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Research article

Management thresholds stemming from altered fire dynamics in present-day arid and semi-arid environments

Clare E. Aslan[a,b,*], Leah Samberg[b,c], Brett G. Dickson[a,b], Miranda E. Gray[b]

[a] Landscape Conservation Initiative, PO Box 5694, Northern Arizona University, Flagstaff, AZ 86005 USA
[b] Conservation Science Partners, 11050 Pioneer Trail, Suite 202, Truckee, CA 96161 USA
[c] Institute on the Environment, 1954 Buford Ave, University of Minnesota, St. Paul, MN 55108 USA

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ABSTRACT

Changes in fire frequency, size, and severity are driving ecological transformations in many systems. In arid and semi-arid regions that are adapted to fire, long-term fire exclusion by managers leads to declines in fire frequency, altered fire size distribution, and increased proportion of high severity fires. In arid and semi-arid systems where fire was historically rare, factors such as invasion by highly combustible non-native plants elevate fire frequency and size, elevating mortality of native species. Altered temperature and precipitation regimes may exacerbate these changes by increasing biomass and flammability. Current transformation in fire dynamics carry social as well as ecological consequences. Human cultures, livelihoods, values, and management behaviors are attuned to fire dynamics. Changes can make it costly or impossible to maintain traditional landscape use and economic activities. We review the ecological and social science literature to examine drivers of altered fire dynamics in arid and semi-arid systems worldwide and the conditions representing fire dynamics thresholds—points at which altered conditions may make it difficult or impossible to achieve management objectives, even via traditional adaptive management focusing on alternative management activities to achieve objectives. Such thresholds could force a wholesale shift in management objectives and practices and a new approach to adaptive management that redefines objectives when no viable adaptive action can be undertaken.

1. Introduction

Fire frequency (i.e., fire return interval at any given point), size (i.e., extent of a burned area), and severity (i.e., degree to which a site has been altered by fire, a result of heat at the fireline combined with fire residence time at the site; NWCG, 2018) are actively changing in many systems (Dale et al., 2001; Keeley, 2009). Human management of any given landscape is influenced by the historical fire dynamics typical of that system (e.g., Cissel et al., 1999). Changes in fire dynamics can therefore force management changes, impacting land use activities as well as the achievement of management objectives (Baker, 1994; Brockway et al., 2002; Conedera et al., 2009; Noss et al., 2006a). For this article, we define *fire dynamics* as the combination of fire size, frequency, and severity typifying a particular system at a particular point in time.

The state of the art response to environmental change in managed systems is adaptive management (Briske et al., 2010), whereby managers implement sequential interventions accompanied by data collection to inform adaptive shifts in those interventions. Adaptive management permits flexibility and resilience, experimentation in management, and continuous learning in the face of rapidly changing conditions (Gunderson, 1999). However, adaptive management as normally practiced assumes consistent objectives guiding human activities at a particular location; those objectives are met via a shifting toolkit of actions. When fire dynamics depart sufficiently from the natural range of variation, systems may reach thresholds beyond which established land management objectives become unachievable even through traditional adaptive management. Such thresholds vary among systems and among objectives (Bowman et al., 2011; Groffman et al., 2006; Pausas and Fernández-Muñoz, 2011). In this manuscript, we discuss the combined social and ecological (*socioecological*) circumstances that may lead to such thresholds that necessitate a shift in how managers select, identify, and define management objectives themselves. This may compel a new form of adaptive management that focuses on shifts in objectives as well as activities. Although fire dynamics in many parts of the world have been influenced by human activities for

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[*] Corresponding author. Box 5694, Landscape Conservation Initiative, Northern Arizona University, USA.
E-mail addresses: clare.aslan@nau.edu (C.E. Aslan), lsamberg@gmail.com (L. Samberg), brett.dickson@nau.edu (B.G. Dickson), miranda@csp-inc.org (M.E. Gray).

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thousands of years, for our purposes we focus on *modern shifts in fire dynamics* that are actively occurring in present-day managed environments, reviewing how fire size, frequency, and severity are currently and actively changing as a result of anthropogenic influences on arid and semi-arid ecosystems.

We focus on arid and semi-arid systems for tractability. Fire dynamics in these systems are affected by non-native species invasion, human-caused ignitions, climate-induced drought, and decades of anthropogenic fire suppression (Garfin, 2013). Arid and semi-arid systems include forested, woodland, shrubland, grassland, and desert zones and occur in patchy distribution in western North America, western South America, South Africa and northern Africa, interior Asia, and western and interior Australia (Scanlon et al., 2006).

2. Background: present-day changes in fire dynamics in arid systems

Fire dynamics are changing in arid and semi-arid systems across the globe as a result of anthropogenic drivers such as fire suppression and exclusion, livestock grazing, non-native plant invasions, intentional ignitions, and climate change (Bowman et al., 2011; Swetnam et al., 2016). Changes can include both increases and decreases in fire frequency and size, depending on whether a system is historically fire-adapted or non-fire-adapted. In fire-adapted systems, fire plays a fundamental role in the formation of vegetation patterns (Bowman et al., 2009), which can be affected by decreases in fire frequency and size. In a Swaziland savanna, for example, livestock grazing combined with fire suppression increased shrub cover from 2 to 31% between 1947 and 1990 (Roques et al., 2001). Suppression of fires in South African grasslands has led to similar growth in cover of woody species (Uys et al., 2004). The same pattern can be seen in native grasslands in the southwestern US, with encroachment of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*) (Grover and Musick, 1990) (Fig. 1). Increased cover of western juniper (*Juniperus occidentalis*) in a south-central Oregon sagebrush steppe over the past century was driven by fire suppression and livestock grazing in combination with climate change (Miller et al., 2008). Woody encroachment resulting from fire suppression has occurred in Australia (Noble, 1998) and Venezuela (Silva et al., 2001), as well. Thus, in many parts of the world, vegetation patterns have been dramatically transformed as a result of fire suppression and exclusion in historically frequent-fire systems. By introducing woody vegetation, these changes transform rangelands and agricultural areas in working landscapes, as well, with consequences for regional economies (e.g., Moleele et al., 2002).

In the American West, long-term exclusion of fire by managers in woodland and forest ecosystems began in the late 1800s, leading to accumulation of fuels and increased fuel continuity in many historically frequent-fire regions (Littell et al., 2009; Romme and Despain, 1989; Stephens and Ruth, 2005). After a series of destructive fires, culminating in the Big Blowup of 1910, the US Forest Service was charged with wildland fire suppression to protect the nation's timber (as an economic resource) as well as human lives and property (Busenberg, 2004; Pyne, 2011). Suppression was highly effective; in a particularly dramatic example, fire frequency in ponderosa pine (*Pinus ponderosa*) forests in a southwestern study site decreased from one fire every 3.7 years before 1883 to only one fire event during the 112 years between 1883 and 1994, a 30-fold decrease in frequency (Fulé et al., 1997). Similar changes have occurred in other sites around the Southwest (Noss et al., 2006b). These rapid changes in fuel loads, structure and composition in many fire-adapted arid and semi-arid systems across the US paved the way for escalating fire intensity and fire severity (Pyne et al., 1996).

Fig. 1. Example of a socioecological threshold emerging from changing fire dynamics and leading to altered management objectives: ongoing shrub encroachment stemming from decades of combined fire suppression and grazing reduces the livestock carrying capacity of rangelands (Tobler et al., 2003; Anadón et al., 2014). Since this diminishes ranching profitability, it contributes to a widespread decadal trend of ranch sell-off for development in arid and semi-arid habitats (Sheridan, 2001). Photo by Emily Yurcich.

Table 1
Arid and semi-arid systems in which fire dynamics are changing, the drivers of such changes, and potential management responses.

Habitat type	Changes in fire dynamics	Ecological and social consequences	Adaptive management tools to meet objectives
Savanna and grassland	Woody encroachment due to livestock grazing and fire suppression leads to increasingly severe fires; global climate change and exotic grasses increase the frequency and extent of higher-intensity fires (Grover and Musick, 1990; Milberg and Lamont, 1995; Miller and Rose, 1999; Rocques et al., 2001; Uys et al., 2004; Miller et al., 2008; Steffen et al., 2015)	Elimination of wildlife habitat and forage, crops, and livestock; losses of life, homes, properties, and food; declines in housing prices; reduced regional biodiversity (Iddrisu, 1995; Provencher et al., 2007; Mueller et al., 2009; Andersen et al., 2012; Dube, 2013; Redsteer et al., 2013; Steffen et al., 2015)	Combined prescribed fire and grazing for conservation objectives; prescribed fires to maximize carbon sequestration and grazing yield and maintain grassland health (Bashari et al., 2008; Augustine and Derner, 2014; Scheiter et al., 2015)
Forest, shrubland, and woodland	Accumulation of fuels and changes in fuel structure and composition due to fire exclusion and suppression leads to increasingly severe and large fires (Romme and Despain, 1989; Fule et al., 1997; Stephens and Ruth, 2005; Noss et al., 2006b; Littell et al., 2009)	Loss of biodiversity; decreases in recreation; more costly fire management priorities; losses of life, homes, properties; decline in housing prices (Starbuck et al., 2006; Miller et al., 2017; Mueller et al., 2009; Calkin et al., 2013)	Timber harvest pre-fire to make post-fire restoration more cost-effective; landowners pay for fuels management activities; use of artificial habitat for threatened species conservation (Kaval et al., 2007; Taylor et al., 2015; Miller et al., 2017)
Desert	Exotic grasses lead to increasing fire frequency, size, intensity (Van Devender et al., 1997; Rao et al., 2010; McDonald and McPherson, 2011; Balch et al., 2013)	Loss of native species and habitat (Brooks et al., 2004)	Incorporation of objective-change thresholds into scenario planning (current ongoing Sonoran Desert work by these authors)

In non-fire-adapted systems such as many deserts, fire frequency and size are historically low (Allen et al., 2011): if native vegetation is not dense enough to carry fire, native species may lack fire adaptations (Alford et al., 2001). Increased fuel loading and continuity in such non-fire-adapted communities may increase fire frequency and size and negatively impact native species (Brooks and Chambers, 2011). Anthropogenic nitrogen deposition has boosted annual grass productivity in southern California deserts, for example, increasing fire risk (Rao et al., 2010). Exotic grass species in many arid and semi-arid regions represent a novel fuel source, because they can occur in relatively high densities and often grow and cure quickly; this has happened, for example, in many parts of the American West (Balch et al., 2013; Brooks et al., 2004; D'Antonio and Vitousek, 1992). (See Table 1).

One of the major contributors to this pattern in the western US is introduced cheatgrass (*Bromus tectorum*), which is characterized by continuous coverage of annual biomass, rapid green-up followed by early-season senescence, and high litter accumulation (Whisenant, 1990; Germino et al., 2016). Fire return interval at Great Basin sites dominated by *B. tectorum* has been estimated at 49–78 years, in contrast with an average fire return interval for native-dominated sites (including sagebrush, pinyon-juniper, desert shrub, montane shrub, and agriculture) of 294 years (Balch et al., 2013). Additionally, *B. tectorum* fires are larger in extent than other fires in the region (Balch et al., 2013). In the Sonoran Desert, the introduction of African buffelgrass (*Pennisetum ciliare*) has exerted a similar effect, providing a continuous and fast-growing source of fine fuels (Van Devender et al., 1997). Native Sonoran Desert plants recover poorly after fire, creating a feedback cycle wherein post-fire systems are even more heavily dominated by *P. ciliare* (McDonald and McPherson, 2011). The link between invasive species and fires exemplifies a threshold-driven system, in which managers strive to maintain or increase ecological resistance to plant invasions before it becomes difficult or impossible to return the system to its prior state (Brooks and Chambers, 2011; Chambers et al., 2014, 2016).

Historical fire dynamics emerged in part from historical climate conditions driving vegetation patterns; many arid and semi-arid regions are therefore likely to exhibit changed fire dynamics under ongoing global climate change (Lenihan et al., 2007; Williams et al., 2001; Moritz et al., 2012). Climate influences fire potential by affecting both the flammability of vegetation and the production of biomass (Abatzoglou and Williams, 2016; Dale et al., 2001; Jolly et al., 2015; Whitlock et al., 2003). In the American Southwest, precipitation extremes in winter are projected to become more frequent and more intense under climate change, and summer heat waves are projected to become longer and hotter (Garfin, 2013). This may result in increased occurrence of extreme wet periods, during which biomass accumulates at higher rates than normal, followed by extreme hot and dry conditions, during which biomass becomes exceptionally flammable. Such patterns have been recently observed, for example, for non-native annual plant-invaded deserts (Gray et al., 2014; Hegeman et al., 2014) in southwestern North America and fine fuels-dominated grasslands and shrublands in the Great Basin (Balch et al., 2013).

2.1. *Ecological consequences of present-day shifts in arid and semi-arid system fire dynamics*

Where fire frequency and size are increased in non-fire-adapted systems, plant communities are altered as a result of repeated burning cycles (Brooks et al., 2004; D'Antonio and Vitousek, 1992). Increased non-native *Tamarix* occurrence in xeroriparian areas in Mexico and the US lead to increased frequency of fire in riparian areas, for example, and *Tamarix* resprouts more quickly after fire than native species (Mandle et al., 2011). Exotic roadside grasses in western Australia increase fire probability and then increase in density after burning (Milberg and Lamont, 1995). Via these feedback cycles, the introduction of fire-adapted species can lead to novel species assemblages in arid and semi-arid regions. Where fire frequency and size have decreased in fire-adapted systems, fire intensity is often heightened due to fuel accumulation (North et al., 2015), lengthening recovery times (Savage and Mast, 2005). High severity fire over large patches may be followed by erosion events, weed invasions, or vegetation type transformations (Pierson et al., 2011). Thus, modern changes in fire dynamics can dictate a suite of ecological patterns, influencing hydrological regimes, soil characteristics and runoff, and habitat condition (Bond and Keeley, 2005; Syphard et al., 2007). Crucially, these changes represent important management challenges and may impact present-day management objectives (Millar et al., 2007; Russell-Smith et al., 2003; Whisenant, 1990).

2.2. *Social consequences of present-day shifts in arid and semi-arid system fire dynamics*

Severe fires can affect livelihood activities that are environment-dependent, such as ranching, agriculture, timber harvest, fishing, and recreation (Bowman et al., 2011; MacLean, 1990; Mason et al., 2006). In Ghana, crops and livestock are lost each year to bush fires, which can lead to local desertification and food insecurity (Iddrisu, 1995). Increasingly severe fires in Botswana put humans, livestock, and wildlife at risk and eliminate both habitat and forage (Dube, 2013). Native American communities in the southwestern US have experienced losses of life, homes, properties, and traditional food plants as a result of severe fires in recent decades (Redsteer et al., 2013). Escalating fire intensity and frequency in Australia carry significant economic threat, through livestock losses, for the agricultural industry in western Australia (Steffen et al., 2015). Such impacts can transform the economy and social fabric of a region, resulting in rural-urban migration, residential development, and loss of cultural practices (Trainor et al., 2009).

3. Impacts of changing fire dynamics on land management in arid and semi-arid landscapes

The impacts of changing fire dynamics on socioecological systems suggests a need for assessment of changes in socioecological resistance and resilience to guide management efforts (e.g., Briske et al., 2010; Chambers et al., 2017; Wisdom and Chambers, 2009). Managers and management regimes can resist change or be unable to alter objectives, resulting in static land use objectives in the face of variable or shifting conditions; the factors influencing when and how land managers are able to adapt are still being explored (Groffman et al., 2006).

Adaptive management as commonly practiced may allow managers to sequentially alter their methods in response to changes in fire dynamics as they attempt to meet their management objectives (Folke et al., 2004). However, this activity-focused adaptive management may no longer suffice when dynamics have changed enough that current management objectives cannot be reached through any management actions. In such circumstances, a shift in management objectives themselves may be necessary. Below, we discuss how shifting fire dynamics currently affect selected static management objectives common to many arid and semi-arid socioecological systems—livestock grazing, timber harvest, recreation, and protection of lives and property. These management objectives, which are not themselves explicitly centered on fire but are directly impacted by it, exemplify the complex ways in which economic and social values are intertwined with fire management.

3.1. Fire and grazing management

The combined effects of grazing and changing fire dynamics have the potential to drive changes in species abundance and composition (e.g., Bashari et al., 2008; Creutzburg et al., 2015; Scheiter et al., 2015). In northern Australian savannas, carbon sequestration is maximized with early dry season fires and long fire return intervals, while economic productivity of rangelands is maximized with late dry season fires and intermediate fire return intervals (Scheiter et al., 2015). In eastern Nevada, livestock remove fine fuels but also lead to grassland degradation, thus working against fire and vegetation management goals (Provencher et al., 2007). In the rangelands of central Argentina, a combination of prescribed burns and intensive cattle grazing may cause soil loss and rangeland degradation, making commercial livestock production unsustainable (Cingolani et al., 2013). In each of these examples, then, fire dynamics affect managers' long-term objective of grazing management.

In some cases, fire and grazing management can be combined to achieve management objectives. Frequent fire mitigated negative impacts of selective grazing on species composition and thus promoted grassland health in ironbark-spotted gum woodland systems in Queensland, Australia (Bashari et al., 2008). Cattle selectively grazed burnt areas in semi-arid rangelands in Colorado, indicating that grazing rotation and fire management can be combined to meet conservation and production goals (Augustine and Derner, 2014). In these examples, therefore, grazing objectives can be bolstered by fire occurrence, depending on relative timing.

3.2. Timber harvest

Deriving economic gain from timber harvest is common management objective in some arid and semi-arid forests, and fire dynamics affect such economic gain. In southwestern US ponderosa pine forests, present-day fuel management activities designed to prevent an ecological regime shift carry high costs ($500-$2000 per ha), but those costs are more than offset by avoidance of the costs of catastrophic fire and resulting transitions from pine forest to grassland/shrubland, estimated at more than $10,000 per ha (Wu et al., 2011; Wu and Kim, 2013). As a result of these benefits, Thomas et al. (2016) report that every $1 million US dollars invested in ecosystem restoration resulted in $2.2–3.4 million in total economic gain. Incorporating the value of harvested timber can also make post-fire restoration more cost-effective, depending on timber prices (Taylor et al., 2015).

3.3. Recreation and tourism

Many fire-prone landscapes have economies that depend on outdoor amenity, recreation, and tourism objectives. Perceptions of fire in recreational areas vary by stakeholder group, location, and over time. In a study examining several Western US forest regions, hikers reacted positively to landscapes in the first few years following a fire, due to the novelty of the burnt landscape as well as increased opportunity for wildflower and wildlife viewing (Loomis et al., 2001). By contrast, in New Mexico, surveyed hikers and bikers had less positive views of a landscape up to 40 years after a fire, with visits declining as the local prevalence of burned area increased (Hesseln et al., 2003). The results of stakeholder surveys based on simulations of fire scenarios in New Mexico suggested that large, severe burns will lead to an estimated 7% decrease in visits to National Forests in the state, with losses of US$81 million in output, US$36.5 million in earnings, and 1941 jobs (Starbuck et al., 2006). Low-intensity burns, by contrast, were predicted to boost visits, as thinned forests are attractive to trail users, though economic benefits will be short-lived as sites recover (Starbuck et al., 2006). Achieving recreational management objectives can therefore be impacted in various ways by fire.

3.4. Homes, property, and lives

Naturally, federal wildfire policy establishes firefighter and public safety as the highest priority wildfire management objective (Venn and Calkin, 2011). Fire managers in the western US tend to favor fire management strategies that reduce risk to homes or high-value watersheds even when those strategies are more expensive than alternatives (Calkin et al., 2013). In many fire-adapted ecosystems, conservation or ecosystem goals are subordinate to the need to prioritize protection of people and property (van Wilgen et al., 2011). This creates a perceived conflict between public safety and the desire to restore historical fire regimes, even though such restoration is necessary to reduce severe fire risk in the long term (Noss et al., 2006a; Schoennagel et al., 2009). Such conflicts require re-evaluation of approaches to both fire management and urban planning and development (Moritz and Stephens, 2008), for example via planning for fire that is spatially-explicit and includes variable management approaches over a heterogeneous landscape (Thompson et al., 2016). Current and projected increases in fire frequency imply that a growth in both acceptance of fire and adaptability to fire on the part of human communities is essential (Schoennagel et al., 2017).

The objectives of landowners and ecosystem managers are not always in conflict, as preventative fire management is often in the best interest of homeowners. In illustration of this, housing prices in fire-threatened parts of Los Angeles County fell 9.7% after a first wildfire and 22.7% after a second (Mueller et al., 2009). In Arizona and Colorado, landowners have shown willingness to pay for fuels management activities with benefits to forest ecosystems (Kaval et al., 2007; Kim and

Wells, 2005; Miller et al., 2017).

3.5. Tradeoffs between management objectives

Fire management may entail tradeoffs between values. Fire dynamics affect economic resources such as timber and livestock, property and infrastructure, and recreation and tourism, in addition to non-market forest goods and services including air quality (e.g., smoke occurrence and quantity), soil productivity, water quality and quantity, habitat, and cultural heritage (Thompson and Calkin, 2011; Venn and Calkin, 2011). As fire patterns change, it becomes increasingly important to understand and balance those values in order to recognize those thresholds at which management no longer meets desired objectives (Costanza and Moody, 2011). When government management priorities reflect the values of local and regional stakeholders, the public is more supportive of fire management activities (Vaske et al., 2007). However, policy-makers and managers often have limited information about the values placed by stakeholders on goods and services, and this stymies efforts to develop mutually-acceptable strategies (Venn and Calkin, 2011). Nevertheless, understanding how values impact fire management is crucial to predicting likely management responses to future fire.

4. Changing fire dynamics create challenging socioecological management thresholds

In cases of extreme change, landscapes may reach a threshold beyond which it may become impossible to achieve land management objectives even with a traditional adaptive management approach of sequentially employing various activities. This socioecological scenario represents a *critical threshold beyond which the management objectives for a particular site are forced to change*. An example of such a change in objectives might be a fire-induced shift from timber harvesting to recreation or ranching. That is, managers may need to explore alternative objectives, each with their own set of potential actions. This represents a more extreme form of *adaptive management focused on objectives*, that may require collaboration among broadly diverse segments of society.

In classic ecological resilience literature, the characteristics of an ecological system are collectively known as a state (Holling, 1973). Disturbance has the potential to force a state change. The resilience of the system measures the amount of disturbance a system is able to absorb without changing states or how easily the system returns to its previous state following a disturbance (Holling, 1973). Ecological state change can be proximally driven by changes in the extent, severity, or frequency of fire, such as when grasslands are converted to shrublands, or desert scrub to annual invasive grasslands (McDonald and McPherson, 2011; Miller and Rose, 1999). Adaptive management that responds to such shifts in fire dynamics can in some cases permit a socioecological system to return to its previous ecological and social conditions after disturbance, demonstrating socioecological resilience (Higgs et al., 2012). Such adaptive management benefits from a mechanistic understanding of an ecosystem's responses to fire (Driscoll et al., 2010; Roe and Van Eeten, 2001). Successful adaptive management also explicitly acknowledges uncertainty and human behavior and employs monitoring, evaluation, and revision (Groffman et al., 2006; van Wilgen et al., 2014).

When fire dynamics change enough that no amount of strategizing and flexibility may permit current objectives to be achieved, a socioecological threshold has been reached beyond which traditional adaptive management may no longer be effective. Instead, a new style of adaptive management entailing recognition of the threshold and identification of new objectives may be required (Fig. 2). As an example, following decades of fire suppression an unusually severe fire in 2011 burned in high-elevation conifer forest of the Chiricahua Mountains in southeastern Arizona (Falk, 2013). Both groundcover and canopy were lost in many parts of the Horseshoe 2 Fire, resulting in erosion of burned hillsides and sedimentation of mountain streams (Youberg et al., 2012); as a result, aquatic habitat quality was degraded by debris and coarse sediment that thereafter choked the five canyons and waterways burned by the fire (Youberg et al., 2012). This substantial loss of habitat represented a threshold beyond which management objectives changed: the decision was made to move an endemic population of an endangered fish, the Yaqui chub (*Gila purpurea*), into artificial habitat until the Chiricahuan streams recovered or could be restored. In this case, fire resulted in such an extreme ecological state change that conservation objectives could not be reached *in situ*; that is, no management strategies could meet the objective of conserving the Yaqui chub within its stream. Instead, managers adapted by adopting a new set of objectives: establishing and safeguarding a captive population of the chub.

In the context of this discussion, thresholds occur when system changes due to fire result in a shift in management objectives and thus activities (Fig. 2). As another example of this phenomenon, severe fires resulting in “hazard trees” and other dangers to the public can result in multi-use forests that become closed to recreation, either temporarily or over long time periods (McCaffrey, 2006). In Australia, decreasing use of aboriginal fire to clear patchy hunting and foraging areas has resulted in an increase in more severe lightning-strike fires in some regions, decreasing biodiversity and rendering such areas unsuitable for hunting as an objective (Bliege et al., 2008). Stand-replacing fires in some cases have been the impetus for salvage timber harvesting, even in previously protected areas—leading to controversies as road construction and increased soil erosion compound the effects of the fires themselves (Lindenmayer and Noss, 2006).

Recognizing management objective thresholds could enable managers to prepare for them and permit a deeper understanding of the socioecological implications of changing fire dynamics. Insights from land managers can pinpoint thresholds that will require changes in management objectives; scientists may then be able to develop models to predict such management thresholds. Various modeling approaches can be used to incorporate adaptive management into landscape scenarios (e.g., Bashari et al., 2008; Driscoll et al., 2016; Spies et al., 2014); incorporating management thresholds into these models may improve their utility and lead to better and more informed decisions.

5. Conclusions: the need to prepare for thresholds and promising approaches

Fire dynamics are changing across arid and semi-arid regions of the world, with consequences for both ecological and social systems. Traditional adaptive management that sequentially adopts various actions may enable socioecological systems to meet current management objectives if changes in fire dynamics are mild or the socioecological system is flexible and responsive. When management objective thresholds have been reached, however, and it is no longer possible for current management objectives to be achieved, stakeholders may be forced to adopt new objectives (Fig. 2). A deeper understanding of the interaction between shifting fire dynamics and static management objectives may help stakeholders prepare for upcoming changes. Changing management objectives may require shifting values or priorities, or may require policy change or carry substantial economic costs (Kwadijk et al., 2010).

While fire managers are experienced in handling uncertainty (Thompson and Calkin, 2011), many standard decision-support frameworks do not incorporate concepts of thresholds or allow for shifts in longer-term objectives. Fire and climate models are becoming increasingly adept and accurate at identifying potential ecological thresholds, but these approaches are rarely accompanied by social science research designed to identify values, capabilities and limitations, and likely responses to change scenarios—that is, to identify socioecological thresholds. Researchers in the Netherlands, for example, worked with managers to identify potential tipping points associated with sea level

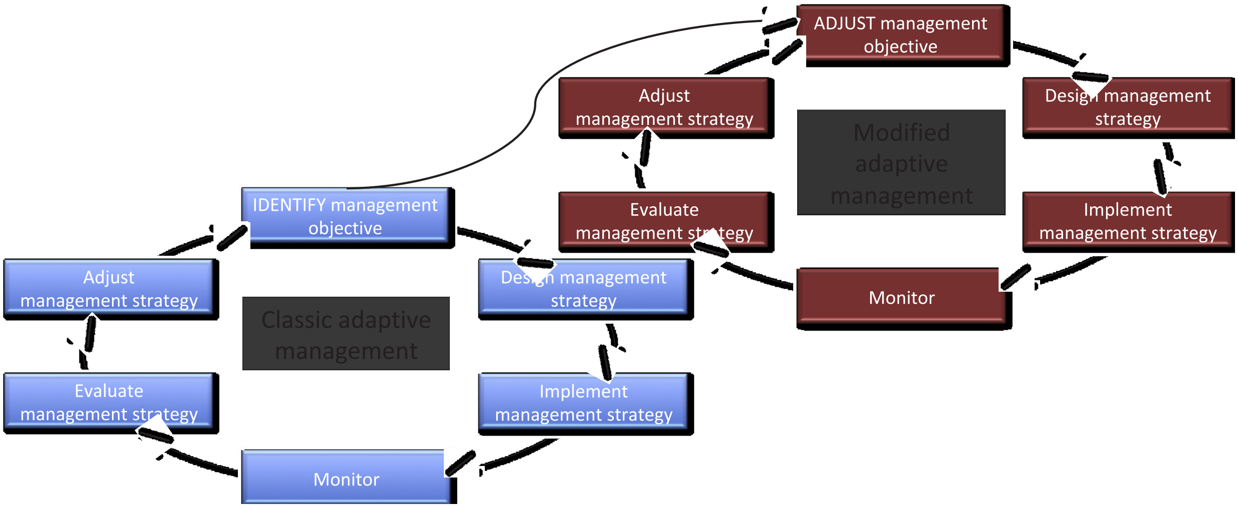

Fig. 2. Modification of classic adaptive management cycle to explicitly incorporate adjustments in management objectives as well as management actions. When classic adaptive management is being practiced and no effective management strategies remain to meet current objectives, a practitioner or group may adjust management objectives (black arrow), thus diverting into a new adaptive management cycle exploring management strategies to meet the new objectives.

rise scenarios, and found that objectives regarding drinking water would become unachievable in advance of other management thresholds, allowing planners to prioritize appropriately (Kwadijk et al., 2010). In an ongoing research project, the authors of this review are working with land managers in the Sonoran Desert to assess fire and fuel scenarios to both identify potential management thresholds requiring a change in objectives and to explore barriers to changing objectives (e.g., cost, public opinion, and agency mandates).

Because changing fire dynamics involve ecological thresholds, decision-support frameworks and adaptive management frameworks should be adapted to specifically consider potential management thresholds. There are a number of approaches to incorporating these concepts into decision contexts for land managers. Long-term scenario planning that accounts for the response of multiple values to wildfire is a growing component of fire management (Thompson and Calkin, 2011) and could help managers anticipate thresholds requiring a change in objectives as well as actions (Moore et al., 1999). Increasing decision support time horizons may also help managers recognize approaching socioecological thresholds before they have arrived (e.g., Podur and Wotton, 2010). In addition to increasing temporal scales, integrating collaborative responses across multiple jurisdictions provide both greater management resources and an opportunity to shift management objectives by adopting landscape-scale approaches such as ranching cooperatives or regional tourism initiatives (Fleeger, 2008). Improving tools to understand tradeoffs between a range of market and non-market landscape values, as well as refining approaches to ensure participation of multiple stakeholders, are important components of understanding thresholds and identifying viable alternative objectives (Pacheco et al., 2015; Thompson and Calkin, 2011; Venn and Calkin, 2011). Scenario planning and collaborations may be facilitated by landscape-scale conservation design efforts that collate existing data to assist in prioritization of vulnerable sites for fire management (e.g., http://southernrockieslcc.org/southrock/wp-content/uploads/2015/06/GRB-LCD-description-July-2015.pdf; https://lccnetwork.org/group/desert-lcc-landscape-conservation-planning-and-design-core-team).

Arid and semi-arid system managers and stakeholders face a daunting challenge: to respond to fire dynamics in managed environments that differ from those within which static management objectives arose, are subject to high uncertainty, and are driven at least in part by global change drivers that are beyond their control. It is thus critical that the scientific and management communities together develop an enhanced understanding of management thresholds, identification of diverse and viable management objectives, and effective responses to novel conditions.

Authors' contributions

All authors conceived the ideas. CA led the writing of the manuscript, with substantial contributions from LS, MG, and BD.

Declarations of interest

None.

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