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Fire and climate change: conserving seasonally dry forests is still possible

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The destructive wildfires that occurred recently in the western US starkly foreshadow the possible future of forest ecosystems and human communities in the region. With increases in the area burned by severe wildfire in seasonally dry forests expected to result from climate change, judicious, science-based fire and restoration strategies will be essential for improving the resilience of forest ecosystems. We argue that fire use treatments (including prescribed fires and managed wildfires) as well as restoration thinning strategies, rather than conflicting with existing environmental objectives, will provide numerous co-benefits, including enhanced biodiversity, increased water availability, greater long-term and more sustainable carbon storage, improved forest resilience and adaptation to climate change, and reduced air pollution. Timber production, however, may have to be better aligned with fire management goals to achieve these co-benefits. Taking immediate actions today to promote positive ecological outcomes in seasonally dry forests should be a primary focus of management, particularly in the western US.

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For millennia, most western US forests were maintained by fire, with flora and fauna dependent on low- and moderate-severity fire until Native American burning was largely terminated and Euro-American fire exclusion and suppression began in the late 19th century. Increases in small, shade-tolerant trees and a buildup of fuels as a result of fire exclusion, coupled with the loss of larger, more fire-resistant trees from selective logging (Collins *et al.* 2017), have produced fire regimes in seasonally dry forests that are now characterized by a greater proportion of continuous high-severity fire (Singleton *et al.* 2019). Ongoing climate change and drought-induced mortality of trees previously damaged by bark beetles can influence the occurrence and severity of fire, and are likely to do so even more as areas become warmer and drier (Stephens *et al.* 2018; Westerling 2018). California exemplifies the interaction between land use and climate change, as increases of 77% (Figure 1) and 178% in annual area burned and maximum area burned, respectively, are projected for the state by the late 21st century under high global greenhouse-gas (GHG) emissions pathways (Westerling 2018). Across the state, the frequency of extreme wildfire events is also expected to increase, with fires greater than 10,000 ha occurring nearly 50% more often. Likewise, as for fire intensity, forecasts under projected climate with current high fuel loads in the Sierra Nevada indicate that 40% of the burned area will be attributable to high-severity fire (Westerling 2018).

In a nutshell:

- Wildfires in the western US are increasingly large and more severe
- In some forests with a dry warm season, wildfires are damaging key services that those forests provide
- However, actions such as the increased use of fire and restoration thinning, if taken today, may counter this problem
- Restoring a more natural role for fire will help forests to continue to provide needed services (eg water, clean air, carbon storage, habitat, wood products, recreation) over the long term, while at the same time making forests more resilient to climate change

Given that seasonally dry forests in the US are predicted to experience increases in severe wildfires, it is essential for resource managers to consider sensible, evidence-based strategies to improve forest ecosystem resilience. Promisingly, we believe that conventional treatments like fire use and restoration thinning – instead of counteracting other environmental objectives – will provide numerous co-benefits, including enhanced biodiversity, increased water availability, greater long-term and more sustainable carbon (C) storage, improved forest resilience and adaptation to climate change, and reduced air pollution. Achieving these co-benefits will require designing prescribed fire and restoration thinning treatments to better mimic historical conditions (Collins *et al.* 2017), given that many contemporary treatments do not enhance forest resilience, especially at landscape scales (Fulé *et al.* 2006; Lydersen *et al.* 2019). In contrast to many prescribed fires and restora-

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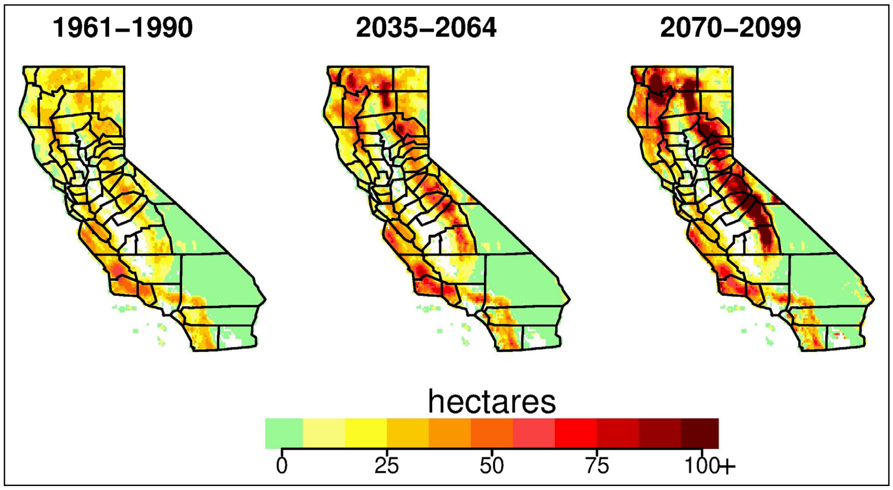

Figure 1. One-sixteenth-degree gridded average 1961–1990 (left), 2035–2064 (center), and 2070–2099 (right) annual area burned maps for California. Colored shading shows annual average area burned in increments from near zero (green) to 100 or more (dark red) hectares. Annual averages are constructed from 1000 random monthly simulations of large (>400 ha) fires over 30-year periods for ten global climate models, using the representative concentration pathway (RCP) 8.5 global emissions pathway and a mid-range population growth trajectory for California (ie each map is the average of 3,600,000 gridded monthly maps of simulated large fire events). Data are from California's Fourth Climate Change Assessment report (Westerling 2018).

tion thinning treatments, wildfires managed for positive ecological outcomes commonly bolster forest resilience (Hessburg *et al.* 2016). In addition, because greater emphasis is placed on prioritizing forest resilience to conserve ecosystem characteristics and services, managing for fire may also require a departure from managing for commodity production as a primary management goal in many places (González-Sanchis *et al.* 2019). Nonetheless, on US Forest Service lands, striking a balance among these considerations in order to preserve ecological resilience while also supporting social and economic sustainability is not only possible but expected, based on both the National Forest Management Act's multiple-use mandate and current implementing regulations (see 36 CFR 219 et seq).

Restoration and adaption strategies

Management responses to increasing area and patch sizes of high-severity fire include two general categories: (1) fire use and (2) restoration thinning. Fire use treatments include prescribed burning (Figure 2, a and b), whereby managers intentionally burn an area in accordance with a site-specific plan. Prescribed fires are effective at reducing the most hazardous fuel layers in seasonally dry forests, including downed dead wood and litter (surface fuels) and small- to medium-sized trees and shrubs (ladder fuels) that can provide vertical continuity and the energy for fires to burn tree crowns (Stephens *et al.* 2009). Managing wildfires ignited by lightning is an alternative fire use treatment (Figure 2c). Lightning fires ignited in remote areas can produce positive ecological outcomes, as has occurred in several US national parks and on occasion in US national forests (Collins *et al.* 2009). Allowing wildfires to burn poses challenges, however, such as smoke management and the risk of changing weather producing undesired fire outcomes. Restoration thinning (Figure 2d), which consists of such activities as chipping, shredding, and whole-tree removal, targets smaller trees and shrubs to reduce ladder fuels, and can be effective for reducing crown fire potential (Stephens *et al.* 2009). However, if the harvest system discards logging debris within treated stands, thinning treatments can instead increase fire hazards. Restoration thinning normally retains larger trees and is used to increase spatial heterogeneity, mimicking the forest structural characteristics resulting from low- to moderate- and mixed-severity fire regimes (Hessburg *et al.* 2016).

Biodiversity

Forest restoration practices, particularly forest thinning, offer potential trade-offs for biodiversity. A key uncertainty pertains to whether the possible negative effects of fuels reduction, such as simplification of complex canopied forests, are outweighed by the benefits of avoiding severe fires and generating more heterogeneous landscapes. However, recent research into the effects of pyrodiversity (defined as the degree of heterogeneity in the age and size of a burned landscape, as well as in the severity of fires and in the time of year when fires occur) has demonstrated benefits for biodiversity. More pyrodiverse landscapes support more diverse bird, pollinator, and flowering plant communities, and may protect pollinators against drought-induced scarcity in floral resources (Ponisio *et al.* 2016; Tingley *et al.* 2016). Even post-fire specialists like the black-backed woodpecker (*Picoides arcticus*), which is a focal species in the management of seasonally dry forests, appear to benefit from a mosaic of patches burned at different severities and may be adversely affected by large, homogeneous, high-severity "megafires" (Stillman *et al.* 2019a,b). Although concerns about degradation of habitat quality for species that depend on complex canopied forests, such as the spotted owl (*Strix occidentalis*), have slowed the pace of forest restoration in the western US (Stephens *et al.* 2019), these species are also adversely affected by large, severe wildfires (Jones *et al.* 2016, 2020). Given the benefits of heterogeneous landscapes for biodiversity and of avoided megafire and drought-related tree mortality, the pertinent challenge is to mitigate the effects of restoration on forest complexity. Landscape-scale restoration activities that retain and promote large trees and snags (standing dead trees), complex canopied forest in topographically appropriate

Figure 2. Fire and restoration thinning treatments in mixed-conifer forests in the Sierra Nevada, California. (a) First entry prescribed fire in 2002, with high forest density and small trees burning; (b) similar area in the same experiment illustrated in (a) after three prescribed fires (2002, 2009, and 2016) showing restored forest conditions (see Collins *et al.* [2014] for details on experiment); (c) wilderness site in Yosemite National Park that was burned by lightning-ignited wildfire and was managed for positive ecological objectives (Collins *et al.* 2009); and (d) multiple restoration thinning treatments (2001 and 2019) showing reduced tree density and surface fuels in the same experiment as depicted in (a) and (b).

areas, and hardwoods (deciduous trees) and shrubs could minimize short-term effects on species of concern so that the long-term benefits of restored forest ecosystems are realized (Figure 3; Churchill *et al.* 2013; North *et al.* 2017).

US National Forest Management Act regulations promote the restoration of ecological integrity and natural processes like fire but also recognize that species-specific management standards and monitoring may be necessary for some at-risk species (36 CFR 219.9). Robust implementation of these provisions in land and resource management plans can balance the need to restore ecosystems and also conserve at-risk species, although current legal requirements do not guarantee this outcome and must be coupled with a commitment to high-quality, science-based implementation and monitoring (Schultz *et al.* 2013). For species listed under the US Endangered Species Act (ESA), opportunities exist during the consultation process under Section 7 of the ESA to explore options to allow for increased fire and restoration thinning without jeopardizing these species or their habitat. Close collaboration among federal and state wildlife and land management agency staff can yield creative strategies to support restoration while also protecting listed species from the effects of restoration thinning and fire at critical times in their life cycles; determining whether such collaborative efforts are successful in achieving their goals will in part require monitoring of conditions before, during, and after treatments. For instance, in the Four Forest Restoration Initiative area in the southwestern US, forest managers work with US Fish and Wildlife Service personnel to monitor active nest sites of Mexican spotted owls (*Strix occidentalis lucida*); this information is then used to support the management of natural ignitions so that such fires will have no detrimental effects on the nesting of this listed species.

Water

Fire-excluded forests not only increase the risk of large, severe wildfires, but by virtue of their high stand density and leaf area, they also reduce the fraction of snow and rainfall that reaches the ground, and exhibit increased

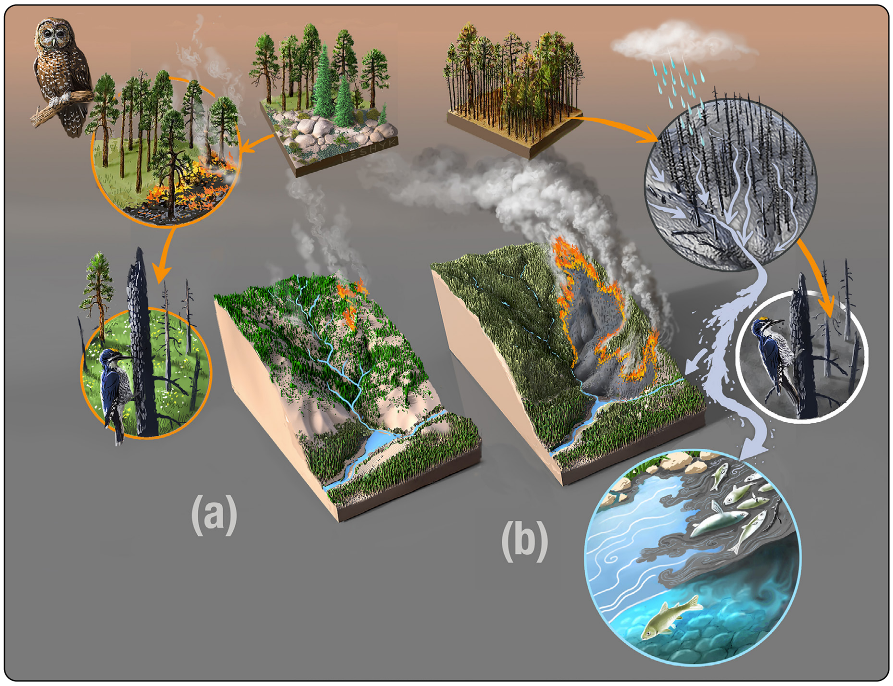

Figure 3. Depiction of two options for a fire-adapted forested watershed. (a) The fire-maintained condition creates forest heterogeneity, provides a range of habitat types, and increases water availability, whereas (b) the fire-excluded condition is at risk of high-severity wildfire because of homogeneous, hazardous forest conditions, which reduce the number of available habitat types and negatively affect water availability; in addition, associated fire emissions degrade air quality.

water demand relative to sparser forest stands or more heterogeneously vegetated landscapes. With seasonally dry forests supplying most of the flow to the Colorado River and the Rio Grande River, and to the Californian water supply system as a whole, there is potential for wildfire and restoration thinning to increase the fraction of water from rainfall and snowmelt that reaches rivers and reservoirs. Wildfire restoration treatments (Figure 2c) can increase landscape heterogeneity and alter water supply by reducing the total cover and average patch size of forested areas (Boisramé *et al.* 2017). Less forest cover in smaller patches reduces precipitation losses to canopy interception; delays snowmelt relative to dense (untreated) forest canopies, where warmer air temperatures drive earlier melt; and reduces summer transpiration. The net result can be increases in streamflow of up to 50 mm yr^{-1} (Boisramé *et al.* 2019). In contrast, heavy thinning can increase streamflow yields by as much as 200 mm yr^{-1} (Roche *et al.* 2018).

Immediate increases in streamflow following forest treatment, however, typically decline as forests regrow in subsequent years. Sustaining the water supply benefits of treatment therefore requires ongoing maintenance treatments. Although some management regimes, such as wildfire restoration, can rely on natural sources of disturbance (eg lightning ignitions; Collins *et al.* 2009), in many situations maintenance treatments should be deliberately incorporated into forest management programs. Other impacts of fire on hydrology, including changes to soil hydraulic and roughness properties associated with hydrophobicity, ash clogging of soil pores, or loss of surface organic matter, also tend to diminish over time, although the importance of these processes in changing hydrological responses under thinning or wildfire management remains unknown (conversely, they have been shown to promote flooding and erosion following large, severe wildfires).

Restoration thinning, prescribed burning, or wildfire restoration that prevent extreme fires also protect water resources from post-fire erosion in severely burned forested landscapes (Figure 3), which poses major threats to water quality and water infrastructure. Indeed, it is these effects that have led some municipalities to invest in forest fuels reduction work in US national forests to avoid the costs associated with post-fire effects on water infrastructure (Huber-Stearns and Cheng 2017). Emerging watershed collaborations, like New Mexico's Rio Grande Water Fund and Colorado's Forests to Faucets partnership, leverage funds from downstream water users to implement fuels reduction and forest restoration treatments, including restoration thinning and prescribed fire, on public forestlands.

Carbon

Fire exclusion has caused artificially high C densities in seasonally dry forests in the western US, and when combined with climate-driven increases in area burned, seasonally dry forests have an increased chance of burning at high severity. Excessive rates of fire-induced tree mortality can transition a forest from C sink to C source. Allowing increasingly large areas to be burned by high-severity fire has the potential to facilitate transition to a non-forest, lower C state, especially with ongoing climate change (Liang *et al.* 2017). Furthermore, when an area burns at high severity, there is a greater likelihood that subsequent fires will also be of high severity, which can reinforce a lower C, non-forested condition (Coppoletta *et al.* 2016; Liang *et al.* 2017). Treatments aimed at reducing high-severity fire through restoration thinning and burning yield an immediate reduction in forest C storage. However, when wildfire burns through a restored area, C emissions and tree mortality are lower, leading to reduced variability in the amount of C stored in the forest (Hurteau *et al.* 2019). Restoring ecologically appropriate fire frequencies can increase C stability, because despite frequent fire events increasing C emissions, low overstory tree mortality leads to C being reabsorbed by the ecosystem (Wiechmann *et al.* 2015).

Quantifying C dynamics associated with restoring fire regimes requires selecting appropriate spatial and temporal scales for evaluation. The probability that wildfire occurs in a given location is projected to increase with ongoing climate change in many seasonally dry forests (Westerling 2018). The widespread application of restoration thinning and the re-establishment of traditional fire regimes can drive initial higher total C losses as compared to a no-management alternative at the mountain-range scale because fire is relatively rare and initial C removal results in a major loss of C from the system (Liang *et al*. 2018). However, projected increases in area burned yield lower total C losses over time from forests with an active fire regime (Liang *et al*. 2018). This outcome is driven by an overall reduction in area burned by high-severity fire and by higher rates of post-fire C uptake that occur when tree mortality is low (Figure 3).

Recognition of this reality has led the California state government to use revenues from its C market to invest in forest restoration efforts, including thinning and prescribed fire, as part of a long-term C sequestration strategy (FCAT 2018).

Air pollution

Although carbon dioxide (CO_2) emissions from wildfire contribute to atmospheric concentrations of GHGs, smoke constituents (eg particulate matter) also affect climate. Moreover, smoke constituents have a greater impact on air quality because they are associated with negative outcomes for human health, with considerable long-term impacts on morbidity and mortality that are projected to increase in the future (Ford *et al.* 2018). In California, particulate emissions from wildfires are expected to increase by up to 101% on average by late century (Hurteau *et al*. 2014). Although most of this projected increase will come from large fires burning in the mid-elevation mixed-conifer forests of the Sierra Nevada, where fuel loads are substantially greater today due to a century of fire exclusion (Hurteau *et al*. 2014), much of this projected increase could be avoided if fuels are restored to pre-fire exclusion conditions (Westerling 2018). Only a limited fraction of the area that requires treatment could be feasibly treated initially with restoration thinning (Liang *et al*. 2018), with the remainder having to be treated with wildfire and prescribed fire, with repeat burning necessary to limit fuels accumulation (North *et al*. 2012). This involves a trade-off for the public, between intense acute emissions from uncontrolled high-severity wildfires and lighter but chronic emissions in spring, fall, and winter from lower intensity fire. While regulators can determine when conditions are most favorable for protecting human health, the scale of the burning required means that the public would be exposed to more smoke from prescribed fires and wildfires managed for fuels reduction and restoration.

Land and air-quality managers have a variety of options at their disposal to mitigate smoke impacts during fire events. Given the projected increases in wildfire and in the application of fire as a management tool, these practitioners will need to offer the public more information and tools, including high-efficiency particulate air (HEPA) filters and evacuation options, to help control their exposure to smoke. An increasingly common practice implemented by the US Forest Service – namely, of assigning air resource advisors to manage and communicate the impacts of wildfire-derived smoke on human health – is a positive step in this direction and could be extended to the prescribed fire context. Air-quality regulators are doing more to support the application of prescribed fire as a way to mitigate the substantial smoke impacts from wildfire (Schultz *et al*. 2019). For example, the US Environmental Protection Agency has revised Clean Air Act regulations (81 FR 68216) to allow prescribed fires to be classified as exceptional events, so that reporting of such incidents does not lead to exceedances of the National Ambient Air Quality Standards; however, no state has yet utilized this provision. The California Air Resources Board has recently expressed a commitment to substantially increase permitting of prescribed fire acreage. Efforts on some national forests (eg the San Juan and Sierra National Forests) to undertake National Environmental Policy Act analyses for prescribed fire and wildfire at unprecedented extents hold promise for supporting more burning in the future.

Commodity production

Commodity production is one area of historical use of the US national forest system that may become increasingly challenging with the realities of fire management, particularly in the fire-prone forests of the western US. Managing for timber harvest in some locations appears to increase fire hazards (Vogler *et al*. 2015; Zald and Dunn 2018), while in other areas, such as in the southern US, timber production and fire hazard reduction are complementary (Stephens *et al*. 2019). Where timber production is a desired activity, tools exist that allow planners and collaborators to consider the trade-offs among management for timber versus fuels reduction and strike a balance among objectives (Ager *et al*. 2014). A more systemic challenge is that state agencies may be less supportive of allowing fires to burn when they have a timber production mandate. However, some harvested areas can successfully support suppression activities (Moghaddas and Craggs 2007), further complicating the issue. Despite the opportunities to manage for multiple objectives, we suggest that, in light of the projected increases in fire extent and severity, timber harvesting practices in fire-prone areas of the western US should be consistent with fire management objectives. Research suggests that there are opportunities to increase fuels reduction work and the flow of restoration wood byproducts from national forests, although a lack of viable markets and industry partners has limited these options (Schultz *et al.* 2019).

Conclusions

Climate change will continue to produce conditions more conducive to severe wildfire across much of the western US. Increases in severe wildfire will further stress many ecosystems and human communities, but actions can be taken today to promote positive ecological outcomes in seasonally dry forests. Restoration treatments can be applied to reduce future fire severity, which would be desirable in terms of conserving biodiversity, increasing water availability, stabilizing C storage, and improving forest resilience and adaptation to climate change. Achieving these outcomes will require collaborative institutions, robust science-based planning and monitoring processes, and the funding necessary to increase the pace and scale of beneficial fire and restoration thinning. Treatments may conflict not only with efforts to maximize commercial timber production but also with other national forest multiple uses, such as recreation. Whether communities support such activities depends on a wide range of factors, including their history of communication and collaboration with land managers and the nature of their social and economic connections with the forest (Ryan and Hamin 2008).

The southern US can provide some insights into how to proceed. In this region, prescribed fire is strongly supported and promoted, and manager application of fire is facilitated through state law. Restoration thinning is also supported in the southern US, and when combined with prescribed burning, provides timber resources for local governments and produces positive results for associated wildlife species, including rare taxa (Stephens *et al.* 2019). In contrast, the western US continues to struggle with fire and forest management, in part due to the lack of agreement on public land management goals, the legacies of federal fire management, and responses to fire hazard reduction that are sometimes ineffective (eg restoration treatments that are disconnected spatially or that do not focus on reducing surface and ladder fuels).

Proactive fire use and restoration thinning will be key to the long-term conservation of seasonally dry western forests and the benefits they provide to society (Stephens *et al.* 2013). Western US state and local governments and federal land management agencies should consider how revised policies and other organizational characteristics, public–private partnerships, collaborative processes, and increased funding and capacity could be achieved. Such a shift may result in near-term reductions in some ecosystem services but will likely accrue longer term benefits in the face of large wildfires and climate change. There is an urgent need to take immediate actions to promote positive ecological outcomes in seasonally dry forests in the western US.

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