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Review

Fire and Forest Management in Montane Forests of the Northwestern States and California, USA

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Abstract: We reviewed forest management in the mountainous regions of several northwestern states and California in the United States and how it has impacted current issues facing these forests. We focused on the large-scale activities like fire suppression and logging which resulted in landscape level changes. We divided the region into two main forests types; wet, like the forests in the Pacific Northwest, and dry, like the forests in the Sierra Nevada and Cascade ranges. In the wet forests, the history of intensive logging shaped the current forest structure, while fire suppression played a more major role in the dry forests. Next, we looked at how historical management has influenced new forest management challenges, like catastrophic fires, decreased heterogeneity, and climate change. We then synthesized what current management actions are performed to address these issues, like thinning to reduce fuels or improve structural heterogeneity, and restoration after large-scale disturbances. Lastly, we touch on some major policies that have influenced changes in management. We note a trend towards ecosystem management that considers a forest's historical disturbance regime. With expected climate induced changes in fire frequency, it is suggested that fuel treatments be implemented in dry forests to ensure an understory fire regime is restored in these forest systems. With respect to wet forests in this region, it is suggested that there is still a place for stand-replacing fire regimes. However, these forests will require structural changes incorporating heterogeneity to improve their resiliency and health.

Keywords: climate change; fire management; mechanical thinning; montane forests; prescribed fire

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1. Introduction

Disturbance, both biotic and abiotic, plays a very important role in shaping the montane forests in the northwestern United States and California. In the drier forests, the natural fire regime is typically characterized as low-severity or understory fire regime, keeping forests with an open canopy condition [1,2]. A low-severity regime is characterized as generally being non-lethal to the dominant above-ground vegetation where the survival rated of the dominant vegetation is 80% or more with low fire return intervals (1–30 years). The main exception to this is the dry, high-elevation forests which tend to experience high-severity, stand-replacing fires [3]. The wetter forests also experience high-severity fires, with very long fire return intervals [3]. High-severity fires are characterized as generally being very lethal to the dominant vegetation which experiences mortality rates of 80% or more [1]. Compared to the low-severity regimes, high-severity regimes typically have longer fire return intervals (100–400 years). Mixed-severity fire regimes have effects that are intermediate to understory and stand-replacement regimes mainly due to variations in topography (elevation and aspect) and microclimate that in turn lead to variations in forest vegetation type [1,2].

Human activities have altered these forests because humans have lived in these forests for many centuries. Native Americans used fire as a tool for cooking, hunting, fishing, range management to encourage game animal foraging, manipulate plant growth, land clearing, and warfare [1,4,5]. However, it was not until European settlement, which began in the 18th century, that large-scale landscape alterations occurred. Practices from the past two centuries have altered historical disturbance pattern, forest structure, and species. Historical ecology-based natural archives such as tree-rings have been used to reconstruct historical disturbance regimes before the pre-European settlement phase [6]. There has been a loss of structural heterogeneity and an increase in density. These changes affect fire behavior, wildlife habitat, and ecosystem function. Land managers and scientists have noticed the ramifications of the past land management and have been working to find new management practices that incorporate landscape-scale forest restoration by maintaining natural disturbance regimes. In particular, the practice of fire suppression has shifted fire regimes to having a higher proportion of stand-replacement fires and lower proportion of low-severity fires compared to the pre-settlement fire disturbance regime [2].

The objective of this review paper is to provide a synthesis of fire management issues facing the mountainous regions of several northwestern states and California in the United States. The scope of fire management that is examined in this review paper primarily includes preventative activities such as fuel treatments and the policies set in place by state and federal agencies that drive management activities. We focused on the large-scale activities that have resulted in landscape scale changes in the forests. We divided the region into two main forests types—wet, like the forests in the Pacific Northwest, and dry, like the forests in the Sierra Nevada and Cascade ranges. Among these two types, we noted past logging history along with fire policies, like fire suppression. Next, we looked at how historical management has influenced new forest management challenges, like catastrophic crown fires, decreased heterogeneity, and climate change. We then synthesized what current management actions are done to address these issues, like thinning and fuel treatments to reduce fire severity or improve structural heterogeneity, and restoration after large-scale disturbances. Lastly, we take a brief look into the policy that has shaped these management actions.

2. Study Area

The northwestern United States and California have a large diversity of mountain ranges and forest types. The Rocky Mountains, which run 4800 km from Canada to New Mexico, are a major mountain range in western North America. Closer to the Pacific Coast, there are several mountain systems including the Coast Range, Sierra Nevada, Cascades, and Klamath ranges in California, Nevada, Oregon, and Washington (Figure 1). The forest types can be broken down into two major categories, dry and wet forests; this is predominately due to rain shadow and elevational effects from the mountain ranges. There are several different forest types found in the dry forests. In the mid elevations of the Sierra Nevada and Cascades, mixed conifer forests are comprised of ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson), sugar pine (*Pinus lambertiana* Douglas), white fir (*Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr.), incense cedar (*Calocedrus decurrens* (Torr.) Florin), and several oak species (*Quercus* spp) [7]. In the Rocky Mountains, mixed conifer forests contain more Douglas-firs (*Pseudotsuga menziesii* (Mirb.) Franco), and western larch (*Larix occidentalis* Nutt.) [8]. There is a continuum of moisture availability in mixed conifer forests, with moisture increasing as one travels upslope and to northerly aspects [9]. There are also dry ponderosa pine and Douglas-fir forests in these ranges at low to mid elevations. Many dry forests in higher elevations consist of lodgepole pine (*Pinus contorta* Douglas ex Loudon) and whitebark pine (*Pinus albicaulis* Engelm) [10]. The wet forests are mainly found in the coast ranges of Oregon and Washington. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg) is a common species found in these forests, often mixed with Sitka spruce (*Picea sitchensis* (Bong.) Carrière) or Douglas-fir. Western redcedar (*Thuja plicata* Donn ex D. Don) and Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes) are commonly found in earlier successional forests [11].

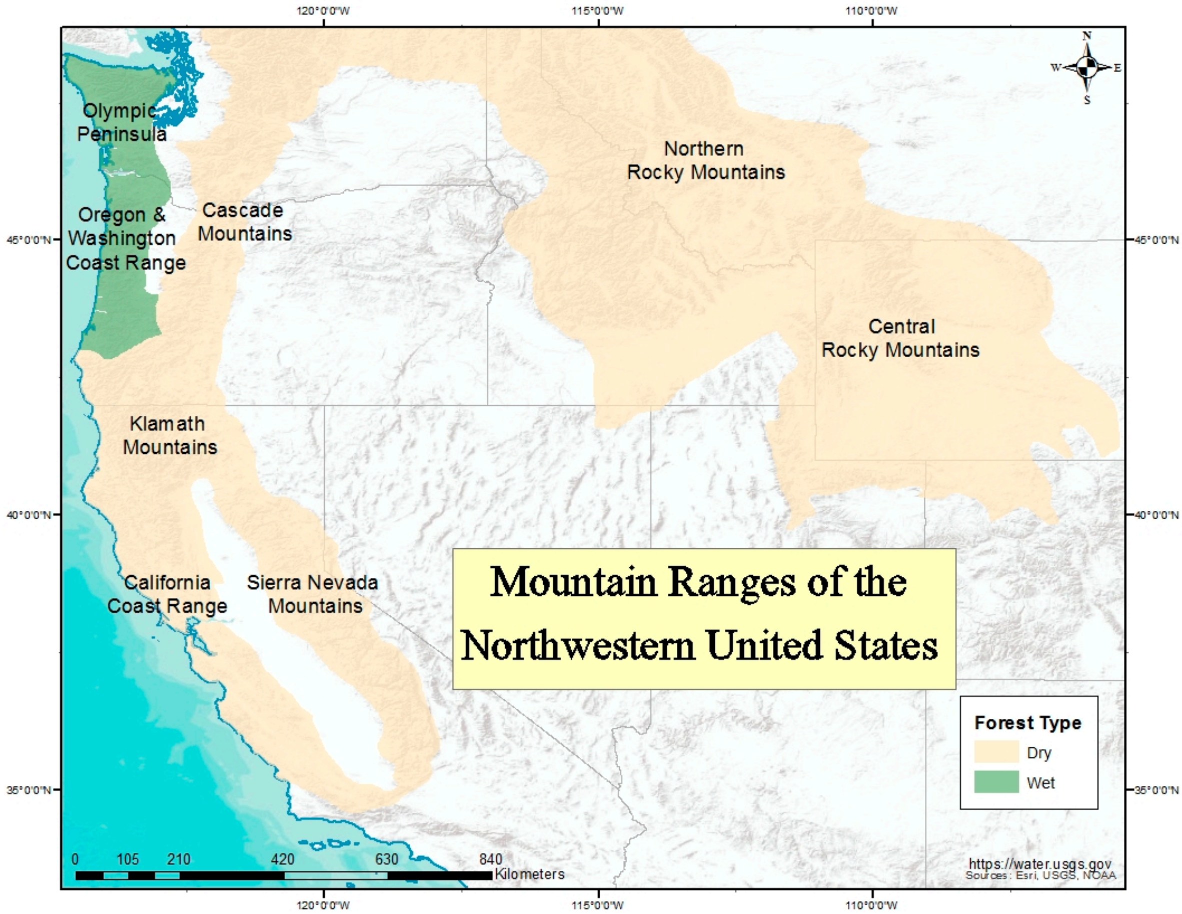

Figure 1. Map of mountain ranges of the northwestern United States and California showing the distribution of wet and dry forest types.

3. History of Management

3.1. Fire Suppression

Forests in the dry regions of the northwestern United States and California are shaped by fire, thus humans' manipulation of fire has had a large impact (Figure 2). Fire regimes in the west ranged from low, mixed, to high severity, depending on the forest type [9]. The drier forests like Mixed Conifer and ponderosa pine dominated forests tended to have frequent, low- to mixed-severity fires [3]. Higher elevation forests like lodgepole pine dominated forests and the wetter forest closer to the coast are adapted to large stand-replacing fires [3]. Aspect also played a role on potential fire behavior as more southerly aspects had an understory fire regime while more northerly aspects had a stand-replacement fire regime [1]. The history of humans using fire to manage lands began long before European settlement in the Western United States in the late 18th century. Native Americans would use fire to control the growth of certain plants and maintain grasslands to improve foraging for deer, a common source of food [4]. Their use of the land had a substantial impact on resource availability and diversity of flora and fauna; at one point, there were around 100,000 Native Americans living in the Sierra Nevada [4]. Unfortunately, during the 19th century, Native American populations dramatically reduced due to multiple factors, including diseases from European settlers, (often forced) cultural assimilation, and violence [12]. This major declines in Native peoples' populations in the late 18th century ended their widespread use of fire for land management [13]. The Native American communities use of fire for land management [5] were a source of traditional fire knowledge (e.g., fire effects on plants and animals) passed down from generation to generation within these communities [14,15].

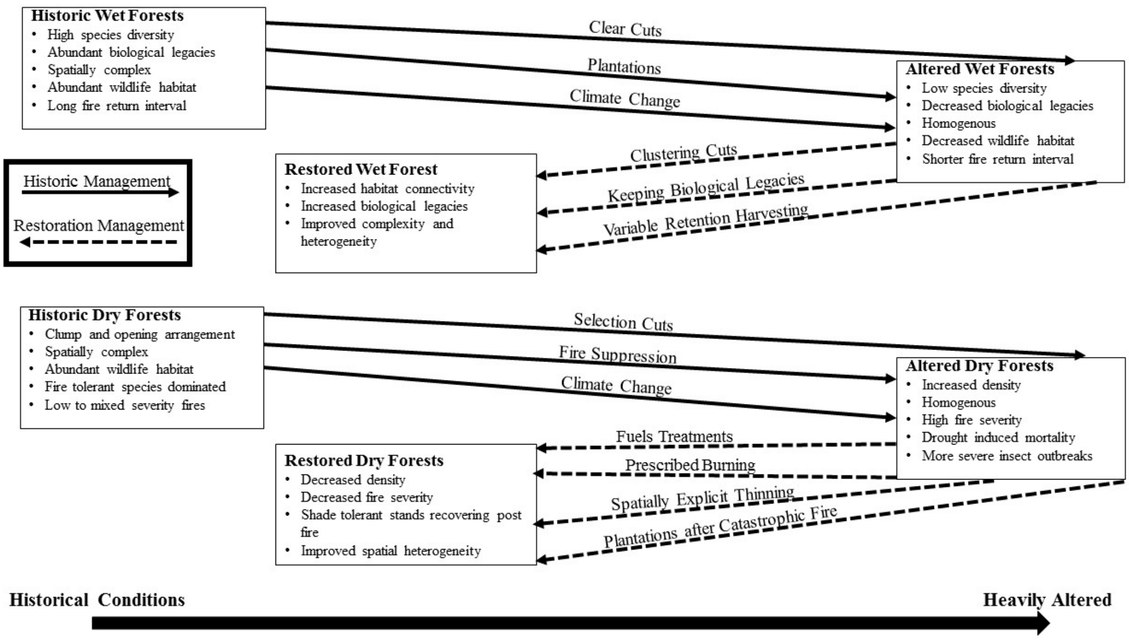

Figure 2. Effects of historic and restoration management on the wet and dry forests of the northwestern United States and California.

After the major decrease in Native American populations, there were not any widespread fire management policies until the United States federal government began managing land. The practice of fire suppression occurred mainly on public land managed by federal agencies such as the US Forest Service and National Park System [16,17]. The practice of fire suppression began after the creation of the National Parks when the U.S. Army started to patrol them in the late 19th century [16]. Reduced fire in the late 19th century also coincided with heavy fuel removal from extensive livestock grazing [1]. In 1898, Gifford Pinchot was appointed as the head of the Federal Forestry Program, which then became the Bureau of Forestry in 1901, and then the US Forest Service in 1905 [18]. In 1908, after a series of extensive western fires, the prevention and control of fires was added to the charge of the US Forest Service [18]. The first two chiefs of the US Forest Service were strong proponents of fire suppression, believing that it was necessary in protecting forests [16]. The Great Fire of 1910 in Montana, Idaho, and Washington further cemented the zero-tolerance policy for fires on federal land [17]. This fire burned over 1.2 million hectares of land, killed 85 people, and destroyed several towns [19]. With the passage by the US Congress of the Weeks Act in 1911, this allowed cooperative agreements and matching funds between the US Forest Service and state forestry management agencies to broaden fire protection on public and private lands [2]. The Weeks Act also provided for the US government to purchase land to set up the National Forest system which enabled the government to more effectively manage the lands. The Agricultural Appropriations Act of 1912 allowed 10% of the funds generated from the National Forests to be used in the construction of roads and trails which in turn improved access in the event of fires. In 1916–1917, the National Park Service was established, and 13 National Parks were founded primarily in the western United States [20]. The passage of the Clarke McNary Act in 1924 greatly expanded the cooperative fire protection program between the federal and state agencies [2]. The 10 a.m. policy was put in place in 1935, stating that all fires on federal land should be extinguished by 10 a.m. the next day [21]. The two decades leading up to the implementation of the 10 a.m. policy was a period of time that the scale of fire suppression effectively influenced fires in the western United States [22]. The Civilian Conservation Corps (CCC) program was established by the US Government and ran from 1933–1942 [18]. The CCC contributed to fire prevention and fire fighting, including the construction of fire lookout towers. For instance, the CCC assisted with fighting the 1933 Tillamook Fire [18]. This remained the Forest Service's fire policy until the 1970s [17]. During this time period, there were voices in the Forest Service and National Park System that were calling for a better understanding on fire's use in the ecosystem, but they did not have any large effect over national policy until later in the 20th century [17]. Some other federal agencies such as the US Fish and Wildlife Service (FWS) conducted the first recorded prescribed fire in 1927 in the St. Mark's National Wildlife Refuge [23]. Recognition of the benefits of prescribed burning for land management were noted by ecologists working in the southeastern pine forests [24,25]. In Idaho and Montana, Koch [26] promoted wilderness values and expressed concerns with fire suppression. Effects of prescribed burning were examined in ponderosa pine forests [27,28]. It was not until the 1960s that the National Park System began to allow fires to burn on their land and some prescribed burning [16,17].

Large fires in the late 20th century did lead to a more cohesive approach to managing fire on a national level. The Yellowstone fires and the Canyon Creek Fire both occurred in the summer of 1988 and burned 500,000 and 100,000 hectares of land, respectively [17,29]. After these fires, the Secretaries of Interior and Agriculture performed a review on fire policy on National Park and Forest Service wilderness lands [17]. This review called for a change in fire management policy, to make it more straightforward and improve interagency cooperation. After this review the National Parks and Forest Service began to allow more fire on their lands [17,30]. Another fire that shaped more recent fire policy is the 1994 South Canyon fire in Colorado. This fire killed 12 firefighters after a blow-up following suppression activities [17]. After this fire, the review and update of fire management and policy on all federal lands was written [17,31]. This report prioritized firefighter and public safety, but also acknowledged the ecological need for fire on the land and provide recommendations on how to reintroduce fire back onto federal lands [31]. In 2000, the Departments of the Interior and Agriculture created the National Fire Plan [32]. The plan focused on collaboration between federal, state, tribal, and local agencies to identify areas at high fire risk and develop strategies to restore fire-adapted ecosystems in these areas [32]. Another aspect of the plan was to assess the feasibility of creating a uniform fire planning system across the different agencies [33]. Jim Hubbard, a state forester from Colorado, was assigned that task and created the "Hubbard Report" which lead to the creation of the Fire Program Analysis system [33]. In 2009, the FLAME act was passed which lead to the creation of the National Cohesive Wildland Fire Management Strategy [34]. The National Strategy includes guidelines for fire management activities that prioritize safety, fuel management, and community engagement, and is still the Nation's fire policy [34]

However, despite the advances in fire policy, fire suppression is still a major practice in the US Forest Service [16,35]. Despite the progress made in understanding the important role fire plays in these ecosystems and implementation of prescribed fire and fuel reductions, there are still major risks and limited incentives to let fires burn [36], partly because many people now have been moving and living in the forests and in the Wildland Urban Interface neighborhoods, areas where homes are located amongst unoccupied spaces, like forests and grasslands [37]. As a result, the US Forest Service spends nearly 50% of their annual budget on fire suppression [35]. By altering the natural disturbance pattern of the landscape, fire suppression has also altered the structure and function of the landscape (Figure 2).

3.2. Logging

The historic logging regime in montane systems usually depended on the forest type. The management of wetter forests, found further north and closer to the coast, historically relied on clear cuts (Figure 2). Large-scale logging began in the Pacific Northwest to supply California's population boom associated with the gold rush in the mid-19th century [38]. As more people moved into the Pacific Northwest, more of the huge old growth forests were cleared to create mill towns to house the lumber workers and their families [38]. The timber industry employed 63% of wage earners in Washington State and 52% in Oregon in 1915 [39]. The completion of a railroad lines in the late 19th century and the depletion of timber in the Lake States greatly increased timber demand on the Pacific Northwest, making it one for the main suppliers for lumber in the United States [40]. In the early 20th century, Frederick Weyerhaeuser (timber mogul and founder of Weyerhaeuser timber company) purchased over 405 thousand hectares of timber land in Washington which greatly expanded industrial forestry in the PNW [40]. Industrial loggers worried that the creation of the Forest Reserve Act and the Forest Service would slow down the rate of harvest, but Gifford Pinchot, the first head of the US Forest Service, was a supporter of the timber industry. He encouraged companies to cut "virgin" forests and regenerate them to allow for sustainable yields over time [40]. This system of cutting old growth forests and replacing them with single species plantations continued after Pinchot and was the main forestry practice from the 1940s to the 1980s [41]. The Rise of conservationism in the mid-20th century and environmentalism in the later 20th century, including concern with the Northern Spotted Owl, eventually lead to a decline, or complete elimination in many places, of the timber industry [39]. However, the legacy of those practices is still felt on the land since these logging operations had a tendency to shorten the fire return interval in the wet forest regions (Figure 2).

The drier forests, found further south and inland, did not experience the same intensity of clear cuts, but these lands were still harvested, which has resulted in lasting impacts (Figure 2) [28–30]. Unlike the clear cuts found in the moist forests in the Pacific Northwest, the drier forests had more selection cuts performed (Figure 2). These dry forests mostly consist of ponderosa pine or mixed conifer forest type, which used to have many more large trees, when compared to today, that were interspersed with openings [42]. Logging efforts in these forests were focused on the largest, most timber worthy trees, usually ponderosa, Jeffery, and sugar pine [9,43,44]. This left much smaller residual trees; in the Sierra Nevada mountains, this often meant there were trees smaller than 31 cm diameter at breast height (DBH), although by the 1930s there were requirements for leaving trees 61 to 71 cm on some lands [43]. This practice of high-grading, selectively harvesting the best, largest trees, leaving behind the small trees, was common practice in the dry forests of California along with the Inland Northwest [43,44]. The harvests also required an extensive number of roads and train tracks be put in, to get the logs to the mills [44]. Harvests would usually work across large sections of land, as the earnings from the harvest needed to outweigh the cost of roads and train tracks, so it was more cost effective to stay in one large area [43]. While these logging practices differed from the wet forests, these methods also altered and fragmented the forests. These logging practices in dry forests induced structural changes that decreased the dominance of fire tolerant species.

3.3. Land Ownership

In addition to the management history of these lands, land ownership patterns also provide important context for understanding the issues that forests in the United States face. One usually finds different management, historical and current, on private and public forests. In the western United States, a majority of the forested land is public, with 64% of the forested area under the federal government [45]. In terms of forest type, the wet forests in the Olympic Peninsula and Oregon and Washington Coast range have a higher proportion of private ownership compared to the dry forest mountain ranges of the northwestern United States and California [46] (Figure 1). In California's 13.4 million hectares of forests, 56% is managed by the federal government, with 47% in national forests, 5% in Bureau of Land Management land, and 4% in the National Park System [47]. In Washington State, about 57% of the forested land is public [48]. The remaining forested areas belong to small local and state agencies or are on private hands. Having a majority of the land under federal control has positives and negatives. This allows for management at the landscape scale, which can help control the spread of disturbances like fire and insects. However, this also means resources for management of these areas are controlled by the federal budget, which is increasingly limited due to more and more of the budget going towards firefighting efforts in the recent years [49]. Also, having such a large area of land can make it challenging to have a management plan that address all of the area's needs. Each national forest is guided by its unique management plan.

4. Current Issues

4.1. Increasing Fire Severity and Area

In dry, northwestern, and Californian forests, fire suppression has altered structure, which in turn has increased fire risk [1,2,50]. Mixed conifer and dry pine forests, common forest types out west, historically had a fire regime with frequent surface fires of low to mixed severity [3] (Figure 2). These fires shaped the relatively open canopy forest structure [51]. This historical fire regime has changed in the past century due to fire suppression (Figure 2). Due to lack of fires, unforested openings have become smaller and fragmented [52]. Forest that were historically kept less dense by fire now have increased canopy cover due to lack of fire [53] (Figure 2). This pattern of increased forest cover due to fire suppression has been detected in the Rockies, Sierra Nevada, Cascade, and Klamath ranges [9,52–54]. In response to increases in forest density and cover, changes in fire behavior have been observed in areas with historically low to moderate fire regimes [55] (Figure 2). However, there is still debate over exactly how fire trends are changing, especially when it comes to areas of high-severity fires [55–58]. While the specifics of fire regime change are not clear, the past few years have witnessed several fires that approach state records. In 2013, the third largest fire in California's history burned through a mixed conifer forest on the Stanislaus National Forest and Yosemite National Park. The fire was over 100,000 hectares, and pre-fire forest structure suggested that a majority of the burned area had not experienced a fire for more than a century [59].

The shift in fire regimes in western systems has adverse effects on human livelihoods and wildlife habitat. Approximately 39% of housing units in the United States are located in the wildland urban interface (WUI) [37]. Many of these homes are found in the western United States especially in California and Colorado, and homes located in the WUI are at greater risk for wildfires [60]. Given this, and the fact that annual area burned by wildfire has increased in the past decade, these homes will soon be in direct danger from fire, if they have not already [9,16]. In addition to damages to human structures, these atypical (i.e., arising from an altered fire regime) large fires harm the forest health and structure. The California spotted owl, *Strix occidentalis occidentalis,* is a species of concern that is negatively affected by large wildfires [61–63]. They are associated with late successional forests, with high canopy cover and complex structure [61]. However, their preferred habitats now have a high-severity fire risk due to an accumulation of fuels from fire suppression [61–63]. When high-severity wildfires burn the owls' range, they lose nesting habitat and the canopy cover they require, which has resulted in a sharp decline in their populations [62,63]. In addition to the loss of habitat, the forests have trouble recovering from the atypical large fires, as they are not adapted to function with them [64,65]. Often, seed trees are killed, impeding natural regeneration [66,67]. This often delays their recovery, further displacing wildlife. It is important to note that not all fires cause this damage, only the large, atypical ones.

4.2. Structural and Functional Changes

Historic silviculture practices before the 1990s in the moist forests of the Pacific Northwest have decreased stand structural complexity, which in turn can affect wildlife habitat and watershed conditions (Figure 2). Before human intervention, these forests were old, over 175 years, and structurally complex (Figure 2) [68]. There was a mix of trees of all sizes, including very large, old trees, along with standing dead trees, snags, and diverse understory plant species [11]. The diversity of structure and dead and decaying material created habitat for many species and facilitated nutrient cycling [11]. However, most of this structural diversity is lost when areas are clear cut and replaced with either natural regeneration or plantations (Figure 2). The loss of complex habitat harms species like the Northern Spotted Owl, which was listed on the Endangered Species Act in 1990 due to habitat loss and fragmentation from forest management and logging [69]. This loss of woody debris also affects forest streams as many aquatic species rely on in stream wood for habitat [70].

Drier forests have also experienced a decrease in habitat diversity, but to a different extent. These forests were previously characterized by a horizontally heterogeneous landscape with trees clustered in groups ranging in age and size, spaced out with openings filled by grasslands or shrub lands [51] (Figure 2). However, due to fire suppression and logging, the forests have become more dense and homogenous [9,71] (Figure 2). Due to selection harvesting of the largest pines in the past, the density of large trees in stands has decreased [9,53] (Figure 2). The amount of shade-tolerant conifers, like white fir and incense cedar, have also increased [53]. These trees would have been controlled with low-severity fires but are now able to outcompete shade-intolerant pines due to fire suppression (Figure 3). The competition in return increases mortality of the larger old trees. Fire suppression is also responsible for a decrease in non-forested area. Shrubs and chaparral used to be a common element in dry western forests, often resprouting after fires. Shrub lands have been replaced by forest, in turn reducing the landscape heterogeneity [72]. The decrease in heterogeneity and increase in density also puts the forests at a greater risk for large scale insect and fungal outbreaks [73] (Figure 2). Increased tree mortality from insect pests and fungal pathogens in turn increase the likelihood that surface fires will easily transition into crown fires [74]. The landscape heterogeneity can act as ecological insurance, allowing for the forest to persist even if a small section was harmed. However, as the forests become denser and homogenous, large disturbances, such as diseases, insects, wildfires, and drought are able to spread throughout the whole stand. There are similar concerns for altered fire regimes in forests that historically had mixed-severity fire regimes. These forests also showed increases in stand density during the 20th century with negative implications for stand structural complexity and reduced functional aspects such as beta diversity (which is the ratio between regional and local species diversity), providing heterogeneity of successional stages, and safeguarding forest health [75,76].

Figure 3. A fire-suppressed mixed-conifer stand in the Sierra Nevada region of northern California. The overstory is dominated by sugar pine and ponderosa pine. The stand contains a dense understory of shade tolerant, fire sensitive white fir, and incense cedar.

4.3. Climate Change

Climate warming principally stems from anthropogenic emissions and this trend from the pre-industrial period to the present will persist for centuries [77]. Some authors suggested that it is imperative that forest resource managers develop adaptation strategies to climate change and induced changes in disturbance regimes [78]. With this altered climate, warmer temperatures, decreased snowpack, earlier snowmelt, increased summer evapotranspiration, and more frequent and severe droughts are expected [79]. All of these changes will affect forest health and function, and some already have (Figure 2). Warmer temperatures may increase productivity in some forests, however trees have a heat injury threshold, which, if passed, can damage cells, affecting metabolic processes [79,80]. Drought can harm trees by causing cavitation of water columns and water-stress-induced carbon starvation, reducing ability to defend against biotic attacks [81]. Often, the combination of elevated temperatures and drought is what kills trees [82]. Large patches of water-stressed, and even dead, trees can be seen throughout the northwestern United States and California, with extreme mortality events in the southern Sierra Nevada Mountains [80,83].

Climate change's effects on weather in turn is altering forests' disturbance regimes [29]. Many of the dry forest areas already have weather systems that support fire. Foehn winds, often called "chinook" winds in the Rockies and "mono" winds in the central Sierra Nevada, are fast, dry, warm winds that flow downslope [84]. The high peaks of the ranges also block and divert moisture away from the region. These hot, dry, windy characteristics create conditions conducive to the ignition and spread of fire [84]. Climate change is making areas that are already prone to fire even more prone to it [85] (Figure 2). Climate change is predicted to cause warmer temperatures, which have been modeled to increase fire frequency, especially in areas that are historically wetter [86] (Figure 2). Wetter forest types tend to have longer fire return intervals and climate change inducing more frequent fires disrupts this pattern (Figure 2). There are also climate change predictions for decreased or less consistent precipitation, which creates drier fuels, thus increasing flammability [87]. The effects of drought have already been observed in California. Fires are burning longer, and the fire season has lengthened due decreased snow pack [88]. This increased climate related fire risk compounds with the increased forest density, putting these forests at a real risk for large, stand-replacing fires.

In addition to increasing fire hazard, climate change is also changing forest structure and exacerbating other issues, like fungal pathogens and insect pests. Warming temperatures shift many species habitats up in latitude and or elevation [89]. This is especially a problem for species that live on mountains, as they have a limited amount of space to move up [89]. Another problem faced is the increased outbreaks of fungal pathogens and insect pests; the landscape scale morality events in recent years are outside of historical norms (Figure 2) [80]. A warming climate has allowed pathogens into areas that used to be too cold for survival, thus infecting more trees [90]. In Yellowstone National Park, the high-elevation whitebark pine forests historically only faced short, infrequent outbreaks of mountain pine beetles. This was due to the high-elevation conditions being too cold for the beetle. However as high elevations warm from climate change, the beetle is able to overwinter in whitebark pine stands, and in some areas killing more than 95% of the cone-bearing trees and is projected to continue as the climate warms more [91]. As mentioned before, climate change has created more drought conditions in dry forests [80,81] (Figure 2). These drought conditions create stressed trees, which make them more susceptible to attack [80]. The large mortality event seen in the southern Sierra Nevada Mountains has been exacerbated by bark beetles killing the already water-stressed trees [80]. Tree mortality during a hot and dry decade (2003–2012) in the western United States showed regional differences where mortality was attributed more to harvesting in the states of Washington and Oregon, while mortality due to bark beetles was more of a concern in Colorado and Montana, and mortality was mainly driven by fire in the state of California [92]. Climate change is adding another degree of complexity to current problems already faced in forests.

5. Current Management

5.1. Fuels Treatment

In efforts to restore historical fire regimes and reduce fire hazard, thinning and fuel reduction treatments to decrease fire risk are often used (Figure 2). Given the amount of change that has happened in these forests, active management is needed to adequately restore them [93]. Fuel reduction can be a strong tool but given the extent of fire suppression in the western United States, specific strategies are needed to make it effective. Focusing fuel reduction in areas with low- to mixed-severity fire regimes will provide the largest impact, as these are the forests that have diverged the most from their historic structure and disturbance regimes [93] (Figure 2). Performing the right type of fuels reduction is also important. Agee and Skinner [94] laid out four principles for effectively reducing fire behavior in fire adapted, dry forests: (1) Surface fuels must be reduced to decrease potential flame length; (2) height to live crown must be reduced so that longer flames lengths are required for a torching; (3) the overall density of trees should be reduced to decrease the ability for a crown fire to spread; and (4) maintain the largest, fire-resilient species because larger trees are more resistant to fatal fire damage [94]. A common technique to alter the nature of fine fuels is mastication [95–98]. Mastication usually shreds or chips smaller trees, branches, and understory shrubs, thus relocating ladder fuels to the surface [95]. However, especially when used in young stands and plantations, it often needs to be accompanied by prescribed fire to do an effective job at reducing fire behavior [96,98,99]. Reducing fuels using these principles has been shown to reduce high-severity fire risk in many scenarios [10,61,94,96,98–103]. Spatial arrangement of the treatments also influences their effectiveness. Strategically placed area treatments (SPLATs) are areas of thinning placed in the forest so fire spreads through them as fast as it does around them [104]. When fire behavior is modeled, SPLATs effectively reduce high-intensity areas burned [102].

Prescribed burning is another common fuel-reduction technique, and when used in tandem with thinning, is most effective at restoring systems (Figure 2). One of the main problems with only thinning forests to reduce fuels is that it can often leave residues, actually increasing surface fuels [94]. Prescribed burning can significantly reduce litter and surface fuels, reducing fire intensity [101]. When forests have an abundance of ladder fuels, thinning medium-sized trees followed by prescribed burning has the largest effect on fire behavior [101,102]. Besides reducing fuel loading and fire danger, prescribed burning can be used for restoration. Giant sequoia, the world's largest tree that is naturally only found in California's Sierra Nevada, relies on fires for regeneration [105]. Unfortunately, due to a history of fire suppression, many white firs have encroached on their habitat, affecting regeneration. However, understory thinning and prescribed burning positively affect seedling success as it reduces light competition and encourages the serotinous cones to open [106]. It is important to note that prescribed burning is not a perfect solution for all restoration projects [107]. Prescribed burns do have an extremely low risk of getting out of control and causing damage, which has resulted in the public viewing it as risky [108]. Prescribed burning can be risky in areas with steep topography, as fire travels quickly up steep slopes, so it is difficult to control prescribed burns in steep areas [109]. Prescribed burning in unthinned, dense stands also poses a risk of uncontrollable wildfires, as the ladders fuels that are responsible for crown fires are still there [75,76]. While there are some very small risks associate with prescribed burning, in an overwhelming majority of its uses, little damage is done [108].

5.2. Thinning to Increase Heterogeneity

Land managers are now factoring in ecological concepts into their practices in order to encourage and create structural heterogeneity in forests. The pattern of spacing out cuts throughout the landscape is still being used, but with modifications. The size and structure of the patches have a large influence on habitat. Evenly spaced cuts increase the amount of habitat fragmentations, so clustering cuts and maintaining undisturbed connectivity is an important practice [110] (Figure 2). Cuts can also be used to increase woody debris in streams, improving fish habitat [70]. Another important ecological principle included in new management plans is the inclusion of biological legacies, like old trees and standing dead trees (Figure 2). Leaving these legacies help maintain important habitat and function [11]. Franklin and Johnson [111] created a management plan for wet western forests that attempts to do so. They suggest a variable retention harvesting system, creating a heterogeneous landscape with patches of cuts (Figure 2). The cuts would be focused in previously harvested stands and would maintain 30% of the preharvest stand structure, like live trees, snags, and logs [111]. The variable retention harvesting system could also encourage development of diverse early seral ecosystems, an important functional stage in western mesic forests that is in limited supply [111]. However, these practices are often encouraged but not wholly implemented. The balance between retaining ecosystem function and structure and the economic drives of timber harvest are often put up against each other.

While a majority of the suggested thinning treatments in dry western forests focus on reducing fire danger, increased stand heterogeneity is another important driver (Figure 2) [9]. There is a shifting focus to a local scale for implementing restoration techniques. Adapting crown class, species preference, and stocking density requirements for individual stands help meet the specific needs of each stands [61]. Using local topography to determine target densities and species helps emulate the original composition of the landscape and help create stand heterogeneity [10]. These forests were originally composed of a patchwork of clusters of trees and openings. Specifically incorporating these elements into restoration treatments ensures that those historic structures return. A new approach incorporating individuals, clumps, and openings (ICO) has created a framework to categorize and create these elements [112]. Focusing on retaining spatially explicit elements in the forest helps maintain important ecological process and maintain wildlife habitat [113]. This less-dense structure also benefits the tree's physiology. Dry forests that are more open and heterogeneous are less susceptible to drought damage [51]. Thinning has also been shown to reduce water stress [10]. However, it is important to acknowledge that creating local scale management plans requires an immense amount of work and will take coordination across different agencies and land owners to implement.

5.3. Use of Plantation after a High-Severity Fire

Conifer regeneration after high-severity fires is extremely variable [64,65]. Often shrubs will dominate the post fire landscape due to their persistent soil seed bank [72]. Shrubs can out compete the conifer seedlings for light and water, delaying conifer regeneration for decades, if not centuries [114]. In addition to the increased competition, seed source trees are killed during stand-replacing fires, preventing the establishment of the next generation of trees [67]. To aid with forest reestablishment, targeted tree species are often planted after stand-replacing fires and are usually more successful than natural regenerating stands [65] (Figure 2). However, these plantations require intensive management to survive. Salvage logging is often performed before planting to remove fuels and safety hazards and provide income to fund other management activities [115], although salvage logging does not yield any ecological benefits [76]. Slash leftover from the fire and logging can hinder the success of plantations, so it is often piled and burned to encourage or discourage certain species from regenerating [116]. Controlling for shrubs is also extremely important in plantation success, as shrubs can outcompete tree seedlings [117,118].

While plantations can be successful at establishing trees quickly, there are several common criticisms. Their dense, homogenous nature gives them a high canopy-bulk density of continuous fuels, which put them at risk for high-severity fire [96,103,119,120]. Plantations at high density are also at risk for drought-induced damage or mortality [121]. When compared to natural regenerating stands, plantations often exhibit lower vegetative diversity in the early stages [122]. Plantations are also lacking in spatial heterogeneity, so many of the problems associated with homogenous stands, like quick spread of disease and lack of wildlife habitat, are found in them [73]. As forest plantations become a more common method for rapid forest restoration, all aspects of ecosystem health and structure need to be addressed if they are to achieve their target of restoring the older forests conditions.

While most plantations are historically planted in evenly spaced rows, some restoration projects plant them in small, clustered aggregates, (Figure 4) [119,123]. This is attempting to mimic the natural clumping pattern of historical mixed conifer forests. Until the 2019 Tamm Review [119], there have not been any formal publications on this style of plantations in the United States. Commonly used square planting patterns were designed to capture the productive capacity of the site by offering each seedling an opportunity for a relatively equal share of sunlight condition as well as site nutrients and moisture resources. Although many foresters wonder if this arrangement will yield a forest stand within a reasonable time frame, there could be some potential benefits to a clumped arrangement. Tree ring analysis has shown trees in clumped patterns are resilient to moisture and fire stress [119]. Having a spatially heterogeneous stand can break up crown and fuel continuity, thus reducing fire severity [51,124]. Most conifers require bare mineral soil, adequate soil moisture, light shade, and minimal competition for regeneration [118]. All of these variables could potentially be altered by the spatial arrangement of the planted seedlings. The clumped nature of aggregate plantations could affect the patterns of soil moisture and light in stand, also impacting understory diversity and soil characteristics.

Figure 4. Comparison of a traditional, evenly spaced plantation (**a**), and a novel clustered arrangement (**b**) in the mixed-conifer forest region of the Sierra Nevada, Eldorado National Forest.

5.4. Shift in Policy

The Forest Reserve Act in 1891 allowed the president to set aside forest reserves on public land [16]. Over the next few years, the extent of these reserves expanded along with the Forest Service Organic Management Act of 1897, which gave the secretary of the interior the power to regulate use on the reserves [125]. This network of public lands, which later became the National Forest system, allowed for policies, like the "10 a.m." fire suppression policy to be widely implemented. It was not until later in the 20th century that new policy began to come out with the goal of restoring ecosystems to historical structure and function. There were policies like the Resource Planning Act of 1974 and the National Forest Management Act of 1976, which required the National Forests to make forest management plans and regulate timber harvesting, and also outlined a planning rule that describes how public stakeholders can be involved in the planning process and how decisions are subject to objections [126]. The Endangered Species Act, which came out in 1973, has very strong language, stating that critical habitat of listed species cannot be harmed [127]. This had a huge impact for management of species like the Spotted Owl. It created regulations on private lands, which have fewer protections than federal lands [128]. Another impactful piece of legislation was the 1994 Northwest Forest Plan (NWFP). The NWFP created a network of reserves throughout the Pacific Northwest and worked to relieve part of the burden put on private landowners to manage wildlife species [129]. A new science synthesis for the NWFP recently came out that has new science informing management in the PNW since the original publication [130]. There is a similar plan for the forests of the Sierra Nevada called the Sierra Nevada Forest Plan [126]. These laws and plans had a significant impact of forest management since it provided administrative control of larger and more contiguous areas of public land, which makes it more effective for addressing issues related to forest health, including fire management [131].

In 2003, the Health Forests Initiative was implemented as a response to the severe 2002 fire season. Its goals were to expedite fuels treatments by reducing regulations surrounding forest cuttings [132]. Unfortunately, many people viewed this policy move as simply a way to reduce environmental regulations for the benefit of logging companies [133]. Another problem with current national fire policy is that there is still a lot of operating budget put into fire suppression and there is not enough left for fuels reduction. However, this issue is expected to improve starting in 2020 following the firefighting bill that the Congress has passed in 2018 [82]. Annual spending on fire suppression is over 1 billion dollars. Also, many fuel treatments that are implemented focus on only reducing the amount of fuels instead of looking how to reduce severe fires on the landscape level [16]. Schoennagel et al. [50] caution that site-level fuel treatment reductions will not have a substantial impact on affecting regional wildfire behavior. Schoennagel et al. [50] promote a system of treatment triage in which critically important ecosystems and communities in the wildland urban interface areas are initially targeted for fuel reductions. There is also conflict between protecting wildlife and fuel treatments. The strict protections under the Endangered Species Act can often delay or hinder fuel reductions when they need to occur in critical habitat [16]. The NWFP has also experienced some pushback. It has not met its commitment for timber sales, and many argue that it is harming the rural communities that rely on logging [129]. There is no definite policy solution to perfectly manage forests. That is why it is important to make legislation adaptable to new science and incorporate all stakeholders.

There are differences in terms of policy and management framework for addressing wet and dry forest types in the mountain ranges of the northwestern United States and California. In comparatively wetter forest types, stand-replacing fires still serve an ecological role. The key concern in these wetter forest types is that a potential shortening of the fire return interval associated with climate change may lead to recruitment failure because trees may not get a chance to reach a seed-bearing age [134]. In the drier forest types, the main policy push is to restore an understory fire regime in these forest types [134].

6. Conclusions

The legacy of past management in northwestern and Californian montane systems is still seen. Fire suppression in frequent fire forests and logging practices throughout the ranges left many of these forests more homogenous, fragmented, and overly dense. The transformed forests experience problems with wildfire, lack of wildlife habitat, and loss of function. In their current state, the disturbance regimes in these forests has been altered to the point that they have trouble bouncing back from the new disturbances. However, some management practices work to restore ecosystem function and historic disturbance regimes. Through different thinning and fuels treatments, structural heterogeneity and old fire regimes can be worked back into these systems. There has also been an increase in policy working to help these forests, although some legislation is more effective than others. Restoring these systems' structure and function will require active management implemented on the local and landscape scale while taking into account climate change. With expected climate-induced changes in fire frequency and scale, fuel treatments will likely need to be implemented in dry forests to ensure they have an understory fire regime. With respect to wet forests in this region, it is suggested that there is still a place for stand-replacement fire regimes. However, these forests will require structural changes incorporating heterogeneity to improve their resiliency and health.

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