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ECOLOGICAL RESTORATION INSTITUTE

Working Paper 45

Evidence for Widespread Changes in the Structure, Composition, and Fire Regimes of Western North American Forest Landscapes

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NAU NORTHERN ARIZONA UNIVERSITY
Ecological Restoration Institute

Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability … Restoration attempts to return an ecosystem to its historic trajectory" (Society for Ecological Restoration International Science and Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

ERI working papers are intended to deliver applicable science to land managers and practitioners in a concise, clear, non-technical format. These papers provide guidance on management decisions surrounding ecological restoration topics. This publication would not have been possible without funding from the USDA Forest Service. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the opinions or policies of the United States Government. Mention of trade names or commercial products does not constitute their endorsement by the United States Government or the ERI.

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Cover photo: View from atop Leecher Mountain in northeastern Washington, looking southwest. In the black-and-white photo (top, 1930, National Archives at Seattle), dry mixed-conifer forests are apparent. These open-canopy forests were regularly burned by frequent fires until the start of the 20th century which also maintained extensive areas of grassland cover. Note how densely forested the same area has become (bottom photo, 2011, John Marshall Photography), and that many grassland areas now support dense forest cover. These forests burned with uncharacteristic high severity in the 2014 Carlton Complex wildfires.

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Executive Summary

For more than a century, federal land management policies favored fire exclusion. As a result, live and dead fuels became profoundly more abundant in the fire-dependent forest landscapes of western North America. Trees and shrubs filled in gaps in the forest and expanded into neighboring meadows. Dead trees, needles, cones, and branches piled up on the forest floor.

Combined with a rapidly warming climate, this accumulation of fuel contributes to today's increasingly challenging wildfire seasons. Climate- and wildfire-adaptation strategies for fire-dependent forests promote the use of fuel reduction techniques, including mechanical thinning, prescribed fire, and managed wildfire. These techniques have repeatedly proven effective at mitigating fire intensity, even during extreme fire weather.

Ecologically based fuel reductions go beyond simple uniform fuel load reduction to incorporate a vast range of spatial patterns in forest structure and composition that historically or currently demonstrate resistance and resilience to fire and drought. These fuel reductions increase the likelihood of conserving and restoring ecological, social, and cultural values imperiled by more than a century of fire exclusion. As with any credible management strategy, ongoing evaluation and refinement of implementation and effectiveness are essential. This is particularly true given the dynamic nature of today's rapidly warming climate.

Recent literature reviews and syntheses provide valuable references for land management practitioners and stakeholders engaged in designing, evaluating, and implementing scientifically credible wildfire- and climate-adaptation strategies. These syntheses are supported by thousands of peer-reviewed articles that evaluated the benefits and constraints of restoring fire to fire-dependent forest landscapes. This working paper summarizes key insights from the review of studies, described in detail below, that documented unprecedented, human-caused fire exclusion and its impacts on fire-dependent forest landscapes in western North America.

Introduction

Wildfire seasons are growing longer and more challenging as the climate continues to warm and droughts lengthen and intensify. Whether those fires encroach on our doorsteps or smoke from thousands of miles away reduces our air quality, more and more of us are experiencing first-hand the benefits and limitations of forest and fire management. To aid the ongoing development of policy and management intended to mitigate wildfire intensity, a team of forest and fire ecologists from leading research universities, conservation organizations, and government laboratories collaborated to review and synthesize the scientific literature about fuel treatments in fire-dependent forests of western North America (Figure 1).

In three peer-reviewed syntheses (Hagmann et al. 2021; Hessburg et al. 2021; Prichard et al. 2021), this team addressed key questions about the advisability of ecologically based fuel reductions to better adapt forest landscapes and communities to wildfire and a warming climate. Ecologically based management of fire-dependent forest landscapes seeks to conserve and restore ecosystem functions by restoring and maintaining fuel loads at levels that have demonstrated resistance to fire and drought. Management implications and recommendations from these syntheses have been summarized in a fact sheet,[1] story map,[2] and policy brief.[3]

This working paper reviews the impacts of more than a century of unprecedented, human-caused fire exclusion on the structure and composition of fire-dependent forest landscapes. By the late 19th century, the decimation of Indigenous populations, intensive livestock grazing, road building, and the suppression of fires and Indigenous burning practices had all contributed to a notable reduction in fire frequency and extent (Figure 2). The science supporting this summary is based on more than a century of observation and documentation and is reviewed in greater detail by Hagmann et al. (2021).

Before the current era of fire exclusion, fire regimes maintained multi-scale resistance to fire and drought as well as other functions of fire-dependent forest ecosystems. Fire kills trees and consumes forest fuels. Thus, the presence or absence of fire influences the abundance, distribution, structure, and composition of forests and forest fuels. When fire is excluded from frequent-fire ecosystems, tree density increases; the proportion of fire-intolerant species increases; and surface, ladder, and canopy fuels accumulate. These widespread changes associated with fire exclusion provide the ecological basis for fuel reductions designed to restore greater resistance and resilience (Box 1) to fire and drought.

Combined with a rapidly warming climate, uncharacteristically dense and extensive forest cover contributes to today's uncontrollable, peak-season wildfires. Prior to European colonization, abundant low- to moderate-severity fire (Box 1) limited the extent and density of forest cover and the abundance of forest fuels. High-severity fires are also essential elements of fire-dependent forest landscapes, and some high-severity fire effects occur in essentially all fires, even those that are predominantly low severity. However, prior to the current era of fire exclusion, abundant low- to moderate-severity fire limited the extent, patch size, and location of high-severity fire effects.

For more than a century, modern wildfire management sought to extinguish essentially all fire starts. The absence of fire provided opportunities for abundant tree recruitment, particularly on more productive sites and during wet periods. Over time, forests filled in with trees and expanded into openings and meadows (Figure 3 and cover photo). This increase in forest density and extent contributed to the degradation of fire-dependent forest and nonforest ecosystems and increased the homogeneity of landscape conditions (Figure 4). The loss of

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[1] Fact Sheet: Adapting western North American forests to climate change and wildfires: Ten common questions. Sponsored and hosted by Northern Arizona University: Ecological Restoration Institute. https://cdm17192.contentdm.oclc.org/digital/collection/p17192coll1/id/1102/rec/6

[2] Adapting western US forests to climate change & wildfires: Ten common questions. Sponsored and hosted by Sustainable Northwest. https://storymaps.arcgis.com/stories/64f55848f690452da6c58e5a888ff283

[3] Climate Change and Western Wildfires: The Science Supports Restoration with Climate Adaptation. Sponsored and hosted by Northern Arizona University: Ecological Restoration Institute. https://cdm17192.contentdm.oclc.org/digital/collection/p17192coll1/id/1103/rec/2

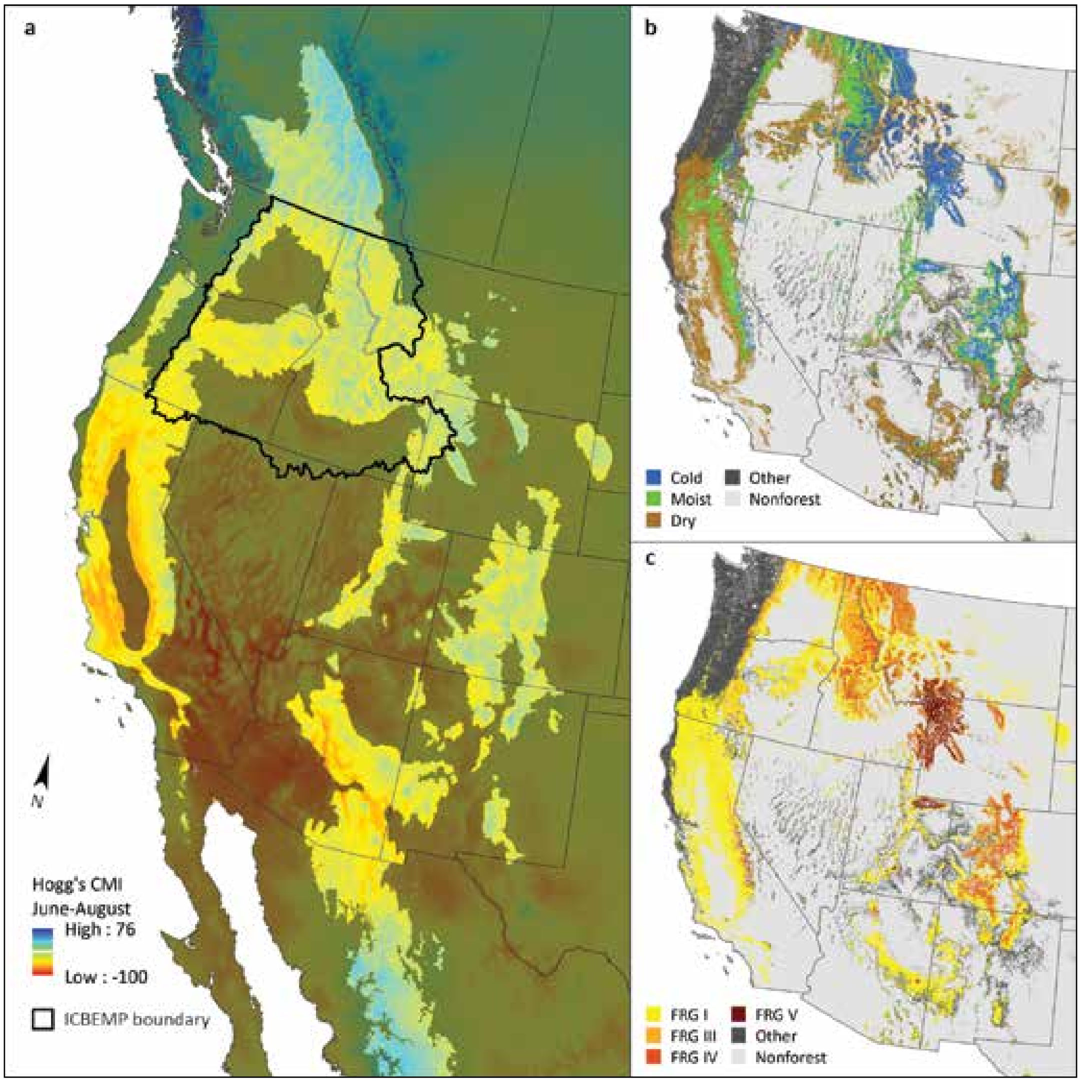
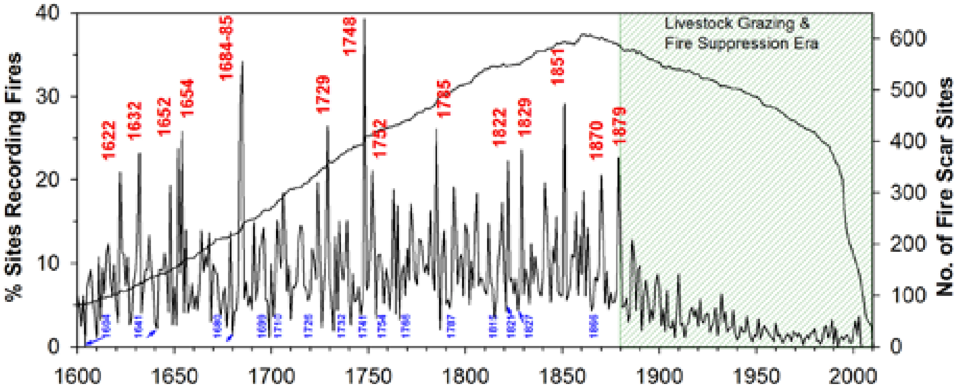


Figure 1. Forest landscapes of western North America span broad climate gradients as reflected in the amount of moisture available to trees in summer months (a). We used existing ecoregional classifications to roughly indicate the area of fire-dependent forest landscapes; nonforest and other forest types are masked out (a). We classified forest types across this gradient as either cold, moist, or dry (b). Cold, moist, and dry forests may share the same fire regime group (FRG) class (c). FRG I: fire return interval ≤ 35 years, low and mixed severity; FRG III: fire return interval 35–200 years, low and mixed severity; FRG IV: fire return interval 35–200 years, replacement or high-severity; FRG V: fire return interval >200 years, any severity. Portions of the study area that extend into Mexico and Canada are not shown in b and c because Landfire data are not available for these regions. Data sources are: a) Hogg's Climate Moisture Index (Hogg 1997) from ClimateWNA (Hamann et al. 2013, climatewna.com), The Nature Conservancy Terrestrial Ecoregions (geospatial.tnc.org) for parts of Washington and southern BC, [K1] and EPA Ecoregions of North America (epa.gov/eco-research/ecoregions-north-america; and b,c) Landfire (Rollins 2009, landfire.gov).

Figure 2. By the late 19th century, area burned had decreased substantially across western North America. This regionwide decrease in fire was recorded by trees on more than 800 forest and woodland sites, the largest network of tree-ring-based fire-scar chronologies in the world. Following expansion of colonization by Europeans, intensive livestock grazing, decimation of Indigenous populations, and suppression of Indigenous burning and other fires, the influence of fire was essentially absent from landscapes where it had historically been abundant. Reprinted from Swetnam et al. (2016) with the author's permission.



patchiness and multi-aged forest cover historically maintained by recurring and overlapping fires increases the likelihood of extensive high-severity fire- and drought-related mortality which would reinforce this homogeneity. Increased evapotranspiration caused by denser and predominantly younger forests can divert water from downslope terrestrial and aquatic ecosystems and increase vulnerability to drought stress or conversion from wetter to drier ecosystem types. Thus, nonforest ecosystems (*i.e.*, herbland/grassland, shrubland, woodland, and, often, open-canopy forest) may also be directly or indirectly impacted by fire exclusion.

Numerous regional syntheses have summarized and interpreted more than a century of research and observation documenting these and other changes to fire regimes, forests, and landscapes caused by a deficit of low- to moderate-severity fire (Table 1; page 9). As reviewed by Prichard et al. (2021), where pre-fire exclusion conditions existed or were restored, the preponderance of evidence documented greater resilience and resistance to contemporary drought and fire. Research published even more recently continues to document these benefits as management approaches are refined, the climate continues to warm, and fires and droughts intensify.[4] Thus, understanding the types and extent of change that occurred in dry, moist, and cold fire-dependent forests (Figure 1, Box 1) during more than a century of fire exclusion helps us adapt forests and communities to current climate conditions as well as to drought and fire.

Evaluating Changes Associated with Fire Exclusion

In regional syntheses, researchers have integrated mounting evidence of fire exclusion as a driver of change to ecosystems and their functions (Table 1). These syntheses draw on more than a century of evaluation and observation of fires; fire regimes; and forest and landscape structure, composition, and function — including response to disturbance. Hagmann et al. (2021) focused on key elements of this vast body of work to illustrate the magnitude of change in fire-excluded forest landscapes and contemporary fire regimes.

As summarized in this working paper, Hagmann et al. (2021) discussed differences between today's fires and those that influenced forest landscapes before more than a century of fire exclusion. The authors also reviewed key changes in landscape structure and composition associated with the absence of abundant low- to moderate-severity fire effects and fires across a wide range of sizes, severities, and frequencies. The departures and changes described are derived from a multitude of studies that compared contemporary fires and forest landscape conditions to "reference conditions" (Box 1), *i.e.*, those that existed, or in rare cases still exist, in the absence of human-caused fire exclusion.

Hagmann et al. (2021) highlighted the value of incorporating a diversity of methods that span spatial and temporal scales — from trees to regions and from a single fire event to thousands of years (Box 2). By integrating across multiple methods and scales, we gain greater insight into variation in fire and forest conditions over space and time. We also gain greater confidence in our interpretations when they are re-affirmed by repeated studies based on records as diverse as Indigenous knowledge, oral accounts, tree rings, aerial imagery, pack rat middens, pollen and charcoal in sediment cores, and early surveys and inventories.

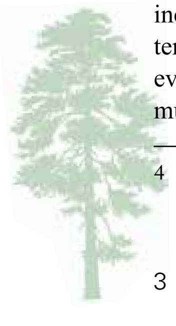
Throughout their review, Hagmann et al. (2021) also referenced the ways that computer models have been used to integrate a vast array of empirical, *i.e.*, field based, studies to provide insights into fire and forest landscape conditions in places or at times where physical data is lacking or not yet available, *e.g.*, the future. Landscape models combine fire histories with knowledge about the geophysical drivers (*e.g.*, climate, topography, soils) of fires and vegetation growth and decay to inform simulations of past, present, and future landscape-wildfire dynamics. Perhaps most importantly, these models can inform and evaluate management scenarios. They can be used to simulate multiple climate, management, and species scenarios that can then be compared with simulated historical conditions under a consistent framework to evaluate risks, tradeoffs, synergies, and uncertainties.

Changes in Fire Regimes

As physical evidence of a fire event, tree-ring fire scar records remain a primary means of exploring historical fire ecology within the lifespan of long-lived trees. Over time, the methods for evaluating tree-ring fire scar records have been repeatedly tested and refined to yield greater confidence and insights into historical fire regimes. Today, networks of fire-scar studies emerging from a century of tree-ring studies enable insights into landscape and climate controls on fire. Because tree-ring fire scar records are quite simply more abundant in areas where subsequent disturbance, *e.g.*, high-severity fire, has not obliterated them, other records and methods supplement tree-ring fire scar records to evaluate evidence of moderate- to high-severity disturbances.

One of the key findings to emerge from nearly every tree-ring reconstruction of fire history in western North America was a widespread reduction of fire in the 20th century compared to preceding centuries (Figure 2). In some studies, sedimentary charcoal records from the same locations were used to extend the time span of tree-ring records. These studies showed that 20th-century decreases in fire events were unprecedented for thousands of years.

When fire is excluded from fire-dependent ecosystems, tree density increases; the proportion of fire-intolerant species increases; surface, ladder, and canopy (*i.e.*, the fuels from forest floor to treetops) fuels accumulate; and resources available for forest growth decline. These conditions can foster large and intense fires with effects that have not been observed in historical ranges. Indeed, numerous studies of recent fires have documented more abundant and larger patches of high-severity fire than historically occurred in forest that once supported predominantly low- to moderate-severity fires. Even in forest types that were historically dominated by infrequent high-severity fire, the suppression of most fire starts and the absence of fires spreading in



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[4] Studies published since Prichard et al. 2021: Furniss et al. 2022; Knapp et al. 2021; Murphy et al. 2021; Restaino et al. 2019; Stoddard et al. 2021

Figure 3. Repeat photography shows change in forest cover during the current era of fire exclusion and suppression in hills west of Boulder, Colorado (Veblen and Lorenz 1991). In less than a century (1910-1985), once sparsely forested hills became densely forested as trees established and forest cover expanded into grasslands. Photo credits: 1900-1910: Louis C. McClure Courtesy Denver Public Library, Western History Collection, MCC-306, 1985: TT Veblen and DC Lorenz, 2016: TT Veblen.

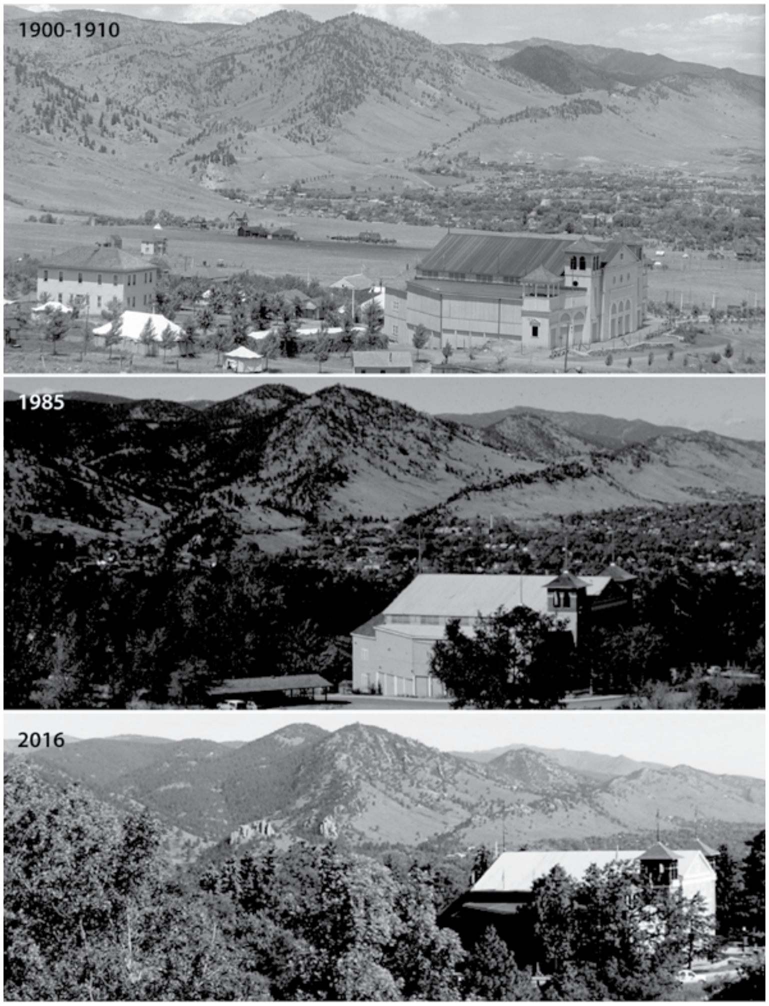


Figure 4. Top photo: View from atop Slate Peak in northeastern Washington, looking southwest, 1934, George Clisby photograph, National Archives at Seattle. The 1934 panoramic view shows extensive evidence of prior wildfires, varied age classes of cold forest, and recently burned and recovering areas. 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.

Box 1. Terms and Concepts

Forests and fire regimes are highly variable, complex, dynamic systems. To communicate about them in general terms to broad audiences, we rely on commonly used terms, like those listed below. These terms enable conversations because they reduce enormous variability into broad categories. However, for the same reason, they can also inhibit conversations (and potentially agreement) when more nuance could add clarity.

Fire severity

Severity, only one aspect of a fire regime (Hessburg et al. 2021: Table 1), commonly refers to the percentage of tree biomass killed by fire. However, these same categories (low-, moderate-, and high-severity) are also used to quantify other fire effects, e.g., the impact of fire on soil conditions. Thus, it is essential to ensure that the same metrics are used in comparisons of fire severity.

Percentage of basal area (area occupied by trees) or canopy cover killed by fire:

- Low: <20%
- Moderate: 20-70%
- High: >70%

Dry, moist and cold forest types

Fire-dependent forests across a region as large and diverse as western North America (Figure 1) support a wide range of forest types composed of broadleaf and coniferous species.

- Dry Forests: Dominant species include ponderosa and Jeffrey pine (*Pinus ponderosa* and *P. jeffreyi*) and some oak species (*Quercus spp*).
- Moist Forests: As moisture increases or fire frequency decreases, species with higher shade tolerance and lower drought and fire tolerance increasingly dominate. These include Douglas-fir (*Pseudotsuga menziesii*); western larch (*Larix occidentalis*); sugar, western white, and southwestern white pine (*Pinus lambertiana, P. monticola,* and *P. strobiformis*); incense-cedar (*Calocedrus decurrens*); and grand and white fir (*Abies grandis* and *A. concolor*).
- Cold Forests: As mean annual temperatures decrease with elevation or cold air drainage, cold forests are increasingly dominated by lodgepole pine (*Pinus contorta*); aspen (*Populus tremuloides*); red, silver, and subalpine fir (*Abies magnifica, A. amabilis,* and *A. lasiocarpa*); mountain hemlock (*Tsuga mertensiana*); Engelmann spruce (*Picea engelmannii*); or whitebark pine (*Pinus albicaulis*).

Reference conditions

The conditions that existed prior to (or, in rare cases, in the absence of) fire exclusion provide a baseline for evaluating the magnitude, rate, and direction of change associated with fire exclusion.

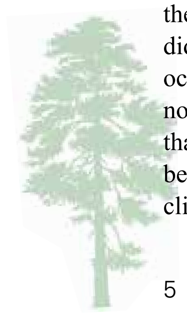
- Timing of fire exclusion varied widely, but was commonly associated with disruption of Indigenous burning and expansion of unregulated grazing of livestock by European settlers.
- Often many decades after these early forms of fire exclusion, the onset of mechanized fire suppression, logging, and land development perpetuated the exclusion of fire.
- Current conditions on sites with restored or less disrupted fire regimes also inform contemporary management focused on restoring resilience to drought and fire.

Resilience and resistance

- Resilience is the capacity of an ecosystem to return to prior conditions following a disturbance (including taxonomic composition, structure, ecosystem function, and process rates).
- Resistance is a key component of resilience and reflects the capacity of an ecosystem to remain essentially unchanged when disturbed.

from adjacent forest and nonforest areas is likely changing contemporary fire-severity patterns.

Although relatively rare, landscapes not impacted by fire exclusion show us how fire-maintained forests operate under today's climate conditions. These forests experienced the climate variations of the 19th and 20th centuries, but they did not exhibit the changes in structure and composition that occurred in fire-excluded forests. Similarly, these forests have not experienced the increased severity of disturbance events that occurred in comparable areas where fires have long been excluded. Lessons learned from these forests inform climate- and wildfire-adaptation strategies that incorporate fuel reduction techniques, including mechanical thinning, prescribed fire, and managed wildfire, to mitigate the deleterious impacts of human-caused fire exclusion.



Changes in Forest Landscapes

Numerous regional studies have synthesized and summarized more than a century of documentation of the impacts of fire exclusion (Table 1). Early studies generally focused on the influence of frequent fire in maintaining open-canopy forests and woodlands where fire-scarred trees, *e.g.*, ponderosa or Jeffrey pine, were abundant. Increasingly, however, studies of

Box 2. Multiple Methods Strengthen Confidence and Provide Insights

Integrating multiple ways of knowing and a broad range of scientific methods increases our understanding of ecosystems and their functions. Additionally, consistent results from multiple independent evaluations using diverse methodologies and data sources strengthens our confidence in the inferences supported by those studies.

Every method used for reconstructing historical forest and fire conditions has strengths and weaknesses (ERI Working Paper No. 32: An Evaluation of Fire Regime Reconstruction Methods).

These attributes influence the capacity of each method to provide detailed insights at specific spatial (tree, stand, landscape, or region) and temporal scales (one point in time, centuries, or millennia).

Tree rings, for example, can provide highly detailed information about fire events for the recent past, typically 200–300 years. Charcoal and sediment records can provide insight into forest composition and variation in fire regimes further back in time, but at much coarser spatial and temporal scales. Neither of these records document detailed spatial patterns, e.g., the shape and size of unique forest and nonforest types. Aerial imagery can reveal patterns in forest structure and composition at multiple spatial scales, however, the earliest images only date back to the 1930s.

Evaluations that fail to consider variation over multiple spatial and temporal scales and multiple aspects of forest conditions and fire regimes may mislead interpretation of historical conditions and resilience to fire and drought.

Studies conducted at plot or patch-scales may fail to capture change in vegetation conditions and fire severity across larger landscapes. For example, changes in one or more aspects of a fire regime, e.g., percent land affected by high-severity fire, may not be evident in all locations in a larger landscape. The inverse is also true. Changes at fine spatial scales may be masked when only average values at larger scales are considered.

Similarly, while one aspect of a fire regime may not have changed, e.g., percentage of the land area affected by high-severity fire, changes in patch size and shape, which strongly influence ecosystem functions, may have occurred.

Thus, it is essential to integrate multiple scientific methods and scales with other sources of knowledge to generate a comprehensive and robust understanding of the role of fire over time.

diverse landscapes that include colder and wetter forest and nonforest types show the influence of fires that historically burned some part of these fire-dependent landscapes with high frequency. The preponderance of evidence demonstrates that even if a particular area appears unchanged, fire exclusion has very likely changed the landscape surrounding it. In other words, both the abundance and continuity of fuels may be higher than historical levels across a landscape, although not necessarily for all areas within that landscape.

To illustrate the influence frequent fire can have across a range of forest and nonforest systems from dry to moist to cold, Hagmann et al. (2021) highlighted the Interior Columbia Basin Ecosystem Management Project (ICBEMP). The ICBEMP provided a landscape evaluation of change in vegetation spatial patterns and fire regimes across a uniquely large spatial extent (150 million acres). Landscape assessments that evaluate a broad range of attributes of forest and landscape conditions can reduce the risk of oversimplifying or misrepresenting historical variability in those conditions. This assessment encompasses the highest concentration of cold and moist forest in the interior western US (Figure 1). Nonetheless, the substantial changes documented in this assessment are consistent with those documented in numerous other studies both within this region and in predominantly warmer, drier ecoregions (Table 1).

The ICBEMP documented widespread forest expansion and densification between the middle (primarily 1930s–1950s) and end (primarily 1990s) of the 20th century. Comparison of aerial photos from both time periods and simulation modeling based on those images were used to quantify change and identify drivers of change in forest and landscape structure and composition. Before fire exclusion, a combination of infrequent high-severity and frequent low- to moderate-severity disturbances kept total forested area lower than what could exist (and what does exist today) in the absence of disturbance. Further, the widespread distribution of forest and nonforest types with relatively low fuel

loads tended to support lower intensity fire across the landscape under most weather conditions (Figure 5).

By the late 20th century, forest cover had become denser and more extensive than it was in the mid-20th century. These changes were apparent despite extensive logging in the mid to late 20th century and the impacts of fire exclusion before the mid-20th century. By the late 20th century, the area likely to support fire regimes of low-severity had been reduced by 53%, mixed-severity remained roughly the same (although it shifted to sites that had supported low-severity fire regimes prior to fire exclusion), and high-severity nearly doubled (Figure 5).

Other studies in cold forests that documented changes associated with fire exclusion include: lodgepole pine in the foothills of the Rocky Mountains in Alberta and in cold-air drainages in the central Oregon Pumice Plateau ecoregion; mixed-conifer and subalpine forests in the Canadian Cordillera and southwestern US; and red fir forests in California's Sierra Nevada ecoregion. Additionally, today's increased surface fuel loads and canopy connectivity in mid-elevation forests likely influence the frequency of crown fire spread into more mesic and colder high-elevation forests.

Repeat photography from other regions across western North America also show the expansion and densification of forest area and the consequent reduction in open-canopy forest and nonforest areas associated with fire exclusion. Examples include high-elevation ecosystems in the Pecos Wilderness, New Mexico; pine and mixed-conifer forest over 250,000 acres in northern Sierra Nevada, California; ponderosa pine in the Black Hills, South Dakota and Colorado Front Range; and widespread change across elevations in the Canadian Rocky Mountains.

Oblique and aerial imagery from the early to mid-20th century documented abundant nonforest cover in dry, moist, and cold forest landscapes. The William Osborne survey of Oregon and Washington in the 1930s–1940s (Figure 4) encompasses nearly 1,000 panoramas (120°) taken on ridgetops and at fire lookouts, and the Geological Survey of Canada systematically collected approximately 120,000 high-resolution oblique images from 1880–1950 across the mountains of western Canada.

The nonforest areas influence the delivery of fire to adjacent forested areas. For example, fine fuels like grasses and long pine needles combust readily (*i.e.*, flashy fuels) and can carry fire into adjacent, less combustible cover types. These flashy fuels may also impede fire spread as they are typically the first to recover moisture content in the hours after sunset. In addition to influencing the delivery of fire to adjacent areas, these fine-scale treeless openings (Figures 3 and 4), provided numerous functions, including nutrient cycling and fostering biodiversity. Increased forest cover and the loss of the once widespread nonforest and open-canopy conditions (Figures 3 and 4) can substantially reduce the accumulation and persistence of snow packs and the amount of water available to downstream ecosystems.

Changes in High-Severity Fire

High-severity fire is an essential component of many forested landscapes. These fires contribute to the provision of unique habitat types, like areas with abundant snags (dead trees) and nutrient-rich shrub and herbaceous plant cover (flowers, seeds, and tender leaves). They also influence numerous other ecosystem functions, including nutrient and hydrological cycles and the rate and abundance of debris flow and sediment deposition. Landscape diversity maintained by characteristic disturbance regimes is critical to maintaining the diverse and unique ecosystem characteristics of seasonally dry forested landscapes.

Some of today's conversion of forest to nonforest may aid climate and wildfire adaptation. This may be particularly true where forest expansion and densification in the 20th century degraded nonforest ecosystems, *e.g.*, meadows and woodlands, or where conversions to more drought-tolerant cover types are inevitable as landscapes adjust to a warming climate. However, today's fires burn in fire-excluded landscapes that lack the constraints historically imposed by abundant low- to moderate-severity fire. As a result, abundance and patch sizes of high-severity fire have been higher than historical values. These fires are contributing to type conversions on sites that would otherwise have been likely to maintain or regenerate forest cover even under a rapidly warming climate.

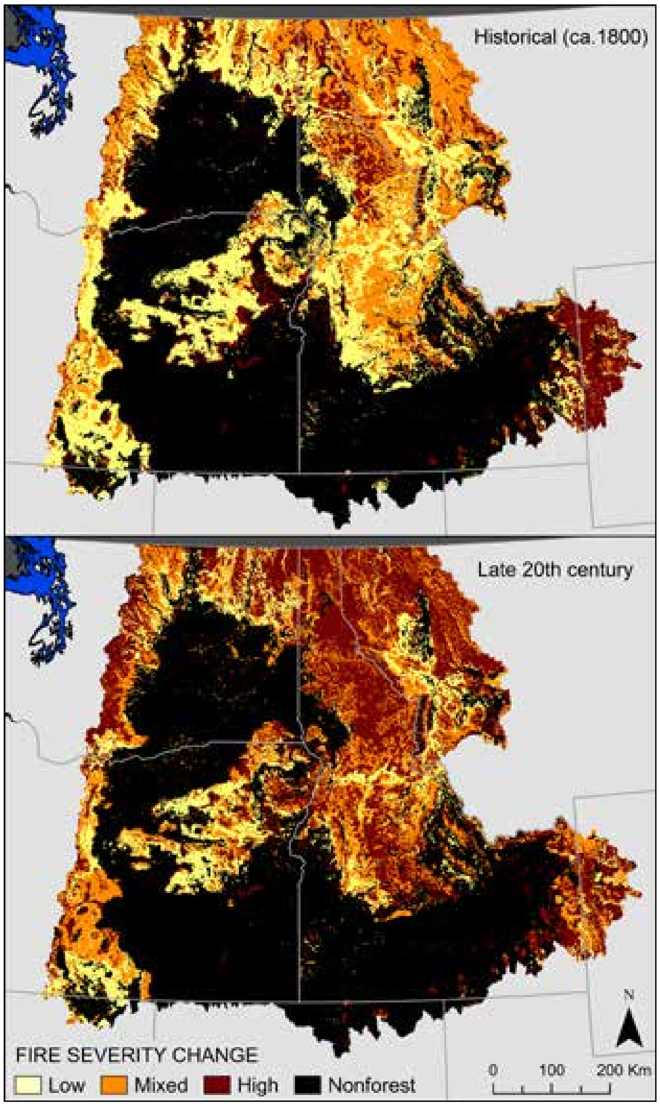


Figure 5. Broadscale (1-km2 pixel) map of transitions from historical (ca. 1800) to late 20th century fire-severity classes in the Interior Columbia Basin. Adapted from Hessburg et al. (2005).

Increases in high-severity fire are further reducing the number and distribution of large and old (>150 years) fire- and drought-tolerant trees. These oldest of these trees thrived through seasonal and episodic increases in fire and drought for decades to centuries before fire exclusion. Large and old fire- and drought-tolerant trees were heavily logged in the 20th century. Their populations have continued to decline due to drought stress, bark beetle outbreaks, and wildfire. High forest densities exacerbate drought stress and facilitate bark beetle outbreaks, and in ponderosa and Jeffrey pine forests, bark beetles preferentially target larger individuals. Where old and large trees were once widespread in fire-dependent landscapes, today they are less abundant or absent and highly vulnerable to both fire and drought in fire-excluded forests.

Constraints on tree regeneration are an inevitable consequence of a warming climate. However, high-severity fire also limits forest regeneration. Reduced seed dispersal capacity and hotter, drier site conditions in large severely burned areas impedes conifer regeneration on sites where low- to moderate-severity fire does not. Additionally, high-severity fires can have long lasting negative impacts on soil organic carbon and nutrient cycling.

Conclusion

Excluding fire from fire-dependent forest landscapes for more than 100 years has radically altered fire regimes, structure and composition, and ecosystem functions. Long-term fire exclusion has compromised the capacity of fire-dependent forest landscapes to resist or recover after disturbance, especially in a rapidly warming climate. Fire exclusion has likely also impacted cold and wet forest and nonforest types either directly through forest densification and expansion or indirectly by influencing ecosystem functions, such as the delivery of fire and water.

During recent droughts, increases in forest density and forested area have contributed to uncharacteristically high mortality of fire-resistant, drought-tolerant trees. Additionally, ignitions in forests with high fuel loads can overwhelm fire suppression capacity, especially during extreme fire weather (hot, dry, and often windy conditions). At those times, only a change in the weather will reduce fire intensity enough to allow fire fighters and the tools at their disposal to effectively manage wildland fires.

Warmer, drier climates reduce the moisture content of both live and dead fuels, making them more flammable. As a result, area burned increases. Thus, despite increasing expense and effort focused on fire suppression, area burned has increased in the late 20th and early 21st century as the climate warmed. This trend is expected to continue as the climate continues to warm. Currently, the area burned in most forested ecosystems is much lower than would be expected given the warmth of the current climate. This is due to ongoing policies that continue to favor fire suppression even when the weather conditions are conducive to managing fires to provide ecological, social, and cultural benefit.

Recapturing the once extensive influence of the low- and moderate-severity fires that shaped and maintained these ecosystems for millennia requires a paradigm shift from strategies favoring fire suppression to those that facilitate the use of fire when circumstances allow. As the climate continues to warm and burned area increases, high-severity burn area and early seral habitat will likely proliferate. However, maintaining and fostering a diverse mix of forest structures and ages may best be served through climate- and wildfire-adaptation strategies that incorporate ecologically based fuel reductions through the use of thinning, prescribed fire, and managing wildfires to further resource objectives.

The cautious reintroduction of frequent low- to moderate-severity fires can and has reduced the intensity and severity of subsequent fires by maintaining tree densities and live and dead fuel loads that are in synch with the prevailing climate. Enormous effort and expense have been invested in evaluating the advisability of restoring abundant low- to moderate-severity fire in the fire-dependent forest landscapes of western North America. Ongoing evaluation and refinement of implementation and effectiveness of these approaches is essential for any credible management strategy. Additionally, objective evaluation can aid us in differentiating warranted from unwarranted uncertainties and enable timely paradigm shifts to policies and management actions that favor fire- and climate-adapted forests and human communities.

Table 1. A sample of the regional syntheses and meta-analyses that integrate insights from assessments of historical and contemporary forest and fire ecology. These reviews reflect the use of multiple complementary methods across spatial scales, from individual trees to regions.

Region	Description	Citations
Western North America	More than 800 fire-scar studies documented abrupt decline in fire frequency in the late 19th century and provide ecological insights into variation in top-down and bottom-up drivers of historical fire regimes	Falk et al. 2011 Swetnam et al. 2016 Daniels et al. 2017
	Substantial departures in contemporary fire regimes and live and dead vegetation patterns across dry, moist, and cold forested landscapes increase vulnerability of forest ecosystems to drought and fire	Hessburg et al. 2019
	Evaluation of key aspects of the scientific evidence of the impacts of fire exclusion using a framework for objectively assessing change in the structure, composition, and fire regimes of seasonally dry, fire-excluded forest landscapes.	Hagmann et al. 2021
Canada	Development and paradigm shift in wildland fire research over past 50 years	Coogan et al. 2020
	Climate change impacts on fire regimes and impacts of contemporary fire regimes on social and ecological systems	Coogan et al. 2019
Western United States (US)	Variation in fire activity over the past 3,000 years	Marlon et al. 2012
	Fire deficit relative to area expected to burn without fire suppression given contemporary climate 1984-2012; area burned and fire severity increased 1985-2017	Parks et al. 2015 Parks and Abatzoglou 2020
	Influence of traditional tribal perspectives on ecosystem restoration	Long et al. 2020 Roos et al. 2021
	Correspondence between conifer species traits conferring fire resistance and independent assessments of historical fire regimes	Stevens et al. 2020
	Human influence on contemporary fire regimes	Balch et al. 2017
	Evaluation of conifer regeneration up to 69 years post fire	Stevens-Rumann and Morgan 2019
Colorado and Wyoming Front Ranges	Historical and contemporary ecology of ponderosa pine and dry mixed-conifer forests	Addington et al. 2018
	Fire regimes in ponderosa pine forests	McKinney 2019
	Historical and contemporary ecology of selected national forests	Dillon et al. 2005 Meyer et al. 2005a, 2005b Veblen and Donnegan 2005
Southwestern US	Historical and contemporary ecology of ponderosa pine and dry mixed-conifer forests and forest-grassland landscape complexes	Reynolds et al. 2013 Dewar et al. 2021
Sierra Nevada bioregion of California	Historical and contemporary ecology of ponderosa and Jeffrey pine and mixed-conifer forests	SNEP 1996 North et al. 2009, 2016 Safford and Stevens 2017 van Wagtendonk et al. 2018
	Historical and contemporary ecology of red fir and subalpine forest types	Meyer and North 2019 Coppoletta et al. 2021
Northeastern California plateaus	Historical and contemporary ecology of dry conifer forests	Riegel et al. 2018 Dumroese and Moser 2020
Northern California	Historical and contemporary ecology of forested landscapes	Skinner et al. 2018 Spies et al. 2018, 2019 Stephens et al. 2018b, 2019 Bohlman et al. 2021
Pacific Northwest	Departures in contemporary fire regimes	Reilly et al. 2017 Metlen et al. 2018 Haugo et al. 2019
	Historical and contemporary ecology of ponderosa pine forests in Oregon and Washington; vulnerability of contemporary forests and expanding wildland urban interface to increasing drought and fire severity	Merschel et al. 2021
	Historical and contemporary ecology of moist mixed conifer forests in seasonally dry landscapes in Oregon, Washington, and Northern California	Perry et al. 2011 Stine et al. 2014 Hessburg et al. 2016
Columbia River Basin in northwestern US	The Interior Columbia Basin Ecosystem Management Project (ICBEMP) used standard aerial photogrammetric methods, repeat photo-interpretation, and a quantitatively representative sampling scheme to build a dataset of wall-to-wall, meso-scale landscape reconstructions for 337 watersheds, mean area 9500 ha. ICBEMP also incorporated broad-scale succession and disturbance simulation modeling calibrated with the meso-scale results	Lehmkuhl et al. 1994 Huff et al. 1995 Hann et al. 1997 Hessburg et al. 1999, 2000, 2005 Wisdom 2000 Raphael et al. 2001 Hessburg and Agee 2003

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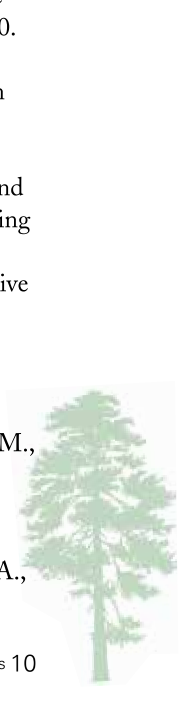

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