaining the full range of species, landscape types, knowledge systems, actors, cultural groups, or institutions maximizes options for responding to change and dealing with uncertainty and surprise.	Structural and compositional heterogeneity in fire-prone landscapes results from mosaics of different postfire ages. These mosaics maintain the diversity and redundancy that support biodiversity and ecological integrity.
Principle 2: manage connectivity	Connectivity refers to the spatial structure through which resources, species, or actors disperse, migrate, or interact. High connectivity can facilitate adaptation or recovery from disturbance but may also enhance the spread of disturbances, such as disease.	Connectivity facilitates dispersal and postfire recovery. In fire-prone landscapes, connectivity depends on landscape heterogeneity and a mosaic of postfire ages. In some systems, fire suppression has led to homogenized, overconnected landscapes, in which fuel accumulation supports anomalously large and intense fires. In these landscapes, heterogeneity can be restored through prescribed burning, grazing management, and fuel manipulations.
Principle 3: manage slow variables and feedbacks	Variables that change over timescales of centuries to millennia define the boundary conditions within which faster variables interact. Interactions across scales influence internal feedbacks in social-ecological systems. Understanding and predicting changes in resilience therefore require understanding slow and fast variables and their feedbacks over a range of timescales.	Fire regimes are the result of an interplay between slow and fast variables. Slow variables such as long-term trends in climate and vegetation set the boundary conditions for fire. Knowledge of slow variables provides context for current and future decisions that affect the fire regime through faster variables, such as interactions between vegetation and herbivory, changes in fuel connectivity, and shifts in ignition sources, which can often be managed at a landscape scale.
Principle 4: foster complex adaptive systems thinking	Complexity in social-ecological systems arises from nonlinear interactions and feedbacks between processes. Properties emerge from these interactions that could not have been predicted from understanding each process in isolation. Management based on “complex adaptive systems thinking” acknowledges these interactions and a willingness to adapt to the inevitable surprises.	Fire-prone landscapes often support complex social-ecological systems in which environmental and social factors interact to shape fire regimes. There is a long history of interaction between human society and fire, but recent policies focused on fire suppression have disrupted the cultural use of fire and have homogenized fire mosaics in many places. Therefore, a flexible and adaptive approach to fire management is needed to explore the complexity of processes acting at different spatial and temporal scales, including traditional management of fire and the effects of fire suppression.
Principle 5: encourage learning	Knowledge of complex social-ecological systems is always incomplete, requiring continuous learning, experimentation, and adaptation.	Adaptive management of fire requires cycles of learning by doing, which enables managers to consider fire history and past management actions, to accommodate change and respond to emerging knowledge, changing climate, and shifting social priorities.
Principle 6: broaden participation	Participation through active engagement of all relevant stakeholders improves understanding of complex systems and enhances legitimacy of decision-making processes.	Fire management affects multiple stakeholder groups that need to explore interactions between economic viability, community sustainability, public health, heritage values, biodiversity, and ecosystem services.
Principle 7: promote polycentric governance systems	Polycentricity is a form of governance in which multiple governing bodies interact to make policy decisions. Polycentric governance provides a means of including diverse sources of knowledge and promoting inclusivity, participation, and learning. It achieves collective action in the face of change, by enabling multiple stakeholders to have a voice in decision-making processes.	Successful adaptive management requires strong partnerships between various stakeholder groups and incorporates stakeholder knowledge and values to facilitate learning and collaboration between scientists, land managers, communities, and government at local, national, and international levels.

activity reached its highest levels during the Iron Age (Pyne 1997, Bowman et al. 2011, Navarro et al. 2015). As landscapes became more fragmented, the use of fire became utilitarian, for uses such as crop enhancement, charcoal production, and smelting activities. A further peak occurred when Europeans colonized the Americas, Australia, and Africa and embarked on broadscale forest clearance and burning (Pausas and Keeley 2014). A general reduction in fire activity took place in the first half of the 20th century in many regions as a result of deliberate fire suppression and fire elimination; increases in settlement density and associated land use fragmented the fuel load and reduced the spread of fire and area burned (Archibald et al. 2013). Recently, these trends have been reversed in places where fire size, intensity, and frequency have increased because of a combination of changing climate and the legacy of past fire management (North et al. 2015). Recent decades of increased burning in many regions are the outcome of high levels of fuel biomass in dry forest and grassland ecosystems, warming climate, flammable nonnative species including forest plantations, and deliberate burning (Archibald et al. 2013).

At the same time, recognizing the importance of fire as an ecological process has increased acceptance for the use of prescribed burns (Burrows and McCaw 2013, Kobziar et al. 2015). The practice maintains more manageable fuel loads that dampen wildfire risks, and economic costs, while conserving or restoring ecosystem processes, heterogeneity, and native biota (Freeman et al. 2017). However, scientists, policy makers, and indigenous communities in fire-prone regions vary in their motivations for and approaches to prescribed burning (Freeman et al. 2017). Inevitably, decisions about wildfire management are complex, uncertain, and controversial, as fire involves risk, affects human health and property, and potentially alters critical ecosystem goods and services. Current fire management is rooted strongly in the idea that different landscapes are characterized by distinctive fire regimes (i.e., a general description of fire expressed as frequency, season, size, type, severity and intensity, and areal extent in a particular vegetation type), but that in some regions, natural fire regimes have been altered by fire suppression, deliberate burning, or other land-use activities (North et al. 2015). Decisions on whether to add or eliminate fires benefit from an understanding of the extent to which current conditions depart from past fire regimes as inferred from historical or paleoecological data (North and Keeton 2008), including past fires set by indigenous peoples.

Historical range of variability and disturbance processes

Fire management strategies that attempt to maintain or restore a fire regime draw on the range of processes that have shaped fire variability in the past (Johnstone et al. 2016). The use of historical and paleoecological data provides (1) a reference period against which current conditions are compared and (2) a functional understanding of the feedbacks and dynamics that link climate, vegetation, fire, and human management. Historical baselines should identify the timescales that are relevant to the climate, fire regime, and vegetation type in question. Some forest ecosystems have naturally burned on timescales of centuries, and a suitable reference period would span millennia. Other ecosystems burn on decadal scales, requiring a reference period of centuries. Whitlock et al. (2010, 2015) suggest using tree-ring data and lake-sediment charcoal records to lengthen the time span of observation and capture a broader range of disturbance conditions. A reference period that spans the last few millennia usually offers a very different picture of ecosystem resilience to fire than one that spans only a few decades.

Reliance on the historical range of variability for fire management is challenged by the fact that we are moving into novel climate conditions in terms of the magnitude of human impact and the rate of climate change (Moritz et al. 2012, Johnstone et al. 2016, Falk 2017). Future ecological adjustments to climate change will be further amplified by the effects of land-use changes, including land abandonment and urbanization, agriculture and forest clearance, tree plantations and nonnative plant invasion, and increased human occupation in fire-prone regions (Falk 2016). In addition, vegetation composition and structure represent legacies from past disturbances that set the stage for future fire activity and vulnerability (Schoennagel et al. 2017). As climate tolerance thresholds are crossed, the relative dominance of existing species will change and novel species combinations may arise, changes that will both respond to and drive changes in fire conditions.

In addition to considerations of temporal scale, insights about past resilience to fire also should be tempered by the fact that society and environments are continually evolving, and at any point in time, wildfire management is driven by local circumstances, including society's needs for ecosystem services and perception of risk. The long-term benefits of fire have been largely neglected until recently in fire management, especially when lives and property are under threat in the short term. Current fire management responses, e.g., actively suppressing fires, allowing fires to burn, and undertaking fuel treatments, are decisions that require continual learning and adaptation. More recently, indigenous and traditional historical fire practices and the role of fire in cultural landscapes have been incorporated into contemporary fire management, particularly in northern Australia (Russell-Smith et al. 2003, 2017, Moura et al. 2019) and southern Africa (Brockett et al. 2001, Trollope 2011, Ministry of Environment and Tourism 2016).

In summary, paleoecological and historical information helps clarify long-term ecosystem dynamics, including fire, and helps define conservation and management objectives based on disturbance history and ecological function. However, managing for resilience is more than restoring previous conditions; it also requires understanding of processes and considering the adaptive capacity of an ecosystem to respond to future conditions (Johnstone et al. 2016, Falk 2017). Management strategies thus need not only information about vegetation and fire history, but also a mechanistic understanding of the specific climate-fire-vegetation interactions that have led to current landscape conditions. These mechanisms also need to be considered in the context of future climate conditions that might affect resilience (Gavin et al. 2007, Falk 2017). Expanding the temporal-spatial dimensions of the historical reference period increases our understanding of how ecosystems may respond to fire under a wider range of conditions than have been observed in recent decades. In turn, this information becomes the basis for assessing the precedence of current conditions and identifying novel conditions in the future. Efforts to model fire activity under an array of climates can support paleoecological insights by suggesting places and conditions where changes in fire activity have or will permanently shift vegetation to a new state (Kitzberger et al. 2012, Iglesias et al. 2015, Loehman et al. 2018).

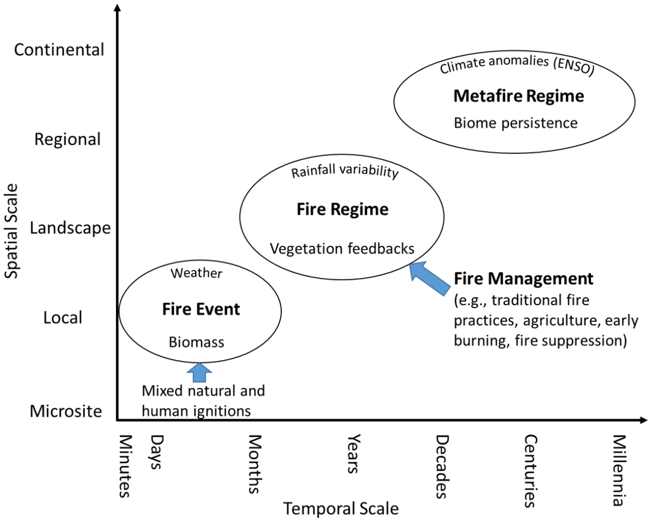
Principle 1: maintain diversity and redundancy

The first principle for ecosystem resilience offered in Biggs et al. (2015) is based on the recognition that ecosystems are complex with many interacting components, and that complex systems tend to be more resilient than simple ones. The loss of one component is less likely to lead to system collapse if another component is available to take over its function. In other words, functional redundancy provides "insurance" in the face of change, thereby increasing resilience (Biggs et al. 2015). Diversity and redundancy in fire-prone ecosystems often relate to the level of landscape structural and compositional heterogeneity created by past fires (Parr and Andersen 2006). Different postfire ages and patch sizes, i.e., pyrodiversity, as well as the patch connectivity, maintain biodiversity and ecological integrity and function (Beale et al. 2018).

Landscape mosaics are maintained by fire, vegetation, climate, land use, and, in some cases, herbivory. Patch sizes vary from hectares to thousands of kilometers depending on the vegetation type, land use, and links between climate and fire. These mosaics are maintained by feedbacks between fire, vegetation, and, in some cases, herbivory and often support a wide suite of species adapted to different postfire ages (Bowman et al. 2016, West et al. 2016). Mosaics represent the informational, material, compositional, and structural legacies of past disturbance events (Johnstone et al. 2016). Fine-grained vegetation mosaics create easy connections for seed dispersal, colonization, and, ultimately, recovery from disturbance, whereas coarse mosaics or uniform landscapes are slower to change and more vulnerable to subsequent disturbance (Fletcher et al. 2014, Ziółkowska et al. 2014, North et al. 2015, Oliver et al. 2015). Fires change landscape complexity by shifting the landscape mosaic to include different age classes, vegetation structures, and flammabilities.

Humans manipulate fire over multiple temporal and spatial scales through changing the season of burning and the amount, type, and connectivity of fuel, as well as the frequency of ignitions (Fig. 1). They may also directly or indirectly manipulate vegetation cover and herbivory, altering the landscape mosaic. Thus, on short timescales, humans are an important ignition source for fire events, and on decadal to century and landscape to regional scales, various management actions shape and alter fire regimes through changes in fuel type and connectivity. On millennial timescales, slow variations in climate change, vegetation, and prehistoric burning practices alter ecosystem development and the nature of “metafire” regimes over broad scales (see Fig. 1).

Fig. 1. Controls of fire at multiple spatial and temporal scales, including the role of humans in shaping fire dynamics (adapted from Whitlock et al. 2010, Bowman et al. 2011). ENSO, El Niño–Southern Oscillation.



In many fire-prone ecosystems, human-related changes, such as fire suppression, have homogenized and simplified landscapes and eroded their ability to recover from disturbance. Direct fire suppression has led to accumulation of biomass and subsequent large, intense fires. Recovery from these fires is often slow and yields a more uniform vegetation structure (North et al. 2015). A long-term perspective on fire and vegetation change and fire management is therefore critical for maintaining or restoring ecosystem heterogeneity and associated resilience.

In many forests, climate change, fire suppression, changes in herbivory, deliberate or accidental introduction of nonnative trees, and commercial timber activities have transformed structure, composition, and diversity. The ecological consequences depend on the nature and history of the ecosystem, with some forests becoming more vulnerable to disturbance and some less so (Johnstone et al. 2016). For example, in pyrophobic ecosystems, like the wet forests of New Zealand and Patagonia, initial anthropogenic fires quickly exceeded the historical range of natural variability, and conservation strategies now require active fire suppression and monitoring to maintain native podocarp-beech (*Podocarpus-Nothofagus*) forests (North and Keeton 2008, Kitzberger et al. 2016). In contrast, fire-prone dry ponderosa pine (*Pinus ponderosa*) forests of the U.S. Southwest are historically adapted to frequent, low-intensity fires. Decades of fire suppression have led to high fuel accumulations across the region (North and Keeton 2008) and a 10-fold increase in fire size, from 10-100 to 1000-10,000 ha (Guiterman et al. 2018). Mature ponderosa pines can survive surface fires but have poor seed dispersal abilities (Falk 2013), and the seedlings cannot withstand sustained periods of drought and high temperatures, reducing the likelihood of postfire regeneration (Falk 2013). As a result, large, severe fires cause extensive tree mortality and alter the biophysical template for subsequent forest recovery (Falk 2013). Such fires promote conversion of conifer forests to shrub fields dominated by Gambel oak (*Quercus gambelii*), which resprouts rapidly after fire. Multicentury dendrochronological studies from the Jemez Mountains, New Mexico, show that small shrub field and extensive forest patches coexisted in the past and burned concurrently. Recent, high-severity fires, however, have triggered substantial departures from historical conditions, with a transition to much larger areas of shrub fields (Guiterman et al. 2018). Restoration of surface fire regimes would require intensive management through controlled burns and thinning to counter the effects of recent fire suppression (Guiterman et al. 2018), but the effectiveness of such actions will depend on the severity of future climate change (Fulé 2008). Forest fire model simulations suggest that fuel treatments will become less effective with increasing severity of climate change, leading to a shift from ponderosa pine forest to oak shrub fields (Loehman et al. 2018). Recovery of conifer forests thus seems unlikely in the face of hotter temperatures, more severe droughts, high-severity fires, and bark-beetle (Curculionidae: Scolytinae) outbreaks (Falk 2013, 2017, Guiterman et al. 2018).

As the dynamic nature of forest ecosystems is increasingly recognized, there is an accompanying paradigm shift in the ecological restoration community from strategies that promote restoration of a prior condition to restoration of process and function (Higgs et al. 2014, Falk 2016). In ecosystems showing evidence of new stable states outside of the historical range of variability, adaptive approaches that focus on building resilience become critical. In these cases, historical data can guide functional and evolutionary objectives, concerning the management of key habitat types, species of special concern, genetic diversity, and important ecosystem services (Fulé 2008, Loehman et al. 2018). Furthermore, paleoecological data can help to assess migration rates in response to past variations in climate and fire (Fulé 2008). Assisted migration of lower elevation species that are adapted to warmer and drier conditions could facilitate ecosystem adaptation at higher elevations (Loehman et al. 2018). Reference conditions from low-elevation and low-latitude sites might provide insights into how ecosystems at higher elevation and latitude will appear in the future. Such information could also inform planning decisions, such as (re)location of human settlements to areas of lower fire risk (Schoennagel et al. 2017, Stephens et al. 2018).

In summary, the recommendation of Biggs et al. (2015) to maintain diversity and redundancy requires strategies that are based on knowledge of past and present ecosystem dynamics, as well as current and future conditions. In particular, fire management plans need to consider the role of fire in shaping present and historical vegetation mosaics. The scale of management action will depend on the magnitude of ecosystem transformation, the compatibility of restored ecosystems with current and future climate scenarios, and the social and economic demands for particular ecosystem services. In planning management responses, long-term data enable managers to (1) distinguish whether present ecosystem dynamics are operating as they have in the past; (2) the extent to which ecosystem resilience has been compromised under current climate, land-use, and disturbance conditions; and (3) the capacity of the ecosystem to withstand future conditions.

Principle 2: manage connectivity

Connectivity refers to the structures through which resources or species disperse, migrate, or interact across patch mosaics, habitats, landscapes, or social domains. High connectivity can facilitate recovery from disturbance and enable dispersal and gene flow. In fire-prone ecosystems, however, homogenized, overconnected landscapes are often the result of fire suppression and accumulated fuel loads. Such conditions can artificially augment the spread of fire and erode landscaped heterogeneity and biodiversity. Closely connected to principle 1, maintaining connectivity in relation to fire management depends on restoration of landscape heterogeneity and fuel loads through prescribed burning, managed grazing, and fuel manipulations. Information on fire history and previous vegetation structure is essential in this regard.

In some regions, anthropogenic fires have also helped maintain landscape mosaics and ecosystem resilience. For example, indigenous burning practices in fire-prone ecosystems have occurred over millennia and contributed to habitat complexity and biodiversity. Maintaining diversity and redundancy and appropriate levels of connectivity in these ecosystems requires consideration of an often long legacy of cultural as well as ecological and climatological factors. Moreover, the present mosaic in such locations often has high conservation or heritage value, and efforts to restore climate-driven vegetation and fire patterns should be careful to not conflict with goals to protect or enhance cultural landscapes (Whitlock et al. 2018). The savannas of Australia, for example, have a long history of deliberate burning and fuel management to support indigenous pastoral and hunter-gatherer activities (Gammage 2011). In western Australia, Martu Aboriginal burning techniques enhance hunting in the spinifex (*Triodia*) grasslands, and small, early season fires contribute to habitat diversity and reduce the mortality of small-mammal populations (Bird et al. 2008). Burned spinifex grasslands have more microclimatic variability and habitat heterogeneity than adjacent landscapes where fires were dominantly set by lightning (Bird et al. 2012). By keeping intense late-season fires in check, traditional fire management techniques promote resilience, as well as conserve biodiversity and ecosystem services. Similarly, traditional early dry-season burns in southern Africa are also small and serve to fragment the savanna fuel base, reducing fire intensity and the likelihood of intense, late-season fires (Archibald et al. 2012). Deliberate early season burning helps maintain a fine-grained patch mosaic with high species richness (Beale et al. 2018).

The savannas of sub-Saharan Africa and grasslands of the U.S. Great Plains have a long history of fires and herbivory that also should be considered in management strategies. Savanna fire regimes have been disrupted in recent centuries by indigenous relocation, loss of native grazers, agriculture, and fire-suppression policies (Moura et al. 2019). Reinstating patch mosaic burning and rewilding, i.e., reintroduction of native herbivores, provides several benefits. It helps to break up the fuel base, thereby reducing the risk of widespread fires; maintains active seed sources and below-ground biomass for postdisturbance revegetation; and provides a wide array of habitats for biodiversity and other vital ecosystem services (Le Page et al. 2010, Archibald et al. 2012, Laris 2013, Moura et al. 2019). Integration of herbivore and fire management, also known as pyric herbivory, restores ecosystem heterogeneity through the positive and negative feedbacks between fire and herbivory, which create a shifting mosaic of disturbance and function (Fuhlendorf et al. 2009). For example, restoration of the tallgrass prairie in the U.S. Great Plains has involved reintroduction of free-roaming bison (*Bison bison*) and random fires. The herbivores selectively graze newly burned areas, and the combination of fire and herbivory together creates a complex shifting mosaic that provides a wide range of habitats (Fuhlendorf et al. 2009).

To summarize, connectivity and heterogeneity are closely related and reflect the spatial dimensions of disturbance legacies. Long-term data not only generate information about the structure and function of mosaic ecosystems in the past (as discussed in *Principle 1: maintain diversity and redundancy*), but also incorporate knowledge of how people managed fuel connectivity prior to the implementation of fire suppression policies. Furthermore, there are opportunities to integrate fire management and rewilding through pyric herbivory in fire-prone areas where large herbivores were once common. The aim should be to develop a tailored response for each ecosystem, one that restores the relationship between disturbance and heterogeneity while considering future conditions and cultural dimensions.

Principle 3: manage slow variables and feedbacks

Understanding and predicting changes in resilience requires information about the drivers of change over a range of temporal and spatial scales. Slow variables that occur over centuries to millennia create the boundary conditions within which faster variables interact. Regime shifts in social and ecological systems emerge as a result of the feedbacks between slow and fast variables. Slow changes in temperature, for example, may elicit nonlinear responses when critical thresholds of fast-changing variables erode the resilience of ecosystems (Scheffer and Carpenter 2003, Carpenter et al. 2011). Climate sets the boundary conditions for fire, defining areas that are too wet (ignition restricted) or too arid (biomass restricted) to burn (Murphy et al. 2011). Within these boundaries, fire regimes respond to a range of factors including rainfall variability, feedbacks with vegetation and herbivory, and changes in fuel connectivity. Individual fire events are governed by fuel conditions, fire climate and weather, landscape characteristics, and fire management strategies (Whitlock et al. 2010; Fig. 1). As mentioned previously, the mosaic created by past fires, herbivory, and land use is the biophysical template for disturbance events. Identifying these legacies and the slow- and fast-varying drivers of ecological change can help define a safe operating space for fire management (Johnstone et al. 2016).

At multimillennial timescales, slow variations in solar radiation, ice-sheet extent, and CO_2 drive changes in fire activity at regional to global scales through their effects on temperature, rainfall, and vegetation (Daniau et al. 2012, Marlon et al. 2016). They provide a template on which smaller scale and faster variables play out. On millennial and centennial timescales, biomass burning was low during the last glacial maximum, when cold, dry conditions and low levels of atmospheric greenhouse gases limited biomass production and ignition (Thonicke et al. 2003, Daniau et al. 2012). Fires generally increased at the close of the glacial period, when temperatures rose (Power et al. 2008). In Australia and southern South America, high fire activity was registered in the last few millennia and attributed to the combined effects of increased interannual climate variability and growing human populations (Whitlock et al. 2007, Mooney et al. 2011). In western North America, charcoal records show a decline in fire at this time as conditions became cooler than before, but fire increased from ca. 900 to 1300 years ago during the warm and dry Medieval Climate Anomaly (Marlon et al. 2012, Calder et al. 2015).

Future fire regimes will be shaped by similar hierarchical interactions between temperature, water availability, ignitions, and fire-climate-vegetation feedbacks, interacting over multiple temporal and spatial scales (Kitzberger et al. 2017). Predicting future fire regimes requires a consideration of how slow “top-down” variables, such as global and regional climate, interact with small-scale “bottom-up” drivers, such as topography, vegetation heterogeneity, and human management, over decadal to centennial timescales. Model simulations of future conditions suggest that fires will become more frequent and widespread in the coming century (Murphy et al. 2011, Moritz et al. 2012, Huntingford et al. 2013). However, future fire conditions are uncertain at subregional, i.e., landscape, scales where climate change is harder to project and the effects of nonclimatic factors, such as land-use change, become important. The climate effects will also vary depending on whether the ecosystem is ignition or fuel limited (Whitlock et al. 2010, Kitzberger et al. 2017). Decreases in fire, for example, may occur in wet forests if precipitation increases and in drylands if fuels become too sparse.

Discerning the effects of regional and global top-down drivers versus local bottom-up drivers in the paleoecological record requires comparison of multiple paleoecological records (Gavin et al. 2007). Patterns of change in fire and vegetation that occur synchronously across wide regions are likely to reflect large-scale drivers, whereas asynchronous changes reflect local influences, such as topography, hydrology, local management, and fuel fire feedbacks. For example, studies from the boreal forests of Fennoscandia show broad regional synchrony of fires between AD 1500 and 1900 during periods of low summer rainfall, despite local differences in land use and fire management (Aakala et al. 2018). Fire occurrence was strongly influenced by climate during overall dry periods, and results suggest high fire years might be expected during droughts, whereas humans were more important as an ignition source during wetter periods. Such findings could provide the basis for adaptive fire management responses in this region that reflect the high probability of climate-driven fire during droughts and fuel-driven human-set fires in wetter periods.

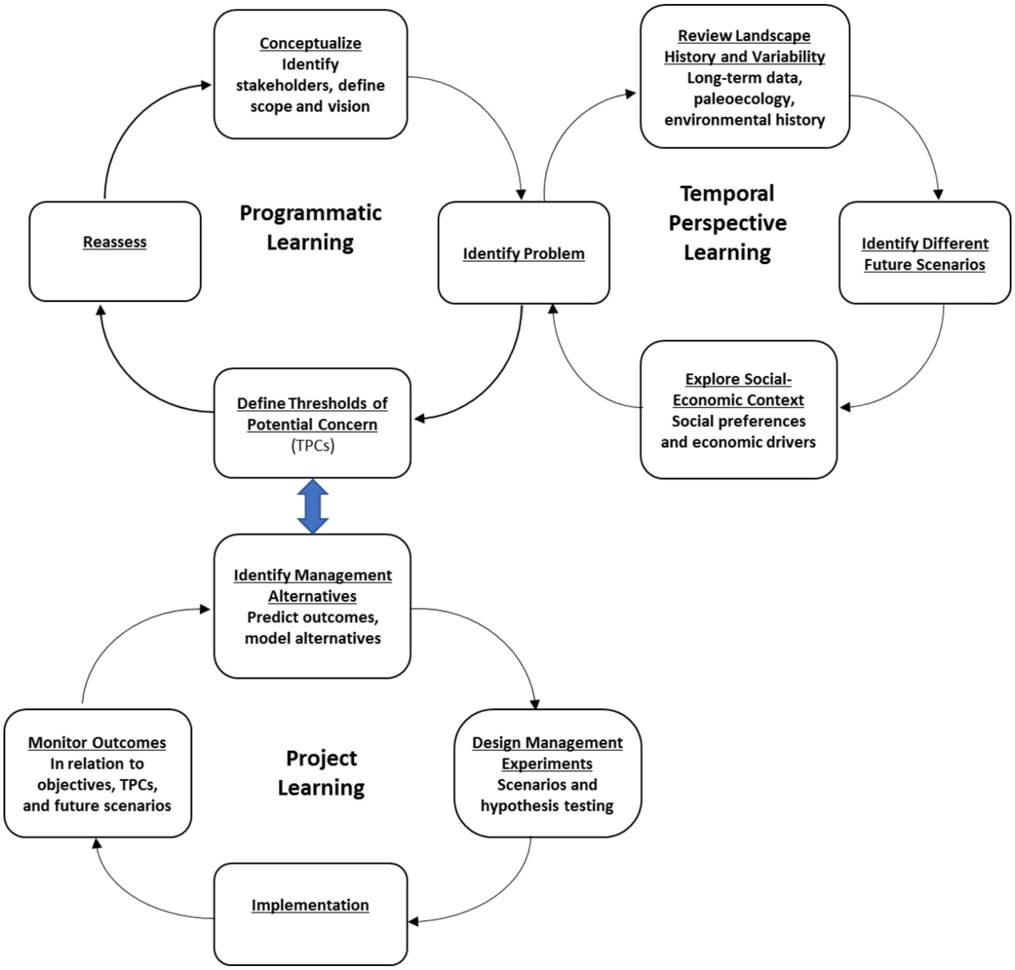
Regional, subcontinental, and continental comparisons of fire history are enhanced by access to the Global Charcoal Database (https://www.paleofire.org), which provides open access to charcoal records from around the world. Furthermore, the Global Modern Charcoal Dataset enables the calibration of paleofire data using other modern data sets, such as fire occurrence data from satellite images, vegetation occurrence, and land-cover change (Hawthorne et al. 2018). Information on the dynamics that link climate, fire, and land use on multiple timescales is useful for validating ecosystem models that explicitly consider the role of fire, thereby improving confidence in future predictions (Henne et al. 2013, Pfeiffer et al. 2013). Young et al. (2019) developed a statistical model of recent fires and climate in the boreal forest and tundra of Alaska to evaluate the probability of fires and identify a temperature threshold for fire occurrence. The model was used to reconstruct fire activity from AD 850 to 1850, and the accuracy of model outputs was quantified by comparison with fire return intervals estimated from lake-sediment charcoal records. Modeling the location of the threshold using future climate projections indicated that > 50% of Alaskan tundra and boreal forest would burn by 2070-2099. The results point to the importance of threshold relationships and the utility of paleoecological records for evaluating fire projections outside the observational record (Young et al. 2019).

In summary, long-term data can assist in elucidating how slow top-down variables, such as climate, provide a backdrop on which faster bottom-up variables operate. Even though slow large-scale variables often cannot be managed, examining their interaction and feedback with faster variables that possibly can be managed is informative and potentially useful in mitigating or adapting to current and future fire activity. Knowledge of these multiscale interactions can help in exploring future scenarios that are the basis for discussions about what is environmentally possible and socially desirable.

Principles 4 and 5: foster complex adaptive systems thinking, encourage learning

Fire-prone landscapes often support complex social-ecological systems that are influenced by the feedbacks between subsystems, emergent properties, and stochastic events. Regional to local fire conditions reflect complex interactions between climate, vegetation, local topography, hydrology, and land use, as well as social-economic and cultural considerations (Moritz et al. 2012). People have long had the capacity to alter fire regimes and, in the process, promoted and eliminated different species and vegetation types through deliberate burning or fire suppression (Bond and Archibald 2003, Bowman and Murphy 2011, Archibald et al. 2012). This historical use of fire contrasts with current management decisions that are often event-driven responses, with little consideration of natural and human-driven processes operating at longer and larger scales. Pyrogeography, the study of

Fig. 2. Adaptive management planning strategy that incorporates programmatic, temporal perspective, and project learning cycles, enabling the historical range of variability and future projections to be incorporated into thresholds of potential concern (Gillson and Marchant 2014, Gillson 2015).



past, present, and projected distribution of fire, has emerged as a framework for understanding the feedbacks between the multiscale interacting factors that determine fire conditions and for tackling urgent social-ecological fire management decisions (O'Connor et al. 2011, Bowman et al. 2013). Knowledge of the available options and possible future scenarios is important when making decisions about fire management. Present and future fire management must be flexible and adaptive, allowing change to be incorporated in cycles of "learning by doing." This more nimble response ensures that fire management does not become entrenched and out of step with emerging knowledge, changing climate, and shifting social priorities (Penman et al. 2011, van Wilgen and Biggs 2011).

Early adaptive management strategies focused on "project learning" through iterative cycles of implementation, monitoring, and adjustment (Fig. 2). This project learning cycle is underpinned by a "programmatic learning cycle" that conceptualizes the management process and allows stakeholders to articulate their goals and vision. The connection between the project learning and programmatic loops, known as double-cycle learning (Fig. 2), encourages exploration of stakeholder preferences and perspectives (programmatic learning) as a direct feed to project implementation (project learning). In both cycles, stakeholders help define and adjust problems in a social framework. In fire management, programmatic learning allows reflection on how management aims are developed as a result of stakeholder input and recognition of the impacts of changes in past and present management practices.

We suggest that adaptive fire management strategies need to incorporate a third cycle (temporal perspective learning) that includes insights from long-term fire history, traditional burning practices, the impacts of fire management, and future climate projections (Gillson and Duffin 2007, Gillson and Marchant 2014). This cycle provides a basis for decisions about the appropriate upper and lower limits of fire frequency, intensity, and size, based on knowledge of the historical range of variability, role of indigenous practices, and future climate scenarios (van Wilgen et al. 2003, 2012, Penman et al. 2011). The "triple cycle" adaptive management strategy (Fig. 2) is designed to integrate temporal variability into the programmatic learning cycles, thereby helping stakeholders to reframe the assumptions that underlie perceptions of environmental change (Fontaine 2011, Gillson and Marchant 2014, Gillson 2015).

In the programmatic learning cycle, stakeholder groups are identified, and the problem is conceptualized. To do so, knowledge of past ecosystem variability and scenarios of future conditions need to be considered as described in the temporal perspective learning cycle. The latter cycle is intended to help stakeholders understand the history and dynamics of present-day landscapes and decide what landscape conditions are important and possible in the future. With this knowledge, the desired range of variability, the thresholds for management intervention, and even the goals themselves can be developed. With these "thresholds of potential concern" defined, it is then possible to implement an adaptive cycle of management that includes experimentation, implementation, and monitoring (project learning). In turn, this activity informs how problems are framed and identifies future thresholds of concern (programmatic learning). Connections between the different elements of the loops are possible, and the process needs to be managed adaptively and iteratively so that new perspectives can be incorporated as they emerge.

In summary, fire management is complicated because the interactions and feedbacks between social and environmental factors operate over a range of temporal and spatial scales and because future conditions are uncertain. Learning and complex systems thinking are required for successful management outcomes. We envisage that stakeholders might change their expectations and develop different desired future scenarios if they have a more realistic understanding of past conditions and variability and how these relate to possible future scenarios. As ecosystems become increasingly stressed by human activities and climate change, there is an even greater need to learn from the past and to share knowledge about historical perspectives, current management priorities, and future fire scenarios among scientists and other stakeholders.

Principles 6 and 7: broaden participation, promote polycentric governance systems

The management of fire-prone landscapes is often a controversial and emotive issue, fraught with scientific uncertainty, economic ramifications, and social nuance. Fire management decisions have implications for economic viability, community sustainability, heritage values, and ecosystem services (Noss et al. 2006, Franklin and Johnson 2011, Turner et al. 2013). Public health concerns, cultural values, traditional management of natural resources, and land ownership all affect how fire regimes are perceived and what opportunities exist for fire restoration and management. Therefore, fire management needs to incorporate complexity thinking and be adaptive enough to respond in a timely manner to changing environmental conditions, social demands, emergent properties, and extreme events. Successful adaptive management requires strong partnerships between various stakeholder groups and incorporates stakeholder knowledge and values to facilitate learning and collaboration between scientists, land managers, and communities (Penman et al 2011). This polycentric approach to governance also requires management objectives that are feasible, ecologically realistic, and socially acceptable to justify implementation by land resource agencies and local communities (Penman et al. 2011).

Polycentric governance is needed to manage and predict changes driven by global and regional drivers that have impacts at landscape and local scales. Polycentric governance promotes broad participation as a means to achieve large-scale environmental objectives. One example comes from the U.S. Great Plains, where paleoecological evidence shows that grasses have been dominant for the past 5000 to 8000 years (Twidwell, Fuhlendorf, et al. 2013). Fire frequency has reduced in the 20th century, as a result of agriculture and landscape fragmentation, combined with a loss of indigenous burning practices and native herbivores. Grassland communities in this region are degraded and, in many places, have been replaced by juniper (*Juniperus*) shrubland and woodland, which have a capacity for more severe fires (Ratajczak et al. 2014). The vegetation changes are associated with loss of ecosystem services, including decreased grassland biodiversity and production, carbon sequestration, and water storage (Twidwell, Fuhlendorf, et al. 2013, Twidwell, Rogers, et al. 2013). In response, local communities have organized prescribed burn co-operatives with the aim of preventing further juniper encroachment and restoring grasslands. In most areas, these burn co-operatives operate under strict legislation that forbids burning when the danger of wildfire is high. However, experimental and modeling studies indicate that high-intensity burns are exactly what is required to stop juniper spread and restore grasslands (Twidwell, Fuhlendorf, et al. 2013). Results of this research are now being used to initiate legislative changes that would allow burning under more extreme wildfire conditions, thus increasing the opportunities for grassland restoration (Twidwell, Rogers, et al. 2013). The example illustrates a polycentric approach in which communities, scientists, and legislators all contribute to the development of fire management policy and practice.

In regions with long histories of human activity, fire management benefits from an understanding of the cultural landscape and the degree to which natural processes have been altered. A central challenge is to find ways to couple local knowledge of traditional fire management with fire management plans and policy at the regional and national levels. Integration of diverse knowledge systems, perspectives, needs, and governance structures is challenging but could potentially build redundancy and hence resilience into governance systems. The desired outcome is to sustain livelihoods, improve relations among stakeholders, and increase responsiveness for coping with heightened fire activity in the future (Biggs et al. 2015). An example of shared governance that incorporates indigenous practices comes from the West Arnhem Land Fire Abatement (WALFA) program in northern Australia. This program incorporates and restores aboriginal fire management, which was disrupted by European settlement and centralization. WALFA is the first-ever carbon offset project based on fire management (Russell-Smith et al. 2017), and it provides cultural, natural resource, and biodiversity benefits at local levels, while addressing climate change issues at the global level. WALFA illustrates the possibility of addressing both local and national priorities and policy drivers (Russell-Smith et al. 2017). Such initiatives are needed urgently as the Australian continent is predicted to become increasingly drier and fire prone in the coming decades (Bowman and Murphy 2011), and WALFA provides a model for polycentric governance that could potentially be applied elsewhere.

In summary, reconciling international, national, and community-level objectives for future fire management and policy requires a polycentric approach involving multiple stakeholder groups. A flexible, adaptive, and participatory approach to fire management is needed based on input from multiple stakeholders, including local and indigenous communities, scientists, managers, and policy makers who develop and work toward a shared vision that maintains ecosystem dynamics and services, as well as protects communities in the face of future fires and meets national and international environmental objectives (Rogers et al. 2013).

CONCLUSIONS

Fire regimes, landscapes, climate, and society are dynamic components of the earth system, and an adaptive approach to fire management is needed that considers a temporal perspective. Evaluating the legacy of past fire conditions in the context of current social and economic needs and future ecosystem resilience is central to successful ecosystem management. Key elements for future fire management planning are knowledge of (1) the long-term fire-climate linkages and the historical range of fire variability; (2) the legacy of past land uses including indigenous burning practices; (3) the cultural and economic goals that motivate current and future conservation goals; and (4) future climate and fire activity and identification of alternate possible future scenarios. We have shown how the seven principles of Biggs et al. (2015) can be used to build resilience into fire management planning:

- In fire-adapted ecosystems, attempts to suppress and eliminate fire and attendant afforestation by fire-prone species have homogenized landscapes and led to more and larger fires in many regions. Restoring heterogeneity to these ecosystems requires a combination of prescribed burns and fuel treatments, as well as restoration of fire-grazing interactions. Even so, transitions to new stable states are likely to occur in the future in many regions given projected climate change.
- Connectivity needs to be managed alongside heterogeneity. Restoring the burn mosaic in fire-prone ecosystems helps maintain vegetation heterogeneity, biodiversity, and ecosystem services. In this regard, paleoecological information can provide important information about the historical range of variability in disturbance regimes, under a range of climate and land-use conditions.
- Fire regimes are the result of many interacting variables operating on different timescales from seasons to millennia. Although fire itself is a fast variable, it is important to understand that the slow variables, i.e., broad changes in climate and vegetation, provide the template for today's fire regimes. Even when slow variables cannot be managed, better prediction and adaptation is possible when they and their associated feedbacks are considered.
- Because fire-adapted systems are complex and have social dimensions, it is essential that complex adaptive systems thinking is integrated into fire management plans. This strategy includes ongoing adaptation strategies that integrate information on landscape and fire history, traditional burning practices, fire management legacies, and future climate projections.
- The complexity and unpredictability of future environmental and ecological change, and the need to accommodate contrasting viewpoints in governance systems, present challenges for fire management strategies. Applying resilience principles requires an appreciation of local context, scale issues, and stakeholder needs. Understanding and defining resilience under different economic, social, and ecological constraints, as well as at different levels of jurisdiction, is a daunting challenge, but one that is essential if polycentric governance is to be achieved.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11022

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