Wildfire and climate change adaptation of western North American forests: a case for intentional management

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Abstract. Forest landscapes across western North America (wNA) have experienced extensive changes over the last two centuries, while climatic warming has become a global reality over the last four decades. Resulting interactions between historical increases in forested area and density and recent rapid warming, increasing insect mortality, and wildfire burned areas, are now leading to substantial abrupt landscape alterations. These outcomes are forcing forest planners and managers to identify strategies that can modify future outcomes that are ecologically and/or socially undesirable. Past forest management, including widespread harvest of fire- and climate-tolerant large old trees and old forests, fire exclusion (both Indigenous and lightning ignitions), and highly effective wildfire suppression have contributed to the current state of wNA forests. These practices were successful at meeting short-term demands, but they match poorly to modern realities. Hagmann et al. review a century of observations and multi-scale, multi-proxy, research evidence that details widespread changes in forested landscapes and wildfire regimes since the influx of European colonists. Over the preceding 10 millennia, large areas of wNA were already settled and proactively managed with intentional burning by Indigenous tribes. Prichard et al. then review the research on management practices historically applied by Indigenous tribes and currently applied by some managers to intentionally manage forests for resilient conditions. They address 10 questions surrounding the application and relevance of these management practices. Here, we highlight the main findings of both papers and offer recommendations for management. We discuss progress paralysis that often occurs with strict adherence to the *precautionary principle*; offer insights for dealing with the common problem of irreducible uncertainty and suggestions for reframing management and policy direction; and identify key knowledge gaps and research needs.

Key words: Climate Change and Western Wildfires; climate warming; forest landscape changes; Indigenous fire use; landscape realignment; landscape resilience; landscape resistance; social-ecological systems; wildfire regime changes.

INTRODUCTION

Western forests are rapidly changing

Starting in the mid-1980s, area burned in seasonally dry forests of western North America (wNA) began a steady rise (Westerling et al. 2006), despite increasing investment in fire suppression (Calkin et al. 2005). Seasonally dry forests are those pine, dry or moist mixed-conifer, and cold forests that are available to burn most

years during the wildfire season (refer to forest type definitions and discussion in Hessburg et al. 2019). Increased burned area is attributed to combinations of warmer seasonal temperatures, longer wildfire seasons, drier summers, below-average winter precipitation and earlier snowmelt, and increasing human ignitions (Westerling et al. 2006, Morgan et al. 2008). The incidence of large wildfires has likewise increased across wNA over the last three decades (Schoennagel et al. 2017, Parks and Abatzoglou 2020), while burned area in the Inland Northwest and American Southwest has risen most noticeably over the last two decades (Westerling 2016). These increases are occurring not only in dry pine and mixed-conifer forests, but also in moist and cold

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forests, and in nearby nonforest vegetation (preforest, grassland, shrubland, and sparse woodland; Parks et al. 2015). Based on climate change predictions, burned area in wNA will at least double or triple by mid-century (McKenzie et al. 2004, Westerling et al. 2011).

While increase in burned area is strongly associated with climatic warming, changes to other aspects of wildfire regimes (Table 1) more directly reflect the influence of human activities. For example, in many wNA forests, land and resource management decisions and actions led to abrupt and persistent declines in fire frequency (and hence, burned area) beginning more than 170 yr ago. Decreased fire frequency led to increased continuity and accumulation of live and dead fuels (Stephens et al. 2009), both of which contribute to increases in fire severity as burned area increases (Parks and Abatzoglou 2020). Likewise, while human-caused ignitions continue to contribute to increasing burned area (Balch et al. 2017), they also reflect contemporary land development and access patterns. With ongoing fire suppression, lengthening wildfire seasons, and the increased likelihood of extreme fire weather, fire effects are broadly becoming more severe than those experienced in the last two centuries (North et al. 2015, Parks and Abatzoglou 2020). As a result, forests developing after large contemporaneous wildfires little resemble forests evolving under a more characteristic wildfire regime (Keane et al. 2002, Hessburg et al. 2005, Coop et al. 2020).

The challenge of larger and more intense wildfires

The increasing impacts that large and intense wildfires will have on social and ecological systems will be the major challenge facing managers of seasonally dry forests over the 21st-century. Prolonged smoke production and human health effects, chronic soil erosion and mass wasting, degraded water supplies, loss of cultural and natural resources, increased greenhouse gas emissions and reduced carbon storage are all growing issues (Spies et al. 2014). Management capacity to influence how much area burns will be somewhat limited (cf. Taylor et al. 2016), but fuel reduction treatments, including prescribed burning, coupled forest thinning and prescribed burning, and managed wildfires, are proven methods to influence the ecological impacts of wildfire, and mitigate impacts of extreme fire events on social systems (Taylor et al. 2016; Prichard et al. 2021). To date, mechanical fuel reduction treatments have been applied to small portions of wNA forested landscapes (Barnett et al. 2016, Vaillant and Reinhardt 2017, Kolden 2019, Kolden and Henson 2019). One reason is that land allocations amenable to mechanical treatments (via their enabling legislation) represent a dwindling fraction of public lands (Fig. 1); another is a lack of sufficient experience with prescribed burning and managing wildfires in front or backcountry locations. However, scaling-up a broad variety of fuel reduction treatments can tip landscape dynamics in favor of more benign fire behavior and effects (Stevens et al. 2014, Parks et al. 2016, Taylor et al. 2016, Ager et al. 2020).

The assertion of regional-scale adaptation needs

The need for broad-scale climate and wildfire adaptation across wNA is predicated on two main assertions. The first is that most seasonally dry forest landscapes, and some drier coastal forests (Hessburg et al. 2019), have significantly changed over at least the last two centuries under the influences of curtailed Indigenous burning before 1850 (Kay 2000, Stewart 2002); wildfire exclusion (beginning with domestic livestock grazing in the mid-1850s, Belsky and Blumenthal 1997); and decades of selection cutting of large, old, early seral tree species (Hessburg and Agee 2003, Lydersen et al. 2013). The resultant stand- to landscape-scale changes in forest structures and fuels have left these seasonally dry forests vulnerable to the direct and indirect effects of climate warming, drought, and wildfire (Allen et al. 2002, Noss et al. 2006, Keane et al. 2018, Bryant et al. 2019, Hessburg et al. 2019). The second assertion is that climate change and wildfire adaptation treatments implemented at large regional landscape scales can effectively moderate many ecosystem transitions, conserve greater area and heterogeneity of forest successional conditions (Moritz et al. 2013, Coop et al. 2020), better foster native biodiversity (Raphael et al. 2001, Bisson et al. 2003, Isaak et al. 2010, Rieman et al. 2010), and maintain essential and desirable ecosystem services and processes (e.g., see Dale et al. 2001, Millar et al. 2007, Hurteau et al. 2014).

Public land management: political and paralyzed

As with many topics in conservation biology (Soulé 1985), active or intentional management of public

TABLE 1. Components of an active fire regime.

Component	Definition
Amount	total amount of area burned annually or decadally
Distribution (severity)	distribution of severity class patch sizes
Distribution (event areas)	distribution of fire event patch sizes
Frequency	average fire return interval, and variation around the mean
Spatial distribution	the geographic distribution of fires†
Intensity	the energy release from surface and crown fires at the flaming front
Duration	the length of time fires burn‡
Seasonality	the time of the year when fires burn

Note: Components may vary by climatic period.

†The spatial distribution of fires is dictated by biophysical setting, climate, and weather conditions, forest or nonforest type, ignition probability, and the propensity for reburning.

‡The period of fires is dependent on the climate, weather, and fuel bed characteristics.
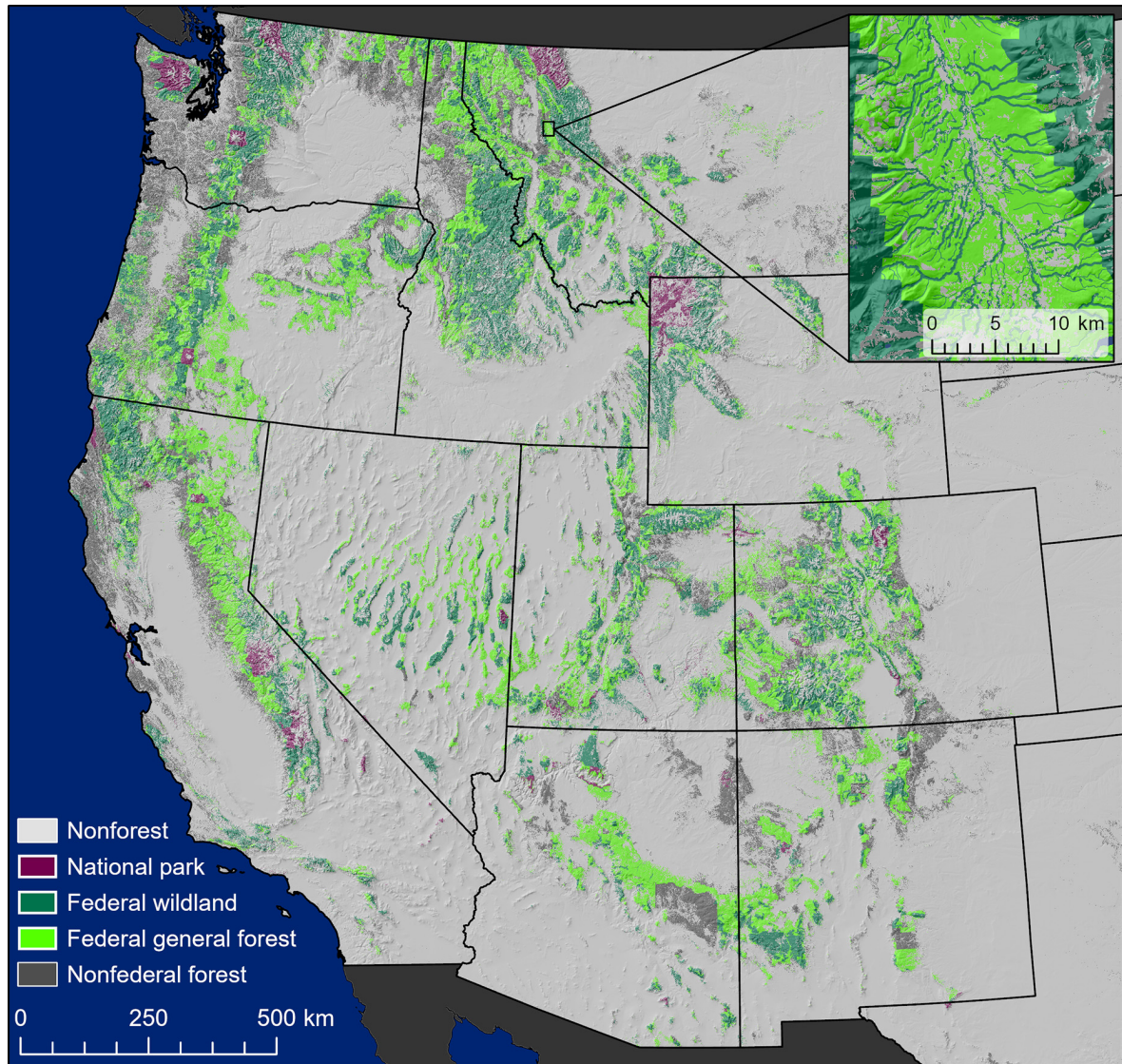
Fɪɢ. 1. Map of forested areas and their primary public land management allocations in the western United States. Federal wildlands include administratively withdrawn roadless areas, congressionally designated wilderness, and terrestrial habitat reserve networks. General forest areas are those remaining that are ostensibly amenable to mechanical thinning and prescribed burning treatments. Riparian reserves are generally not shown due to map scale, but they represent a significant area in general forest. The inset map at top right shows an example of riparian reserves in the Swan sub-basin of northwest Montana. Riparian buffers are 100 m on either side of perennial streams and 30 m on ephemeral streams. Most federal wildlands and national parks are available in concept for using managed wildfires and prescribed burning as fuel reduction treatments, but application of these tools remains uneven. Data sources for map development are (1) for forested areas, National Land Cover Database, NLCD (2006); https://www.mrlc.gov/data/nlcd-2006-land-cover-conus) for inventoried Roadless Areas (2001), https://www.fs.usda.gov/detail/roadless/2001roadlessrule/maps/?cid=stelprdb5382437, USDA-FS internal enterprise data layer name: S_USA. InvRoadlessArea_2001; (2) for Northwest Forest Plan Land Use Allocations (2013), https://www.fs.fed.us/r6/reo/landuse/, USDA-FS internal enterprise data layer name: S_R06.NWFP_LandUseAllocation_2013; (3) for designated Wilderness Areas (2020), USDA-FS internal enterprise data layer name: S_USA.Wilderness; (4) for Other National Designated Areas (2020), USDA-FS internal enterprise data layer name: S_USA.PADUS_DESIGNATION; (5) for US National Atlas Federal and Indian Land Areas (last updated 2004), USDA-FS internal enterprise data layer name: S_USA.OtherNationalDesignatedArea.

forestlands often devolves into value-laden discussions and politicized views of appropriate contexts and frames of reference (Peery et al. 2019). Here, we define intentional management as the planned application of silvicultural and prescribed fire treatments and managed

wildfire to meet a variety of specific landscape-level objectives in predefined conditions and contexts. This can include opportunities in Indigenous communities for more decentralized stewardship practices related to resource tending, subsistence activities, and spiritual or

religious observances (Norgaard 2014). In contrast, under passive management (i.e., continued fire suppression with little intentional forest or fuel management), many assume that existing conditions and processes will naturally sort out an effective remedy without benefit of intentional management (Carey 2006).

Owing to extensive 20th-century harvest of large trees and old-growth forests, public trust in forest management eroded. In response, an emphasis emerged to conserve the victims of that history, large trees and old forests, and native species and their habitats, by minimizing further forest management actions. This emphasis is commonly underscored with policies that emphasize riparian and terrestrial habitat reserves and related conservation areas (Spies et al. 2019, Stephens et al. 2019), by legal injunction of active management projects (Prichard et al. 2021), and by maintaining a relatively small footprint of areas available for active management (Fig. 1). Opposition to active forest management is reflected in statements like "active forest management is unwarranted because the effects of fire exclusion and forest changes are overstated; ...is ineffective and counterproductive; ... should be focused on the wildland urban interface; or wildfires alone can do the work of fuel treatments." On the other hand, support for active management from the commercial sector suggests that "forest thinning alone can mitigate wildfire severity; forest thinning and prescribed burning can solve the problem; or managed wildfires hold no real promise." Each statement polarizes debates and oversimplifies the problems and the solutions (Prichard et al. 2021). Given rapid climate change and a legacy of excluding most natural and Indigenous ignitions, effective forest landscape restoration and adaptation strategies are more complex and nuanced than any of these statements imply.

Advocacy and objectivity: is it one or the other?

The polarization and politicization of scientific evidence impedes implementation of effective land management plans, policies, and management by raising the volume of the disagreement; obscuring the line between facts, opinions, and legal requirements; creating the impression that knowledge is more uncertain than it is; and increasing the time to resolution. Wellerstein (2018) argue that the premise of science as apolitical is simply a myth, since all science takes place and is supported within a highly political environment. Nonetheless, when scientists affiliate themselves with one-sided or partisan views and activism, they inevitably minimize their value and that of the applied science (Lackey 2007, Pielke 2007).

Scientists are increasingly asked to comment on forest policy and management recommendations. Facilitating communication among stakeholders of public land management by providing practical access to the best-available science can more effectively ensure scientifically credible decision-making (Komatsu and Kume 2020). However, while some encourage scientists to be responsible informants for species or ecosystem conservation (e.g., Lach et al. 2003), others worry that their objectivity in conservation or ecological research may be compromised (e.g., Scott et al. 2007), especially during volatile times, and with arguments that are already polarized or politicized.

Garrard et al. (2016) argue that scientists are not compromised when they transparently evaluate policies or recommendations for their consistency with the best available science, its weight of evidence, and any associated uncertainties. A systematic evaluation of best available science would include careful examination of Indigenous and western data, information, knowledge, and wisdom from a variety of locally and regionally relevant sources (Varghese and Crawford 2020). Garrard et al. (2016) further suggest that in the face of serious societal, economic, or existential issues, "the standard of debate about conservation is impoverished when scientists with relevant knowledge remain silent outside the pages of their academic journals."

Peery et al. (2019) provide a framework for evaluating agenda-driven science and a case example of controversy in the scientific literature that has impacted management of the California spotted owl and its habitats. They discuss professional norms for scientist engagement with management and policy issues and conclude "that intentionally engaging in activities outside of these professional norms to promote desired political outcomes, as part of either the production or dissemination of science ...constitute[s] agenda-driven science."

Recent controversy involving the creation and dissemination of agenda-driven science is creating uncertainty for forest managers and policy-makers throughout wNA. Contributing to the controversy are publications that challenge the significance of forest condition and wildfire regime changes, and the advisability of proactive management without addressing the core arguments (e.g., compare Hessburg et al. [2020] and Mildrexler et al. [2020] and their discussion of trade-offs between wildfire dynamics, carbon sequestration, and forest adaptation to climate warming). To aid those engaged in designing, evaluating, and implementing science-based adaptation options, we examine the strength of evidence pertaining to these topics.

We first provide a framework for characterizing and evaluating changes in forest conditions and fire regimes in Hagmann et al. (2021). We then review the strength of evidence documenting changes or lack thereof. Similarly, in Prichard et al. (2021), we review the strength of evidence surrounding the usefulness of various passive and active management treatments to provide remedies to current conditions. We then discuss 10 key questions related to application of methods as viable treatments.

FOREST CONDITIONS AND WILDFIRE REGIMES

Advances in fire and landscape science over the past several decades enable rigorous multi-proxy and multi-

scale assessments of variation in historical fire regime and forest vegetation conditions. These insights build on more than a century of assessment of changing fire behavior and forest landscape conditions. Beginning in the 1930s, fire histories based on tree-ring and fire-scar records have provided high-resolution, cross-dated, multi-centenary evidence of the spatial point patterns of fires, which have enabled precise interpretations of fire frequency associated with recorder trees. While fire-scar records remain a primary means of exploring historical fire ecology, more recently developed methodologies and multi-proxy assessments have expanded the potential to evaluate broader temporal and spatial patterns. New insights into complex relations between variations in climate, fire, and vegetation emerge from multi-proxy and trans-disciplinary studies that combine sedimentary pollen and charcoal records (Higuera et al. 2007), large-scale tree cohort analyses (Schoennagel et al. 2011), early 20th-century land system inventories and surveys (Hagmann et al. 2013, 2014, Levine et al. 2017), landscape reconstructions from historical black and white photographic imagery (oblique, panoramic, stereo photo pairs, Hessburg et al. 1999, 2000, Stockdale et al. 2015, 2019), forest inventories and land system surveys (Williams and Baker 2012, cf. Fulé et al. 2014, Odion et al. 2014, cf. Stevens et al. 2016), and simulation modeling of landscape succession and disturbance regimes (Keane et al. 2004, 2018, McGarigal and Romme 2012). Additionally, trans-disciplinary studies that employ fire-scar research, climate, archaeological, and ethnographic studies show that many different Indigenous cultures were significant contributors to the magnitude and extent of fire influence on the wNA landscape (e.g., see Taylor et al. 2016, Lightfoot et al. 2013).

Over the past two decades, a series of publications using novel techniques has suggested that 19th- to 21st-century changes in western forests and their fire regimes have been less substantial than a much larger and more diverse body of scientific evidence has long indicated. Hagmann et al. (2021) provide a comprehensive review of these papers and studies that directly evaluated them. They show that methods and inferences in these articles failed independent validation by other research groups and lend their support to the findings of the larger body of evidence.

The evidence for change in forest conditions

Hagmann et al. (2021) relied on several hundred research articles from research groups throughout wNA that examined historical changes to seasonally dry forests patterns and processes to illustrate key departures from conditions that existed prior to European colonization. They found that changes in forest successional landscapes are significant in all forest types, whether dry, moist, or cold. Changes are prominent at tree, patch, and local and regional landscape levels, and these changes explain important shifts in numerous habitats and ecosystem processes. Conditions of nonforest vegetation (grasslands, shrublands, sparse woodlands) are likewise altered as a consequence of fire exclusion and forest encroachment. While some forest and nonforest ecosystems may not have been directly altered by fire exclusion, the magnitude of changes suggests that it is likely that all were indirectly impacted by alteration of the landscape ecology and disturbance regimes that surround them. Based on a preponderance of scientific evidence, there can be little doubt that long-term fire exclusion and other associated social-ecological influences contributed to extensive modification of landscapes across wNA, and that the magnitude of the departures in fire regimes and landscape conditions has increased the vulnerability of contemporary forested landscapes to fire and drought-related stressors.

The evidence for change in fire regimes

Hagmann et al. (2021) also review the evidence for changes in the dimensions of fire regimes (Table 1). Fire exclusion has reduced fire frequency in all forest types, with the degree of change generally declining with increasing elevation, owing to orographic effects on moisture and temperature, and topo-edaphic effects on insolation. As a consequence, surface and ladder fuel abundance generally increased in historically fuel-limited frequent-fire forests, while forest cover at higher elevations expanded and became more successionally homogenized (Fig. 2). In both cases, crownfire vulnerability increased. Long-term fire exclusion reduced the total amount and spatial distribution of wildfires resulting in a nearly universal fire deficit in forests (Parks et al. 2015, Parks and Abatzoglou 2020).

ADAPTING FORESTS TO WILDFIRES AND CLIMATE CHANGE

Prichard et al. (2021) address 10 key questions surrounding active forest management, address the assumption that historical fire regimes were "natural" rather than cultural, and describe conditions where specific management actions are appropriate and effective for adapting current forests to wildfires and climate change. The authors again use a strength of scientific evidence approach to show why the answers to the 10 questions are relatively straightforward. In addition to evaluating the efficacy of diverse treatments to moderate expected fire severity, they discuss these questions in the context of their consistency with more holistic climate- and wildfire-adaptation strategies that are designed to achieve many social and ecological benefits. Moreover, they discuss how methods designed to achieve a single objective often fail given contemporary goals for multi-objective landscape management. We summarize their responses to the 10 questions here.

1) *Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive?*
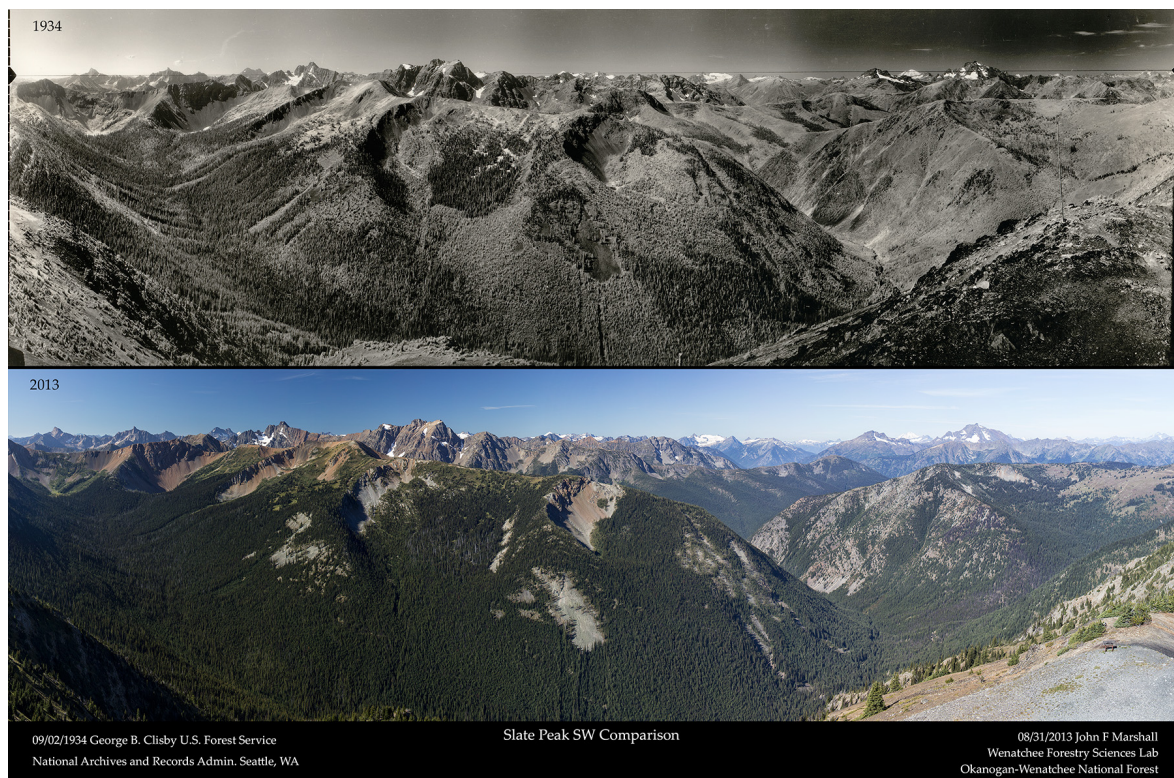
Fig. 2. Top photo: View from atop Slate Peak in northeastern Washington, looking southwest, 1934, George Clisby photograph, National Archives, Seattle, Washington, USA. The 1934 panoramic view shows extensive evidence of prior wildfires, varied age classes of cold forest, and recently burned and recovering areas. In the same view nearly eight decades later (bottom photo, 2013, John Marshall Photography), note the complete absence of recent fire evidence, widespread ingrowth creating denser forests, loss of nonforest, and lack of forest successional heterogeneity.

Prichard et al. (2021) dispute all parts of this question. They reveal four crucial components in their answer, not the least of which is that increasing forest resilience and resistance to wildfires and climate change provides positive societal and ecosystem benefits, which overwhelm uncertainties about prior historical conditions. They also show that intentional forest management is effective and corrective where practiced, but its pace and footprint are insufficient to current needs.

2) *Is forest thinning alone sufficient to mitigate wildfire hazard?* Whether forest thinning achieves adaptation objectives depends on several factors, including its timing, location, rate, and spatial scale. Reducing canopy layering and density limits crownfire potential, but unless the abundance and connectivity of surface fuels and fuel ladders is also reduced, thinning can have limited effectiveness in mitigating wildfire severity, and may make matters worse. In forest thinning for adaptation to climate change and wildfires, emphasis is placed on residual forest structure, composition, and understory fuels rather than on the trees that are removed (Larson and Churchill 2012, Churchill et al. 2013).

3) *Can forest thinning and prescribed burning achieve climate adaptation?* Coupled thinning and prescribed burning treatments are proven approaches to mitigating wildfire severity in many seasonally dry forests, but they are not appropriate to all forest types, land allocations, and conditions. These treatments require regular maintenance application of prescribed or cultural burning to maintain low surface fuel levels and remove developing fuel ladders. The vast scale of ongoing fuel reduction necessitates wise use of naturally ignited future fires during moderate fire weather as well.

4) *Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)?* Fuel treatments in the WUI are critically important as is reducing continued development in high fire danger areas (Balch et al. 2017, Radeloff et al. 2018). People living in the WUI have ample incentive to reduce their vulnerability to wildfires (Cohen 2000), and many resources are available to

help them do so (Syphard et al. 2012; *resources available online*).[7,8] However, this logic, concentrating treatments in WUI, fails to address interconnectedness between social and ecological systems in landscapes beyond the WUI. Examples include wildfire emissions and broad-scale smoke movement in the atmosphere; water quality and quantity provided by municipal watersheds distant from population centers; ember attack on WUI areas from wildfires burning several kilometers away; wildfire effects on power, WIFI, and broadband transmission and distribution networks; and tribal connections to ancestral territories and resources. It also avoids core decisions related to human social values for forested landscapes and long-term ecosystem dynamics. Alternatively, intentional forest management both within and beyond the WUI offers the greatest social and ecological benefits.

5) *Can wildfires on their own do the work of fuel treatments?* Many forests are experiencing rapid WUI expansion, leaving land managers and citizens increasingly unwilling to accept the risks of managed wildfires In the backcountry, some wildfires are allowed to burn under specified conditions to achieve incident and resource management objectives. However, the effects of fire exclusion are varied and extensive, and managed wildfire is a spatially imprecise tool. To increase predictability of outcomes, application during benign to moderate fire weather may be preferred; this, however, necessitates numerous follow-up treatments to meet objectives, and it broadens the period of landscape vulnerability to more extreme wildfires. Considering the narrow seasonal operating window and spatial imprecision concerns, managed wildfires cannot be a cure-all, but can be one of several options in a broader toolkit.

6) *Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment?* The central objective of fuel treatments is to moderate fire behavior when fire inevitably returns, not to stop fire spread or reduce ignitions If fuel treatments simply improve suppression success, less area is burned in the short term but more area will escape control in the future, resulting in deferred risk and contributing to larger and more often severe wildfires.

7) *Do fuel treatments work under extreme fire weather?* Many studies show that fuel reduction treatments are effective at moderating subsequent fire severity, even under extreme weather Far fewer experimental or empirical studies challenge this premise. Moreover, there is strong evidence that some prior burn and reburn mosaics reduce landscape contagion, which limits subsequent spread and severity of wildfires.

8) *Is the scale of the problem too great? Can we ever catch up?* Given the scale of the area burned by wildfires each decade compared to area treated, some surmise that fuel treatments are futile Nevertheless, a large body of work shows that fuel reduction treatments, including portions of some past wildfires, effectively mitigate subsequent fire behavior and effects. It follows that strategies can be developed to increase rather than decrease the role of fuel reduction treatments. The key to defining the locations, spatial scale, timing, rate of treatment, and methods used is the desired forest–nonforest conditions that result, their degree of adaptation to changing climate and fire regime conditions, and the degree of comfort with spatial uncertainty of outcomes. Moreover, coupling Indigenous cultural burning, fuel reduction, and prescribed fire treatments furthers Indigenous fire stewardship and food security (Sowerwine et al. 2019*a,b*), and recovers opportunities for tribal engagement in resource management within their ancestral territories (Long and Lake 2018, Long et al. 2020).

9) *Will planting more trees in wNA forests help to mitigate climate change?* Widespread tree planting has been proposed as a key climate change mitigation (Bastin et al 2019). This premise has poor scientific support in many fire-prone regions of the world (e.g., Grainger et al. 2019, Lewis et al. 2019, Veldman et al. 2019). An increasing body of evidence reveals that proactive management to restore more resilient forest and nonforest structure and composition over large areas, and diversifying tree planting species mixes, can more effectively maintain or increase carbon stores relative to the effects of modern wildfires (e.g., see Hof et al. 2017).

10) *Is post-fire management needed or even ecologically justified?* Prior to fire exclusion, historical landscapes in seasonally dry regions of wNA were the product of complex mosaics of low-, moderate- and high-severity fire patches, which yielded highly variable patterns of surviving forest and scattered fire refugia (ie., unburned patches that functioned as seed sources for postfire tree regeneration in their vicinity). After contemporaneous wildfires, this mosaic is often simplified by large high-severity fire patches, and fire refugia are operationally burned out in closing suppression actions. Within one to two decades after a high-severity fire, dead wood accumulations contribute to uncharacteristically high surface fuel loads. Post-fire removal of the dead understory stems (i.e., those that had previously colonized the landscape during the lengthy period of fire exclusion) by harvest or reburning can mimic this historical reburn influence, thereby minimizing surface fuels in some developing new forests (Stevens-Rumann and Morgan 2016), and reducing future wildfire vulnerability (Coppoletta et al. 2016). The ecological justification for this post-fire removal of the smaller dead understory trees can be

observed in the low surface fuel loads associated with the frequent reburning of pre-management era landscapes and modern-day wilderness areas. It is also clearly revealed in intentional Indigenous cultural burning practices. Indigenous fire stewardship actively mediated post-fire landscape effects to stagger the availability of desired resources and species over time, and ensure their quality, quantity, and abundance (Boyd 1999, Lake and Christianson 2019).

STRATEGIES FOR ADAPTING WESTERN LANDSCAPES

Changes in forested landscapes throughout wNA are somewhat unique geographically, as are the stories of change. To consider appropriate climate and wildfire adaptation strategies, managers are compelled to evaluate current vegetation and fuel conditions, the influences that precipitated changes in conditions, the magnitude of the changes, ecological and social constraints to adaptation, patch to landscape vulnerability to changing climatic and wildfire regimes, and nonnative species and any sensitive or endangered species concerns.

Stephens et al. (2010) recommend four strategies for adapting western landscapes to changing climatic and wildfire regimes, and they can be applied in a variety of contexts. 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 disturbances occur. Finally, they present *response* work as any intentional facilitation to achieve socially and ecologically desirable results that are otherwise difficult to achieve. Each of these strategies can play a role in proactive management going forward. Where their application also considers Indigenous cultural adaptations to climate, vital ecosystem processes, and active cultural use of fire, there will be greater likelihood that resulting vegetation conditions are strongly linked to culturally valued resources and services (Power et al. 2018).

Whether reactive or proactive fire management

Modern wildfire suppression extinguishes essentially all fire starts except those that overwhelm fire suppression capacity and can only be extinguished when aided by a significant change in the weather (North et al. 2015). Fires burning under extreme fire weather often burn vast areas, much larger than the current footprint of managed wildfires and other fuel treatment projects. As a consequence, wildfires that escape initial suppression efforts burn under the most extreme fire weather conditions and do most of the vegetation management in wNA ecosystems (Calkin et al. 2005, North et al. 2015). Appropriately designed

thinning, burning, and managed wildfire treatments, that are tailored to topo-edaphic conditions would be helpful additions to this scenario (sensu Taylor and Skinner 2003, Hessburg et al. 2015). Such treatments would prepare landscapes for wildfires that will inevitably follow.

Managing wildfires that burn under extreme fire weather is a blunt management response, which most often results in failure to meet resource management or conservation objectives. Science-based strategies for forest and fuel management are well known, but lack of social license and sufficient financial and personnel resources currently limit fuel reduction programs to a small percentage of wNA forestlands (Hessburg et al. 2020). Increasing costs of fire suppression and lack of control during large fire growth days reveals a reactive management posture that is progressively prone to failure, despite ever-increasing investments (North et al. 2015, Stephens et al. 2020). Thus, a business-as-usual approach to wildfire in fire-prone regions will not solve the current wildfire dilemma (Moreira et al. 2020). Strategic management of regional landscapes is needed that establishes topographically sensible (sensu Povak et al. 2018 and Taylor and Skinner 2003), fire-maintained, control and anchor points (e.g., see Wei et al. 2019). This would improve fire manager usage of future wildfires as adaptation tools.

A more proactive and evidence-based management goal is to restore active wildland fire regimes and landscape resilience to climate change, and actively enable future wildland fires, prescribed and cultural burning, and managed wildfire to provide a higher standard of social-ecological work. To achieve this goal, massive progress and investment are needed (Madeira and Gartner 2018) to transition management from a reactive to a proactive, forward-looking stance. Such an approach allows for the direct adaptation of wildfire regimes by intentionally crafting landscape patterns that drive more benign fire behavior and less severe drought effects. This will require radically increasing the areal extent of restorative and adaptive fuel reduction treatments as is appropriate to conditions and land allocations. It will also require increased use of natural wildfire ignitions (as above) under moderate fire weather conditions, to recapture the once extensive moderate influences of wildfires, and then maintain that progress with controlled (prescribed and cultural) burning and thinning as needed.

The nested character of regional landscapes holds adaptation clues

The hierarchical organization of historical wNA landscapes influences countless ecosystem functions, including scale-dependent spatial and temporal controls that drive wildfire behavior and effects, and the cross-connection between levels of organization. Characteristics of this organization and its influence on ecosystem

functions can inform realignment of current systems with early 21st-century and projected future climates (Hessburg et al. 2016, 2019). Three important ideas associated with that nested structure are that (1) at a fine spatial scale, species traits and adaptations drive within-patch structure, composition, and response to disturbances; (2) cross-connections between fine-scale patch structure and composition and meso-scale landscape patchworks influence fire frequency and severity because they form the percolation surface where disturbance propagates, and the manner of propagation; and (3) cross-connections between non-forest and forested landscapes mediate broad spatial patterns of fire behavior attributes and their effects. These three ideas help shape a scientifically supported landscape adaptation framework (Hessburg et al. 2015, 2019).

Additionally, we are learning through integration of western science with traditional ecological knowledge that Indigenous fire use and broader landscape stewardship practices were upheld in tribal communities as human services for ecosystems. Indigenous tribes acknowledged and promoted multi-generational contributions to foster landscape resistance and resilience. Trans-generational fire use also promoted post-fire recovery of landscapes and habitats where culturally valued drought-tolerant, fire-adapted plant species were adversely influenced by a fire (Huffman 2013).

BEYOND THE PRECAUTIONARY PRINCIPLE

The precautionary principle holds that when the potential for adverse effects is unknown or difficult to quantify; the burden of proof rests on the proponent of an activity to demonstrate that lack of harm is the most likely outcome. However, it is virtually impossible to demonstrate lack of harm for most any activity, including no action, especially in a rapidly changing environment. Moreover, one-sided, or single-issue application of the principle can overlook desired ecosystem services, species, and processes that proactive work could have protected. Given human influence on climate and wildfire regimes the world over, a no-action alternative that purports to let so-called natural processes like modern wildfires operate unfettered is grossly misleading. These processes are operating within a human-influenced template globally, and their regime characteristics and fuel conditions have been altered by humans, increasing the likelihood that large portions of many modern wildfires are unnatural.

Modern wildfire management dominated by fire suppression is perceived by many as a no-action alternative when compared to active restoration and adaptation in planning and management. However, active suppression of 98% of wildfire ignitions (North et al. 2015) hardly qualifies as no action, as we have shown earlier. The small proportion of wildfires that escape containment all too often rapidly and indiscriminately convert forest to non-forest conditions. This is an altogether unevaluated

planning outcome, and the recovery of forest structure and processes can take decades to centuries, if it occurs at all. Furthermore, fire suppression costs currently exceed US$2 billion annually, not including loss of life and property, and detrimental impacts to lifeways, human health, and livelihoods, while the total annualized economic burden of wildfires ranges from US$71 billion to US$347 billion (Thomas et al. 2017; data *available online*).[9]

The precautionary principle is indeed useful guidance, but it must be applied equally to what are often mistakenly perceived as no-action alternatives. Lacking this clarity, broad application of the precautionary principle as a conservation approach can result in greater long-term harm than more ecologically intuitive remedies, as can be seen within the Northwest Forest Plan area of the eastern Cascade and Klamath Mountain regions (Spies et al. 2019, Stephens et al. 2019). There, networks of late-successional reserves (LSRs) for the northern spotted owl in seasonally dry, historically frequent-fire forests increase the likelihood of their elimination by extreme wildfire events (Henson et al 2013, Spies et al. 2018, 2019). There is simply too much at stake to require unattainable certainty about potential risk of harm or losses (Wood and Jones 2019).

The precautionary principle can become the "paralyzing principle" given irreducible uncertainty about risk of loss associated with action and no-action alternatives (Sunstein 2003). The loss of ˜30 million mature and old pine trees during a recent extreme drought in south-central California (Asner et al. 2016) is a stark reminder of the pitfall of requiring unduly high certainty despite decades of established science showing the efficacy of treatments that foster resilient forest structure and composition (Henson et al. 2018, Fettig et al. 2019). Absent 150–170 yr of frequent fires, overgrown forest density conditions produced a massive and predictable die-off event, facilitated by tree-killing bark beetles and drought, that proactive implementation of climate- and wildfire-adaptation strategies could have mitigated (Stephens et al. 2018, Fettig et al. 2019). Remedying such conditions would have required careful consideration of changes over the period of fire exclusion, the effects of climatic changes looking forward, and any related ESA (Endangered Species Act) concerns.

Dealing with uncertainty

There is much uncertainty to science, including that surrounding our knowledge of historical and contemporary forest ecology, future conditions, and adaptive forest management. In that light, active forest management projects with objectives of restoring more resilient and resistant structure and composition can be assessed using a set of questions to address the relative

[9] https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf.

uncertainty associated with proactive versus reactive treatment alternatives. For example, in the context of changing wildfire regimes and climatic conditions, what are the uncertainties, trade-offs, and likely consequences to U.S., Canadian, and Mexican Indigenous and non-indigenous people, infrastructure, ecosystems, native species and habitats of

1) Restoring active fire regimes to dry, moist, and cold forest ecosystems,
2) Continued fire suppression in these same forest types,
3) Proposed proactive, reactive, and no-action management alternatives,
4) Post-fire forest regeneration under action and no-action alternatives, and
5) Post-fire harvest/non-harvest of the younger fire-killed trees to mimic reburns?

REFRAMING MANAGEMENT AND POLICY

As demonstrated in literature reviews, the disturbance ecology of an ecosystem may still be the most valuable lens through which climate-related events and outcomes may be understood (Long 2009, Newman 2019, Franklin and Johnson 2013). Over millennia, Indigenous fire use in many areas amplified fire frequency to reduce the likelihood of more extreme wildfires and their effects on culturally valued resources and conditions. This culturally modified disturbance regime increased the resilience and resistance of vegetation and landscape conditions to changing climatic conditions and associated disturbances.

More recently, ecological forestry principles recognize the value of management planning that incorporates the influence of natural disturbance processes on forest dynamics (Franklin et al. 2018). Additionally, as shown by Indigenous experience, natural lightning ignitions can be supplemented to achieve desired conditions. In uncertain times, management might better focus on the long-term persistence of that native biodiversity that evolved within the local, culturally enhanced, disturbance regime, and will likely go extinct with rapid or extreme changes to those regime properties (Newman 2019). Where possible, adapting local landscapes to conserve key aspects of culturally enhanced disturbance regimes could be vital to preserving functioning ecosystems and to the native biodiversity that requires non-extreme disturbance for its continued existence (Franklin and Johnson 2012, North et al. 2014), even where single-species conservation and broader ecosystem goals may appear to be in conflict at other scales (Henson et al. 2013).

Managers and scientists have repeatedly proposed management directions that incorporate knowledge of disturbance ecology and methods that adequately mimic and recover local disturbance regimes; however, socioeconomic challenges have impeded widespread implementation of these strategies (Long 2009). Effective direction would be proactive rather than reactive, recognizing that just as with human society, all desired ecological outcomes are not possible in the same place, at the same time.

Recommendations

In this light, what constitutes adaptation of wNA forests in these uncertain times? Is bias for action rather than inaction recommended?

Scientific knowledge is always growing and incomplete. However, a preponderance of evidence suggests that proactive management can prepare many landscapes for future wildfires and the maintenance work they can provide. This would also reduce emphasis on high-maintenance solutions and the overarching and increasingly burdensome role of wildfire suppression and its expenditures.

Emphasize whole landscape and multi-scale adaptation.—Stand management as applied to western U.S. and Canadian public lands typically emphasizes forested areas where there are commercial opportunities for mechanical treatments in specific stands of trees. This focus misses many locations where proactive treatments may be most useful to adapting an entire landscape. Conducting whole landscape evaluations of forest conditions, fire regime departures, and expected future climate and weather conditions can powerfully aid in defining those places that would most benefit from adaptation treatments (North et al. 2009, Hessburg et al. 2013, 2016, Meyer et al. 2021).

Ongoing collaborative partnerships also recommend that emphasis on timber volume production from public lands has a negative influence on partner support for projects and trust maintenance (Hessburg et al. 2020), and it tends to force the hand of managers to rank commercial treatments over others that may be more truly adaptive. Alternatively, management and planning that emphasizes area restored and adapted could build trust and a broader base of support, while still providing timber volume to sustain rural mills and economies (Rummer et al. 2005). Increasingly, collaborative restoration partnerships with Indigenous communities, having tribes as part of the leadership and management, can increase opportunities for reinstating tribal stewardship practices, with tribes, local communities, and the broader society as beneficiaries of active management that achieves shared values (Lake et al. 2018, Long and Lake 2018).

Large and old trees.—Most research reveals that broadly conserving large and old fire-resistant trees and replacing those that were removed or killed by harvest, drought, insects, pathogens, and wildfires provides a strong backbone of resilient structure and habitat to seasonally dry pine and mixed-conifer ecosystems (Spies et al. 2018, 2019).

Clumped and gapped trees.—As is appropriate to local seasonally dry forest types, restoring tree clump and gap patterns, and increasing area of these conditions will provide a solid patch-to-local landscape bet-hedging strategy in a warming future with increasing burned area (Larson and Churchill 2012, Churchill et al. 2013, LeFevre et al. 2020).

Successionally heterogeneous forests.—Successional heterogeneity, whether fine-, meso-, or coarse-grained, was an historical consequence of patterns of environmental productivity and fire–climate interactions with vegetation. It reinforced a continual shifting of diverse but similar patterns of heterogeneity at each scale of observation. As is appropriate to forest types and physiographic domains, restoring and maintaining forms of this heterogeneity will encourage a wider variety of wildfire and habitat outcomes, and reduce the need for aggressive fire suppression in many areas (Perry et al. 2011). This can be accomplished by adapting current spatial patterns of seral stages to more frequent burning and reburning (Stephens et al. 2020). Indigenous and Western knowledge can jointly aid in determining how best to adapt current and projected future conditions.

Using the topo-edaphic template.—Throughout wNA, topography, geomorphology, lithologies, and soils provide the template for spatially varying forest cover types, structural conditions, and their variations (Taylor and Skinner 2003, Hessburg et al. 2015). Fire exclusion and other influences have weakened connections to this template. Realigning spatial patterns of nonforest and forest successional pattern conditions (e.g., open vs. closed canopy, fire-tolerant vs. intolerant species) to this template will aid in adapting landscapes to changing climatic and wildfire regimes. For example, restoring non-forest and low-density forest cover patches to south-facing slopes and ridgetops and higher-density forest cover patches on north aspects and valley bottoms are examples of strengthening connections to the topographic template (Hessburg et al. 2015, 2019). These underlying conditions continually co-create the environments for disturbance and revegetation as the climate changes (Taylor and Skinner 2003, Hessburg et al. 2015, 2016).

Forests and their nonforests.—Meadows, shrublands, savannahs, and preforest conditions result from natural succession, disturbance dynamics, and reburning (Prichard et al. 2017). Restoring more characteristic nonforest-forest patterns in and among all forest types at fine, meso, and broad scales could significantly realign primary ecosystem processes, carbon storage, and hydrologic regimes with the warming climate (Shakesby and Doerr 2006). As recent history has shown, many pre-fire-suppression era nonforest areas throughout wNA became forested absent active fire regimes during the mild mid-20th-century climatic period (Hessburg et al. 2019).

Research Needs

The reviews of Hagmann et al. (2021) and Prichard et al. (2021) show deepening understanding of the fire and landscape ecology of wNA forests; however, substantive knowledge gaps remain. Here, we discuss the following research needs that emerged from this review:.

1) *Fortifying future vegetation and wildfire projections with insights from landscape ecology research* Most continental to regional projections of climate influence on biotic conditions and physical processes use a range of intuitive climatic drivers to explain responses to warming (Rosenzweig et al. 2008, Parks et al. 2015, Abatzoglou and Williams 2016). Outcomes are presented as ostensibly unaffected by bottom-up or meso-scale spatial variation in biotic, environmental, disturbance history, or topoedaphic conditions inherent to the system(s) of interest. From the standpoint of landscape ecology theory and practice, this approach misses key cross-scale interactions between the climate system and highly varying biophysical settings, which are known to modify climate system inputs and alter spatial and temporal patterns of realized conditions (Wu and Loucks 1995). Hurteau et al. (2019) for example, showed that future projections of burned area under climate change, which accounted for interactions among prior fires on surface and canopy fuel availability, reduced area burned by 14.3% in the Sierra Nevada compared to projections where only climate drivers were considered. Hybrid research and modeling are needed among climate change scientists and landscape ecologists to improve projections of vegetation and burned area changes, and species ranges.

2) *Multi-proxy evidence is more informative than single proxy* Observing and integrating knowledge of the multi-level dimensions of forest landscapes and their wildfire regimes provides deeper insight into how patterns influence processes, and it improves change detection (Hagmann et al. 2021). Some regions are already represented by multi-level studies, but in some cases, they could be better integrated. Multi-scale and multi-proxy historical reconstructions are still needed for other regions of wNA to better understand variations in forest–nonforest relations and successional heterogeneity that are better aligned with changing climatic and wildfire regimes. With these insights, managers and policy-makers will be better able to understand how warming and drying may affect adaptation strategies.

3) *More wildfire–forest dynamics carbon research is needed* Recent studies show that strategies for adapting current forests to wildfires and climate change may result in more terrestrial carbon storage than business-as-usual scenarios. The reason is that large fuel buildup under fire exclusion renders forest carbon stores vulnerable to large, high-severity fire

events (Liang et al. 2018, Hurteau et al. 2019). This nascent inquiry area deserves significant investment and increased scope to determine suitable landscape management strategies, and where they may best apply.

4) *Disturbance–fish-and-wildlife-habitat connections* As Newman (2019) suggests, native species and their habitats are tied to disturbance regimes of local and regional landscapes. Our current knowledge of these species-disturbance regime linkages is weak in many areas and could be much better understood. Even where 25 yr of research is available for one of the most intensively studied bird species, that knowledge is not preventing population declines for Northern Spotted Owls (Spies et al. 2019, Stephens et al. 2019). As a result, Henson et al. (2018) advocated a coarse-filter approach that incorporates disturbance ecology in management for spotted owl habitat. Understanding and managing spatial domains to restore these more functional disturbance regimes is an intuitive coarse-filter conservation strategy for terrestrial and aquatic species.

5) *A role for decision support tools* Predicting future vegetation, climate, and wildfire conditions, and trade-offs among various habitats and resources across a set of potential management scenarios is intellectually and computationally challenging. Considering the large number of data layers, the one-to-many and many-to-one interactions among conditions represented by these layers, and variation in these relationships by scenario thwarts careful evaluation by even the best planning intellects. Decision support tools are designed for this complex and integrated planning environment and are useful for evaluating trade-offs among changing conditions, outcomes, and management scenarios (Kangas and Kangas 2005, Reynolds et al. 2014). Using such tools, managers and scientists can observe trade-offs and related positive and negative cascades associated with varied management scenarios and discover their primary drivers.

6) *Innovation and investment in multi-party monitoring and adaptive management* Adaptive forest management has been recommended by scientists and managers for decades (Lee 1999), however, it has functioned more as an abstraction than an applied reality (Bormann et al. 2007). While adaptive management provided the core of Indigenous landscape management methods (Anderson 2013), there are several key reasons for delayed application in contemporary management. Adaptive management depends on watchful learning; what we today call ecosystem monitoring, which can be time consuming and expensive, and results often come after lengthy delays. Sufficient monitoring is rarely budgeted for, and consequently, an adaptive process is inhibited. Without agreement on the monitoring questions and goals of management, disputes remain unresolved. Innovation and investment are needed in this area to develop better methods of multi-party goal setting, and efficient and inexpensive means of monitoring; for example, multi-scale photography or remote sensing in addition to intensive plot and survey application. Another monitoring approach proposed by Tribes is to use cultural keystone species as indicators of ecosystem integrity and function (Garibaldi and Turner 2004). Results from monitoring a representative subset of forest conditions and projects could be extrapolated to similar conditions. This would enable more rapid learning and implementation, which are core concerns. Effective learning of this sort will become more essential as expanding human populations search for better ways to live sustainably on increasingly dynamic wNA landscapes.

CONCLUSIONS

Here, we have described how policy and management choices of the last two centuries yielded forest conditions throughout much of wNA that are vulnerable to the effects of rapid climatic warming, including increasing fire and drought severity. We summarized core messages of Hagmann et al. (2021) and Prichard et al. (2021), detailing widespread changes in forested landscapes and wildfire regimes since the influx of European colonists, and addressing popular questions about the capacity of management practices to reverse or mitigate the worst effects of these changes. We address concerns about the influence of agenda-driven science and reiterate that the *precautionary principle* can become the *paralyzing principle* given uncertainty about the risk of losses associated with action and no-action alternatives. We discussed the near impossibility of demonstrating lack of harm for most any action, including inaction, especially in a rapidly changing environment.

We provided recommendations for reframing forest and fire management and their related policy underpinnings, emphasizing (1) whole landscape and multi-scale adaptation; (2) protection of large and old fire- and drought-tolerant trees and old forests; (3) restoration of clumped and gapped tree patterns at fine and meso spatial scales; (4) creation of successionally heterogeneous forests; (5) use of topography to realign current conditions to the biophysical template; and (6) restoration of nonforest conditions. Climate change will create more nonforest and more young open canopy forest conditions (Parks et al. 2016, Hessburg et al. 2019, Coop et al. 2020); the opportunity for management is to place those conditions and patch sizes in locations that provide the greatest social and ecological benefits while conserving and recruiting old trees and old forest where possible.

Some today call for cultivating pyrodiversity to advance biodiversity (Parr and Andersen 2006, Taylor et al. 2012, Bowman et al. 2016). However, not all heterogeneity is equally well adapted to the topography, soils, and varied environmental settings and fire

regimes of wNA landscapes, and thus may endanger native biodiversity. Climate and wildfire adaptation requires structural and compositional patterns and pattern variations that are in synch with biophysical settings, reinforce the desired fire regimes, and reduce undesirable impacts of climatic warming to socioecological communities.

We close our review with a short list of research needs. Key among them is the need to better understand the disturbance regimes that native plants and animals evolved with and through which persistence occurred even as we act proactively to restore pattern–process interactions and adapt these landscapes to warming climate. Most legal battles concerning forest management today are about native biodiversity, old tree or old forest conservation, conservation of threatened and endangered species, and impacts of timber harvesting. Yet, native species and their habitats are tied to disturbance regimes of local and regional landscapes and their pattern variations. Our current knowledge of these species-disturbance regime linkages is weak, yet these dynamics might become a focal means of biodiversity conservation (Henson et al. 2013).

Finally, we discussed how some of these climatic and fire regime effects were common to landscapes inhabited by the Indigenous people of wNA, and in closing, we return to those ideas. Because of significant vulnerabilities linked to native wildfire regimes, Indigenous people intentionally managed wildfire for millennia to provide a broad variety of life-supporting resources, food and medicine security, protect lifeways, sacred places, and deeply held traditions, and to increase personal safety. This intentional management was a transgenerational commitment; prior generations took responsibility for the quality and abundance of desired conditions they passed on to subsequent generations. Since the mid-1850s, the majority of EuroAmerican colonists and present-day citizens have neither practiced this intentional management nor passed on a transgenerational commitment. Yet, we are ever more dependent as a society on the ecosystem services that functional fire-adapted landscapes provide. Given the known risks of modern wildfires and climate change, embracing the role of fire and a return to intentional transgenerational management is of critical importance.

Disclaimer

The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the U.S. Fish and Wildlife Service or the USDA Forest Service.

Literature Cited

Abatzoglou, J. T., and A. P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences USA 113:11770–11775.

Ager, A. A., A. M. Barros, R. Houtman, R. Seli, and M. A. Day. 2020. Modelling the effect of accelerated forest management on long-term wildfire activity. Ecological Modelling 421:108962. https://doi.org/10.1016/j.ecolmodel.2020.108962

Allen, C. D., M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, and J. T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12:1418–1433.

Anderson, M. K. 2013. Tending the wild: Native American knowledge and the management of California's natural resources. University of California Press, Berkeley, California, USA.

Asner, G. P., P. G. Brodrick, C. B. Anderson, N. Vaughn, D. E. Knapp, and R. E. Martin. 2016. Progressive forest canopy water loss during the 2012–2015 California drought. Proceedings of the National Academy of Sciences USA 113:E249–E255. https://doi.org/10.1073/pnas.1523397113

Balch, J. K., B. A. Bradley, J. T. Abatzoglou, R. C. Nagy, E. J. Fusco, and A. L. Mahood. 2017. Human-started wildfires expand the fire niche across the United States. Proceedings of the National Academy of Sciences of the United States of America 114:2946–2951.

Barnett, K., S. A. Parks, C. Miller, and H. T. Naughton. 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests 7:237. https://doi.org/10.3390/f7100237

Bastin, J. F., Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M. Zohner, and T. W. Crowther. 2019. The global tree restoration potential. Science 365:76–79.

Belsky, A., and D. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior west. Conservation Biology 11:315–327.

Bisson, P. A., B. E. Rieman, C. Luce, P. F. Hessburg, D. C. Lee, J. L. Kershner, G. H. Reeves, and R. E. Gresswell. 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. Forest Ecology and Management 178:213–229.

Bormann, B. T., R. W. Haynes, and J. R. Martin. 2007. Adaptive management of forest ecosystems: did some rubber hit the road? BioScience 57:186–191.

Bowman, D. M., G. L. Perry, S. I. Higgins, C. N. Johnson, S. D. Fuhlendorf, and B. P. Murphy. 2016. Pyrodiversity is the coupling of biodiversity and fire regimes in food webs. Philosophical Transactions of the Royal Society B 371:20150169.

Boyd, R. 1999. Indians, fire and the land. Pages 54. Oregon State University Press, Corvallis, Oregon, USA.

Bryant, T., K. Waring, A. Sánchez Meador, and J. B. Bradford. 2019. A framework for quantifying resilience to forest disturbance. Frontiers in Forests and Global Change 2:56. https://doi.org/10.3389/ffgc.2019.00056

Calkin, D. E., K. M. Gebert, J. G. Jones, and R. P. Neilson. 2005. Forest service large fire area burned and suppression expenditure trends, 1970–2002. Journal of Forestry 103:179–183.

Carey, A. B. 2006. Active and passive forest management for multiple values. Northwestern Naturalist 87:18–30. https://doi.org/10.1898/1051-1733(2006)87[18:AAPFMF]2.0.CO;2

Churchill, D. J., A. J. Larson, M. C. Dahlgreen, J. F. Franklin, P. F. Hessburg, and J. A. Lutz. 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management 291:442–457.

Cohen, J. D. 2000. Preventing disaster: home ignitability in the wildland-urban interface. Journal of Forestry 98:15–21. https://doi.org/10.1093/jof/98.3.15

Coop, J. D., et al. 2020. Wildfire-driven forest conversion in Western North American landscapes. BioScience 70:659–673.

Coppoletta, M., K. E. Merriam, and B. M. Collins. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications 26:686–699.

Dale, V. H., et al. 2001. Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience 51:723–734. https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2

Fettig, C. J., L. A. Mortenson, B. M. Bulaon, and P. B. Foulk. 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, US. Forest Ecology and Management 432:164–178. https://doi.org/10.1016/j.foreco.2018.09.006

Franklin, J. F., and K. N. Johnson. 2012. A restoration framework for federal forests in the Pacific Northwest. Journal of Forestry 110:429–439.

Franklin, J. F., and K. N. Johnson. 2013. Ecologically based management: A future for federal forestry in the Pacific Northwest. Journal of Forestry 111:429–432.

Franklin, J. F., K. N. Johnson, and D. L. Johnson. 2018. Ecological forest management. Pages 646. Waveland Press, Long Grove, Illinois, USA.

Fulé, P. Z., et al. 2014. Unsupported inferences of high-severity fire in historical dry forests of the western United States: response to Williams and Baker. Global Ecology and Biogeography 23:825–830.

Garibaldi, A., and N. Turner. 2004. Cultural keystone species: implications for ecological conservation and restoration. Ecology and Society 9:1.

Garrard, G. E., F. Fidler, B. C. Wintle, Y. E. Chee, and S. A. Bekessy. 2016. Beyond advocacy: making space for conservation scientists in public debate. Conservation Letters 9:208–212.

Grainger, A., L. R. Iverson, G. H. Marland, and A. Prasad. 2019. Comment on "The global tree restoration potential". Science 366:eaay8334.

Hagmann, R. K., et al. 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecological Applications e02431. https://doi.org/10.1002/eap.2431

Hagmann, R. K., J. F. Franklin, and K. N. Johnson. 2013. Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central Oregon. Forest Ecology and Management 304:492–504.

Hagmann, R. K., J. F. Franklin, and K. N. Johnson. 2014. Historical conditions in mixed-conifer forests on the eastern slopes of the northern Oregon Cascade Range, USA. Forest Ecology and Management 330:158–170.

Henson, P., J. Thrailkill, B. Glenn, B. Woodbridge, and B. White. 2013. Using ecological forestry to reconcile spotted owl conservation and forest management. Journal of Forestry 111:433–437.

Henson, P., R. White, and S. P. Thompson. 2018. Improving implementation of the Endangered Species Act: finding common ground through common sense. BioScience 68:861–872. https://doi.org/10.1093/biosci/biy093

Hessburg, P. F., et al. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landscape Ecology 30:1805–1835.

Hessburg, P. F., et al. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. Forest Ecology and Management 366:221–250.

Hessburg, P. F., et al. 2019. Climate, environment, and disturbance history govern resilience of western North American forests. Frontiers in Ecology and Evolution 7:239. https://doi.org/10.3389/fevo.2019.00239

Hessburg, P. F., et al. 2020. The 1994 Eastside Screens large-tree harvest limit: review of science relevant to forest planning 25 years later. Pages 114. General Technical Report PNW-GTR-990. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA.

Hessburg, P. F., and J. K. Agee. 2003. An environmental narrative of inland northwest United States forests, 1800–2000. Forest Ecology and Management 178:23–59.

Hessburg, P. F., J. K. Agee, and J. F. Franklin. 2005. Dry forests and wildland fires of the inland Northwest USA: Contrasting the landscape ecology of the pre-settlement and modern eras. Forest Ecology and Management 211:117–139.

Hessburg, P. F., K. M. Reynolds, R. B. Salter, J. D. Dickinson, W. L. Gaines, and R. J. Harrod. 2013. Landscape evaluation for restoration planning on the Okanogan-Wenatchee National Forest, USA. Sustainability 5:805–840. https://doi.org/10.3390/su5030805

Hessburg, P. F., B. G. Smith, and R. B. Salter. 1999. Detecting change in forest spatial patterns from reference conditions. Ecological Applications 9:1232–1252.

Hessburg, P. F., B. G. Smith, R. B. Salter, R. D. Ottmar, and E. Alvarado. 2000. Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA. Forest Ecology and Management 136:53–83. https://doi.org/10.1016/S0378-1127(99)00263-7

Higuera, P. E., M. E. Peters, L. B. Brubaker, and D. G. Gavin. 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews 26:1790–1809. https://doi.org/10.1016/j.quascirev.2007.03.010

Hof, A. R., C. C. Dymond, and D. J. Mladenoff. 2017. Climate change mitigation through adaptation: the effectiveness of forest diversification by novel tree planting regimes. Ecosphere 8:e01981.

Huffman, M. R. 2013. The many elements of traditional fire knowledge: synthesis, classification, and aids to cross-cultural problem solving in fire-dependent systems around the world. Ecology and Society 18:3.

Hurteau, M. D., J. B. Bradford, P. Z. Fulé, A. H. Taylor, and K. L. Martin. 2014. Climate change, fire management, and ecological services in the southwestern US. Forest Ecology and Management 327:280–289.

Hurteau, M. D., S. Liang, A. L. Westerling, and C. Wiedinmyer. 2019. Vegetation-fire feedback reduces projected area burned under climate change. Scientific Reports 9:1–6.

Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes, and G. L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures

and salmonid thermal habitat in a mountain river network. Ecological Applications 20:1350–1371.

Kangas, J., and A. Kangas. 2005. Multiple criteria decision support in forest management—the approach, methods applied, and experiences gained. Forest Ecology and Management 207:133–143. https://doi.org/10.1016/j.foreco.2004.10.023

Kay, C. E. 2000. Native burning in western North America: implications for hardwood forest management. Pages 19–27 in A. D. Yaussy, comp. Proceedings: Workshop on Fire, People, and the Central Hardwoods Landscape. General Technical Report NE-274. US Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, Pennsylvania, USA.

Keane, R. E., G. J. Cary, I. D. Davies, M. D. Flannigan, R. H. Gardner, S. Lavorel, J. M. Lenihan, C. Li, and T. S. Rupp. 2004. A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics. Ecological Modelling 179:3–27. https://doi.org/10.1016/j.ecolmodel.2004.03.015

Keane, R. E., R. A. Loehman, L. M. Holsinger, D. A. Falk, P. Higuera, S. M. Hood, and P. F. Hessburg. 2018. Use of landscape simulation modeling to quantify resilience for ecological applications. Ecosphere 9:e02414.

Keane, R. E., K. C. Ryan, T. T. Veblen, C. D. Allen, J. A. Logan, and B. Hawkes. 2002. The cascading effects of fire exclusion in Rocky Mountain ecosystems, Chapter 7. Pages 133–152 in J. Baron, editor. Rocky Mountain futures: An ecological perspective. Island Press, Washington, D.C., USA.

Kolden, C. A. 2019. We're not doing enough prescribed fire in the Western United States to mitigate wildfire risk. Fire 2:30. https://doi.org/10.3390/fire2020030

Kolden, C. A., and C. Henson. 2019. A socio-ecological approach to mitigating wildfire vulnerability in the wildland urban interface: a case study from the 2017 Thomas Fire. Fire 2:9.

Komatsu, H., and T. Kume. 2020. Modeling of evapotranspiration changes with forest management practices: A genealogical review. Journal of Hydrology 585:124835.

Lach, D., P. List, B. Steel, and B. Shindler. 2003. Advocacy and credibility of ecological scientists in resource decision-making: a regional study. BioScience 53:170–178. https://doi.org/10.1641/0006-3568(2003)053[0170:AACOES]2.0.CO;2

Lackey, R. T. 2007. Science, scientists, and policy advocacy. Conservation Biology 21:12–17.

Lake, F. K., and A. C. Christianson. 2019. Indigenous fire stewardship. Pages 1–9 in S. Mazello, editor. Encyclopedia of wildfire and wildland-urban interface (WUI) fires. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-51727-8_225-1

Lake, F. K., J. Parrotta, C. P. Giardina, I. Davidson-Hunt, and Y. Uprety. 2018. Integration of traditional and Western knowledge in forest landscape restoration. Pages 214–242 in S. Mansourian and J. Parrotta, editors. Forest landscape restoration: integrated approaches to support effective implementation. Routledge, Abingdon-on-Thames, UK.

Larson, A. J., and D. Churchill. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. Forest Ecology and Management 267:74–92.

Lee, K. N. 1999. Appraising adaptive management. Conservation Ecology 3:1–21.

LeFevre, M. E., D. J. Churchill, A. J. Larson, S. M. Jeronimo, J. Bass, J. F. Franklin, and V. R. Kane. 2020. Evaluating restoration treatment effectiveness through a comparison of residual composition, structure, and spatial pattern with historical reference sites. Forest Science 66:578–588.

Levine, C. R., C. V. Cogbill, B. M. Collins, A. J. Larson, J. A. Lutz, M. P. North, C. M. Restaino, H. D. Safford, S. L. Stephens, and J. J. Battles. 2017. Evaluating a new method for reconstructing forest conditions from General Land Office survey records. Ecological Applications 27:1498–1513.

Lewis, S. L., E. T. Mitchard, C. Prentice, M. Maslin, and B. Poulter. 2019. Comment on "The global tree restoration potential". Science 366:eaaz0388.

Liang, S., M. D. Hurteau, and A. L. Westerling. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. Frontiers in Ecology and the Environment 16:207–212.

Lightfoot, K. G., et al. 2013. Anthropogenic burning on the central California coast in Late Holocene and early historical times: findings, implications, and future directions. California Archaeology 5:371–390.

Long, J. N. 2009. Emulating natural disturbance regimes as a basis for forest management: a North American view. Forest Ecology and Management 257:1868–1873.

Long, J. W., and F. K. Lake. 2018. Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. Ecology and Society 23:10.

Long, J. W., F. K. Lake, R. W. Goode, and B. M. Burnette. 2020. How traditional tribal perspectives influence ecosystem restoration. Ecopsychology 12:71–82.

Lydersen, J. M., M. P. North, E. E. Knapp, and B. M. Collins. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: Reference conditions and long-term changes following fire suppression and logging. Forest Ecology and Management 304:370–382.

Madeira, L., and T. Gartner. 2018. Forest resilience bond sparks innovative collaborations between water utilities and wide-ranging stakeholders. Journal American Water Works Association 110:42–49. http://doi: 10.1002/awwa.1097

McGarigal, K., and W. H. Romme. 2012. Modeling historical range of variation at a range of scales: an example application. Pages 128–145 in J. Wiens, C. Regan, G. Hayward, and H. Safford, editors. Historical environmental variation in conservation and natural resource management. Wiley, New York, New York, USA.

McKenzie, D., Z. E. Gedalof, D. L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18:890–902.

Meyer, M. D., J. W. Long, and H. D. Safford. 2021. Postfire restoration framework for national forests in California. Pages 204. General Technical Report PSW-GTR-270. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, California, USA.

Mildrexler, D. J., L. T. Berner, B. E. Law, R. A. Birdsey, and W. R. Moomaw. 2020. Large trees dominate carbon storage in forests east of the cascade crest in the United States Pacific Northwest. Frontiers in Forests and Global Change 3. http://dx.doi.org/10.3389/ffgc.2020.594274

Millar, C. I., N. L. Stephenson, and S. L. Stephens. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17:2145–2151.

Moreira, F., et al. 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environmental Research Letters 15:011001.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89:717–728.

Moritz, M. A., M. D. Hurteau, K. N. Suding, and C. M. D'Antonio. 2013. Bounded ranges of variation as a framework for future conservation and fire management. Annals of the New York Academy of Sciences 1286:92–107.

Newman, E. A. 2019. Disturbance ecology in the Anthropocene. Frontiers in Ecology and Evolution 7:147.

Norgaard, K. M. 2014. The politics of fire and the social impacts of fire exclusion on the Klamath. Humboldt Journal of Social Relations 36:77–101.

North, M., B. Collins, J. Keane, J. W. Long, C. Skinner, and B. Zielinski. 2014. Synopsis of emergent approaches. Pages 55–70 in J. W. Long, L. Quinn-Davidson, and C. N. Skinner, editors. Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range. General Technical Report PSW-GTR-247. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, California, USA.

North, M. P., S. L. Stephens, B. M. Collins, J. K. Agee, G. Aplet, J. F. Franklin, and P. Z. Fule. 2015. Reform forest fire management. Science 349:1280–1281.

North, M., P. Stine, K. O'Hara, W. Zielinski, and S. Stephens. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. Pages 49. General Technical Report PSW-GTR-220 (Second printing, with addendum). US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, California, USA.

Noss, R. F., J. F. Franklin, W. L. Baker, T. Schoennagel, and P. B. Moyle. 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and the Environment 4:481–487.

Odion, D. C., et al. 2014. Examining historical and current mixed-severity fire regimes in ponderosa pine and mixed-conifer forests of western North America. PLoS ONE 9:e87852.

Parks, S. A., and J. T. Abatzoglou. 2020. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. Geophysical Research Letters 47:e2020GL089858. https://doi.org/10.3389/ffgc.2021.629198

Parks, S. A., C. Miller, J. T. Abatzoglou, L. M. Holsinger, M. A. Parisien, and S. Z. Dobrowski. 2016. How will climate change affect wildland fire severity in the western US? Environmental Research Letters 11:035002.

Parks, S. A., C. Miller, M. A. Parisien, L. M. Holsinger, S. Z. Dobrowski, and J. Abatzoglou. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. Ecosphere 6:1–13. https://doi.org/10.1890/ES15-00294.1

Parr, C. L., and A. N. Andersen. 2006. Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. Conservation Biology 20:1610–1619.

Peery, M. Z., G. M. Jones, R. J. Gutiérrez, S. M. Redpath, A. B. Franklin, D. Simberloff, M. G. Turner, V. C. Radeloff, and G. C. White. 2019. The conundrum of agenda-driven science in conservation. Frontiers in Ecology and the Environment 17:80–82. http://doi:10.1002/fee.2006

Perry, D. A., P. F. Hessburg, C. N. Skinner, T. A. Spies, S. L. Stephens, A. H. Taylor, J. F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. Forest Ecology and Management 262:703–717.

Pielke, R. 2007. The honest broker: making sense of science in policy and politics. Cambridge University Press, London, UK.

Povak, N. A., P. F. Hessburg, and R. B. Salter. 2018. Evidence for scale-dependent topographic controls on wildfire spread. Ecosphere 9:e02443.

Power, M. J., B. F. Codding, A. H. Taylor, T. W. Swetnam, K. E. Magargal, D. W. Bird, and J. F. O'Connell. 2018. Human fire legacies on ecological landscapes. Frontiers in Earth Science 6:151.

Prichard, S. J., et al. 2021. Adapting western US forests to wildfires and climate change: ten common questions. Ecological Applications. http://dx.doi.org/10.1002/eap.2433

Prichard, S. J., C. S. Stevens-Rumann, and P. F. Hessburg. 2017. Tamm review: shifting global fire regimes: lessons from reburns and research needs. Forest Ecology and Management 396:217–233.

Radeloff, V. C., et al. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences USA 115:3314–3319.

Raphael, M. G., M. J. Wisdom, M. M. Rowland, R. S. Holthausen, B. C. Wales, B. G. Marcot, and T. D. Rich. 2001. Status and trends of habitats of terrestrial vertebrates in relation to land management in the interior Columbia River Basin. Forest Ecology and Management 153:63–87.

Reynolds, K. M., P. F. Hessburg, and P. S. Bourgeron. 2014. Making transparent environmental management decisions. Springer, Berlin and Heidelberg, Germany.

Rieman, B. E., P. F. Hessburg, C. Luce, and M. R. Dare. 2010. Wildfire and management of forests and native fishes: conflict or opportunity for convergent solutions? BioScience 60:460–468.

Rosenzweig, C., et al. 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453:353–357.

Rummer, B., et al. 2005. A strategic assessment of forest biomass and fuel reduction treatments in Western States. Pages 17. General Technical Report RMRS-GTR-149. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Schoennagel, T., et al. 2017. Adapt to more wildfire in western North American forests as climate changes. Proceedings of the National Academy of Sciences USA 114:4582–4590.

Schoennagel, T., R. L. Sherriff, and T. T. Veblen. 2011. Fire history and tree recruitment in the Colorado Front Range upper montane zone: implications for forest restoration. Ecological Applications 21:2210–2222.

Scott, J. M., J. L. Rachlow, R. T. Lackey, A. B. Pidgorna, J. L. Aycrigg, G. R. Feldman, L. K. Svancara, D. A. Rupp, D. I. Stanish, and R. K. Steinhorst. 2007. Policy advocacy in science: prevalence, perspectives, and implications for conservation biologists. Conservation Biology 21:29–35.

Shakesby, R. A., and S. H. Doerr. 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74:269–307.

Soulé, M. E. 1985. What is conservation biology? BioScience 35:727–734. https://doi.org/10.2307/1310054

Sowerwine, J., D. Sarna-Wojcicki, M. Mucioki, L. Hillman, F. K. Lake, and E. Friedman. 2019a. Enhancing indigenous food sovereignty: a five-year collaborative tribal-university research and extension project in California and Oregon. Journal of Agriculture, Food Systems, and Community Development 9:167–190. https://doi.org/10.5304/jafscd.2019.09B.013

Sowerwine, J., M. Mucioki, D. Sarna-Wojcicki, and L. Hillman. 2019b. Reframing food security by and for Native American communities: a case study among tribes in the Klamath River basin of Oregon and California. Food Security 11:579–607. https://doi.org/10.1007/s12571-019-00925-y

Spies, T. A., et al. 2014. Examining fire-prone forest landscapes as coupled human and natural systems. Ecology and Society 19:9. http://dx.doi.org/10.5751/ES-06584-190309

Spies, T. A., et al. 2019. Twenty-five years of the Northwest Forest Plan: what have we learned? Frontiers in Ecology and the Environment 17:511–520.

Spies, T. A., P. F. Hessburg, C. N. Skinner, K. J. Puettmann, M. J. Reilly, R. J. Davis, J. A. Kertis, J. W. Long, and D. C. Shaw. 2018. Old growth, disturbance, forest succession, and management in the area of the Northwest Forest Plan. Pages 95–243, 966 in T. A. Spies, P. A. Stine, R. Gravenmier, J. W. Long, and M. J. Reilly, tech. coords. Synthesis of science to inform

land management within the Northwest Forest Plan area. General Technical Report PNW-GTR-966. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA.

Stephens, S. L., et al. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19:305–320. https://doi.org/10.1890/07-1755.1

Stephens, S. L., et al. 2019. Is fire "for the birds"? How two rare species influence fire management across the US. Frontiers in Ecology and the Environment 17:391–399. https://doi.org/10.1002/fee.2076

Stephens, S. L., C. I. Millar, and B. M. Collins. 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environmental Research Letters 5:024003.

Stephens, S. L., B. M. Collins, C. J. Fettig, M. A. Finney, C. M. Hoffman, E. E. Knapp, M. P. North, H. Safford, and R. B. Wayman. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. BioScience 68:77–88.

Stephens, S. L., A. L. Westerling, M. D. Hurteau, M. Z. Peery, C. A. Schultz, and S. Thompson. 2020. Fire and climate change: conserving seasonally dry forests is still possible. Frontiers in Ecology and the Environment 18:354–360.

Stevens, J. T., H. D. Safford, and A. M. Latimer. 2014. Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forests. Canadian Journal of Forest Research 44:843–854.

Stevens-Rumann, C., and P. Morgan. 2016. Repeated wildfires alter forest recovery of mixed-conifer ecosystems. Ecological Applications 26:1842–1853.

Stevens, J. T., et al. 2016. Average stand age from forest inventory plots does not describe historical fire regimes in ponderosa pine and mixed-conifer forests of western North America. PLoS One 11:e0147688.

Stewart, O. C. 2002. Forgotten fires: native Americans and the transient wilderness. University of Oklahoma Press, Norman, Oklahoma, USA.

Stockdale, C. A., C. Bozzini, S. E. MacDonald, and E. Higgs. 2015. Extracting ecological information from oblique angle terrestrial landscape photographs: performance evaluation of the WSL Monoplotting Tool. Applied Geography 63:315–325. https://doi.org/10.1016/j.apgeog.2015.07.012

Stockdale, C. A., S. E. MacDonald, and E. Higgs. 2019. Forest closure and encroachment at the grassland interface: a century-scale analysis using oblique repeat photography. Ecosphere 10:e02774. https://doi.org/10.1002/ecs2.2774

Sunstein, C. 2003. The paralyzing principle: Does the precautionary principle point us in any helpful direction?. Regulation, Winter, 2002–2003.

Syphard, A. D., J. E. Keeley, A. B. Massada, T. J. Brennan, and V. C. Radeloff. 2012. Housing arrangement and location determine the likelihood of housing loss due to wildfire. PLoS ONE 7:e33954.

Taylor, A. H., and C. N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13:704–719.

Taylor, A. H., V. Trouet, C. N. Skinner, and S. L. Stephens. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. Proceedings of the National Academy of Sciences USA 113:13684–13689.

Taylor, R. S., S. J. Watson, D. G. Nimmo, L. T. Kelly, A. F. Bennett, and M. F. Clarke. 2012. Landscape-scale effects of fire on bird assemblages: does pyrodiversity beget biodiversity? Diversity and Distributions 18:519–529.

Thomas, D., D. Butry, S. Gilbert, D. Webb, and J. Fung. 2017. The costs and losses of wildfires. NIST Special Publication 1215. http://dx.doi.org/10.6028/NIST.SP.1215

Vaillant, N. M., and E. D. Reinhardt. 2017. An evaluation of the Forest Service Hazardous Fuels Treatment Program—Are we treating enough to promote resiliency or reduce hazard? Journal of Forestry 115:300–308.

Varghese, J., and S. S. Crawford. 2021. A cultural framework for Indigenous, Local, and Science knowledge systems in ecology and natural resource management. Ecological Monographs 91:e01431.

Veldman, J. W., et al. 2019. Comment on "The global tree restoration potential". Science 366:eaay7976.

Wei, Y., M. P. Thompson, J. H. Scott, C. D. O'Connor, and C. J. Dunn. 2019. Designing operationally relevant daily large fire containment strategies using risk assessment results. Forests 10:311. https://doi.org/10.3390/f10040311

Wellerstein, A. 2018. The myth of apolitical science. Science 362:1006. http://doi.org/10.1126/science.aav4900

Westerling, A. L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B 371:20150178.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943. http://doi.org/10.1126/science.1128834

Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme, and M. G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences USA 108:13165–13170.

Williams, M. A., and W. L. Baker. 2012. Spatially extensive reconstructions show variable-severity fire and heterogeneous structure in historical western United States dry forests. Global Ecology and Biogeography 21:1042–1052.

Wood, C. M., and G. M. Jones. 2019. Framing management of social-ecological systems in terms of the cost of failure: the Sierra Nevada, USA as a case study. Environmental Research Letters 14:105004.

Wu, J., and O. L. Loucks. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. Quarterly Review of Biology 70:439–466. https://doi.org/10.1086/419172