Temperate and boreal forest mega-fires: characteristics and challenges

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Mega-fires are often defined according to their size and intensity but are more accurately described by their socioeconomic impacts. Three factors – climate change, fire exclusion, and antecedent disturbance, collectively referred to as the "mega-fire triangle" – likely contribute to today's mega-fires. Some characteristics of mega-fires may emulate historical fire regimes and can therefore sustain healthy fire-prone ecosystems, but other attributes decrease ecosystem resiliency. A good example of a program that seeks to mitigate mega-fires is located in Western Australia, where prescribed burning reduces wildfire intensity while conserving ecosystems. Crown-fire-adapted ecosystems are likely at higher risk of frequent mega-fires as a result of climate change, as compared with other ecosystems once subject to frequent less severe fires. Fire and forest managers should recognize that mega-fires will be a part of future wildland fire regimes and should develop strategies to reduce their undesired impacts.

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Many researchers believe that large fires (those with an areal extent > 10 000 ha, often termed "mega-fires") are ecological disasters because they burn vast areas of land and are characterized by high intensities that are seemingly outside of observed historical ranges (Figure 1; Daniel *et al.* 2007; Bradstock 2008). Little is known about the short- and long-term ecological impacts of mega-fires on historical and contemporary landscapes, and this knowledge gap has promoted debates about their causes and consequences (Daniel *et al.* 2007). Although often defined according to their size, mega-fires are more accurately characterized according to their impacts on human society (Williams *et al.* 2011; Williams 2013).

Mega-fires differ from historical fires in several ways. Mega-fires are more difficult and costly to fight, and their subsequent effects may be more economically demanding (Butry 2001; Adams 2013). Such fires tend to involve more firefighters working in dangerous conditions, therefore increasing the chance of human casualties. Because of their great size, mega-fires also tend to affect more people and destroy more property, especially at the urban–wildland interface (Figure 1a; Hudak *et al.* 2011). Finally, mega-fires produce more smoke over shorter time periods, which often results in degraded air quality and poses serious public-health hazards to nearby populations, sometimes for months (Leenhouts 1998). Note that none of these social concerns are related to the ecology of mega-fires. Indeed, mega-fires are not only a biophysical phenomenon but also an increasingly salient social issue, particularly in densely populated areas. Mega-fires therefore need to be approached from an interdisciplinary perspective, given that many of these events take place in forest ecosystems that can be defined as coupled human–natural systems (Liu *et al.* 2007).

In a nutshell:

- The current focus on fire suppression will not reduce mega-fire incidence, extent, or damage
- Land-use changes, as well as moderate to severe drought, often precede mega-fires
- Intact fire regimes (those minimally affected by fire exclusion for several decades) can restrict the size and severity of some mega-fires
- Changing governance structures can quickly alter land-use patterns and subsequent fire regimes

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Critical importance of fire regimes

Several characteristics of fire are used to define fire regimes (Sugihara *et al.* 2006). Temporal attributes include seasonality and fire return interval; spatial attributes include fire size and spatial complexity; and magnitude attributes include fire line intensity, fire severity, and fire type. Understanding mega-fire dynamics requires a long-term perspective that compares the characteristics of historical and contemporary fire regimes (Keane *et al.* 2008).

Although individual fire size was probably smaller, the annual area burned before European settlement in the western US was much larger than the annual area burned by mega-fires in the same area today (Marlon *et al.* 2012). Fire severity patterns produced by mega-fires are an important point of comparison to pre-industrial fire

Figure 1. *(a) Mountain ash (*Eucalyptus regnans*) forests around Marysville, Victoria, Australia, burned in the 2009 Black Saturday Fires that killed 173 people. (b) Lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*) forests with areas of subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) at higher elevations, from the 2009 Kelly Lake Fire, British Columbia, Canada. This area experienced extensive mortality as a consequence of mountain pine beetle (*Dendroctonus ponderosae*) infestation, resulting in an increased fire hazard, especially during the red-needle phase of tree death. (c) Ponderosa pine (*Pinus ponderosa*) forests and shrublands in Cochiti Canyon, New Mexico, burned in the 2011 Las Conchas Fire that led to extensive mortality of trees not adapted to high-severity fire.*

regimes because severity has the greatest impacts on vegetation, wildlife habitat, carbon (C) sequestration, and other ecosystem values.

Ecological causes of mega-fires

A number of abiotic and biotic factors are likely causes of contemporary mega-fires. Some factors that contribute to mega-fires operate at large spatial scales and disrupt processes linked to the dynamics of wildland fuels. The three factors that best fit this profile are climate change, fire exclusion, and antecedent disturbance – collectively, the "mega-fire triangle" (Figure 2). With regard to climate change, research in Canada suggests that future fire seasons will be longer and annual average burned area will likely increase (Gillett *et al.* 2004); similar trends have already been observed in the western US (Westerling *et al.* 2006). The second contributing factor – fire exclusion, which includes both active fire suppression and a reduction in anthropogenic fire use – has been practiced intermittently around the world for centuries. As for antecedent disturbance, perhaps the most important examples are related to land-use change (eg encroaching development, an expanding urban–wildland interface) because these place additional assets at risk (Gill *et al.* 2013). Development also reduces management options (eg conducting prescribed burns), which encourages fire suppression (Williams 2013). Likewise, changes to fuels and forest structure, which are generated by natural processes (eg insect and disease outbreaks) and management actions (eg silvicultural activities), represent another type of foregoing disturbance. An example of the compounding effects of mega-fire factors comes from the Canadian province of British Columbia, where one of the largest insect outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) in recorded history occurred. This native insect species, which primarily infests mature lodgepole pine (*Pinus contorta*), was responsible for tree mortality in over 20 million ha of forest in the province (Figure 1b).

At large temporal scales, mega-fires usually occur after years of moderate to severe drought. Naturally occurring cycles of climatic variation, such as the Pacific Decadal and Atlantic Multidecadal Oscillations and the El Niño–Southern Oscillation, often drive the frequency and intensity of drought events that then influence mega-fire activity worldwide (Figure 2; Swetnam and Betancourt 1990; Schoennagel *et al.* 2005). Over shorter time scales, mega-fires often occur during high wind events, frequently under hot, dry conditions (Broncano and Retana 2004).

Many managers and scientists believe that decades of fire exclusion have increased fuels across landscapes to the point where these areas are capable of fostering larger and more severe fires (Keane *et al.* 2002; Stephens *et al.* 2012). While generally true, this statement requires some qualification and cannot be applied everywhere. In the absence of fire, vegetation development generally increases ladder and canopy fuels as tree stands become denser (Hessburg *et al.* 2000), and more surface fuels accumulate as the vegetation shifts from herbaceous plants and shrubs to woody material (Pinol *et al.* 2005). However, weather and topography can have a greater effect on fire behavior than an increase in fuels (Keeley 2009), especially in crown-fire-adapted ecosystems (Bessie and Johnson 1995).

Ecological consequences of mega-fires

Some mega-fires may duplicate historical fire regimes and thereby support healthy ecosystems, particularly in the northern US (Keane *et al.* 2008), northern Australia (Russell-Smith and Edwards 2006), South Africa (De Santis *et al.* 2010), the Andean-Patagonian region (Veblen *et al.* 2008), boreal forests (Burton *et al.* 2008), and the Mediterranean Basin (Pausas *et al.* 2008); other mega-fires have decreased ecosystem resilience, primarily through the creation of large, high-severity patches that limit tree regeneration (Barton 2002; Goforth and

Minnich 2008; Collins and Roller 2013). Mega-fires appear to cause major shifts in structure and composition in areas that are (1) dominated by non-native vegetation, (2) historically open forests with atypically dense tree encroachment, (3) heavily altered by humans, (4) lacking biological and landscape heterogeneity, or (5) subjected to multiple mega-fires (Keane *et al.* 2008; Pausas *et al.* 2008).

In some instances, the overall distributions of burn severity are similar for both large and small fires. A key distinction, however, is that mega-fires create larger and more regular patterns of high-severity patches (Romme *et al.* 1998; Bradstock 2008; Keane *et al.* 2008; Miller *et al.* 2012). These larger burn patches can have substantial ecological impacts, including severe limitations of wind- and animal-dispersed tree seeds from unburned edges, loss of late seral habitat, reduced C sequestration, and increased runoff and erosion but such patches can also improve habitat for some wildlife species (Parr and Andersen 2006).

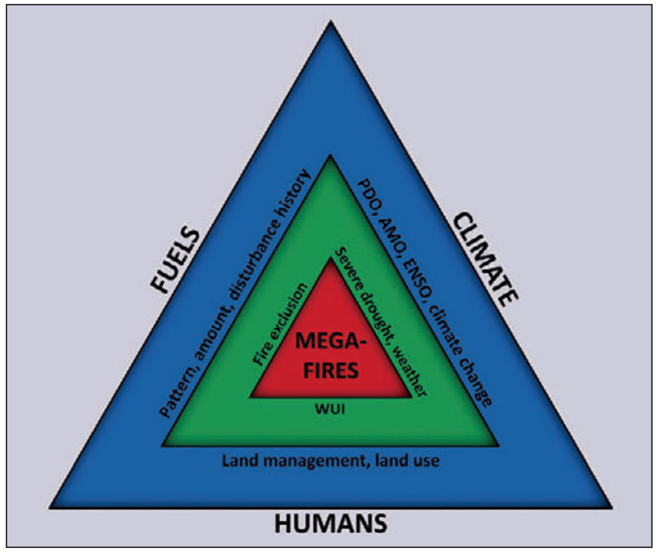

Figure 2. *Major factors governing mega-fires (the "mega-fire triangle"). The blue triangle identifies the main factors that define contemporary fire regimes, the green triangle indicates key processes or conditions that govern fire regimes, and the red triangle identifies those causes, nested under the factors, that influence and predispose landscapes to mega-fires. PDO = Pacific Decadal Oscillation; AMO = Atlantic Multi-decadal Oscillation; ENSO = El Niño–Southern Oscillation; WUI = wildland–urban interface.*

Management and social implications

Many nations that are experiencing an increase in mega-fires are investing in larger fire-detection and fire-suppression organizations. The goals of such organizations are to detect fires early and quickly mobilize professional firefighters or, in some cases, military personnel and volunteers to extinguish fires when small. In contrast, countries that have invested in large, expensive fire-detection and fire-suppression organizations for decades, such as the US, Canada, and Australia, are developing more complex fire-management strategies that are moving away from a focus on suppression to a more integrated approach (although the US Forest Service essentially reinstated a full suppression policy in 2012). Clearly, a focus on fire suppression is not reducing losses associated with mega-fires (Adams 2013; Williams 2013). Countries that are building such organizations today could learn from the mistakes of those that have invested hundreds of millions or billions of dollars annually but still have large mega-fire problems.

Mega-fires are common in Russia (Figure 3), which possesses over 25% of the world's forest resources and therefore plays a prominent role in the global C cycle (Dixon and Krankina 1993; Goldammer and Furyaev 1996). Most fires occur in Siberia and in the country's Far East, which contain more than 80% of Russia's forests. Fires in remote areas are often not suppressed, partly because of low population density and an absence of fire monitoring and control. Human negligence during crop residue burning, forestry operations, and recreational activities cause 70–90% of ignitions in regularly monitored areas. An emerging issue is economically motivated arson, which occurs when timber dealers encourage or bribe locals to intentionally set fires to increase permissible salvage logging in southern Siberia (FAO 2006).

During the past decade, Russia's fire-management system has experienced budget cuts, reductions in personnel and aircraft, and the enactment of the controversial Forest Code in 2007. The Code transferred many responsibilities for forest management to private forest enterprises, which are often reluctant to comply with established rules. Various sources of fire statistics (FAO 2006; Bondur 2010; Vivchar 2011) indicate that large areas have been affected by fires in the past two decades (Figure 3). Total area of burned forest was highest (12 million ha) in 2012, with the majority of large fires occurring in Asian Russia (Laverov and Lupian 2013). Extremely dry and windy summer conditions in 2010 led to many fires in European Russia, causing the loss of 62 lives and more than 2000 homes in over 100 villages, and making that fire season the worst in Russia's recent history (Williams *et al.* 2011).

Mega-fires have also increased in central Asia, where changes in governance structures have taken place. Fire is a natural process in Mongolia's steppe and forested ecosystems. Yet within the past 20 years, mega-fires have increased (Erdenesaikhan and Chuluunbaatar 2008), due in part to the warming climate (D'Arrigo *et al.* 2000) and to the major social, cultural, and economic disruption that followed the collapse of the Soviet Union. With the privatization of many sectors of the Mongolian economy, many rural dwellers were left to base their livelihoods on the exploitation of natural resources and these pursuits were facilitated through burning, leading to increased ignitions. The situation has been further aggravated by the international extent of some fires, which

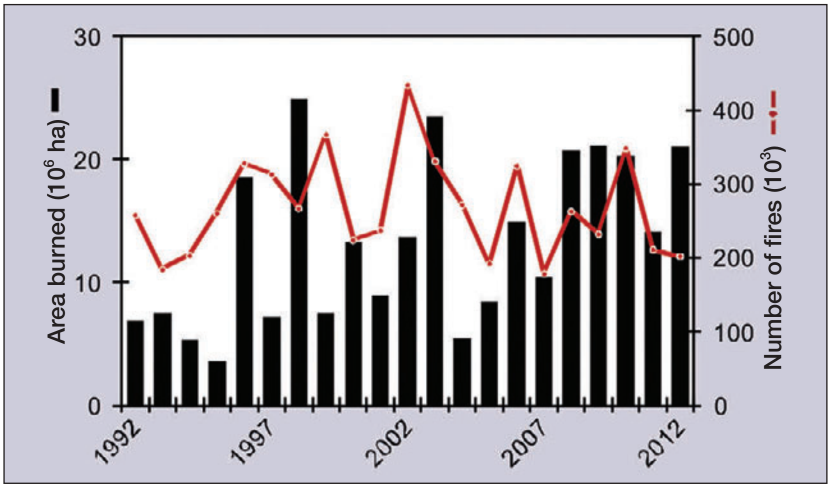

Figure 3. *Burned area and number of fires in Russia from 1992–2012. Data from official report of the Federal State Statistics Service of the Russian Federation (source: www.gks.ru/free_doc/new_site/business/sx/les2.htm). Note that the left y axis has units of 1 × 10^6 ha.*

started in Russia but spread into neighboring countries. In 1996 and 1997, mega-fires originating in Russia burned a combined 4.9 million ha in Mongolia and China. Thus, changing governance structures can quickly alter land-use patterns and fire regimes.

Forest fires have long been recognized as a paramount issue in China (Zhao *et al.* 2009a). In May 1987, a mega-fire in the Daxing'anling region of northeast China burned 1.33 million ha of forest and resulted in 213 deaths. Since the late 1980s, the Chinese Government has increased its investment in fire control agencies and fire prevention infrastructure. Nevertheless, the country's average annual burned area from 2000 to 2009 was 333 796 ha (Figure 4), of which 138 712 ha (42%) were in forests. Of the yearly forest fires within China, 52% occur in the south, followed by 37% in the southwest, 6% in the northwest, and 4% in the northeast and Inner Mongolia (mainly the Daxing'anling region). Though relatively fewer fires occur in Daxing'anling, its burned area is much larger than that in southern China. For example, during 1987–2010, the average annual burned area in the Daxing'anling region was 192 200 ha and the fire rotation was 75 years (Tian *et al.* 2012a,b). More than 98% of forest fires were estimated to be caused by human activities between 2001 and 2010, while climate warming has already exerted a major impact on forest fires (Zhao *et al.* 2009a,b).

In Spain, Portugal, and Greece, state-led afforestation efforts have contributed to larger fires by (1) increasing landscape homogeneity, fuel loads, and flammability (Moreira *et al.* 2011) and (2) changing feedbacks between coupled natural and human systems. Large-scale fire suppression has been linked to increased mega-fire risk in the Mediterranean Basin but was deemed necessary to protect afforested areas. In some areas, afforestation projects have led to conflicts with members of local rural communities over land tenure and traditional fire use, which may explain a subsequent proliferation of arson events and unintentional fires. Finally, the enclosure of village commons has been responsible in large part for rural abandonment; this demographic trend was identified as one of the major factors promoting mega-fires in the Mediterranean Basin (Moreira *et al.* 2011).

Integrated fire management

Managing fire for multiple objectives instead of narrowly focusing on fire suppression is producing some positive outcomes (eg when fire exhibits self-limiting characteristics in some ecosystems). Recurring fires consume fuels over time and can ultimately constrain their own spatial extent and lessen the effects of subsequent fires. In montane forests in California's Yosemite National Park, when the interval between successive adjacent fires is under 9 years, the probability of the latter fire burning into the previous fire area is low (Collins *et al.* 2009). Analysis of fire severity data by 10-year periods revealed that the proportion of area burned over the past three decades remained stable among fire severity classes (unchanged, low, moderate, high). This contrasts with increasing numbers of high-severity fires in many Sierra Nevada forests from 1984 to 2010 (Miller and Safford 2012), which suggests that freely burning fires in some forests can, over time, regulate fire-induced effects across the landscape (Stephens *et al.* 2008; Miller *et al.* 2012; Parks *et al.* 2013).

Mega-fires burn inordinately large areas, but there is some evidence that intact fire regimes (those minimally affected by fire exclusion for several decades) can constrain fire size. For example, in Yosemite's montane forests, where lightning-ignited fires have been allowed to burn under prescribed conditions for 40 years, a pattern of intersecting fires emerged revealing that subsequent fires were limited to less than 4000 ha (van Wagtendonk *et al.* 2012). However, mega-fires have grown to over 100 000 ha in areas within or adjacent to the park where fires had been routinely suppressed and the resulting burn severity (especially large patch sizes) are not within desired ranges to conserve ecosystem resiliency (Miller *et al.* 2012).

The effect of mega-fires on landscapes is highly variable. Sometimes such fires burn with high intensity over large areas (Miller *et al.* 2012), leading to changes in resultant vegetation types, which may alter future fire regimes. For instance, in Yosemite National Park, when fire-excluded ponderosa pine (*Pinus ponderosa*) forests were burned by mega-fires, shrublands and grasslands often replaced these forests (Figure 1c; Thode *et al.* 2011). Similarly, in Yosemite, pre-fire vegetation remained the same after being burned by fires of unchanged, low, or moderate severity but often converted to shrublands after high-severity events (van Wagtendonk *et al.* 2012).

In contrast, ecosystems adapted to large, high-severity fires will respond differently. As long as mega-fires are within the range of historical variation of past fire regimes, such as those commonly experienced in grassland, Rocky Mountain lodgepole pine, and temperate rainforest ecosystems, they will not reduce ecosystem resiliency. Allowing some large fires to burn in these ecosystems when they are not undergoing drought conditions could produce spatial heterogeneity in fuels that would decrease the chances of subsequent severe mega-fires. However, should mega-fires diverge from historical fire regimes, ecological resiliency will be degraded, as has been seen in sagebrush grasslands, dry mixed conifer and ponderosa pine forests, dry eucalyptus forests, and other fire-excluded areas that historically experienced frequent fires.

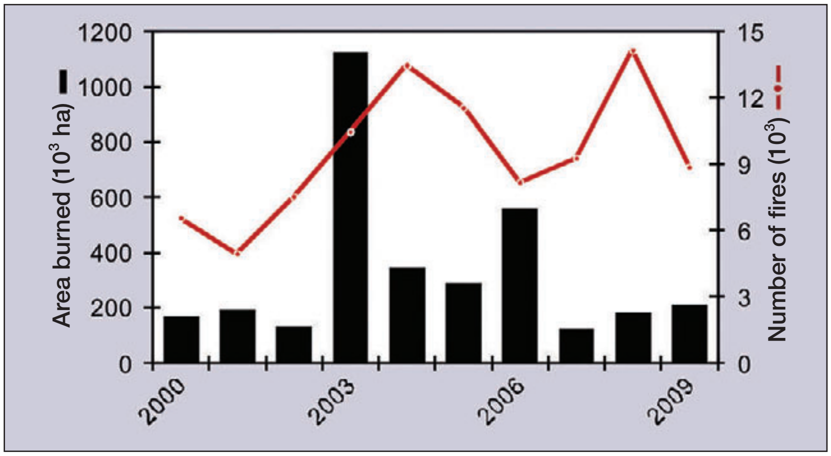

***Figure 4.** Burned area and number of fires in China from 2000–2009. Note that the left y axis has units of 1 × 10^3 ha. Data from the China Forestry Statistical Yearbook, 2011. People's Republic of China: China Forestry Publishing House.*

Boer *et al.* (2009) described one of the world's best examples of a fire management program designed to reduce mega-fire impacts to the urban–wildland interface. In forests and shrublands adapted to frequent fire in southwest Western Australia, prescribed burning of native vegetation is an important management strategy for achieving conservation and land management objectives (Wittkuhn *et al.* 2011; Burrows and McCaw 2013). Prescribed burning carried out at the appropriate spatial and temporal scales reduces the overall flammability and quantity of fuels in the landscape, thereby reducing the intensity and speed of wildfires.

Broad area fuel reduction burning has been used in southwest Western Australia since the mid-1950s to protect key assets (homes, power lines, wildlife habitat). Approximately 8500 prescribed burns have been conducted over a total area of 15 million ha (Figure 5). During this time, an inverse relationship between the area burned by prescribed fire and by wildfire has been established (Boer *et al.* 2009); that is, prescribed burning has reduced the impact of subsequent wildfires by reducing their size and intensity. This evidence from Australia could be of interest to managers elsewhere in the world who continue to focus solely on fire suppression. However, in southwest Western Australia, the annual area burned by prescribed fire has been trending downward since the 1980s, while the annual area burned by wildfires has been trending upward (Figure 5). In recent years, there has been a spate of mega-fires not seen in the region since the 1960s. Key drivers (although associated with southwest Western Australia, they are applicable elsewhere) are:

- Climate change: since the 1970s, the climate has become warmer and drier (IOCI 2001; Bates *et al.* 2008), reducing the window of opportunity for safely carrying out prescribed burning. Longer periods of hotter, drier weather result in longer periods of elevated fire risk.
- Human population growth in the urban–wildland interface: more people are living in fire-prone areas. In many instances, local bylaws and land-use planning policies fail to consider the risk of mega-fires and are inadequately enforced. People are building and living in dangerous locations and are not taking adequate fire protection measures.
- Fire management capacity: resources and personnel for fire management have not kept pace with the increasing demands and complexity of managing fire.
- Smoke management: managing air quality (including the impacts of smoke on adjacent land users or homeowners) further narrows "burning windows" and reduces the size and number of prescribed burns that can be conducted.

Effective mega-fire management will require the incorporation of larger scale (10 000–30 000 ha) management processes – including prescribed burning programs, strategic mechanical fuel treatments, combinations of strategic mechanical and fire treatments, or by allowing wildfires to burn under certain conditions (Stephens *et al.* 2012). Managed wildfire is probably the best option for meeting restoration and fuel-management goals in the western US because it can be implemented at moderate to large spatial scales at the lowest cost (North *et al.* 2012), whereas in Australia, the Mediterranean Basin, the US Great Plains, and the southern US, prescribed burning with or without mechanical fuel treatments may be preferable. Regardless of how a fire is ignited, smoke will likely be a major concern, especially given its negative impact on human health. Smoke from prescribed fires should be compared with smoke from mega-fires, which can affect extensive regions for weeks or months (eg the 1997 mega-fires in Indonesia or the 2010 mega-fires in Russia, where

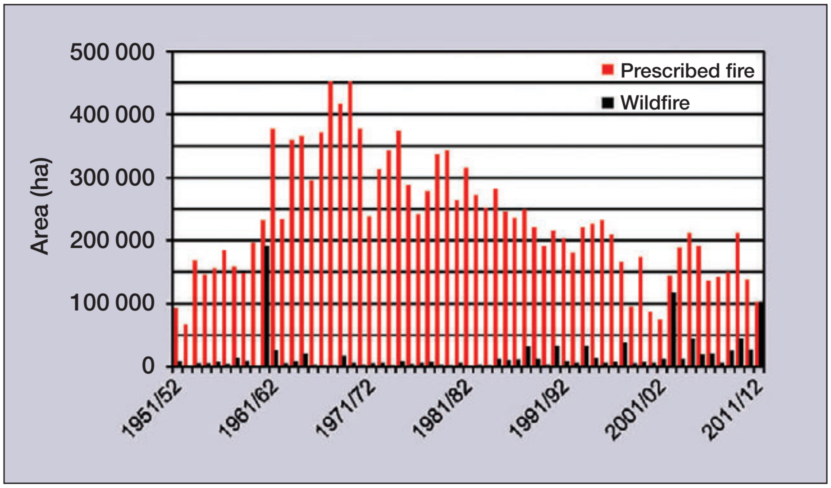

Figure 5. *History of annual area burned by prescribed fire and by wildfire in the forests and shrublands of southwest Western Australia, near Perth. Data from the Forest Department of Western Australia, the Department of Conservation and Land Management, and the Department of Environment and Conservation.*

persistent heavy smoke was caused by the burning of peat fuels).

Climate change probably places crown-fire-adapted ecosystems at high risk for frequent mega-fires when compared to those that once burned frequently. Frequent high-severity burning will disrupt the ability of crown-fire-adapted ecosystems to regenerate since seeds require sufficient time between fires to mature and vegetative resprouting can be exhausted by repeated fires. Increases in mega-fire abundance in these ecosystems may severely reduce resilience because thresholds could be crossed that change ecosystem states (eg forest to shrublands or shrublands to grasslands) over extensive areas (Westerling *et al.* 2011). Ecosystems that have been substantially altered by non-native species and by different land-management practices will also tend to exhibit more severe ecological impacts after mega-fires. Comparing past and current fire regimes is critical in determining whether mega-fires will damage specific ecosystems.

In contrast to crown-fire-adapted ecosystems, areas that once experienced frequent, low- to moderate-intensity fires can be managed to reduce their susceptibility to high-severity mega-fires (Fulé *et al.* 2012, 2013) and increase ecosystem resiliency (Stephens *et al.* 2012). There are few unintended consequences of forest fuel reduction treatments across forests in the US because most ecosystem components (vegetation, soils, small mammals and birds, bark beetles, C sequestration) exhibit very subtle or no measurable effects, although impacts to wildlife with large home ranges have not been fully assessed (Stephens *et al.* 2012). Similar results were found in Western Australia forests and shrublands that had undergone repeated prescribed burns over 30 years (Wittkuhn *et al.* 2011). Thus, in surface-fire-adapted ecosystems, management actions can be taken today to reduce the negative consequences of subsequent mega-fires (ie minimize high severity patch size) and simultaneously achieve restoration objectives; in crown-fire-adapted ecosystems, however, such action (fuel treatments) is largely beyond the scope of restoration objectives (Stephens *et al.* 2013).

Conclusions

Fire managers should accept that mega-fires will be a part of fire management, especially as global temperatures continue to increase. Instead of suppressing all fires indiscriminately, it will be more effective for fire managers to identify those areas at high risk and to concentrate suppression efforts there (Gill *et al.* 2013). The goal should be to reduce high-severity patch size but not area burned (Reinhardt *et al.* 2008), particularly in ecosystems that once experienced frequent, low- to moderate-intensity fire regimes.

Members of the general public need to understand the complexities of fire management posed by mega-fires (Adams 2013), and policy makers need to recognize that fighting mega-fires is economically inefficient – often costing more than the assets being protected – and dangerous. New fire-management strategies should address all fire management problems, not just those posed by mega-fires, given that fire is a critical component of many ecosystems around the world.

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