Ecological Applications, 31(8), 2021, e02433

Adapting western North American forests to climate change and wildfires: 10 common questions

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Citation: Prichard, S. J., et al. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. Ecological Applications 31(8):e02433. 10.1002/eap.2433

Abstract. We review science-based adaptation strategies for western North American (wNA) forests that include restoring active fire regimes and fostering resilient structure and composition of forested landscapes. As part of the review, we address common questions associated with climate adaptation and realignment treatments that run counter to a broad consensus in the literature. These include the following: (1) Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive? (2) Is forest thinning alone sufficient to mitigate wildfire hazard? (3) Can forest thinning and prescribed burning solve the problem? (4) Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)? (5) Can wildfires on their own do the work of fuel treatments? (6) Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment? (7) Do fuel treatments work under extreme fire weather? (8) Is the scale of the problem too great? Can we ever catch up? (9) Will planting more trees mitigate climate change in wNA forests? And (10) is post-fire management needed or even ecologically justified? Based on our review of the scientific evidence, a range of proactive management actions are justified and necessary to keep pace with changing climatic and wildfire regimes and declining forest heterogeneity after severe wildfires. Science-based adaptation options include the use of managed wildfire, prescribed burning, and coupled mechanical thinning and prescribed burning as is consistent with land management allocations and forest conditions. Although some current models of fire management in wNA are averse to short-term risks and uncertainties, the long-term environmental,

Manuscript received 18 November 2020; revised 9 March 2021; accepted 22 March 2021; final version received 4 July 2021. Corresponding Editor: David S. Schimel.
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social, and cultural consequences of wildfire management primarily grounded in fire suppression are well documented, highlighting an urgency to invest in intentional forest management and restoration of active fire regimes.

Key words: adaptive management; carbon; climate change; Climate Change and Western Wildfires; cultural burning; ecological resilience; forest management; fuel treatments; managed wildfire; mechanical thinning; prescribed fire; restoration; wildland fire.

Introduction

Forested landscapes across much of western North America (wNA) are significantly departed from historical structure, species composition, and wildland fire regime characteristics (Hagmann et al. 2021), and as such, their resilience and resistance to rapidly changing wildfire and climatic regimes are compromised (Stephens et al. 2020, Hessburg et al. 2021). Through a variety of causes, including curtailment of Indigenous burning practices, livestock grazing, and modern fire suppression, fire frequency in the 20th century decreased in many wNA forests (Marlon et al. 2012, Hessburg et al. 2019). The absence of fire and past forest management have led to profound changes in ecosystem structure, composition, and processes over the last two centuries (Hessburg et al. 2005, Parks et al. 2015*b*, Haugo et al. 2019). As the climate warms, forested landscapes face increasing vulnerability to rapid and extensive ecosystem changes from severe, large-scale disturbances such as persistent droughts, insect outbreaks, disease epidemics, and high-severity fires (Allen et al. 2010, Bentz et al. 2010, Crockett and Westerling 2017).

Historically, wildland fires, including human and lightning ignitions, varied in size, intensity, duration, and seasonality (Perry et al. 2011, Hessburg et al. 2016). Patterns of burning and re-burning created mosaics of severity, species distributions, and resource conditions within shifting patchworks of forest and nonforest vegetation and fuels, thereby limiting the extent of stand-replacing fire events (Prichard et al. 2017, Nigro and Molinari 2019, Hagmann et al. 2021). In the context of fire exclusion and climate change, many fire-prone forests now exhibit high surface, ladder, and canopy fuel contagion with lasting implications for ecosystem changes, carbon storage, hydrologic regimes, native biodiversity, and terrestrial and aquatic habitats (Ager et al. 2007, Coop et al. 2020).

In recent decades, increased area burned by western wildfires has been associated with uncharacteristically large patches of high-severity, stand-replacing fire (Parks and Abatzoglou 2020, Hagmann et al. 2021). In some regions, such as the Sierra Nevada Range in California and eastern Cascades of Washington state, area burned by high-severity fire is 4–10 times that of historical fire regimes (Mallek et al. 2013, Reilly et al. 2017). Because high-severity fire events can be catalysts for vegetation change, particularly when coupled with warmer and drier climatic conditions, trends in large wildfires and burn severity have implications for rapid ecosystem shifts and declines in valued resources (Kemp et al. 2019, Stevens-Rumann and Morgan 2019, Coop et al. 2020).

There is growing awareness of the vulnerability of many wNA forests and human communities to changing wildfire and climatic regimes (North et al. 2015*b*, Hessburg et al. 2016). Under the United States National Cohesive Wildland Fire Management Strategy (United States Department of Agriculture and United States Department of Interior 2021), multi-entity, cross-jurisdictional partnerships have formed to increase the pace and scale of forest adaptation and restorative treatments to promote broad-based landscape resilience to fire, fire-adapted communities, and safe and effective wildfire responses. Similarly, recent large wildfires (>1.2 million ha in both 2017 and 2018) in western Canada are prompting re-examination of forest fire management practices and the need to restore more fire-resilient landscapes (Parisien et al. 2020, Tymstra et al. 2020). Northern Mexico and Baja peninsula forests have experienced a much shorter period of fire exclusion, but a growing fire deficit mirrors trends in the United States and Canada (Rivera-Huerta et al. 2016, Yocom Kent et al. 2017).

Over the past two decades, there has been confusion in some of the scientific literature and popular media surrounding changes in the nature and extent of forest and fire regime changes (Hagmann et al. 2021), and the need for and efficacy of adaptation or restorative treatments. Since some treatments can involve the commercial sale of timber, they can be viewed through the lens of conflict over the role of timber production on federal, tribal and private forestlands. The legacy of mistrust from these conflicts affects how different groups perceive the science and its application in support of proactive efforts to increase the resilience of forested landscapes (Schultz and Jedd 2012, Dubay et al. 2013). Perceived uncertainty in the science of fuel treatments and adaptive forest management has the potential to hinder collaborative decision-making, weaken public support for adaptive forest management, and slow implementation of needed forest management, particularly where courts rule that the science is yet unsettled. For example, in a recent opinion on a proposed forest restoration project, US State Court of Appeals for the Ninth Circuit Judge Graber wrote, “The project’s proposed methodology of variable density thinning is both highly controversial and highly uncertain.” (*BARK* et al. *v. U.S. Forest Service*. No. 3:18-cv-01645-MO). Given current warming trends, changing wildfire regimes, and climate projections for the balance of this century, the current slow pace and small scale of adaptive management portend that many forest landscapes will experience uncharacteristic, high-severity wildfires and/or insect outbreaks before treatments can occur (North et al. 2015*b*, McWethy et al. 2019). High-severity disturbance events often have long-lasting impacts, including losses to ecosystem services and valued resources, shifts to new ecosystem types, and reduced options for future adaptation (Stevens-Rumann and Morgan 2019).

Under climate change, land development, and the spread of invasive species, adaptive forest management is not intended to return systems to historical reference conditions (Allen et al. 2011, Falk et al. 2019). Nonetheless, adaptive strategies prompt managers to define a set of historical and future reference conditions that can be used to discern the direction and magnitude of changes from the current conditions and continuing trends to develop metrics of success (e.g., see Keane et al. 2009, Safford and Stevens 2017). An evidenced-based approach built on data and the scientific method is the most promising path to promote resilience in forests subject to future wildfires and climate change (Stephens et al. 2016, 2020). Given the historical role of Indigenous land stewardship on many wNA landscapes, combining western science and Indigenous knowledge systems is foundational to intentionally restoring and adapting western forest ecosystems (Kimmerer and Lake 2001, Lake et al. 2017, Roos et al. 2021).

Here, we provide a synthesis of science-based management strategies that include restoring active fire regimes and fostering resilient forest structure and composition. Through a thorough review of the scientific literature, we evaluate the relative effectiveness of forest management strategies. We then address 10 common questions about fuel treatments and forest adaptation to changing climatic and wildfire regimes: (1) Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive? (2) Is forest thinning alone sufficient to mitigate wildfire hazard? (3) Can forest thinning and prescribed burning solve the problem? (4) Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)? (5) Can wildfires on their own do the work of fuel treatments? (6) Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment? (7) Do fuel treatments work under extreme fire weather? (8) Is the scale of the problem too great? Can we ever catch up? (9) Will planting more trees mitigate climate change in wNA forests? and (10) Is post-fire management needed or even ecologically justified?

Fuel treatments and active forest management

Biophysical context and socio-cultural considerations.— Much of the literature on adaptive forest management and fuel treatments in wNA pertains to seasonally dry pine and mixed-conifer forests, including ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), interior Douglas-fir, and mixed-conifer forests of Douglas-fir (*Pseudotsuga menziesii*), grand or white fir (*Abies grandis*, *A. concolor*), and western larch (*Larix occidentalis*) and is concentrated on the western United States. However, as reviewed by Hagmann et al. (*in press*), the effects of fire exclusion are broad reaching and include departures in oak woodlands, mixed broadleaf-conifer forests, and cold forests as well. As we address the topics of forest and fuel management, it is important to provide the context, observation scale, and scope of inference of existing studies to understand where and when active management may be warranted.

Seasonally dry pine and mixed-conifer forests were historically dominated by fire- and drought-tolerant conifers with thick bark; fire-tolerant leaf, branch, and crown morphology; and other adaptations to surviving low- to moderate-intensity surface fires (Agee 1996, Margolis and Malevich 2016, Stevens et al. 2020). Repeated fires removed fuels and created highly varying patterns of individual trees, small tree clumps, and variable sized openings (Jeronimo et al. 2019, Kane et al. 2019). These fuel characteristics collectively contributed to resistance to active crown fires (Ritter et al. 2020) but allowed for individual tree and tree-group torching. Past management and fire exclusion caused tree infilling in many of these forests (Naficy et al. 2016, Hessburg et al. 2019), resulting in substantially denser forests with continuous layered canopies, homogeneous structure, higher density of fire-intolerant species, and high surface fuel loads and fuel ladders connecting surface to crown fuels (Savage et al. 2013, Battaglia et al. 2018, van Mantgem et al. 2018).

Many western oak woodlands and mixed hardwood-pine forests were historically adapted to frequent fire and actively maintained by Indigenous burning practices (Lake et al. 2018). In the absence of frequent fire, oak woodlands and hardwood-conifer forests have been invaded by conifers and other vegetation (Engber et al. 2011, Hoffman et al. 2019). Due to the often extensive fuel ladders and surface fuel loads of contemporary mixed oak-conifer woodlands, reintroducing low-severity fire in forests now dominated by conifers will not likely restore oak woodlands to enable an active fire regime (Barnhart et al. 1996). In some locations, invasion of non-native grasses combined with frequent human ignitions can lead to a decline in oak woodlands and mixed hardwood-pine forests, favoring grassland expansion, and precluding restoration of oak woodlands (Lilley and Vellend 2009).

Moist mixed-conifer and broadleaf deciduous forests (e.g., quaking aspen, black cottonwood, and balsam poplar, *Populus tremuloides*, *P. trichocarpa, and P. balsamifera*) exist throughout wNA, and where they reside in drier climatic settings, they occupy moist sites and valley-bottom locations. These are environments where dense forests with multi-layered canopies are more typical. Historically, moderate- and high-severity fires were common in these topographic settings (Perry et al. 2011, Hessburg et al. 2019). However, where moist mixed forests were interspersed between dry pine and mixed-conifer forest along topographic and edaphic gradients, low- and moderate-severity fires also commonly occurred (Hagmann et al. 2014, Johnston et al. 2016, Merschel et al. 2018, Ng et al. 2020). Historically, frequent fire favored fire-tolerant tree species and open canopy conditions that were well below carrying capacity of many mixed-conifer forest sites (Hagmann et al. 2021). Indigenous burning also intentionally created patches of meadows, prairies and seasonally dry wetlands in some moist conifer forests (Underwood et al. 2003, Storm and Shebitz 2006). With climate shifting to warmer and drier conditions, managers may reduce the vulnerability of these patches by employing variable density thinning and prescribed fire that favor the likelihood of low- to moderate fire effects rather than high severity by creating tree clumps, gaps, and openings within currently continuous forest canopies (Churchill et al. 2013, Knapp et al. 2017). Where reducing the risk of large patches of high-severity fire is the goal, many of the same strategies used in dry mixed-conifer forests are appropriate to moist mixed-conifer forests (LeFevre et al. 2020). However, small patches of dense and older forest can be embedded within the clumped and gapped tree patterns, and large patches are especially appropriate on north aspects and in valley bottoms (Perry et al. 2011, Hessburg et al. 2015).

Montane cold forests are dominated by thin-barked species such as Engelmann spruce (*Picea engelmanii*), subalpine fir (*A. lasiocarpa*), and lodgepole pine (*P. contorta*), and can include white and black spruce (*P. glauca* and *P. mariana*) further north in the Canadian boreal and subboreal zones (Rowe and Scotter 1973, Agee 1996, Morgan et al. 2008). Departures in these forests are primarily manifested in a loss of burned and recovering patchworks, loss of seral stage and patch size complexity, and high crown fire potential over broad areas (Hessburg et al. 2019, Fig. 1) rather than within-patch changes in tree density and composition. Historical resilience in these forests was largely driven by landscape heterogeneity in the form of patchworks of nonforest vegetation (shrublands, wet and dry meadows) and varied successional and surface fuel conditions, which reduced contagion of dense and layered forests (Stockdale et al. 2019). Indigenous fire stewardship in some cold forests varied post-fire effects to stagger availability of desired resources. The condition of the valued resources (e.g., foods, forage for big game, medicines, basketry materials), fuel loading, and fuel continuity determined the frequency, seasonality, and locations of intentionally burning, where lightning ignitions were too few, or fire effects were insufficient to the maintenance of resources (Lake and Christianson 2019).

Fuel treatments and how they contribute to forest adaptation.—Stephens et al. (2010) recommend four strategies for adapting western forest landscapes to changing climatic and wildfire regimes. They define *resistance* work as that which mitigates expected wildfire effects and protects valued resources, while *realignment* work modifies existing conditions to restore key ecosystem patterns and the processes they drive. Creating *resilient* conditions improves the natural capacity of an ecosystem to respond favorably when unplanned or unanticipated disturbances occur. Finally, they present *response* work as any active facilitation to achieve culturally and ecologically desirable results that are otherwise difficult to achieve. Each of these strategies can play a role in wNA forest management.

As wNA forest ecosystems respond to warmer and drier summers and longer fire seasons, some areas that once supported forests will shift to nonforest (Parks et al. 2019, Coop et al. 2020), and historical fire regimes that resulted from feedbacks between past climate and vegetation may no longer be supported (McWethy et al. 2019). With rapid change and ecological surprises, novel ecosystems and disturbance regimes will emerge, and there is a high level of uncertainty in future ecological outcomes. The combined strategies reviewed in Stephens et al. (2010) can be used to prioritize where adaptive forest management may be the most advisable and effective (Box 1). Furthermore, facilitating ecosystem shifts in portions of the landscape can benefit resilience at landscape and regional scales. For example, certain vegetation types (e.g., shrub and grasslands) may be more adapted to future climate conditions and can contribute to landscape heterogeneity. They also may alter fire behavior patterns towards a reduction in crown fire initiation and spread

There are two main types of management actions to modify forest fuels (termed fuel treatments), and they include (1) reducing surface and canopy fuels via prescribed burning, thinning or other mechanical treatments followed by removal or on-site burning of woody debris, or (2) rearranging fuels including thinning or mechanical treatments without slash reduction. Each type of treatment directs how and where potential energy is stored and released at the scale of forest patches to landscapes, and thresholds to burning.

Fuel reduction.—Common *fuel reduction treatments* include a combination of (1) forest thinning to reduce canopy bulk density and ladder fuels, and (2) prescribed burning or biomass removal to reduce surface fuels, including logging slash from the thinning event and prior fuel accumulations (Reinhardt et al. 2008, Kalies and Yocom Kent 2016). Prescribed burning of logging slash generally includes piling and burning concentrated logging slash and broadcast burning dispersed slash. Forest management projects aimed at fuel reduction in dry or moist mixed-conifer forests and pine, Douglas-fir, or oak woodlands are designed to foster the development of forest structure, composition, and configurations that are more resilient to drought and disturbances. These treatments also commonly reduce

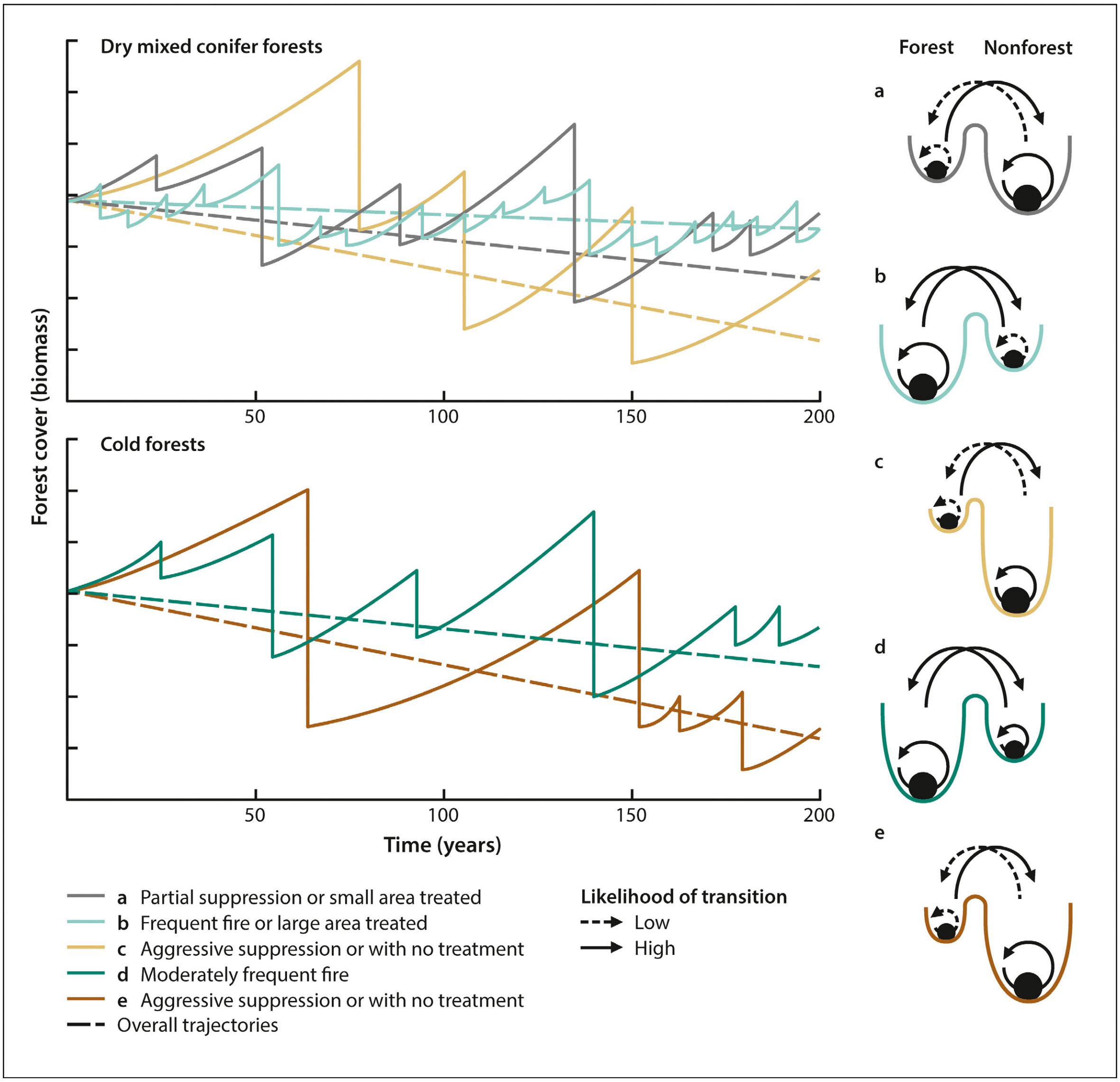

Fig. 1. (A) Dry mixed-conifer forests. Theorized responses of seasonally dry mixed-conifer forest biomass to wildfire and three fire management scenarios under 21st-century climate change. (a) Partial wildfire suppression with only a small fraction of forested landscape treated each year (~1%). In this scenario, escaped high-severity wildfires are the dominant change agent with a high probability of forest conversion to nonforest as represented in the ball and cup figure by a shallow forest basin of attraction and a deep and broad nonforest basin of attraction. (b) A large percentage of the forested landscape (>50%) is treated either by frequent low and moderate severity fires or fuel reduction treatments with ongoing maintenance. Large wildfires are infrequent, and fire severity within the event perimeter is mostly low and moderate severity as represented in the ball and cup figure by a deep and wide forest basin of attraction and a moderately deep and wide nonforest basin of attraction. (c) Aggressive wildfire suppression with no active fuel reduction treatments; similar to scenario A but with even a higher likelihood of forest to nonforest conversion. (B) Cold forests. Wildfire management scenarios represent two levels of wildland fire management under 21st-century climate change. (d) Cold forest area treated with moderately frequent fires of moderate and high severity. Because large fire events are relatively rare, forest regeneration is supported by patchworks of remnant forest, represented by a deep and wide forest basin of attraction. (e) Aggressive fire suppression with no active fuel treatments. In this scenario, escaped wildfires are the major change agent through large, mostly high severity fires. Forest regeneration is limited by large, high severity fire events, and conversion to nonforest is common; represented by a shallow and narrow forest basin of attraction and a deep and broad nonforest basin of attraction.

surface fuel loads to promote lower flame lengths, surface fire intensity and spread, and a reduction in crown fire potential (Agee and Skinner 2005). Forest thinning in these forest types is aimed at retaining larger, more fire-resilient tree species, and restoring open canopy structure. For example, the individuals, clumps, and openings (ICO) method selects trees and tree groups to impart spatial heterogeneity to the forest by varying the

Box 1. Defining restorative and adaptive management

Ecosystem restoration is actively assisting the recovery of an ecosystem that has been degraded, damaged, or transformed (Holl 2020). Adaptive management is a learning-by-doing method of responding to ecosystem changes, informed by effectiveness monitoring (Lyons et al. 2008, Larson et al. 2013*b*). Recent reviews examine in detail research on adaptive and restorative forest fuel treatments, including mechanical thinning, prescribed and Indigenous cultural burning, and management of unplanned ignitions, and their relative effectiveness at mitigating future wildfire spread and severity (Fulé et al. 2012, Stephens et al. 2012, Martinson and Omi 2013, Ryan et al 2013, Kalies and Yocom Kent 2016). Across seasonally dry forests, a promising finding is that treatments involving prescribed or cultural burning or effectively managed wildfires generally mitigate the spread and severity of subsequent wildfires for a period of time after treatment (5–20 yr, depending on site productivity, vegetation, and climate), and are often more effective than mechanical treatments without follow-up prescribed burning (Prichard et al. 2017). Use of these management techniques can therefore improve forest resilience and resistance to change under a warmer, drier climate.

Treatments designed to restore or adapt fire-excluded forests to a changing climate must foster ecosystem resilience and conserve native biodiversity. For example, restoration treatments are often designed to enhance plant vigor, favor fire-adapted species, and create open forest structures, all with the objective of increasing resilience and resistance to climatic warming and severe wildfires (Lehmkuhl et al. 2007, Reinhardt et al. 2008, North et al. 2012). An added benefit of most restorative treatments is that wildland fuel hazard is also reduced (Fulé et al. 2001, Brown et al. 2004). Fire-less fuel reduction treatments rarely mimic the broad role of fire (Reinhardt et al. 2008), which performs many cultural and ecological functions, e.g., nutrient cycling, facilitating tree regeneration by exposing mineral soils, promoting valued cultural and aesthetic resources (Marks-Block et al. 2019). As a result, any area treated using mechanical fuel treatments alone rarely restores fire-adapted ecosystems.

distribution of forest and non-forest cover to achieve a low edge to interior ratio with the goals of refostering drought tolerance and reducing the probability of crown fire (Larson and Churchill 2012, Churchill et al. 2017). Recent evidence suggests that low-intensity fire alone may not increase resilience because it is not sufficiently lethal to shade-tolerant species that established during an extended period of fire exclusion (e.g., Douglas-fir, grand fir, white fir, incense-cedar [*Calocedrus decurrens*]; Cocking et al. 2014, Huffman et al. 2018, Eisenberg et al. 2019). Methods such as ICO are intended to emulate the structural patterns maintained by frequent fires and can be employed where single entry fires may not achieve restoration goals.

Due to altered stand conditions, restoring an active fire regime and reducing climate vulnerability often requires either a managed wildfire that significantly thins forests, consumes fuels, and favors fire-resistant, larger trees (Holden et al. 2010, Kane et al. 2015), or coupled mechanical thinning and prescribed or cultural burning treatment followed by regular maintenance burning (Stephens et al. 2012). Unplanned wildfires that consume surface fuels can also be considered fuel reduction treatments under moderate fire weather conditions (North et al. 2012, Prichard et al. 2017). Mechanical treatments that involve thinning and off-site biomass transport can also be effective fuel reduction surrogates where infrastructure and economics allow (North et al. 2015*a*). In all cases, fuel reduction treatments can be effective at mitigating subsequent wildfire behavior and effects for a period of time after treatment until surface and canopy fuels accumulate through vegetation growth and deposition (Keane et al. 2015).

The key to effective fuel reduction is that it creates gaps in surface and canopy fuel structures and reduces the potential for contagious crown fire initiation and spread (Reinhardt et al. 2008, Martinson and Omi 2013, Fig. 2A). Depending upon the scale of a wildfire event and the underlying climate and weather conditions, past fuel reduction treatments can mitigate fire spread and intensity at very fine to coarse spatial scales (Fulé et al. 2012, Prichard et al. 2017). For example, in a fire-maintained pine forest or savanna, frequent understory burning can maintain low loads of pine needle duff and litter, fine wood and grass to support low-intensity surface fires. In these forest types, the threshold for high-severity fire is only crossed during extreme fire weather and fire behavior, often involving plume-driven fire spread from adjacent forests (Agee and Skinner 2005, Lydersen et al. 2014).

Fuel rearrangement.—Without associated reduction of surface fuels, mechanical thinning and mastication treatments are examples of *fuel rearrangement* treatments (Fig. 2B). Commercial or pre-commercial forest thinning reduces the continuity of tree crowns, their bulk density, and their propensity for spreading crown fire. Consequently, thinning without prescribed burning is considered both a *reduction* of canopy and ladder fuels and a *rearrangement* of fuels from the canopy to the forest floor (Pollet and Omi 2002). Where canopy thinning results in augmented surface fuels, fire behavior and

FIG. 2. Representative photos of (A) fuel reduction treatment (maintenance surface fire in a previously thinned and burned forest); (B) fuel rearrangement (forest residues following mechanical thinning); and (C) fuel accumulation (fire excluded forest with grand fir infilling around western larch trees). Photo credits: Roger Ottmar, Susan Prichard, and John Marshall.

severity can be amplified rather than diminished (Safford et al. 2009, Prichard et al. 2010). Furthermore, many fire-excluded forests have elevated surface fuels associated with more than a century of fire exclusion (Knapp et al. 2013, Keane et al. 2015). Effective treatment therefore necessitates prescribed burning that is intense enough to reduce surface and ladder fuels such that the likelihood of a subsequent intense fire is reduced (Stephens et al. 2012). Wildfires that result in substantial tree mortality may offer a short-term fuel reduction, but over longer time periods (15–25 yr), downed wood accumulations from snag and branch fall can elevate surface fuels and create conditions for high-intensity reburn events (Stevens-Rumann et al. 2012, Dunn and Bailey 2016, Johnson et al. 2020). As such, moderate to high-severity wildfires are generally considered a type of longer-term fuel rearrangement (Lydersen et al. 2019*a*).

Development of landscape mosaics.—Intentional management of landscapes involves the broad-scale planning and spatial design of treatments, including determining where they are most effective on the landscape and assessing how individual treatments will interact with fire over space and time (Ager et al. 2010, Falk et al. 2019). Many historical landscapes, influenced by lightning and Indigenous ignitions, supported a hierarchical patchwork of forest and nonforest vegetation at coarse spatial scales in addition to meso- and fine-grained heterogeneity of forest age classes and vulnerability to fire (Hessburg et al. 2019, Hagmann et al. 2021). Managed landscape mosaics can be designed to restore more characteristic patchworks of open and closed canopy vegetation of different patch sizes, tree ages, and forest densities, and of fuel contagion to facilitate restoring fire as a dynamic and beneficial ecological process (Hessburg et al. 2015).

Fuel treatments that modify within-stand structure to remove small trees and reduce surface fuels while retaining large, more fire-resistant trees and variable stand structure (Stephens et al. 2021) are most appropriate in dry pine, dry to moist mixed-conifer forests and oak woodlands, particularly where there is evidence that older fire-resistant species have been or are being replaced by younger fire-sensitive species (e.g., Yocom-Kent et al. 2015). This mirrors the fine- to meso-scale (i.e., 1–10,000 ha) heterogeneity in forest structure that characterized these frequent-fire forest types historically (Hessburg et al. 2019, Hagmann et al. 2021). In cold forests characterized by greater landscape-scale heterogeneity, fuel treatments including managing unplanned wildfires may be more appropriate at larger scales, particularly where landscape-scale heterogeneity has been lost (Hessburg et al. 2019, Hagmann et al. 2021).

Within this context, reserves and other no-treatment areas can be designated where fuels are left to accumulate over time (Fig. 2C). Competing resource management objectives and consideration of values at risk often inevitably lead to management areas where fuel reduction treatments are not allowed and wildfires are actively suppressed. Examples include late-successional reserves, riparian reserves, and other locations where wildland fires and fuel reduction treatments are restricted to facilitate habitat development. Over time, surface and canopy fuel accumulations and wildfire dynamics will threaten the objectives of these reserved areas (Van de Water and North 2011, Reilly et al. 2018). Stationary reserves will be difficult to maintain in areas where wildfires are the disturbance engine that drives the ecosystem.

TEN COMMON QUESTIONS ABOUT ADAPTIVE FOREST MANAGEMENT

Although the need to increase the pace and scale of fuel treatments is broadly discussed in scientific and policy arenas (Franklin and Johnson 2012, North et al. 2012, Kolden 2019), there is still confusion and disagreement about the appropriateness of forest and fuel treatments. For example, recent publications have questioned whether large, high-severity fires are outside of the historical range of variability for seasonally dry forests, and whether the risk of high-severity fire warrants large-scale treatment of fire-prone forests (Bradley et al. 2016, DellaSala et al. 2017). Others have questioned whether intentional management, including forest thinning, is effective or justified outside of the wildland urban interface (Moritz et al. 2014, Schoennagel et al. 2017). Furthermore, debates around the management of fire-adapted forests are occurring within the context of long running conflicts over timber production on public lands, especially federal lands, leading to questions about science-based benefits of management treatments where they align with economic incentives (Daniels and Walker 1995). Currently, management strategies employing active fire suppression and limited use of fuel reduction treatments are common for most public land management agencies.

Among the many challenges to proactive management on public lands (e.g., funding, adequate and qualified personnel, smoke impacts, and weather and fuel conditions that fall within burn prescription parameters), uncertainty in the scientific literature about forest management and fuel treatments is commonly cited in planning process-public comment periods (Spies et al. 2018, Miller et al. 2020). In the following sections, we examine 10 common questions about forest management and fuel treatments. We summarize them in Table 1 and provide key citations that examine these questions. For each topic, we evaluate the strength of evidence in the existing scientific literature concerning each topic. Our goal is to help managers, policy makers, informed public stakeholders, and others working in this arena to establish a robust scientific framework that will lead to more effective discussions and decision-making processes, and better outcomes on the ground. Additional citations for each question are listed in Appendix S1.

Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive?

Concerns about forest thinning and other forms of active management are sometimes based on the assumption that contemporary conditions and fire regimes in dry pine and mixed-conifer forests are not substantially departed from those maintained by uninterrupted fire regimes (Hagmann et al. 2021). This perspective does not accurately reflect the breadth and depth of scientific evidence documenting the influence of over a century of fire exclusion. Support for the suggestion that ecological departures associated with fire exclusion are overestimated has repeatedly failed independent validation by multiple research groups (Hagmann et al. 2021). In addition, these arguments fail to consider widespread Indigenous fire uses that affected landscape scale vegetation conditions linked to valued cultural resources and services, food security, and vulnerability to wildfires (Lake et al. 2018, Power et al. 2018). As is explored in the following sections, a number of forest management and treatment strategies are shown to be highly effective. Site conditions and history are always important considerations. Moreover, there is no one-treatment-fits-all approach to forest adaptation.

Evidence from a broad range of disciplines documents widespread, multi-regional 20th-century fire exclusion in interior forested landscapes of wNA (see a detailed reference list and discussion in Hagmann et al. 2021). Collectively, these studies reveal extensive changes in tree density, species and age composition, forest structure, and continuity of canopy and surface fuels. Forests that were once characterized by shifting patchworks of forest and nonforest vegetation (i.e., grasslands, woodlands, and shrublands) in the early 20th-century gradually became more continuously covered in forest and densely stocked with fuels (Fig. 4).

However, for over two decades, a small fraction of the scientific literature has cast doubt on the inferences made from fire-scar based reconstructions and broader landscape-level assessments to suggest that estimates of low- to moderate-severity fire regimes from these studies are overstated. Hagmann et al. (*in press*) examine this counter-evidence in detail and identify critical flaws in reasoning and methodologies in original papers and subsequent re-application of these methods in numerous geographic areas. Subsequent research shows that studies relying on Williams and Baker (2011) methods for estimating historical tree densities and fire regimes overestimate tree densities and fire severity (see also Levine et al. 2017). Moreover, established tree-ring fire-scar methods more accurately reconstruct known fire occurrence and extent. Other studies, also based on the methods of Williams and Baker (2011), conflate reconstructed low-severity, high-frequency fire regimes with landscape homogeneity. These interpretations disregard critical ecosystem functions that were historically associated with uneven-aged forests embedded in multi-level fine-, meso- and broad-scale landscapes. By extension, claims that low-severity fire regimes are overestimated then imply that large, high-severity fires were a regular occurrence prior to the era of European colonization. Such interpretations may lead to the conclusion that recent increases in high-severity fire are still within the historical range of variability, and that there is no need of restorative or adaptive treatments (Hanson and Odion 2014, Odion et al. 2014, Baker and Hanson 2017).

Indeed, research from across wNA has shown that high-severity fire was a component of historical fire regimes, and that fires of all severities are currently in deficit (Parks et al. 2015*b*, Reilly et al. 2017, Haugo et al. 2019, but see Mallek et al. 2013). However, reanalysis of the methods of Baker and others shows that their methods inherently overestimate fire severity and the frequency and area affected by high-severity fire (Fulé et al. 2014, Hagmann et al. 2021). In addition, high-severity patches in recent fires are less heterogeneous and more extensive than the historical range of variability for forests characterized by low- and moderate-severity fire regimes (Stevens et al. 2017, Hagmann et al. 2021). Finally, research across wNA reveals key climate-vegetation-wildfire linkages,

TABLE 1. Ten common questions about active forest management.

Question	Summary of evidence	Key citations
(1) Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive?	Broad-scale evidence of fire exclusion is strong across disciplines and western forest ecosystems. Although high severity fire was a component of many historical fire regimes, the frequency and extent of high severity fire over the past few decades is outside the range of historical range of variability	Hessburg et al. (2005), Reynolds et al. (2013), Stine et al. (2014), Safford and Stevens (2017), Stephens et al. (2020), Hagmann et al. (2021)
(2) Is forest thinning alone sufficient to mitigate wildfire hazard?	Thinning alone can sometimes mitigate fire severity, but through residual logging slash, desiccation of understory fuels, and increased surface wind flow without accompanying surface fuel reduction, thinning can contribute to high-intensity surface fires and abundant mortality	Stephens et al. (2009), Fulé et al. (2012), Martinson and Omi (2013), Kalies and Yocom Kent (2016)
(3) Can forest thinning and prescribed burning solve the problem?	Although thinning and prescribed burning have been shown to be highly effective, not all forests are appropriate for this treatment (e.g., thin-barked species common in cold mixed-conifer forests). This type of fuel treatment is also not appropriate for wilderness and other roadless areas	DellaSala et al. (2004), Battaglia and Shepperd (2007), Reinhardt et al. (2008)
(4) Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)?	The majority of designated WUI is in private ownership and hence these lands are sometimes more difficult to treat than public lands. Treating dry and moist mixed-conifer forests beyond WUI buffers can modify fire behavior and change the intensity of wildfires arriving at communities	Kolden and Brown (2010), Bladon (2018), Hallema et al. (2018), Kolden and Henson (2019), Schultz et al. (2019)
(5) Can wildfires on their own do the work of fuel treatments?	Unplanned fires that escape suppression often burn under extreme fire weather and can have severe wildfire effects. In contrast, prescribed burns and managed wildfires generally burn under more moderate weather conditions and contribute to variable fire effects and surface fuel reduction that can mitigate future wildfire severity	Miller and Safford (2012), Parks et al. (2015*a*, 2016), Prichard et al. (2017), Stevens et al. (2017), Kane et al. (2019), Huffman et al. (2020), Rodman et al. (2020)
(6) Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment?	Although fuel reduction treatments can assist in suppression operations, primarily using fuel treatments to suppress future wildfires actually contributes to wildland fire deficit. Adaptive treatments in fire-adapted landscapes aim to restore the patch to landscape role of fire as an ecological process, reduce fire effects and need for aggressive suppression when the fire next occurs	Reinhardt et al. (2008), Safford et al. (2012), Stephens et al. (2020)
(7) Do fuel treatments work under extreme fire weather?	Fire behavior associated with persistent drought, high winds and column-driven spread are associated with higher burn severity in western North American forests. However, strong scientific evidence across dry and moist mixed conifer forests demonstrates effectiveness at mitigating burn severity, often even under extreme fire weather conditions	Arkle et al. (2012), Yocom-Kent et al. (2015), Povak et al. (2020), Prichard et al. (2020)
(8) Is the scale of the problem too great? Can we ever catch up?	The current pace and scale of treatments is decidedly inadequate to restore fire-resilient and climate adapted landscapes. However, evidence strongly supports that expanded use of fuel reduction treatments can be effective	Collins et al. (2009), North et al. (2012), Parks et al. (2015*a*, 2016), Ager et al. (2016), Barros et al. (2018), Liang et al. (2018)
(9) Will planting more trees mitigate climate change in wNA forests?	Temperate rainforests and other wet forests have the capacity to store and sequester high amounts of forest carbon. However, planting to increase tree density and continuity in fire-prone forests is unsustainable due to high fire danger, anticipated climatic water deficits and drought stress	Thompson et al. (2007), Veldman et al. (2019), Holl and Brancalion (2020)
(10) Is post-fire management needed or even ecologically justified?	Active forest and fuels management may be required beyond the initial fire response in order to promote future forest resilience to disturbance and climate change. Due to fire exclusion, uncharacteristically dense patches of dead trees may contribute to high-severity reburns as they fall and create heavy surface fuel accumulations	Peterson et al. (2015), Lydersen et al. (2019*a*), North et al. (2019)

Note: Western North America is abbreviated wNA.

where fire frequency, extent, and severity all increase with increasing climatic warming, suggesting that observed trends in fire patterns are commensurate with predicted relationships with ongoing climate change (McKenzie and Littell 2017, Parks and Abatzoglou 2020).

Another perspective on this debate contends that whether historical records can be agreed upon is of ancillary importance. Adaptive forest management and fuel reduction treatments are primarily aimed at increasing forest resilience and/or resistance to climate change, fire and other disturbances, which has positive societal and ecological impacts that do not require justification based on historical conditions, particularly given the no-analog present and future that climate change presents (Freeman et al. 2017). For example, the most concerning contemporary high-severity fire events are associated with large patches of complete stand replacement (Miller and Quayle 2015, Lydersen et al. 2016). In some cases, high-severity fire events convert forests to shrubland and grassland assemblages as alternative stable states in uncharacteristically large patches (Falk et al. 2019, Kemp et al. 2019, Stevens-Rumann and Morgan 2019). As such, a critical forest management concern is that high-severity wildfires are accelerating rates of vegetation change, forest conversion, and vulnerability of native habitats in response to a warming climate.

Is forest thinning alone sufficient to mitigate wildfire hazard?

While "thin the forest to reduce wildfire threat" is commonly cited in the popular media, the capacity for thinning alone to mitigate wildfire hazard and severity is not well supported in the scientific literature. Thinning treatments require strategic selection of trees to target fuel ladders and fire-susceptible trees, along with a subsequent fuel reduction treatment (Jain et al. 2020). When thinning is conducted without accompanied surface fuel reduction, short and long-term goals may not be realized.

Thinning from below reduces ladder fuels and canopy bulk density concurrently, which can reduce the potential for both passive and active crown fire behavior (Agee and Skinner 2005). For instance, Harrod et al. (2009) found that thinning treatments that reduced tree density and canopy bulk density and increased canopy base height significantly reduced stand susceptibility to crown fire compared to untreated controls. Furthermore, large-diameter trees and snags that provide essential wildlife habitat and other ecosystem values can be retained and fuels can be deliberately removed around these structures using this approach (Lehmkuhl et al. 2015). Where wood from treatments can be marketed, revenues from thinning help to sustain broader management goals on public lands. For example, some landscape restoration collaboratives seek to reinvest profits from commercially viable thinning to off-set costs associated with more labor-intensive manual thinning and prescribed or cultural burning needs (Schultz and Jedd 2012).

Some studies show that thinning alone can mitigate wildfire severity (e.g., Pollet and Omi 2002, Prichard and Kennedy 2014, Prichard et al. 2020), but across a wide range of sites, thin and prescribed burn treatments are most effective at reducing fire severity (see reviews by Fulé et al. 2012, Martinson and Omi 2013, Kalies and Yocom Kent 2016). On most sites, thinning alone achieves a reduction of canopy fuels but contributes to higher surface fuel loads. If burned in a wildfire, these fuels can contribute to high-intensity surface fires and elevated levels of associated tree mortality (e.g., Stephens et al. 2009, Prichard and Kennedy 2012). When trees are felled and limbed, fine fuels from tree tops and branches (termed activity fuels) are re-distributed over the treatment area, thereby increasing surface fuel loads (Martinson and Omi 2013). Mechanical fuel reduction treatments of these activity fuels are possible, but in many locations, biomass removal and utilization (e.g., for bioenergy) after thinning treatments can be cost-prohibitive due to long hauling distances and the economic and technological challenges of building new biomass facilities (Hartsough et al. 2008). Mastication equipment is sometimes used to shred understory trees and shrubs into smaller woody fragments, which are then redistributed and left on site (Kane et al. 2009). However, following mastication, surface fuels are temporarily elevated, and masticated stands that burn in wildland fires can cause deep soil heating from long-duration smoldering combustion and elevated fire intensities (Kreye et al. 2014).

Other unintended consequences of thinning without concomitant reduction in surface fuels can occur. For instance, decreasing canopy bulk density can change site climatic conditions (Agee and Skinner 2005). Wildfire ignition potential is largely driven by fuel moisture, which can decrease on drier sites when canopy bulk density is reduced through commercial thinning (e.g., Reinhardt et al. 2006). Reduced canopy bulk density can lead to increased surface wind speed and fuel heating, which allows for increased rates of fire spread in thinned forests (Pimont et al. 2009, Parsons et al. 2018). Other studies show no effect of thinning on surface fuel moisture (Bigelow and North 2012, Estes et al. 2012), suggesting that thinning effects on surface winds and fuel moisture are complex, site specific, and likely vary across ecoregions and seasons.

In summary, although the efficacy of thinning alone as a fuel reduction treatment is questionable and site dependent, there exists widespread agreement that *combined* effects of thinning plus prescribed burning consistently reduces the potential for severe wildfire across a broad range of forest types and conditions (Fig. 3; Fulé et al. 2012, Kalies and Yocom Kent 2016, Stephens et al. 2021). Given this broad consensus in the scientific literature, some authors suggest that forest thinning should be considered in the context of wildfire hazard abatement, ecological restoration and adaptation, and revitalization of cultural burning (Lehmkuhl et al. 2007, Hessburg et al. 2015, Huffman et al. 2020). Where restoring resilient forest composition and structure and reducing future wildfire hazard are goals of management (Koontz et al. 2020), combined thinning and burning approaches will provide ecological and wildfire-risk reduction benefits (Knapp et al. 2017).

FIG. 3. Active forest restoration treatment, Sinlahekin Wildlife Refuge, Washington Department of Fish and Wildlife. Top left: multi-layered, dense dry mixed conifer forest after 100 yr of fire exclusion. Top right: residual forest after a variable density thinning treatment. Bottom right: treated condition after pile and broadcast burning. Bottom left: post-wildfire photo after the 2015 Lime Belt fire. *Photo credit: John Marshall.*

Can forest thinning and prescribed burning solve the problem?

Fire has been a tool that has been actively used for millennia. Indigenous burning practices maintained prairies, oak and pine savannas, riparian areas, mixed-conifer, hardwood, and dry forests, and high mountain huckleberry and beargrass assemblages for food, medicine, basketry and other resources (Trauernicht et al. 2015, Roos et al. 2021). Following prolonged fire exclusion, many seasonally dry forest landscapes that were once frequently burned now are densely stocked with multi-layered canopies that often require thinning prior to restoring fire (North et al. 2012, Ryan et al. 2013). Prescribed burning on its own and in combination with mechanical thinning are essential fuel reduction treatments with demonstrated effectiveness in reducing fire severity, crown and bole scorch, and tree mortality compared to untreated forests (Safford et al., 2012*a*,*b*, Kalies and Yocom Kent 2016). Thinning and burning in partnership with local Indigenous knowledge and practice can support culturally valued practices, traditions, livelihoods, and food and medicine security (Sowerwine et al. 2019).

Although the use of prescribed burning, often in combination with mechanical thinning, has been shown to be highly effective at mitigating wildfire severity and increasing forest resilience to drought, insects and disease (Hood et al. 2015), these treatments alone cannot address forest management challenges across wNA. Fuel reduction treatments are not appropriate for all conditions or forest types (DellaSala et al. 2004, Reinhardt et al. 2008, Naficy et al. 2016). In some mesic forests, for instance, mechanical treatments may increase the risk of fire by increasing sunlight exposure to the forest floor, drying surface fuels, promoting understory growth, and increasing wind speeds that leave residual trees vulnerable to wind throw (Zald and Dunn 2018, Hanan et al. 2020). Furthermore, prescribed surface fire is difficult to implement in many current mesic forests since fire readily spreads into tree crowns via abundant fuel ladders and can result in crown fires. In other forest types such as subalpine, subboreal, and boreal forests, low crown base heights, thin bark, and heavy duff and litter loads make trees vulnerable to fire at any intensity (Agee 1996, Stevens et al. 2020). Fire regimes in these forests, along with lodgepole pine, are dominated by moderate- and high-severity fires, and applications of forest thinning and prescribed underburning are generally inappropriate. However, landscape burning and maintenance of high elevation forests and meadows is part of cultural burning, and high-intensity crown fire is used

TABLE 2. Examples of wildfire management of unplanned ignitions and the influence of past wildfires in national parks and wilderness areas.

Area	Management objective	Study findings	Biophysical setting	Reference
North Rim Grand Canyon National Park, AZ	Restoring fire; created strategic fuel reductions to allow for natural fire to return	Fires have thinning effect on small diameter trees along with fine fuel and coarse wood consumption	dry ponderosa pine forest and shrublands; cold dry mixed conifer forests	Fulé and Laughlin (2007), Stoddard et al. (2020)
Saguaro Wilderness, AZ	Sky islands; 30 yr of repeated wildland fires	Repeat fires have reduced small density trees but medium trees are still denser than historical stand structures probably supported	dry ponderosa pine forest and shrublands	Holden et al. (2007), Hunter et al. (2014)
Hualapai tribal lands, AZ	Compared fire scars with modern use of low-intensity prescribed burning	Prescribed fires since the 1960s approximate the frequent surface fires of historical record but could incorporate greater variability in temporal schedules of burning	Dry ponderosa pine forests	Stan et al. (2014)
Gila/Aldo Leopold Wilderness, NM	Restore fire as natural process Surface loads and continuity drive high fire frequency on productive sites	Low severity fires beget low severity fires, and high severity fires tend to reburn at high severity in flammable shrub fields. Previous fires reduce size of subsequent fires for a short period of time	dry ponderosa pine forest and shrublands; dry mixed conifer forest; some cold forest	Rollins et al. (2002), Holden et al. (2007, 2010), Hunter et al. (2014), Parks et al. (2014, 2015*a*, 2016, 2018), Holsinger et al. (2016)
Zion National Park, UT	Science-based fire management plan including managed wildfires, prescribed burning, and hazardous fuel reduction	Repeat prescribed fires reduce probability of crown fire and increased grass and forb cover, but not tree density or shrub cover	dry ponderosa pine forest and shrublands	Brown et al. (2019)
Yosemite National Park (YNP), CA	Restore fire as natural process; began with fires within the park interior and gradually worked outward to allow for more fires throughout park	High severity burns favor flammable shrub fields, which perpetuate high severity reburns. Low severity burns perpetuate low severity burns		Boisramé et al. (2017), Collins et al. (2009), Coppoletta et al. (2016), Scholl and Taylor (2010), Thode et al. (2011), van Wagtendonk et al. (2012)
Sequoia and Kings Canyon National Parks, Giant Sequoia National Monuments, CA	Restore fire as natural process	In red fir forests, repeated low- to moderate-severity fire can restore structural heterogeneity		Meyer et al. (2015)
Frank Church – River of No Return Wilderness, ID	Restore fire as natural process	Burn severity is lower within recent fire areas and increases with time since fire. Previous fires reduce size of subsequent fires	dry mixed conifer forests and cold forests	Teske et al. (2012), Parks et al. (2014, 2015*a*, 2016, 2018), Holsinger et al. (2016)
Bob Marshall Wilderness Area, MT	Restore fire as natural process	Previous fires reduce size of subsequent fires	cold mixed conifer forests, Rocky Mountains	Belote et al. (2015), Holsinger et al. (2016), Keane et al. (2006), Larson et al. (2013*a*), Parks et al. (2015*a*, 2016, 2018), Teske et al. (2012)
Selway-Bitterroot Wilderness Complex, ID and MT	Restore fire as natural process; moisture content of large fuels and tree crowns drive fire frequency (higher on drier sites)	Previous fires reduce size of subsequent fires	cold mixed conifer and subalpine forests	Rollins et al. (2002), Parks et al. (2015*a*), 2016, 2018), Barnett et al. (2016*a*), Holsinger et al. (2016), Morgan et al.

Table 2. Continued.

Area	Management objective	Study findings	Biophysical setting	Reference
				(2017), Teske et al. (2012)
Banff, Kootenay and Yoho National Parks (NP), BC & Alberta, Canada	Guard fires to allow for more natural ignitions to burn within park; restoration of aspen and grasslands (bison habitat)	Multiple prescribed burns to reduce dense lodgepole pine (LPP) and allow aspen to regenerate	cold mixed conifer and subboreal forests, Rocky Mountains	White (1985), Park et al. (2019)
Wood Buffalo National Park, AB and NWT, Canada	Restore and maintain fire as natural process	Fire severity is influenced by pre-fire stand structure and composition, topoedaphic context, and fire weather at time of burning. Burned areas less likely to burn again for 33 yr, though this decreases in drought years	vegetation is representative of the western Canadian boreal forest	Parks et al. (2018), Thompson et al. (2017), Whitman et al. (2019)

Note: State and province abbreviations are AZ, Arizona; NM, New Mexico; ID, Idaho; MT, Montana; BC, British Columbia; AB, Alberta; NWT, North West Territory.

operationally on national forests and parks within the United States and Canada for landscape restoration objectives (Table 2).

Even where socially and ecologically appropriate, thinning and low-intensity prescribed burning generally require repeated treatments to meet fuel reduction objectives. For example, without prior thinning, low-intensity prescribed fire, on its own, may not consume enough fuel or cause enough tree mortality to change forest structure and reduce crown fire hazard (e.g., Lydersen et al. 2019*b*). In contrast, prescribed burns in heavy slash may result in high tree mortality. The first harvest entry into fire-excluded stands often leaves high surface fuel loads and dense understories that require one or more prescribed burning treatments to reduce surface and ladder fuels (Goodwin et al. 2018, Korb et al. 2020). Thus, it often takes multiple treatments and/or fire entries, as well as ongoing maintenance, to realize resilience and adaptation goals (Agee and Skinner 2005, Stevens et al. 2014, Goodwin et al. 2020). Given the extent and variability of forest ecosystems that have experienced prolonged fire exclusion, active forest management can be only one tool to increase adaptation to climate and future fires.

Although thinning and prescribed burning have been shown to be highly effective, the current scale and pace of these treatments do not match the scale of the management challenge (Barnett et al. 2016*b*, Kolden 2019). Mechanical treatments are constrained by land management allocations and their enabling legislation (e.g., wilderness and roadless areas), operational constraints (e.g., steep slopes, distance to roads, costs), and administrative boundaries (e.g., riparian areas, areas managed for species of concern). In the central Sierra Nevada for example, these constraints, combined with large areas of non-productive timberland that are unsuitable for commercial treatment due to steep slopes or distance from roads, left only 28% of the landscape available for mechanical thinning and prescribed burning treatments (North et al. 2015*a*). In the remaining area, prescribed burning alone and/or use of managed wildfires may be suitable replacement treatments (Boisramé et al. 2017, Barros et al. 2018). However, prescribed fire-only treatments are frequently limited by cost, liability, air quality regulations, equipment availability, personnel capacity and training, and the need for ongoing maintenance treatments (Quinn-Davidson and Varner 2012, Schultz et al. 2019).

In light of these constraints, some researchers and managers have called for the expanded use of landscape-scale prescribed burns and managed wildfires in addition to fuel reduction treatments as a promising approach to expand the pace and scale of adaptive management (Question 5). Increasingly collaborative restoration partnerships with Indigenous cultures can increase opportunities for re-instating tribal stewardship practices (Lake et al. 2018, Long and Lake 2018). Under appropriate weather and safety conditions, and where infrastructure is not at risk, managed wildfire may serve as a useful and cost-effective tool for reintroducing wildfire to fire-excluded forests and achieve broad-scale management goals.

Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)?

A question often asked by land managers is where to locate fuel treatments to maximize their advantage while minimizing adverse impacts. The 2000 National Fire Plan

(USDA and USDI 2001) and the 2002 Healthy Forests Initiative identified the need to reduce wildfire risk to people, communities, and natural resources. The 2003 Healthy Forests Restoration Act (HFRA, Congress.gov, 2020) then specified that >50% of fuel reduction funding be spent on projects within the Wildland Urban Interface (WUI), and it reduced environmental review within 2.41 km (1.5 miles) of at-risk communities. The significant increase in homes lost and suppression dollars spent in the WUI in subsequent years (Mell et al. 2010) has catalyzed extensive research on the WUI environment and population expansion into wildlands (Radeloff et al. 2018). Subsequent studies demonstrating fuel treatment effectiveness in the WUI (Safford et al. 2009, Kennedy and Johnson 2014) and spatial methods for optimizing WUI fuel treatments (Bar Massada et al. 2011, Syphard et al. 2012) could be taken to suggest that most fuel reduction should be implemented in the WUI to protect homes and lives.

However, prioritizing the WUI-only for fuel reduction treatments is often too narrow in scope to address broader landscape-scale objectives. For example, Schoennagel et al. (2009) found that more than two-thirds of the area within a 2.5 km radius of at-risk communities was privately owned and unavailable for federally funded fuel treatments. This finding partly elucidates why most hazard reduction fuel treatments are implemented outside of HFRA designation. Fuel treatments on federal lands near communities may also be significantly more difficult, expensive, and risky to implement, while air quality regulations and associated risks create disincentives to treating near homes. Alternatively, agencies may be able to meet both annual prescribed burning accomplishment targets and ecological objectives in areas more distant from the WUI with fewer risks, less money, and fewer personnel (Kolden and Brown 2010, Schultz et al. 2019). Further, there is increasing evidence that treating fuels across larger spatial extents in strategically planned wildland locations, rather than immediately adjacent to WUI, can indirectly reduce risk to communities (Smith et al. 2016, Bowman et al. 2020). Benefits of this strategy include increased initial attack and short-term suppression effectiveness, reduced crown fire potential and ember production, reduced smoke impacts to communities, and increased forest resilience (Ager et al. 2010, Stevens et al. 2016).

Fuel reduction treatments also can support cultural, ecological, ecosystem service, and management objectives beyond the WUI. For example, treatments that restore the ecological resilience of old-growth forests and patches with large and old trees are critical to long term maintenance of wildlife habitats (Hessburg et al. 2020) of seasonally dry forests and terrestrial carbon stocks, and slowing the feedback cycle between fire and climate change (Hurteau and North 2009). Treatments in watersheds that are distant from the WUI and protect municipal and agricultural water supplies are critical to minimizing high-severity fire impacts that can jeopardize clean water delivery (Bladon 2018, Hallema et al. 2018). For example, post-fire erosion and debris flows may cause more detrimental and longer-term impacts to watersheds than the wildfires themselves (Jones et al. 2018, Kolden and Henson 2019).

Finally, treated areas outside the WUI can serve as defensible positions for fire suppression personnel that can be used to establish control lines or allow for more flexible suppression strategies, freeing up resources to protect WUI infrastructure or forests in another area (Thompson et al. 2017), or can support rapid and organized evacuation when they are implemented along evacuation routes (Kolden and Henson 2019). Across complex landscapes, it is more effective in the long-term to prioritize fuel treatments that maximize benefits across large areas and over long time frames, rather than constrain them to the WUI.

Can wildfires, on their own, do the work of fuel treatments?

The use of managed wildfires and co-managing incidents (e.g., suppressing in some areas, and allowing other areas to burn) is increasingly promoted in the scientific literature (Stephens et al. 2016, Moreira et al. 2020). Managed wildfires are particularly appropriate in backcountry areas where lack of road access, steep topography, firefighter safety concerns, or management designations limit opportunities for active management (Hessburg et al. 2016, Huffman et al. 2020). However, in many cases the effects of fire exclusion on increased tree density, layering, surface fuels, and fuel ladders are extensive (Meyer 2015). Under these conditions, opportunities for cultural burning, prescribed burning, and managed wildfires are limited to days with low to moderate fire weather, and these windows of opportunity are shrinking under climate change (Westerling et al. 2016).

For the past several decades, land managers have generally followed one of two strategies to respond to wildfires in wNA forests. First, most agencies in the United States and Canada have followed a policy of aggressive fire suppression, and this approach is increasingly used in Mexico (Stephens and Fulé 2005). Under this policy, a small fraction of fires that escape suppression (<3%) are responsible for over 90% of area burned, based on a 1992 to 2015 reference period (Abatzoglou et al. 2018). Second, some land managers, including those managing national parks and wilderness areas, have designated large, remote areas where most wildfires are allowed to burn under moderate fire weather and fuel conditions (Huffman et al. 2020). These are termed managed wildfires, with the goal of restoring more characteristic fire regimes and landscape patterns in the context of incident-specific objectives (Table 2).

In contrast, unplanned fires that escape suppression in fire-excluded landscapes during extreme fire weather do not generally restore forest resilience. Landscapes that are consistently managed with active fire suppression typically have a greater area burned at higher severity than those managed to restore more resilient fire regimes (Stevens et al. 2017, Rodman et al. 2020). In fire-excluded forest landscapes, forest surface and canopy fuels tend to be highly elevated, and despite active fire suppression, forests may eventually burn under extreme fire weather, which is becoming more frequent as the climate warms. For example, Povak et al. (2020) found fire severity during the 2013 Rim Fire was higher in the Stanislaus National Forest, much of which had not burned for >80 yr, compared to Yosemite National Park where past burn mosaics existed. High-severity burn patches in fires that escaped suppression are larger and less complex than in fires managed with less aggressive suppression tactics (Stevens et al. 2017), and seed sources for forest regeneration are more often distant, yielding sparse or non-existent tree regeneration (Shive et al. 2018, Korb et al. 2019, Stevens-Rumann and Morgan 2019). In dry pine and moist mixed-conifer forests, subsequent shrub establishment can lead to a cycle of repeated high-severity fires that perpetuates shrub dominance and a potentially long-term shift in alternative stable states (Collins et al. 2009, Cocking et al. 2014, Coppoletta et al. 2016, Coop et al. 2020).

Where managers allow managed wildfires to burn under prescription, burned areas are typically smaller and have greater proportions of low- and moderate-severity burn patches within the fire perimeter, and high-severity patches are typically smaller (Parks et al. 2014, Stevens et al. 2017). Within low- and moderate-severity burn patches, fuels are reduced, and forest structures resembling more typical historical conditions emerge (Holden et al. 2007, Huffman et al. 2018, Stoddard et al. 2020). In some forests, this includes characteristic patterns of small tree clumps and interspersed openings (Fig. 4; Kane et al. 2014, 2019, Jeronimo et al. 2019). In fire-excluded forests, a first entry with managed wildfire may not meet fuels reduction and management objectives unless allowed to burn at a severity that modifies stand structure (Huffman et al. 2017). Fire resilient landscapes are generally created by burning and reburning, in which prior fires modify the spread, intensity, and severity of subsequent fires (Prichard et al. 2017, Walker et al. 2018, Yocom et al. 2019, Koontz et al. 2020).

Promising strategies are emerging to delineate landscapes into operational units where decisions about applying managed fire can be considered before ignitions even occur (Thompson et al. 2016, Dunn et al. 2017). Managed wildfires are an important management tool and they are increasingly recognized as a vital component of adaptive management. However, relying solely on managed wildfires to achieve management objectives is not possible due to a number of factors that include current restrictions on the use of managed wildfire in the WUI or near other infrastructure, limited burn windows with moderate fire weather, and the potential negative consequences of allowing fire spread into nearby fire-excluded areas with elevated fuel loads.

Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment?

In a review of fuel treatment options for interior western United States forests, Reinhardt et al. (2008) recommend that the central objective of fuel reduction treatments should not be to halt fire spread or reduce ignitions. Rather, fuel reduction treatments could be implemented to modify fire behavior and mitigate fire effects (Safford et al., 2012*a*, *b*), thereby reinforcing the initial resilience of the treated stand by further reducing fuels, introducing greater heterogeneity, and allowing firefighters to fight fires, as needed, using direct techniques (Stevens et al. 2014, Kalies and Yocom Kent 2016). Under adaptive management, fuel treatments are not designed to prevent or stop fires but to moderate fire behavior when fire inevitably returns (Calkin et al. 2014). However, there is a frequent misconception that fuel treatments should facilitate suppression and limit the size of wildfires (Table 1; Cochrane et al. 2012, Schoennagel et al. 2017).

The reasoning behind treating fuels to facilitate fire suppression activities is circular. If fuel treatments make suppression more successful, then wildland fuels continue to accumulate, creating even more hazardous conditions for the entire landscape. Inevitably, this makes subsequent suppression more difficult, and more areas will be burned in fewer, unmanageable events with greater ecological consequences (Collins et al. 2010, Calkin et al. 2015). This phenomenon has been described as “the wildland fire paradox” (Arno and Brown 1991). Rather than creating conditions where wildfire is easier to suppress, fuel treatments designed within a restoration or climate adaptation strategy are engineered to allow subsequent wildfires to burn without the need of full suppression tactics and to increase opportunities for prescribed or cultural burning.

Typical fuel reduction activities near communities illustrate the long-term consequences of using treatments with the expressed objective of suppressing future wildfires. Near communities, fuel reduction treatments are often explicitly implemented to create conditions that enhance fire suppression efficacy in both the surrounding wildland and WUI (Moghaddas and Craggs 2007). Treatment locations are selected based on criteria that involve community protection (Fleeger 2008), suppression concerns (Finney 2001), and fuel hazards (Schmidt et al. 2008), at stand and landscape scales (Chung et al. 2013). Suppression strategies are designed to use treated areas for burnout operations, anchor points for fire lines, and safe zones for firefighters. Some of the challenges associated with this approach are that burnout operations often burn at high severity (Backer et al. 2004), and most fire line and safe zone construction involves the cutting of live and dead trees and mineral soil exposure, all of which result in conditions that can facilitate the spread of invasive species where they are present or nearby, degrade archaeological-heritage sites, and actually

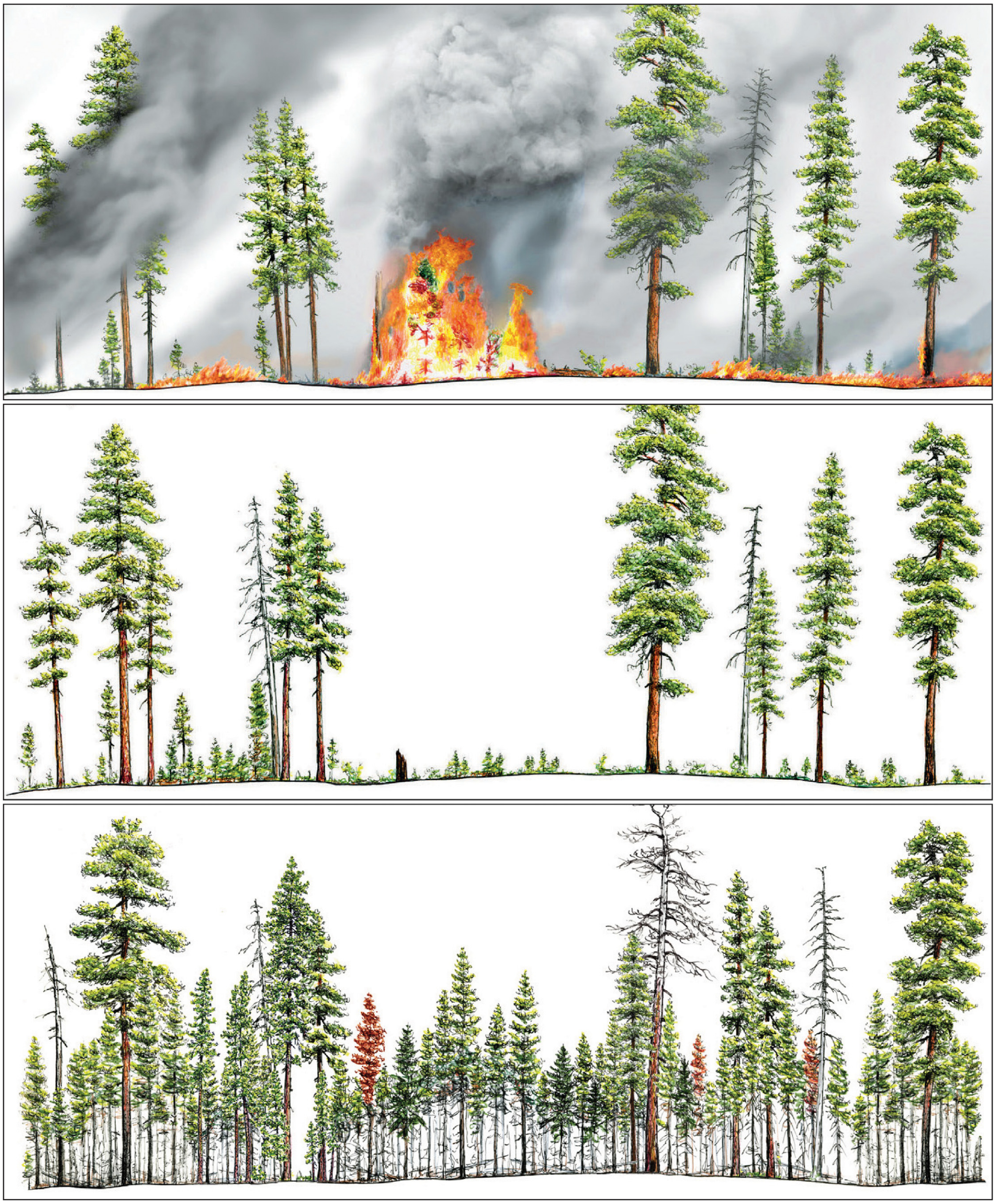

FIG. 4. Conceptual diagram of low and moderate severity fire effects on post-fire residual structure. Top: frequent fire reduces surface and ladder fuels. Middle: gradual accumulation of live and dead fuels between fires. Bottom: conditions after prolonged fire exclusion. Forest is denser and more layered, and high-severity fire is likely. Drawing credit: Robert Van Pelt.

reduce ecological resilience (Davies et al. 2010). Further, if insufficient area is treated on a landscape, the unexpected behavior of large wildfires will overwhelm the ability of small fuel treatments to facilitate effective suppression (Agee et al. 2000, Finney et al. 2001). If fuel treatments are designed such that the next wildfire can be allowed to burn with limited or no suppression, then three economic and ecological objectives might be achieved: reduced suppression costs and actions; management of future wildfires as effective fuel treatment maintenance; and favorable ecological outcomes in areas treated before wildfire.

There is little doubt that fuel reduction treatments can be effective at reducing fire severity and achieving culturally and ecologically beneficial effects, if designed and implemented correctly (Stephens et al. 2009, Fulé et al. 2012). However, fuel treatments intended only for crown fire hazard mitigation rarely constitute effective restoration (Stephens et al. 2020). As the pace and scale of fuel treatments increase, emphasis on resilient forest structure and composition, long-term reduction of surface and canopy fuels, and adaptation to climate change are critical components of treatment objectives rather than creating conditions that are more conducive to fire suppression (Hessburg et al. 2019).

Do fuel treatments work under extreme fire weather?

Although extreme fire behavior including strong winds and column-driven fire spread can overwhelm individual treatments, there is strong scientific evidence that even under extreme weather conditions, fuel reduction treatments are effective at moderating fire severity across a range of forest types and wildfire events. For example, Walker et al. (2018) studied the 2011 Las Conchas fire in New Mexico that burned under extreme weather and found that sites that were previously prescribed burned exhibited higher conifer survival (i.e., lower severity fire) compared to sites that were not treated prior to the wildfire. Similarly, Yocom Kent et al. (2015) found that moderate- and high-severity effects in the Rodeo-Chediski Fire, which burned under extreme fire weather, were reduced from 76% in untreated areas to 57% in prescribed fire, and 38% in thin and burn treatments. Likewise, Povak et al. (2020) presented evidence that some treated areas experienced lower severity fire even under the most extreme fire growth period of the 2013 Rim Fire. Past wildfires also acted as short-term barriers to fire spread and mitigated fire severity in mixed-conifer forests of the interior western United States (Parks et al. 2015*a*, Stevens-Rumann et al. 2016). Lastly, two studies in seasonally dry mixed-conifer forests of north-central Washington State found that thinning followed by prescribed burning was an effective treatment for mitigating wildfire effects under extreme weather conditions (Prichard and Kennedy 2014, Prichard et al. 2020). Results of these observational studies are also supported by numerous modelling studies indicating that fuel treatments reduce fire intensity and effects in dry conifer forests under dry fuels and high wind speeds (Stephens and Moghaddas 2005, Ager et al. 2007, Vaillant et al. 2009, Johnson et al. 2011).

In forests characterized by moderate- and high-severity fire regimes, a limited number of studies suggest that fuel reduction treatments are ineffective at reducing fire behavior and effects, particularly under extreme weather conditions (e.g., Graham 2003, Martinson et al. 2003, Schoennagel et al. 2004). The rationale is that fires burning within moist and cold forest patches are generally controlled by climate (i.e., a warmer and drier than average year) and not controlled by fuel within patches (Turner and Romme 1994, Bessie and Johnson 1995). However, at larger spatial scales, there is strong evidence that patchwork burn mosaics resulting from reburns reduce landscape contagion, and consequently, spread and severity of wildfires, even under extreme fire weather (Stine et al. 2014, Parks et al. 2015*b*, Hessburg et al. 2016, Spies et al. 2018).

Dependent on the forest type and environmental setting, some fuel treatments are more effective at reducing adverse fire effects than others, and this can also contribute to confusion as to whether or not treatments are effective under extreme fire weather. Several studies highlight that the most effective fuel treatments include coupled thinning and burning (Kalies and Yocom Kent 2016), and emphasize the importance of retaining large, fire-resistant trees in dry mixed conifer forests (DellaSala et al. 2004, Agee and Skinner 2005, Stephens et al. 2009). Furthermore, other studies showed that fire severity decreased as wildfires progress further into areas with more treated area (Arkle et al. 2012, Kennedy and Johnson 2014), strongly suggesting that small fuel treatments or those with large perimeter-to-edge ratios are less effective than larger treatments under extreme fire weather conditions (Kennedy et al. 2019).

Finally, fuel treatments generally are designed to mitigate wildfire intensity and effects but they are not necessarily intended to impede fire spread or reduce fire size (Reinhardt et al. 2008). Consequently, when fires burn large areas under extreme fire weather some may conclude that burned-over fuel treatments were ineffective (e.g., Schoennagel et al. 2017). However, the occurrence of large fires does not necessarily suggest that existing fuel treatments were unsuccessful. Large fires have always been a part of fire-prone forests, and within large fire events fuel treatments can allow fires to continue burning but mitigate fire severity and enhance the heterogeneity of fire effects.

Is the scale of the problem too great? Can we ever catch up?

Recent meta-analyses of fuel treatment effectiveness demonstrate that at landscape and regional scales, fuel treatments account for only a small fraction (~1%) of the area burned by wildfires (e.g., Barnett et al. 2016*a*, Kolden 2019). Therefore, there is some concern that treatments are ineffective because under current prescription levels, wildfires may not actually encounter treated areas during the duration of their potential effectiveness (Odion and Hanson 2006, Rhodes and Baker 2008). While this is factually accurate at the current pace and scale of treatment in wNA, the question is not whether every wildfire can be impacted by fuels treatments, but whether treatments can be strategically used to multiply their benefits and promote greater opportunities for applying wildland fire across landscapes. The scientific evidence that fuel reduction treatments can mitigate fire behavior and effects strongly supports a conclusion that expanding treated areas, including the use of forest thinning, prescribed burning, cultural burning, and managed wildfires, will lead to greater landscape resilience to future wildfires.

Ongoing warming and drying are linked to increasing large fire occurrence, contributing to large increases in area burned (Abatzoglou and Williams 2016) and area burned as high severity (Parks and Abatzoglou 2020) in wNA in recent decades. Given projected increases in warming due to climate change, burn probability is increasing in many wNA forests (Littell et al. 2018, Hurteau et al. 2019) along with increasing likelihood that future wildfires will impact a larger proportion of landscapes. In this light, the current pace and scale of fuels treatments is insufficient to address the scale of fire exclusion. Furthermore, treated areas require ongoing maintenance to retain efficacy (Krofcheck et al. 2017, Vaillant and Reinhardt 2017), making it difficult to expand treated areas across a landscape without significant additional financial and personnel investments (North et al. 2015*a*). Thus, the scope, scale, and urgency of adapting wNA forests to climate change and future wildfires is immense.

Given the complexity of forest ecosystems, the economic and personnel investment required, and the policy and management constraints, there is no single management tool that is adequate to increase the resilience of wNA landscapes to future wildfires. Coupled thinning and burning treatments will be especially helpful in dry pine, oak woodlands, and dry mixed conifer forests, while restoration of more characteristic forest successional and nonforest patchworks using managed moderate and high severity wildfires will be key in cold forests. Forest managers in western Australia have reduced the frequency of large and severe wildfires, but only after building extensive landscape networks of strategic treatments (i.e., spatially linked naturally occurring and treated areas of reduced fuels prior to the outbreak of wildfires) and by conducting frequent prescribed burning under moderate fire weather and including Indigenous fire use over large areas (Boer et al. 2009, Sneeuwjagt et al. 2013). Similar approaches are being used in U.S. national forest, wilderness, and park areas to allow for more area of managed wildfires (Table 2). Given limitations on where mechanical thinning, prescribed and cultural burning, and managed wildfire are practical or allowed, combining these tools over broad areas can markedly expand treatment extent and reduce impact of large wildfires.

Fire hazard, burn probability, and fire ecology vary widely across wNA forest landscapes. Prior knowledge of cultural burning practices, ignition and weather patterns, vegetation and fuel distributions, and topography all provide critical information for prioritizing fuel treatments in areas with the highest risk of burning (Ager et al. 2010, 2016). Near population centers, humans are often responsible for the majority of wildfire ignitions, and they provide ignition sources in highly predictable areas and seasons of the year, when natural ignitions are rare (Balch et al. 2017, Keeley and Syphard 2018). Ignition pattern and frequency interact with fuels, weather, and topography to influence fire occurrence, leading to heterogeneous burn probabilities across a landscape (Ager et al. 2012, Povak et al. 2018). Using prior knowledge of human and lighting-caused fire starts coupled with knowledge of the probability of fire spread and likely severity, managers can identify the areas of any landscape where uncharacteristic or impactful fires will likely occur (Parisien and Moritz 2009, Parisien et al. 2012), and decrease the proportion of the landscape that requires treatment.

There are a number of available tools and approaches to identify areas that would benefit from strategically placed fuel treatments. In general, fuel treatments are not implemented at random, and for good reason (Finney et al. 2007). A comparison of random vs. strategically placed treatments showed that a significant reduction in area could be achieved with strategic placement (Ager et al. 2013, 2016), where that opportunity exists. Quantifying the probability of high-severity wildfire across a given landscape and focusing thinning treatments on high-probability areas can decrease the required treatment area by >50% (Krofcheck et al. 2019). However, the success of these strategies depends on maintaining the treatments and reintroducing fire to a larger portion of the landscape (Agee and Skinner 2005, Barros et al. 2018). Where reserved areas are abundant or widely distributed, opportunities for spatially optimizing fuel treatments are limited, and considerably more treated area may be required outside of reserves (Finney et al. 2007).

In summary, justifying inaction based on the scale of the problem is too large is highly circular. Evidence supports increasing the pace of treatments to significantly reduce the area impacted by uncharacteristic wildfire, even under a changing climate (Liang et al. 2018). For example, managers can expand areas where burn prescriptions are applied to reduce fuels and increase forest heterogeneity (Safford et al. 2012*a*,*b*, Striplin et al. 2020). The efficacy of these was historically demonstrated by Indigenous burning practices that amplified natural lightning ignitions in many seasonally dry forests, thereby modifying active fire regimes and fire effects, and diversifying the seasonality and frequency of fires (Crawford et al. 2015, Trauernicht et al. 2015, Taylor et al. 2016). Managed wildfires can also increase forest and fuel heterogeneity, constraining subsequent fire size and severity (Collins et al. 2009, Parks et al. 2015*b*, Barros et al. 2018). When used in conjunction with mechanical treatments and prescribed or cultural burning, managed wildfire presents an opportunity to increase the effectiveness of treatments across large landscapes (North et al. 2012).

Will planting more trees in wNA forests help to mitigate climate change?

Tree plantations have long been a debated aspect of forest management, and more recently, climate change mitigation (Alig 1997, Chmura et al. 2011). Planting after harvest to increase forest productivity were the central justifications for past clearcut logging, even as a growing body of science demonstrated that plantations (1) did not provide the needed ecological structures or functional diversity of old-growth forests, (2) were not necessarily more productive than mature forests (Franklin et al. 2002), and (3) without surface fuel treatment, could be conducive to high-severity wildfires (Thompson et al. 2007). Similarly, planting seedlings after post-fire salvage logging is sometimes used to expedite tree regeneration following high-severity fire. Without strategic management, post-fire plantations may be overstocked, dominated by a single species (North et al. 2019), lack tree clumping and canopy gaps, and pose significant wildfire hazard (Kobziar et al. 2009), particularly without post-harvest slash reduction (Donato et al. 2009).

A recent proposal to combat climate change includes planting a trillion trees globally, including substantial reforestation in the western United States (Bastin et al. 2019). The study suggested that these additional trees would sequester sufficient atmospheric carbon to curb climate change. Baseline assumptions and findings from this study have been contested by scientists (Veldman et al. 2019, Holl and Brancalion 2020) as the study failed to account for forest interactions with climate, drought, and wildfire dynamics. In addition to future disturbance resilience, numerous other barriers currently impede large-scale reforestation efforts (Fargione et al. 2021).

Across wNA, most of the forest carbon is captured in moist temperate forests with high precipitation levels and net primary productivity, including the coastal ranges along the Pacific Coast, western Cascade and western Sierra Nevada Mountain Ranges (Hudiburg et al. 2009). These forests possess complex, heterogeneous structures, some of which developed with infrequent wildfires. Others, including those in southwestern Oregon and northern California, were also influenced by a long legacy of Indigenous burning (Anderson 2013, Merschel et al. 2014). Because most of the standing biomass in high productivity wNA forests occurs in live trees, when these forests burn, relatively low levels of carbon are initially emitted, with most of the biomass retained either in standing trees and snags or to newly downed heavy fuels that slowly release carbon to the atmosphere through decomposition, unless they subsequently burn in a reburn fire event (Stenzel et al. 2019, Lutz et al. 2020). By contrast, even-aged stands, both naturally occurring (e.g., lodgepole pine forests) and in young plantations, are relatively homogeneous in structure, and with elevated surface fuels, can facilitate high-intensity, severe fire (Bowman et al. 2019). Climate change-induced shortening of fire return intervals may ultimately convert some of these live carbon pools from sinks to sources (Turner et al. 2019, Foster et al. 2020).

In fire-adapted dry mixed conifer forests, dense tree plantations are highly susceptible to future wildfires and drought. However, a promising approach to retaining and sequestering carbon in dry, fire-prone forests is to retain existing large-diameter trees and restore characteristic low-severity fire to maintain low-severity fire to maintain resilient forest structure and composition (Hurteau and North 2009). It is still debatable whether prescribed burning and removal of small diameter trees and ladder fuels will actually increase or decrease aboveground carbon stores (Campbell et al. 2012, Restaino and Peterson 2013) and is likely site dependent, but there is broad scientific agreement that these management actions are key to increasing forest ecological resilience, which ultimately stabilizes forest carbon stocks (Hurteau et al. 2019, Krofcheck et al. 2019, Westlind and Kerns 2021). Managed landscape mosaics will be particularly critical to maintaining legacy old-growth forests and minimizing sink-to-source conversions due to fire and other disturbances (Barbero et al. 2015, Liang et al. 2017). Finally, governmental cap-and-trade and carbon taxation programs must accurately account for the complex role fire plays in carbon cycle feedbacks and carbon maintenance, rather than simply characterizing fire as a net carbon loss (Hurteau et al. 2008, North et al. 2009).

Across wNA forests, tree planting can serve as an important tool to nudge the trajectory of post-fire landscapes towards more climate-adapted tree species or genotypes, particularly in areas where seed source is limited (North et al. 2019). However, traditional high density plantations will often predispose forests to high-severity fire where pre-commercial thinning and associated fuel treatments are not implemented, which is increasingly the case (McCarley et al. 2017). Alternatives to traditional plantations are emerging that are designed to promote resilience to future fire and drought from the beginning of the planting process. These include planting drought-conditioned seedlings reared from lower-elevation seed stock, planting discontinuous “founder stands” or “nucleation islands” of trees into portions of stand-replacing patches far from tree refugia, and planning for the reintroduction of fire into younger planted stands as they develop (Peterson et al. 2007, Landis et al. 2011).

Is post-fire management needed or even ecologically justified?

Many contemporary wildfires exhibit a range of post-fire effects (Thode et al. 2011); variable sized patches of stand-replacing or partial stand replacing fire are embedded within a matrix of live forest (Stevens et al. 2017). Among large fires, these patches of stand-replacing fire may themselves contain isolated and variably sized patches of live trees often referred to as fire refugia (Meddens et al. 2018, Krawchuk et al. 2020). Thus, the post-fire landscape can be viewed as a complex patchwork of interconnected surviving forest, the product of low and moderate severity fires, high-severity patches, and isolated refugia (Coop et al. 2019). However, these post-fire landscapes are not necessarily on resilient trajectories. Fire refugia may be in uncharacteristic locations, and active forest and fuels management are often required after the fire to promote future forest resilience to disturbance and climate change and to protect valued cultural resources.

Patches of low- and moderate-severity fire generally have short-term resistance to future fire due to the reduction of surface fuels from the first burn (Prichard et al. 2017). Compared to low-severity fire, moderate-severity fire events can create a residual stand structure that more closely approximates historical conditions (Collins et al. 2011, Huffman et al. 2017). However, moderate-severity fires that burn through previously dense forest also leave considerable standing and down wood, which can lead to elevated fuel loads and high-severity fire in subsequent reburns (Collins et al. 2018). Thus, post-fire fuel reduction of the trees that encroached during the period of fire exclusion can be warranted to improve the fire resilience of residual forests, including fire refugia.

Smaller refugial patches within larger burned patches are increasingly recognized as having significant cultural and ecological value by preserving biological and cultural legacies that can contribute to forest succession via seed dispersal (Johnstone et al. 2016, Meddens et al. 2018). Small refugia in particular make disproportionate contributions to reforestation potential within larger patches of stand-replacing fire (Shive et al. 2018, Coop et al. 2019). However, isolated tree refugia can have a significant standing and down fuel component around their edges due to adjacent high-severity burn effects (Lydersen et al. 2019*a*). Given their outsized importance as biological legacies, surface fuel reduction to "harden" the edges of refugia may be critical to their future resilience and prioritize refugia retention during wildland firefighting operations (Meddens et al. 2018).

Large patches of stand-replacing fire are an increasing focus of research (Coop et al. 2020). Independent of subsequent fire dynamics, regeneration is challenged by seed dispersal limitations and a warming climate (Stevens-Rumann and Morgan 2019). Fuel conditions in large patches of stand-replacing fire are usually dominated by coarse wood, regenerating shrubs, and hardwoods, increasing the risk of subsequent high-severity, and occurrence of long-duration re-burns (Coppoletta et al. 2016, Prichard et al. 2017). Collectively, these conditions pose a substantial management challenge if the objective is to restore at least a portion of large burn patches to conifer forest, as this is unlikely over decades to centuries without management intervention (Coop et al. 2020).

Fuels management and regeneration dynamics in stand-replacing patches are closely related. In high-severity patches, management to reduce coarse wood accumulations and flammable shrubs may promote post-fire tree regeneration and mitigate future fire severity (Peterson et al. 2015, Lydersen et al. 2019*b*). In planted forests, coarse wood presents a different challenge, as downed logs facilitate seedling survival through shading and moisture retention (Castro et al. 2011) but pose a risk to seedlings if they burn (Peterson et al. 2015). Understanding the range and variability of historical reburning would provide essential guidance of restoration targets to improve the post-fire resilience of regenerating landscapes.

Strategic tree planting can be used to encourage the re-establishment of some post-fire landscapes and for climate change adaptation, particularly where conditions are not favorable to natural regeneration (see previous question). Post-fire mechanical thinning (e.g., salvage logging) is often driven by economic and safety considerations but may have some ecological benefits in terms of reduced future surface fuel loads and fire hazard 10–20 yr post-fire (Peterson et al. 2015). Future research in this area is warranted to investigate the impacts of variable density harvests and how potential ecological tradeoffs vary over time (e.g., Ritchie et al. 2013).

Conclusions

During this time of rapid environmental change, the impacts of climatic changes on forests and their associated fire regimes cannot be overstated. In addition to the increased incidence of large wildfires, tree mortality associated with persistent drought and die-off events, chronic forest insect outbreaks, and increasingly common tree regeneration failures are all critical management considerations (Stephens et al. 2016, Coop et al. 2020). In a majority of cases, forest management and fuel reduction treatments will not return landscapes to any historical condition or fire regime, nor is that a particularly useful premise on which to base adaptive forest management (Allen et al. 2011, Hanberry et al. 2015, Falk et al. 2019). Instead, intentional management focused on adapting current forest conditions to a rapidly evolving future climate is needed. Adaptations can foster forest resilience to longer, warmer, drier, and windier fire seasons, increasing incidence of episodic, multi-year to decadal droughts, and increasing dominance of severe wildfire and insect disturbances. Given the rapid increase in human-caused large wildfires, mitigating unplanned human ignitions is another critical wildland fire management issue (Balch et al. 2017), that by itself can reshape wildfire and forest landscape futures.

Although the management situation for wNA forests is daunting, our review of the scientific literature offers clear guidance. In seasonally dry wNA forests that were historically dominated by fire-resistant species, restoring open, fire-tolerant canopy structure and composition, favoring larger tree sizes, and reducing surface fuels can effectively mitigate subsequent wildfire and stabilize carbon stocks (Fig. 1). In many instances, these adaptation actions, with ongoing maintenance, will also enable future wildfire events to continually reinforce resilient structure, composition, and fuels.

Ecological departures associated with fire exclusion are not confined to seasonally dry pine and mixed-conifer forests. Across a wide range of wNA forests, landscape-level treatment prescriptions that promote resilient patchworks with heterogeneous nonforest and forest ages can reduce the extent of high-severity wildfires and make landscapes less susceptible to extensive insect and disease outbreaks. Restoration of fire resilient mosaics in moist mixed-conifer forests, mixed conifer-hardwood forests, fire-prone deciduous forests (e.g., aspen), and cold forests is also needed.

Despite calls to restore fire as a cultural and ecological process (e.g., The U.S. National Wildland Fire Cohesive Strategy), the dominant approach to wildfire management continues to be aggressive suppression. Response to unplanned fire starts is highly successful in the United States and Canada and is becoming increasingly common in Mexico. However, a small fraction of fires that escape suppression (2–3%) generally burn under extreme fire weather conditions, lead to explosive fire growth, and account for >90% of annual area burned (Abatzoglou et al. 2018). The strategy to actively suppress fire is a highly consequential active management prescription, with surface and canopy *fuel accumulation* as a consequence. Continued forest infilling and fuel accumulation predisposes forests to high-severity fire when fire inevitably returns (North et al. 2015*b*).

Not surprisingly, recommendations to increase wNA forest resilience to climate change and wildfires are in close alignment with Indigenous knowledge, cultural resource values, and desired land management strategies (Kimmerer and Lake 2001, Lake et al. 2018, Roos et al. 2021). Over millennia, Indigenous burning practices influenced fire regimes, which contributed to the resilient composition and structure of many historical wNA forest and nonforest ecosystems. Although European colonization severely curtailed and displaced Indigenous land management (Lake et al. 2017, Lake and Christianson 2019), Indigenous knowledge for the maintenance of fire-dependent ecosystems and services endures (Huffman 2013). Given the urgent need for adaptive forest management in the 21st-century, an intentional merging of Indigenous and western knowledge is needed to guide future forest conditions and restore active fire regimes to wNA forests.

Acknowledgments

This synthesis project was funded by the US Forest Service Pacific Northwest and Pacific Southwest Research Stations (P. F. Hessburg, N. A. Povak), California Department of Forestry and Fire Protection (S. J. Prichard, R. K. Hagmann, P. Khatri-Chhetri); Ecological Restoration Institute (D. Huffman, R. K. Hagmann); Washington State Department of Natural Resources (D. Churchill, R. K. Hagmann); the Wilderness Society (R. K. Hagmann); Nature Conservancy–Oregon (R. K. Hagmann); and Conservation Northwest (R. K. Hagmann). We thank Mike Battaglia, Ellis Margolis, and James Rosen for their constructive reviews and the U.S. Fish and Wildlife Service for assistance with publication. The authors also wish to acknowledge NSF's Growing Convergence Research Program (Award Number 2019762) for support of this work.

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