Silvicultural Treatment Impacts on Fuels and Wildfire Behavior in Moist, Westside Pacific Northwest Forests: A Summary of Relevant Literature

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Contents

Introduction

Background

Although the impacts of silvicultural activities on fuels and wildfire behavior in dry conifer forests of the western United States have received considerable attention in recent decades (see Kalies and Yocom Kent 2016 for a review of this literature), few studies have directly evaluated the effects of silvicultural activities on the moist conifer forests of the western Cascades, Olympics, and coastal ranges of Oregon and Washington (Wimberly and Liu 2014). Fire risk is generally considered to be low in these moist conifer forests, and fuel reduction treatments are considered to have limited effectiveness because 1) the weather and fuel moisture conditions that foster large fires and severe fire behavior are uncommon (Brown et al. 2004, Agee and Skinner 2005), 2) rates of biomass recovery are high, necessitating frequent treatments to effectively reduce fuels (Halofsky et al. 2018), 3) treatments that sufficiently reduce fuels to impact wildfire behavior would require significant alterations in forest structure that fundamentally alter ecosystem functioning (Brown et al. 2004, Halofsky et al. 2018), and 4) projected increases in fire frequency and severity for these forests are relatively low (Halofsky et al. 2020). Additionally, fire regimes in many moist conifer forests of the Pacific Northwest (PNW) still appear to fall within the historical range of variation for mean fire return interval and proportion of area burned in different fire severity classes (Morrison and Swanson 1990, Dunn and Bailey 2016, Law and Waring 2015). As a result, the effects of fire suppression on fuel loadings and subsequent risk of high severity fire in moist, westside forests are thought to be negligible (Agee 1996, Brown et al. 2004, Agee and Skinner 2005, Steel et al. 2015, Halofsky et al. 2020).

However, although the overall extent, frequency, and severity of wildfire and associated fire risks will almost certainly continue to be highest in dry Pacific Northwest (PNW) forests in the future (Littell et al. 2010, Halofsky et al. 2020), proportional increases in area burned under future climate scenarios are projected to be greatest in moist forests of the PNW (Littell et la. 2010, Rogers et al. 2011). Further, the moist forests of western Oregon and Washington contain some of the highest resource values in the region due to their proximity to heavily populated areas, high carbon storage potential, significant economic contributions, and provisioning of habitat for several threatened and endangered species. This raises the potential for the re-emergence of large fires with significant resource impacts in moist, westside PNW forests (Wimberly and Liu 2014).

Even in moist forests characterized by infrequent fire and relatively low fire risk, management actions designed to reduce wildfire risk to fire sensitive and high value resources may sometimes be appropriate (Shoennagel et al. 2017, Halofsky et al. 2018, Halofsky et al. 2020). However, understanding the management of fire, and fire's role as an ecological process is critical to land management planning, even in westside forests (Teensma 1996). The lack of research on 1) the ecological impacts of fire in moist, westside PNW forests, and 2) how silvicultural activities impact fuel characteristics and fire behavior in these forests is a significant knowledge gap that limits the ability of land managers and scientists to adequately incorporate the potential for increased fire into their planning and decision-making processes.

Lessons from Dry Conifer Forests

Literature focused on drier forests in the western U.S. suggests that silvicultural treatments designed to reduce surface fuel loadings (or alter surface fuel characteristics), raise crown base heights, lower crown bulk densities, and promote stands with large-diameter trees of fire resistant species can reduce fire severity and associated impacts on resource values (Agee et al. 2000, Agee and Skinner 2005, Hessburg et al. 2016, Kalies and Yacom Kent 2016). Surface fuels consist of live and dead biomass in the forest floor and understory vegetation layer. Fine fuels (defined here as fuels < 3 in diameter, which includes the 1-hr, 10-hr, and 100-hr time lag fuel moisture classes) contribute to fire spread and fireline intensity, while coarse fuels (fuels > 3 in diameter, which includes the 1000-hr + time lag classes) are generally thought to contribute little to spread, but may contribute to fire intensity and severity due to their potential to release more heat over longer periods of time (Agee 1996, Agee et al. 2000).

Fine dead fuels often have low moisture contents during the dry season, promoting higher fireline intensities, while live herbaceous vegetation and shrubs can have varying effects on fire severity depending on their composition and foliar moisture contents (Agree et al. 1996, Agee et al. 2000). Live understory vegetation generally has high moisture contents (Agee 1996, Agee et al. 2002), which typically dampens fire behavior, but cured grasses and forbs can increase fireline intensity (Weatherspoon and Skinner 1996, Agee et al. 2000). Some shrubs with waxy or oily foliage like snowbrush ceanothus (*Ceanothus velutinus*) will also burn much hotter than other live fuels (Agee 1996).

Surface fuels also play a role in the initiation of crown fires (i.e., torching). Torching occurs when surface fuels generate sufficient heat and flame lengths to promote combustion of crown fuels. The potential for crown fire initiation depends on fire weather conditions, surface fireline intensity, the height of the crown's base above the ground, and the moisture content of crown fuels, while the potential for crown fire to spread is heavily influenced by crown bulk density and foliage moisture contents (Van Wagner 1977, Agee 2000).

Silvicultural treatments that reduce or compact surface fuels (e.g., broadcast burning, piling and burning, or crushing and mastication treatments) are generally thought to reduce surface fireline intensities, reducing the potential for tree mortality and decreasing the potential for torching at a given crown base height and foliage moisture content (Agee et al. 2000, Agee and Skinner 2005). Treatments that increase crown base heights (e.g., thinning from below or pruning) are also thought to reduce torching potential, while treatments that reduce crown bulk density (e.g., heavier thinning) should reduce the potential for crown fire spread (Agee 1996, Agee et al. 2000, Agee and Skinner 2005).

Extrapolation to Moist, Westside PNW Forests

Although the impacts of silvicultural activities on fire behavior and management outcomes in dry western forests have been extensively studied (e.g., Agee and Skinner 2005, Kalies and Yacom Kent 2016), there are significant knowledge gaps about these topics in moist forests (Wimberly and Liu 2014). To help bridge this gap, this document was developed to summarize findings from literature about silvicultural treatment impacts on fuels and fire behavior, with an emphasis on findings from studies in low to middle elevation moist, westside PNW forest types such as Douglas-fir (*Pseudotsuga menziesii*)/western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*)/western hemlock, Douglas-fir/grand fir (*Abies grandis*), and coast redwood (*Sequoia sempervirens*)/Douglas-fir/tanoak (*Lithocarpus densiflorus*) forests. Studies from drier Douglas-fir, mixed conifer, and pine dominated systems of the western U.S. are also summarized for topic areas where information from moist, westside systems is lacking. This summary focuses on a set of six questions, generated from input provided by ecologists and silviculturists from the Willamette National Forest, Siuslaw National Forest, and the Bureau of Land Management's Northwest Oregon District:

1. What are the impacts of silvicultural treatments on dead surface fuels?
2. What are the impacts of silvicultural treatments on live understory vegetation?
3. What are the impacts of silvicultural treatments on overstory/aerial/crown fuels?
4. What are the impacts of silvicultural treatments on fuel moisture and microclimate?
5. What are the impacts of stand age, structure, and species composition on fire behavior?
6. How do silvicultural treatments and management area designations impact fire severity?

Q1. What are the impacts of silvicultural treatments on dead surface fuels?

Thinning and Regeneration Harvest Impacts on Dead Surface Fuels

Surface fuel reduction treatments are often recommended to reduce the potential for increased fireline intensities associated with elevated surface fuel levels after thinning and other harvest treatments (Agee and Skinner 2005, Hessburg et al. 2016). Heavier thinning has been associated with higher initial down deadwood inputs in coast redwood/Douglas-fir forests than lighter thinning treatments and unthinned stands (Dagley et al. 2018). Although there were no significant differences in slash depth among heavy thinning, light thinning, and gap-based thinning treatments immediately after harvest in this study, slash depth decreased more rapidly in the heavy thinning treatment, resulting in lower slash depths in the heavy thinning treatment than in light thinning and gap-based thinning treatments four years after harvesting (Dagley et al. 2018). Clearcut and seed tree harvests were also shown to have higher fine woody fuel loads and moderate-sized coarse woody fuel loads (diameters up to 10 inches dbh) than patch cut treatments and unmanaged stands in interior Douglas-fir forests of British Columbia, although there were no significant differences in large, coarse woody fuels (diameters ≥ 10 inches) among any harvest treatments and unmanaged stands (Sullivan et al. 2001).

In drier Douglas-fir and mixed conifer forests, thinning treatments have been shown to increase fine woody debris loadings (Raymond and Peterson 2005, Youngblood et al. 2008, Stephens et al. 2009), increase rotten coarse woody debris loadings (Raymond and Peterson 2005), and either slightly decrease sound, coarse woody debris loadings (Raymond and Peterson 2005) or have no significant effects on coarse woody debris loadings (Stephens and Moghaddas 2005, Youngblood et al. 2008). In contrast, Stephens and Moghaddas (2005) found no significant differences in fuel loads across any time lag category among young plantations, mature stands treated with thinning or individual tree selection harvests, second-growth reserves, and old-growth reserves.

Different harvesting systems also have differing impacts on fuel loads. Whole tree yarding in moist Douglas-fir systems has been shown to reduce coarse woody debris biomass, fine woody debris biomass and depth, and forest floor (litter and duff) biomass and depth when compared with bole-only harvests (Roberts et al. 2005, Ares et al. 2007, Littke et al. 2020). Cut-to-length systems with a processor and forwarder will compact harvest residues, which may reduce their porosity and subsequent fireline intensities, while helicopter yarding and other logging systems that leave tops and limbs scattered tend to create the largest surface fuel increases (Agee 1996, Agee and Skinner 2005).

In the longer-term, dead foliage and fine woody debris decay after harvest activities. Slash will generally decay more slowly in drier and cooler sites than in wetter or warmer sites, because temperature and moisture content are both positively correlated with rates of slash decomposition (Erickson et al. 1985, Edmonds et al. 1986). Woody debris decay rates also vary based on species and contact with soil. Woody debris decay rates for Douglas-fir and red alder (*Alnus rubra*) increased moderately from wood suspended above the soil surface to wood in contact with the soil surface, and increased dramatically in wood that is buried in soil compared to suspended wood and wood on the soil surface (Erickson et al. 1985, Edmonds et al. 1986), but woody debris position relative to the soil was found to have no impact on woody debris decay rates in western hemlock and Pacific silver fir (*Abies amabilis*, Erickson et al. 1985). Edmonds (1986) found that coarse woody debris suspended above the soil surface lost roughly 9% of its mass over five years for Douglas-fir and 44% of its mass over five years for red alder. In contrast, coarse woody debris on the soil surface lost roughly 17% (Douglas-fir) to 62% (red alder) of its mass in five years and coarse woody debris that was buried in soil lost approximately 58% (Douglas-fir) to 79% (red alder) of its mass in five years (Edmonds et al. 1986). Decay rates of fine woody debris were more rapid in these studies, but followed similar general trends in relation to soil position. This may suggest that logging system that leave slash more compacted (i.e., slash moistly in contact with the soil surface or partially buried), such as processor/forwarder systems, will promote more rapid decomposition of woody fuels generated by harvesting.

Ruth and Harris (1975) estimated a period of 1-3 years for foliage to fall from logging slash, and 13-15 years for all 1-hr and 10-hr fuels to decay following clearcuts of mature to late-successional stands in coastal Sitka spruce/western hemlock forests. Other studies in Douglas-fir dominated systems of western Washington and Oregon have found faster rates of decay. Harrington et al. (2018) found that logging debris generated by clearcutting mature Douglas-fir stands lost half of its mass within five years, and estimated the period of increased fire risk associated with harvest residues to be five years. Christiansen and Pickford (1991) found virtually no foliage retention on branches of pre-commercially thinned trees by the second growing season after thinning, and that slash in PCT units lost half its mass and depth within two years. Further, fine fuel loadings in heavy slash resulting from blowdown in the western Cascades were similar to background levels in 2-4 years (Christiansen and Pickford (1991). Edmonds et al (1986), however, reported slower rates of decomposition in western Cascades Douglas-fir systems than Harrington et al. (2018) or Christiansen and Pickford (1991). Edmonds et al's reported rates of decomposition were more similar to those reported by Ruth and Harris for coastal Sitka spruce/hemlock forests. In drier, ponderosa pine-dominated mixed conifer forests, Youngblood et al (2008) found that elevated fine woody debris levels after thinning returned to nearly pre-treatment levels within six years.

When piling woody material after harvests, pile shape, volume, and the timing of pile creation all influence the drying times of woody materials in the pile (Belart et al. 2015). Woody materials from clearcuts in the Oregon Coast Range and western Cascades that were distributed in half-ellipsoid and cone-shaped piles maintained higher summer moisture levels than materials in berm-shaped piles (Belart et al. 2015). Piles constructed in the fall and winter also dries more gradually during the following summer than summer-constructed piles (Belart et al. 2015), potentially shortening the period of low fuel moistures during the dry season.

Prescribed Burning and Wildfire Impacts on Surface Fuels

Fall burning in late-successional Douglas-fir stands in the northeast Olympic peninsula decreased total surface fuel loads, 1-hr fuel loads,1000-hr fuel loads, and duff depths, but not 10-hr and 100-hr fuel loads (Fonda and Binney 2011). However, these dead surface fuel reductions were short-lived as litterfall from burned foliage, branches, saplings, and fallen snags over the first two years after the fire resulted in total fuel loads similar to pre-fire levels. Broadcast burning of slash after clearcuts in Douglas-fir/western hemlock systems of the western Cascades and Oregon Coast Range has been shown to reduce fine and coarse fuel loads for all but the largest size class (logs ≥ 11 inches diameter), and these impacts were estimated to reduce the rate of spread of wildfire by 50% for at least seven growing seasons (Morris 1958). Wildfires in moist, westside conifer forests have also been shown to reduce duff and litter biomass, even in areas that burned with low severity (Peterson et al 2019), providing further evidence that prescribed burning may generate short-term reductions in surface fuel loads in moist, westside PNW forests. However, reductions in fine fuels after broadcast burning may be transient in stand structures with significant small tree components as litterfall and snag fall from fire-killed foliage and understory trees accumulate in the years following the burn (Agee and Skinner 2005, Fonda and Binney 2011).

Studies in drier mixed conifer and pine forests suggest similar effects of prescribed burning on dead surface fuels, including reductions in fine fuels (Knapp et al. 2005, Youngblood et al. 2009, Stephens et al. 2009, Levine et al. 2020) and litter depth (Knapp et al. 2005, Youngblood et al. 2008, Levine et al. 2020) following prescribed burning. Although these studies focus primarily on broadcast burning, both broadcast burning and pile burning treatments can reduce fuel loads (van Wagtendonk 1996). In contrast with stand-alone thinning treatments, which can increase surface fuel loadings (Agee and Skinner 2005), thinning followed by prescribed burning treatments in dry mixed conifer and pine-dominated forests have been shown to generate a net decrease in fine woody debris (Raymond and Peterson 2005, Youngblood et al. 2008, Stephens et al. 2009), suggesting that implementing prescribed burning treatments after thinning can more than offset the increased fine fuel loadings associated with harvest residues from thinning activities. There is, however, some evidence that fuel consumption from spring burns may be less than fuel consumption in fall burns due to higher spring fuel moisture contents (Knapp et al. 2005), so season of burning may be an important consideration for mangers interested in using prescribed fire as a fuel reduction tool.

Q2. What are the impacts of silvicultural treatments on live understory vegetation?

Response of Understory Grasses, Forbs, and Shrubs to Silvicultural Treatments

Live grasses, forbs, and shrubs can have varying impacts on fire behavior. Live fuels with high foliar moisture tend to reduce fireline intensities, while cured foliage from grasses and forbs and shrubs with lower foliar moisture can increase fireline intensities (Agee et al. 2000, Agee et al. 2002). Although curing and foliar moisture reductions are common in live understory fuels late in the fire season in the Pacific Northwest, simulations suggest that the dampening effects of green understory vegetation on fireline intensity last into September in understories dominated by perennial grasses or forbs, and into October in understories dominated by shrubs (Agee et al. 2002). Even in moist coastal forests, however, prolonged periods of dry, east winds can lead to curing and drying of the abundant fuels in these highly-productive systems, promoting high intensity fire behavior (Ruth and Harris 1975, Means et al. 1996). Additionally, foliage of some shrub species with waxy or oily foliage like snowbrush ceanothus will burn hotter, contributing to higher fireline intensities (Agee et al. 1996). Thus, understanding the impacts of silvicultural treatments on the composition and structure of understory vegetation layers is an important facet of predicting potential fire behavior.

Thinning, retention harvests, clearcuts, and gap-based regeneration harvest methods have all been shown to produce a short-term decline in understory grasses, forbs, and shrubs in the moist, Douglas-fir/western hemlock forests and Douglas-fir/grand fir forests of western Oregon and Washington (Halpern et al. 2005, Maguire and Chambers 2005, Chan et al. 2006, Wilson and Puettmann 2007, Halpern et al. 2012, Cole et al. 2017, Dagley et al. 2018, Lilles et al. 2018). Heavier overstory removals (i.e., cutting to lower residual live tree densities) have been associated with a greater short-term reduction in understory cover in some studies (Halpern et al. 2005, Lilles et al. 2018). Prescribed burning has also been shown to reduce understory vegetation cover in Douglas-fir/western hemlock forests (Fonda and Binney 2011). Of the common understory species in their study sites in the northeastern Olympic mountains, Fonda and Binney (2011) found that only salal showed a significant increase in cover from 1-month post-burn to 3-years post-burn, and salal cover was still 50% lower than pre-burn levels at 3-years post-burn. Similarly, broadcast burning of logging slash as a site preparation treatment has been shown to reduce shrub competition in young plantations (Morris 1958, Ruth and Harris 1975), although the impacts of broadcast burning on subsequent vegetation dynamics are highly variable in moist forest of the PNW (Steen 1965), and species with rapid post-fire regeneration strategies such as snowbrush ceanothus may benefit from the burning of harvest residues (Morris 1958).

Although harvesting and burning treatments in moist, westside forests generate immediate reductions in understory vegetation cover, research suggests that live understory vegetation in these forests recovers rapidly after harvesting and fire (Halpern and Spies 1995, Maguire and Chambers 2005, Wilson and Puettmann 2007). The cover of most understory plant functional groups has been shown to meet or exceed pre-harvest levels within 1-10 years of thinning, retention harvests, shelterwood harvests, and patch cut treatments (Maguire and Chambers 2005, Chan et al. 2006, Halpern et al. 2012, Cole et al. 2017, Dagley et al 2018, Lilles et al. 2018). Although grass and forb cover recovers fairly rapidly following thinning and regeneration harvest treatments, shrub cover, particularly tall shrub cover, recovers more (Halpern and Spies 1995, Wilson and Puettmann 2007, Halpern et al. 2012). Increases in understory vegetation cover in the years following thinning are inversely related to residual overstory density (Burton et al. 2014), such that areas of low retention are associated with higher understory vegetation cover over time. However, these increases in understory vegetation cover after thinning can be muted on moist sites if high densities of western hemlock seedlings establish following the harvest (Cole et al. 2017).

Despite the longer recovery times associated with shrubs after harvesting, both herbaceous understory cover and shrub cover are typically higher 10-30 years after thinning than in unthinned stands of similar age (Bailey and Tappeiner 1998, Bailey et al. 1998, Chan et al. 2006, Wilson and Puettmann 2007). However, some studies have found evidence of the beginnings of a decline in understory forb cover by 15 years after thinning, with more rapid declines occurring in treatments that left higher residual overstory densities (Cole et al. 2017).

Different spatial patterns of overstory retention can also influence the understory vegetation response to harvesting, leading to differences in the rate of understory development after harvesting and the spatial variability in understory cover within stands. Unharvested leave islands (i.e., aggregates or "skips") experience less of an initial drop in understory cover than areas of dispersed retention or the harvested matrix in aggregated retention harvests (Halpern et al. 2005). Over a decade following harvesting, however, understory plant communities in the harvested matrix of aggregated retention harvests exhibited larger changes in composition and cover than understory communities under dispersed retention, and the understory understory communities in unharvested leave islands (i.e., aggregates) retain understory community structures similar to unharvested stands (Halpern et al. 2012). This leads to greater variability in understory community cover within aggregated retention treatments than in dispersed retention treatments or unharvested stands. Similarly, Wilson and Puettmann (2007) concluded that variable density thinning treatments that incorporate unharvested leave islands (i.e., skips) and gaps within a thinned matrix promote greater variability in herbaceous and shrub cover than uniform thinning treatments or unharvested stands.

Although increases in understory vegetation cover following thinning and regeneration harvests could increase fire behavior (Agee 2000, Agee and Skinner 2005), the fire risk associated with high live biomass in moist, coastal forests and higher elevation forests of the PNW is generally considered to be low (Halofsky et al. 2020) because live vegetation fuel moistures remain high under most conditions (Agee et al. 2002, Agee and Skinner 2005), and the extreme weather conditions that promote large fires in these forests are rare (Brown et al. 2004, Agee and Skinner 2005). Additionally, Neill and Puettmann (2013) found that increases in understory cover following thinning in moist Douglas-fir/western hemlock forests were also associated with increased cover of fire-tolerant species (e.g., sprouting shrubs), potentially increasing resilience to future wildfire. Further the amount of increase in cover of fire-tolerant understory plants was positively correlated with thinning intensity (Neill and Puettmann 2013), potentially suggesting that understory plant communities in areas with heavier overstory removals may show greater increases in fire resilience in these moist forests.

Response of Understory Tree Layers to Silvicultural Treatments

Thinning has been shown to increase tree seedling and sapling densities in moist conifer forests of the PNW (Bailey and Tappeiner 1998, Miller and Emmingham 2001, Deal and Tappeiner 2002, Williams and Powers 2019), with greater seedling and sapling densities occurring is areas with lower residual overstory densities (Bailey and Tappeiner 1998, Deal and Tappeiner 2002, Dodson et al. 2014, Shen et al. 2019). Understory and midstory tree growth rates, and rates of sapling and midstory tree recruitment also increase as residual overstory densities decrease following thinning (Cole and Newton 2009, Comfort et al. 2010, Dodson et al. 2014, Willis et al. 2018). Similarly, understory tree growth rates increase across a spectrum of decreasing residual overstory densities from untreated stands to thinned stands to patch cuts to shelterwoods to clearcuts (Harrington 2006, Lam and Maguire 2011). Repeated thinning in Douglas-fir/western hemlock stands appears to promote more rapid growth of understory trees than single entries (Andrews et al. 2005, Shatford et al. 2009), resulting in recruitment into midstory positions within 50 years.

Understory tree growth rates have also been shown to be higher in aggregated retention harvests than in dispersed retention harvests in moist conifer forests of the PNW (Urgenson et al. 2013, Jang et al. 2017), and to increase as retention levels decrease in both dispersed and aggregated harvests (Zenner et al. 1998, Urgenson et al. 2013, Jang et al. 2017). Growth rates of tree regeneration following variable density thinning treatments that incorporate gaps, are also greater for seedlings in gaps than in the thinned matrix (Newton and Cole 2009, Willis et al. 2018), with seedling growth rates increasing as gap size increases across a range of westside, PNW species (Gray and Spies 1996, de Montigny and Smith 2017).

Fall prescribed burning was shown to reduce sapling densities by 71% in a late-successional Douglas-fir/western hemlock forest in the northeast Olympics (Fonda and Binney 2011). Low severity wildfires in the western Cascades have also been shown to result in high levels of mortality in small-diameter trees, particularly for shade tolerant species (Dunn and Bailey 2016, Johnston et al. 2018), which supports the notion that prescribed burns could significantly reduce the densities of seedlings and saplings in moist conifer forests of the PNW.

Q3. What are the impacts of silvicultural treatments on overstory/aerial/crown fuels?

Tree diameter, which is used as a surrogate for bark thickness, is one of the most important variables for predicting tree mortality during and after wildfire, with increasing dbh corresponding to a lower probability of mortality in most PNW conifers (Grayson et al 2017, Ganio and Progar 2017, Johnston et al. 2019). A given fireline intensity is more likely to cause mortality in small, thin-barked trees with low crowns than in larger trees with thicker bark and higher crown bases (Agee 1996). However, the effects of dbh on post-fire mortality vary by species (Dunn and Bailey 2016, Hood and Lutes 2017, Johnston et al. 2019) and may interact with the influence of dbh on bark beetle attack in Douglas-fir (Hood and Lutes 2017). Thus, silvicultural treatments that accelerate the development of large-diameter trees or increase mean diameter at a stand scale may foster greater fire tolerance (Agee et al. 2005), but the benefits are likely to vary depending upon species composition.

Studies in Douglas-fir/western hemlock, Douglas-fir/grand fir, and Sitka spruce/western hemlock forests indicate that residual midstory trees (Deal and Tappeiner 2002, Comfort et al. 2010) and residual overstory trees show increased diameter or individual tree basal area growth rates after thinning (Deal and Tappeiner 2002, Latham and Tappeiner 2002, Roberts and Harrington 2008) or greater growth than trees in untreated stands (Latham and Tappeiner 2002, Curtis 2006, Davis et al. 2007, Dodson et al. 2012). Greater increases in residual tree growth and/or greater mean diameters are generally found in areas that were thinned to lower residual densities (Curtis 2006, Roberts and Harrington 2008, Comfort et al. 2010, Dodson et al. 2012, Newton and Cole 2015, Bose et al. 2018). Residual trees near canopy gaps also demonstrate greater growth rates than trees in the thinned matrix or unharvested areas of moist, westside PNW forests (Roberts and Harrington 2008, Dodson et al. 2012).

Some studies in moist, westside PNW forests also suggest that growth increases following thinning are greatest in residual trees with small to moderate diameters (Deal et al. 2002, Dodson et al. 2012, Willis et al. 2018, Crotteau and Keyes 2020), while growth increases following thinning may be more modest in the largest trees in a given stand (Curtis 2006, Dodson et al. 2012, Crotteau and Keyes 2020). In some cases, the largest diameter residual trees have shown no significant increases in diameter growth (or no increases in growth relative to unmanaged stands) after stand density reductions (Deal and Tappeiner 2002, Garber et al. 2011, Willis et al. 2018). However, one study suggests limited impacts of relative tree size on residual tree growth responses to thinning in coastal Douglas-fir (Bose et al. 2018).

Impacts of Thinning Method on Aerial/Canopy Fuels, Torching Index, and Crowning Index

The choice of thinning method (or specific mark and leave tree preferences in a prescription's marking guide) can heavily influence impacts on mean tree size and crown heights. Thinning from below (a.k.a. low thinning) is most effective at increasing mean diameter at a stand-scale since the smaller-diameter trees are preferentially removed during the harvest, creating an immediate increase in mean diameter (Agee et al. 2005, Tappeiner et al. 2015). Total increases in mean diameter over time result from the combined effects of the thinning entry and subsequent years of increased tree growth relative to unthinned stands (Curtis 2006).

Thinning from below treatments are also thought to be the most effective means of reducing crown fire potential due to their impacts on crown variables like crown base height and crown bulk density (Agee and Skinner 2005). Studies in various dry conifer forest types of the west generally support this conclusion. Thinning from below has been shown to increase crown base heights, reduce crown bulk density, and reduce crown fuel loads (Raymond and Peterson 2005, Huggett et al., 2008, Harrod et al. 2009, Cruz and Alexander 2012, McCaskill 2018, Johnson et al. 2019, Korb et al. 2020). These impacts on crown fuels generally increase as thinning intensity increases (Cruz and Alexander 2012), although increasing thinning intensity may not result in an increase in crown base heights in in open-canopied, multi-cohort, and mixed-species stand structures where either low levels of competition for light or variability in individual species' shade tolerances and associated crown architectures can lead to varied crown depths in large and small diameter trees (Cruz and Alexander 2012). This situation can occur when large-diameter, shade tolerant trees may have lower crown bases than smaller-diameter, shade intolerant trees in the same stand, or when open canopies allow both large and small trees to retain live foliage on low branches. A combined thinning from below and crown thinning (i.e., thinning from above in which some codominants are removed to favor other dominants and codominants) treatment has also been shown to increase crown base heights, reduce crown bulk densities, and increase mean dbh (Raymond and Peterson 2005).

Proportional thinning and thinning from above may be less effective at reducing tree mortality during wildfires and crown fire hazard as these methods do not tend to increase mean diameter, leave more ladder fuels and have less impact on crown base height than thinning from below (Agee and Skinner 2005, Tappeiner et al. 2015, Hessburg et al. 2016). For instance, proportional thinning to 30% Max SDI in high fire hazard forests across the west was found to reduce the crowning index and torching index to wind speeds of less than 20 mph in less than half of the treated stands (Miles et al 2005), and treatments that thinned across diameter classes in ponderosa pine and Douglas-fir forests of Colorado were less effective at improving torching index and crowning index (i.e., increasing necessary wind speeds for torching and fire spread between crowns) than thin from below treatments (Huggett et al 2008).

Thin from below treatments may, however, have more transient impacts on canopy fuel characteristics like canopy cover, canopy bulk density, and crown base height in the moist, highly productive forests of western Oregon and Washington than those observed in drier conifer forests. Canopy closure following thinning in Douglas-fir/western hemlock and Sitka spruce/western hemlock forests is rapid due to crown expansion from residual trees (Davis et al. 2007) and rapid development of understory cover (Lilles et al. 2018). Developing understory and midstory trees in these moist forests also grow rapidly in height following thinning (Comfort et al. 2010, Willis et al. 2018), and crown recession slows in residual overstory trees following thinning, leading to deeper, and lower crowns than unthinned stands over time (Curtis 2006, Dodson et al. 2012, Tappeiner et al. 2015). Thus, the increases in crown base height associated with thin from below treatments may dissipate over time in comparison with untreated stands in the moist, westside PNW forests as rapidly growing understory trees and slower crown recession on overstory trees re-establish connections between surface fuels and overstory tree crowns following thinning.

Prescribed Fire Impacts on Aerial/Canopy Fuels

In contrast to thinning, prescribed fire as a stand-alone treatment generally does not promoted increased residual tree growth (Crotteau and Keyes 2020). Studies in dry mixed conifer forests also suggest that prescribed burning, alone or following thinning, does not appear to have significant impacts on crown bulk density or crown base height (Harrod et al. 2009, Korb et al. 2020). However, both prescribed burning and low severity wildfire result in high levels of small tree mortality in mature to late-successional Douglas-fir western hemlock and Douglas-fir/grand fir systems, which are characterized by high densities of fire sensitive, shade tolerant understory trees (Fonda and Binney 2011, Dunn and Bailey, 2016, Johnston et al. 2019). This could suggest the potential for prescribed burning or managed wildfire to temporarily reduce ladder fuel densities and increase crown base heights in moist, westside forests. However, thin plus burn treatments may provide a limited period of reduced sapling densities given the abundant establishment of natural regeneration following thinning in moist conifer forests (e.g., Bailey and Tappeiner 1998, Deal and Tappeiner 2002, Nabel et al. 2013, Shen et al. 2019). Ultimately, further research in moist, westside PNW forests is needed to evaluate the potential impacts of prescribed burns and wildfire on fuel characteristics and subsequent wildfire behavior.

4. What are the impacts of silvicultural treatments on fuel moisture and microclimate?

Thinning and Surface Fuel Moisture

Overstory density reductions can increase daily temperature extremes, VPD, and wind speeds in the forest understory (van Wagtendonk 1996, Weatherspoon et al. 1996, Rambo and North 2009), leading to concerns that thinning could increase fire behavior by drying surface fuels and curing live foliage (van Wagtendonk 1996, Weatherspoon et al. 1996, Agee and Skinner 2005). However, several empirical studies in dry conifer forests suggest that thinning treatments have limited impacts on surface fuel moisture. Estes et al. (2012) found that fuel moistures in 10-hr and 1000-hr fuels did not differ between thinned and burned stands and unthinned stands at any point from May to October, while fuel moistures in 10,000 hr fuels were significantly lower in thinned stands than in unthinned stands only in early May when fuel moisture values in both thinned and unthinned stands were still high and fire danger was low. 10-hr fuels also showed a nonsignificant trend of greater fuel moisture following precipitation events in thinned and burned stands than in unthinned stands. Overall, fuel moistures were generally more responsive to short-term weather variation than to silvicultural treatment effects, despite significantly lower canopy cover and LAI in thinned and burned stands (Estes et al. 2012). Faiella and Bailey (2007) found similar results in ponderosa pine stands in Arizona, where there were no differences in 1-hr or 10-hr fuel moistures between thinned and unthinned stands, and the only significant differences in moisture content of 100-hr fuels between thinned and unthinned stands was immediately following a rainfall event. Multiple studies in dry conifer forests have shown that surface fuels in thinned and unthinned stands converge to similar fuel moistures as the growing season progresses and fire danger increases (Whitehead et al 2006, Faiella and Bailey 2007), often without any significant differences in fine or coarse fuel moistures between thinned and unthinned stands for the majority of the late spring and summer (Faiella and Bailey 2007, Estes et al. 2012). Ottmar and Sandberg (1985) found very similar fuel moistures in 1000-hr fuels of clearcut and partially cut stands in western Oregon, suggesting that seasonal changes in fuel moistures in moist, westside PNW forests may respond similarly to thinning as those in drier forests.

Moisture of surface fuels is also influenced by contact with soil (Pook and Gill 1993), where capillary action can transfer soil moisture to surface fuels, slowing their drying (Samran et al 1995). Working in young, Douglas-fir dominated mixed conifer forests of the inland northwest, Chase et al (2016) found that precommercial thinning increased soil temperatures by 6-7% compared to controls due to reduced canopy light interception, but soil moisture availability increased from 51%-74% in thinned stands compared to controls. Similarly, Devine and Harrington (2008) found that soil moisture increased with decreasing overstory density in Douglas-fir stands. Such increases in soil moisture following overstory density reductions could potentially help offset some of the effects of increased temperatures, VPD, and wind speeds on surface fuel moistures and live vegetation foliage moisture content. This soil moisture-derived wetting effect, paired with the large impact of short-term weather variation on fuel moisture in thinned stands (Estes et al. 2012) may help explain why the studies of thinning impacts on surface fuel moisture summarized above have not shown any consistent impact of thinning on fuel moisture.

Q5. What are the impacts of stand age, structure, and species composition on fire behavior?

Impacts of Stand Age, Structure, and Species Composition on Wildfire Behavior

After fire weather, stand structural variables and ownership patterns that drive structural differences have been shown to be the most important predictors of fire severity in PNW forests (Thompson and Spies 2009, Zald and Dunn 2018). Some studies in dry conifer forests that historically experienced frequent, low severity to mixed severity fire regimes suggest that forests with high basal area or biomass densities experience a greater proportion of high severity fire during wildfire events than forests with lower densities (Shaw et al 2016), or that some stand structures with high basal areas can have increased risk of crown fire (Hessburg et al. 2016). Further, the convention wisdom in dry conifer forests suggests that stand structures with dense overstories and multi-layered canopies may promote increased fire behavior due to their high canopy bulk densities and low crown base heights (e.g., Agee and Skinner 2005). However, there is considerable evidence that this structure-wildfire severity relationship may differ in some westside, PNW forests with mixed severity fire regimes, and in moist forests and high elevation forests with infrequent, high severity fire regimes.

Studies following fires in southwest Oregon and northwest California indicate that stand structures composed of high densities of small trees and lower densities of large trees (i.e., dense, young stands) experienced more high severity fire than stands composed of larger trees (Azuma et al. 2004, Campbell et al. 2007). Odion et al. (2004) found that plantation-origin stands experienced nearly twice the rate of high severity fire as multi-aged stands, and Zald and Dunn (2018) found that mean fire severity was higher on industrial lands composed of dense plantations than on BLM lands that contained a higher proportion of older forests with greater structural complexity. Thompson and Spies (2009) found that closed canopy forests with high levels of large conifer cover (i.e., mature to late-successional stands) were associated with the lowest levels of crown damage during wildfire, while plots with small conifer cover (i.e., younger stands with smaller trees) experienced more crown damage than plots with both large and medium-sized conifer cover. In a related study, older plantations were found to have less canopy damage from wildfire than younger plantations, with the highest levels of damage occurring in 15-25 year-old plantations, and declining levels of damage with age after that period (Thompson et al 2011). Additionally, Zald and Dunn (2018) found that pre-fire biomass density was not an important predictor of fire severity in mixed conifer forests of southwest Oregon. These findings suggest that in at least some westside conifer forests of the Pacific Northwest, closed-canopy stands with mature to late-successional structural characteristics (i.e., multi-storied stands with many large-diameter trees and abundant coarse woody debris) may be less prone to high severity fire than dense young plantations (Odion 2004, Tompson and Spies 2009).

Studies in mixed conifer forests of the Klamath-Siskiyou ecoregion also indicate that open-canopied stands and shrub-dominated systems experience proportionally more high severity fire than closed-canopy forests (Azuma et al. 2004, Odion et al. 2004, Thompson and Spies 2009). Some studies in the same ecoregion have also found that areas that burned at higher severities had lower amounts of coarse woody debris prior to the fire than areas that burned at lower severities (Azuma et al. 2004, Campbell et al. 2007).

Additionally, species composition likely impacts fire severity. Azuma et al. (2004) reported that Douglas-fir dominated stands experienced less moderate to high severity fire than other conifer-dominated forest types in the Biscuit fire, while hardwood dominated stands composed main of tanoak and canyon live oak (*Quercus chrysolepsis*) had the lowest percentage of moderate and high severity burn area relative to their total burn area (15%). Further, a recent review of management in mixed severity fire regime forests suggests that hardwoods rarely act as ladder fuels in forests of the Pacific Northwest and California and hardwoods may, in some cases, reduce the risk of crown fire (Hessburg et al. 2016).

Several lines of evidence suggest that these findings from studies in southwest Oregon and northwest California could be extended to moist conifer forests in the western Cascades and coastal ranges of Oregon and Washington. First, Dunn and Bailey (2016) found that the probability of mortality during wildfire decreased with increasing dbh for all species except western hemlock in Douglas-fir/western hemlock and Douglas-fir/grand fir systems of the west-central Cascades in Oregon. This suggests that mature to late-successional stands with increased densities of large trees should be more resistant to high severity fire effects than younger stands. However, the dbh-fire resistance relationship varies considerably by species in westside forests, and species' fire resistance rankings can vary with size.

Incense cedar (*Calocedrus decurrens*) was found to have the lowest probability of mortality during wildfires in the west-central Cascades of Oregon, followed by Douglas-fir, regardless of size (Dunn and Bailey 2016). In contrast, for small to moderate-sized trees (dbh < 20.5 in) western red-cedar (*Thuja plicata*) was found to have the highest probability of morality during wildfire, while western hemlock had the highest probability of mortality during wildfire for larger trees. Among fire sensitive species groups (i.e., true firs, western hemlock, and western redcedar), western hemlock was found to have the lowest probability of mortality during wildfire for small trees (dbh < 11.8 in) and true firs were found to have the lowest probability of mortality for larger trees, although fire tolerant species (i.e., Douglas-fir, incense-cedar, and sugar pine) had consistently lower probabilities of mortality than fire sensitive species, regardless of size (Dunn and Bailey 2016). With the exception of incense-cedar, common shade tolerant conifers in westside, PNW forests like western hemlock, western redcedar, and several species of true firs generally experience high levels of mortality during fire when small, even in areas that burn with low severity (Fonda and Binney 2011, Dunn and Bailey 2016, Johnston et al. 2019). Thus, while the large-diameter overstory trees characteristic of older moist, westside PNW forests are more likely to survive fires, the smaller, shade tolerant trees that commonly form understory and midstory tree layers in these systems may be more susceptible to mortality during fire events.

Relationships between overstory biomass and fire severity provide additional evidence that older stands in moist, westside PNW forests may be less prone to high severity fire. Pre-fire biomass in mature to late-successional stands in the western Cascades has been positively associated with the occurrence of fire refugia (i.e., areas of no fire or very low fire severity within a fire perimeter; Meigs et al. 2020). High overstory basal areas and canopy cover have also been associated with lower fuel consumption during wildfires in the western Cascades (Larson and Franklin 2005), suggesting reduced fireline intensities under closed canopy forests.

Further, in moist forests and high elevation forests of the Pacific Northwest where fire was historically less frequent, there is evidence that the period of effective fire suppression has been shorter than the mean fire return interval (Morrison and Swanson 1990, Brown et al. 2004), suggesting that fuel accumulations in these moist forest systems are not outside the historic range of variability. There is also evidence that time since fire (used as a proxy for fuel accumulations) has no relationship with fire severity in moist and high elevation forests that historically experienced infrequent, high severity fire (Steel et al. 2015). Instead, fire behavior in moist, westside PNW forests is typically driven by periods of extreme drought and weather (Littell et al. 2009, 2010), so they are often characterized as more weather limited than fuel limited (Steel et al. 2015, Halofsky et al. 2020). Additionally, the proportions of area burning at different fire severity classes in recent fires in moist, westside forests have not been significantly different from historical conditions (Dunn and Bailey 2016, Law and Waring 2018).

Q6. How do silvicultural treatments and management area designations impact fire severity?

Impacts of Thinning, Prescribed Burning, and Regeneration Harvests on Fire Severity in Dry Conifer Forests

Silvicultural treatments such as thinning and prescribed burning have been found to have significant impacts on wildfire behavior in mixed conifer and pine forests across the western US (Kalies and Yacom Kent 2016), but there are few studies examining these relationships in the wetter coastal Douglas-fir/western hemlock, Douglas-fir/grand fir, Sitka spruce/western hemlock, and high elevation systems of the PNW. As a result, this section focuses on inferences from studies in drier mixed conifer and pine forest types, although Kalies and Yacom Kent (2016) provide a more thorough review of fuel reduction treatment impacts on subsequent wildfire outcomes in these drier conifer forests.

The combination of thinning and prescribed burning has been consistently shown to reduce subsequent wildfire severity and/or tree mortality in a variety of dry western forest types (Raymond and Peterson 2005, Omi and Martinson 2002, Pollet and Omi 2002, Raymond and Peterson 2005, Wimberly et al. 2009, Prichard et al 2010, Kennedy and Johnson 2014, Prichard and Kennedy 2014, Kalies and Yacom Kent 2016). This is consistent with basic fuel reduction treatment principles, which suggest that treatments that combine reduced surface fuel loads (i.e., prescribed burning), increased canopy base heights (i.e., thinning from below), and reduced canopy bulk densities (i.e., thinning of sufficient intensity) will moderate wildfire behavior (Agee et al. 2000, Agee and Skinner 2005). Research suggests that thin and broadcast burn treatment combinations reduce levels of tree mortality during subsequent wildfires by 2-10 times when compared to stands that received only thinning with no subsequent slash removal, and untreated stands (Raymond and Peterson 2005, Prichard et al. 2010).

Thinning alone has also been shown to decrease burn severity across varied forest types and fire events in some studies in dry conifer forests (Omi and Martinson 2002, Pollet and Omi 2002, Wimberly et al. 2009, Johnson et al. 2018). However, some authors have found that thinning alone provides smaller reductions in subsequent wildfire severity compared to thin plus burn treatments (Wimberly et al 2009), or may even increase burn severity relative to untreated stands (Raymond and Peterson 2005, Wimberly et al 2009, Prichard and Kennedy 2012). Some studies have shown no difference in burn severity between stands that received only thinning treatments and untreated stands of similar initial age, structure, and species composition (Prichard et al. 2010), or have found that thin-only treatments were only effective at reducing burn severity in mature stands and not in young plantations (Stephens and Moghaddas 2005). Prichard et al. (2010) also found that the reduction in burn severity associated with thin and burn combination treatments compared to thin only treatments was magnified when looking at larger-diameter trees (dbh >20 cm).

The failure to treat increased surface fuels after thinning (i.e., slash and other harvest residues) can result in increased fire severity (Stephens 1998, Agee et al. 2000, Agee and Skinner 2005). As a result, several reviews of fuel and wildfire management have suggested that surface fuel treatments that either 1) remove or redistribute dead surface fuels (Agee 1996, Agee 2000, Agee and Skinner 2005, Hessburg et al. 2016) or 2) increase the abundance of live surface fuels with high foliar moisture contents (Agee 1996, Agee et al. 2000) may be necessary to mitigate the effects of thinning-related surface fuel inputs on subsequent wildfire behavior.

Additionally, decomposition and compaction of slash over time following the harvest can result in stand-alone thinning treatments that initially increase wildfire severity due to heavy surface fuels, but ultimately reduce wildfire severity (Wimberly et al. 2009) or fireline intensity (Youngblood et al. 2008) after several years. Thus, the varied impacts of thin-only treatments on subsequent wildfire behavior that were summarized above are unsurprising. Thinning treatments may generate significant harvest residues, potentially increasing surface fuel loadings (Agee 1996, Agee and Skinner 2005), but increasing time since harvest will reduce fuel abundance, alter fuel characteristics, and reduce fire behavior associated with these fuels (Youngblood et al. 2008,Wimberly et al. 2009).

The choice of harvesting systems utilized will also impact surface fuel loadings, which may further explain some of the variability in observed effects of stand-alone thinning treatments on subsequent wildfire behavior. Whole-tree yarding operations leave significantly less woody material in the harvested unit than harvesting systems that top and delimb trees prior to yarding (Agee 1996, Roberts et al. 2005, Ares et al. 2007, Littke et al. 2020), and the use of whole-tree yarding after thinning has been shown to reduce subsequent wildfire severity (Stephens et al. 2009). Processor/forwarder operations will leave a more compacted fuelbed than lop and scatter operations, which also tends to moderate fireline intensities (Agee 1996, Agee and Skinner 2005) and may increase rates of fuel decay by placing more fuels in contact with the soil (Erickson 1985, Edmonds 1986).

Prescribed burning as a stand-alone treatment has also been shown to decrease subsequent wildfire intensity and severity in several studies (van Wagtendonk 1996, Peterson 1998, Omi and Martinson 2002, Pollet and Omi 2002, Stephens et al. 2009, Wimberly et al. 2009), including broadcast burning as a site preparation treatment (Lyons-Tinsley and Peterson 2012). However, some studies have found no significant impact of stand-alone prescribed burning treatments on subsequent wildfire severity (Wimberly et al. 2009).

The effects of different regeneration harvest methods on fire behavior have been less heavily studied than thinning and prescribed burning, but there is some evidence that retention-based harvest systems such as irregular shelterwoods and variable retention harvests decreased fire severity relative to untreated stands during fires in dry conifer forests (Wimberly et al 2009). Group selection treatments paired with surface fuel reduction treatments (e.g., broadcast burning, piling and burning, or slashing treatments) were also shown to reduce subsequent wildfire behavior relative to untreated stands in a simulation study, although group selection harvests without follow-up surface fuel treatments increased wildfire behavior relative to untreated stands (Stephens 1998).

Effects of Thinning, Prescribed Burning, and Regeneration Harvests on Wildfire Severity in Moist, PNW Forests

There are surprisingly few studies that directly examine the impacts of silvicultural treatments on wildfire behavior in the moist forests of the western Cascades, Olympics, and coastal Ranges of the Pacific Northwest. Several authors suggest that common fuel reduction treatments like thinning and prescribed burning will likely have limited effectiveness in these forests because fires in moist PNW forests burn primarily under extreme weather and fuel moisture conditions that are 1) uncommon relative to the effective lifetime of fuel treatments and 2) likely to promote higher severity fire behavior regardless of previous treatment and fuel conditions (Brown et al. 2004, Agee and Skinner 2005, Halofsky et al. 2018, Halofsky et al. 2020), and because biomass recovers rapidly in these systems after thinning (Halofsky et al. 2018). However, a simulation study of various silvicultural treatment effects on wildfire behavior over multiple centuries indicated that a broad range of silvicultural activities could reduce mean fire severity in Douglas-fir/western hemlock forests of the west-central Cascades and Sitka spruce/western hemlock forests of the Oregon Coast Range (Mitchell et al. 2009). In this study, treatments that removed only understory trees without any accompanying overstory thinning or surface fuel reduction were found to produce minimal reductions in subsequent wildfire severity, while prescribed burning treatments and treatments that combined prescribed burning with understory thinning produced slightly higher reductions in mean fire severity. The greatest reductions in fire severity were associated treatments that either 1) combined overstory thinning with understory tree removal and prescribed fire or 2) clearcut treatments followed by broadcast burning (i.e., treatments that significantly reduced both surface fuels and canopy bulk densities). Reductions in estimated fire severity were generally found to be greatest when simulated in a fire regime with mean fire return intervals on the lower end of the historic range of variability for moist forests in western Oregon (i.e., mean fire return intervals of 143 years for west-central Cascades forests and 250 years for coastal fog belt forests) and when re-treatment treatment frequencies were high (i.e., re-treatment every 25 years vs every 50 years or 100 years).

Impacts of Management Area Designation (i.e., Reserves vs Multi-Use vs Timber Production)

Studies from drier Douglas-fir and mixed conifer forests with mixed severity fire regimes suggest that fire severity may also vary across areas with different management designations and associated differences in management direction, management intensity, and forest structure. Adjusting for all other variables, mean fire severity in southwest Oregon forests was higher on industrial lands composed of dense young plantations than on BLM lands with a greater proportion of older forests (Zald and Dunn 2018). Similarly, Stephens and Modhaddas (2005) found that simulated tree mortality was high in young plantations, and lower in mature stands that were thinned from below, second-growth reserve forests, and old-growth reserve forests. Bradley et al. (2016) found that protected lands managed for biodiversity where fire is allowed to burn had the lowest fire severity, while protected lands where fire is generally suppressed and managed, multiple use lands were intermediate in fire severity and unprotected lands (i.e., forests not managed for biodiversity with no special restrictions on forest harvesting such as private lands) had the highest fire severity. However, closed-canopy forests in roaded areas of the Klamath National Forest experienced the same proportion of high severity fire as closed-canopy forests in roadless areas during the 1987 fires, although open-forests and non-forest vegetation in roaded areas had a greater proportion of higher severity fire than open forests and non-forest vegetation in roadless areas (Odion et al 2004).

These results generally suggest that fire severity may be lower in multiple-use lands and in reserve areas where the proportion of mature to late-successional stands with large trees is high than in landscapes composed of younger plantations managed primarily for timber production (Zald and Dunn 2018). Further, reserve areas are likely to have equal or greater resistance to severe fire as areas managed for multiple uses (Odion et al. 2004, Bradley et al. 2016). Zald and Dunn (2018) suggest that these dynamics may be driven by a greater susceptibility to severe fire in landscapes with dense, homogenous fuels and greater proportions of young trees with thin bark and low crown bases than in landscapes with more structurally diverse stands that have more large trees, and a more varied landscape-scale mosaic of structural conditions. However, it should be noted that these studies were all conducted in the drier mixed conifer forests of the Klamath-Siskiyou ecoregion and southern Cascades. Thus, the results may not transfer directly to moist Douglas-fir/western hemlock, Sitka spruce/hemlock, and higher elevation true fir and mountain hemlock forests of the western Cascades, Olympics, and coastal ranges of Oregon and Washington.

Literature Cited

Agee, JK. 1996. The influence of forest structure on fire behavior. In: Proceedings of the 17th Forest Vegetation Management Conference. Redding, CA. pp. 52-68.

Agee, JK, Bahro, B, Finney, MA, et al. 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127: 55-66.

Agee, JK, and Skinner, CN. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Agee, JK, Wright, CB, Williamson, N, and Huff, MH. 2002. Foliar moisture content of Pacific Northwest vegetation and its relations to wildland fire behavior. Forest Ecology and Management 167: 57-66.

Andrews, LS, Perkins, JP, Thrailkill, JA, et al. 2005. Silvicultural approaches to develop northern spotted owl nesting sites, central Coast Ranges, Oregon. Western Journal of Applied Forestry 20(1): 13-27.

Azuma, DL, Donnegan, J, and Gedney, D. 2004. Southwest Oregon Biscuit fire: an analysis of forest resources and fire severity. USDA Forest Service Pacific Northwest Research Station Research Paper PNW-RP-560. Portland, OR.

Ares, A, Terry, TA, Piatek, KB, et al. 2007. The Fall River long-term site productivity study in coastal Washington: site characteristics, methods, and biomass and carbon and nitrogen stores before and after harvest. USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-691. Portland, OR.

Bailey, JD, and Tappeiner, JC. 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. Forest Ecology and Management 108: 99-113.

Bailey, JD, Mayrsohn, C, Doescher, PS, et al. 1998. Understory vegetation in old and young Douglas-fir forests of western Oregon. Forest Ecology and Management 112: 289-302.

Belart, F, Leschinsky, B, and Sessions, J. 2017. Finite element analysis to predict in-forest stored harvest residue moisture content. Forest Science 63(4): 362-376.

Bose, AK, Weiskittel, A, Kuehne, C, et al. 2018. Tree-level growth and survival following commercial thinning of four major softwood species in North America. Forest Ecology and management 427: 355-364.

Bradley, CM, Hanson, CT, and DellaSala, DA. 2016. Does increased forest protection correspond to higher fire severity in frequent-fire forests of the western United States? Ecosphere 7(10): 1-13.

Brown, RT, Agee, JK, and Franklin, JF. 2004. Forest restoration and fire: principles in the context of place. Conservation Biology 18(4): 903-912.

Burton, JI, Ganio, LM, and Puettmann, KJ. 2014. Multi-scale spatial controls of understory vegetation in Douglas-fir-western hemlock forests of western Oregon, USA. Ecosphere 5(12): 1-34.

Chan, SS, Larson, DJ, Mass-Hebner, et al. 2006. Overstory and understory development in thinned and underplanted Oregon Coast Range Douglas-fir stands. Canadian Journal of Forest Research 36: 2696-2711.

Chase, CW, Kimsey, MJ, Shaw, TM, and Coleman, MD. 2016. The response of light, water and nutrient availability to pre-commercial thinning in dry inland Douglas-fir forests. Forest Ecology and Management 363: 98-109.

Christiansen, EC, and Pickford, SG. 1991. Natural abatement of fire hazard in Doulgas-fir blowdown and thinning fuelbeds. Northwest Science 65(4): 141-148.

Cole, E, and Newton, M. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon Coast Range. Canadian Journal of Forest Research 39: 580-595.

Cole, E, Newton, M, and Bailey, JD. 2017. Understory vegetation dynamics 15 years pos-thinning in 50-year-old Douglas-fir and Douglas-fir/western hemlock stands in western Oregon, USA. Forest Ecology and Management 2017: 358-370.

Comfort, EJ, Roberts, SD, and Harrington, CA. 2010. Midcanopy growth following thnning in young-growth conifer forests on the Olympic Peninsula western Washington. Forest Ecology and Management 259: 1606-1614.

Crotteau, JS, and Keyes, CR. 2020. Restoration treatments improve overstory tree resistance attributes and growth in a ponderosa pine/Douglas-fir forest. Forests 11: 1-20.

Crotteau, JS, Keyes, CR, Hood, SM, et al. 2018. Stand dynamics 11 years after retention harvest in a lodgepole pine forest. Forest Ecology and Management 427: 169-181.

Cruz, MG, and Alexander, ME. 2012. Evaluating regression model estimates of canopy fuel stratrum characteristics in four crown fire-prone fuel types in western North America. International Journal of Wildland Fire 21: 168-179.

Curtis, RO. 2006. Volume growth trends in a Douglas-fir levels-of-growing-stock study. Watern Journal of Applied Forestry 21(2): 79-86.

Dagley, CM, Berrill, JP, Leonard, LP, and Jim, YG. 2018. Restoration thinning enhances growth and diversity in mixed redwood/Douglas-fir stands in northern California, U.S.A. Restoration Ecology 26(6): 1170-1179.

Davis, LR, Puettmann, KJ, and Tucker, GB. 2007. Overstory response to alternative thinning treatments in young Douglas-fir forests of western Oregon. Northwest Science 81(1): 1-14.

Deal, RL, and Tappeiner, JC. 2002. The effects of partial cutting on stand structure and growth of western hemlock-Sitka spruce stands in southeast Alaska. Forest Ecology and Management 159: 173-186.

de Montigny, LE, and Smith, NJ. 2017. The effects of gap size in a group selection silvicultural system on the growth response of young, planted Douglas-fir: a sector plot analysis. Forestry 90: 426-435.

Devine, WD, and Harrington, TB. 2008. Belowground competition influences growth of natural regeneration in thinned Douglas-fir stands. Canadian Journal of Forest Research 38: 3085-3097.

Dodson, EK, Ares, A, and Puettmann, KJ. 2012. Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of western Oregon, USA. Canadian Journal of Forest Research 42: 345-355.

Dodson, EK, Burton, JI, and Puettmann, KJ. 2014. Multiscale controls on natural regeneration dynamics after partial overstory removal in Douglas-fir forests in western Oregon, USA. Forest Science 60(5): 953-961.

Dunn, CJ, and Bailey, JD. 2016. Tree mortality and structural change following mixed-severity fire in *Pseudotsuga* forests of Oregon's western Cascades, USA. Forest Ecology and Management 107-118.

Edmonds, RL, and Vogt, DJ. 1986. Decomposition of Douglas-fir and red alder wood in clear-cuttings. Canadian Journal of Forest Research 16: 822-831.

Erickson, HE, Edmonds, RL, and Petersen, CE. 1985. Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir and ponderosa pine ecosystems. Canadian Journal of Forest Research 15: 914-921.

Estes, BL, Knapp, EE, Skinner, CN, and Uzoh, FCC. 2012. Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, northern California, USA. International Journal of Wildland Fire 21: 428-435.

Faiella, SM, and Bailey, JD. 2007. Fluctuations in fuel moisture across restoration treatments in semi-arid ponderosa pine forests of northern Arizona, USA. International Journal of Wildland Fire 16: 119-127.

Fonda, RW, and Binney, EP. 2011. Vegetation response to prescribed fire in Douglas-fir forests, Olympic National Park. Northwest Science 85(1): 30-40.

Ganio, LM, and Progar, RA. 2017. Mortality predictions of fire-injured large Douglas-fir and ponderosa pine in Oregon and Washington, USA. Forest Ecology and Management 390: 49-67.

Gray, AN, and Spies, TA. 1996. Gap size, within-gap position, and canopy structure effects on conifer seedling establishment. Journal of Ecology 84: 635-345.

Grayson, LM, Progar, RA, and Hood, SM. 2017. Predicting post-fire mortality for 14 conifers in the Pacific Northwest, USA: model evaluation, development and thresholds. Forest Ecology and Management 2017: 213-226.

Godoy, MM, Defosse, GE, Bianchi, LO, et al. 2013. Fire-caused mortality in thinned Douglas-fir stands in Patagonia, Argentina. International Journal of Wildland Fire 22: 810-814.

Halofsky, JS, Donato, DC, Franklin, JF, et al. 2018. The nature of the beast: examining climate adaptation options in forests with stand-replacing fire regimes. Ecosphere 9(3): 1-18.

Halofsky, JE, Peterson, DL, and Harvey, BJ. 2020. Changing wildfire, changing forests: the effects of climatic change on fire regimes and vegetation in the Pacific Northwest, USA. Fire Ecology 16(4): 1-26.

Halpern, CB, and Spies, TA. 1995. Species diversity in natural and managed forests of the Pacific Northwest. Ecological Applications 5(4): 913-934.

Halpern, CB, McKenzie, D, Evans, SA, and Maguire, DA. 2005. Initial responses of forest understories to varying levels and patterns of green-tree retention. Ecological Applications 15(1): 175-195.

Halpern, CB, Halaj, JH, Evans, A, and Dovciak, M. 2012. Level and pattern of overstory retention interact to shape long-term responses of understories to timber harvest. Ecological Applications 22(8): 2049-2064.

Harrington, TB. 2006. Fire-year growth responses of Douglas-fir, western hemlock, and western redcedar seedlings to manipulated levels of overstory and understory competition. Canadian Journal of Forest Research 36: 2439-2453.

Harrington, TB, Peter, DH, and Slesak, RA. 2018. Logging debris and herbicide treatments improve growing conditions for planted Douglas-fir on a droughty forest site invaded by Scotch broom. Forest Ecology and Management 417: 31-39.

Harrod, RJ, Peterson, DW, Povak, NA, and Dodson, EK. 2009. Thinning and prescribed fire effects on overstory tree and snag structure in dry coniferous forests of the interior Pacific Northwest. Forest Ecology and Management 258: 712-721.

Hessburg, PF, Spies, TA, Perry, DA, et al. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and northern California. Forest Ecology and Management 366: 221-250.

Hood, S, and Lutes, D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First Order Fire Effects Model (FOFEM). Fire Ecology 13(2): 66-84.

Huggett, RJ, Abt, KL, and Shepperd, W. 2008. Efficacy of mechanical fuel treatments for reducing wildfire hazard. Forest Policy and Economics 10: 408-414.

Jang, W, Keyes, CR, and Page-Dumroese, DS. 2017. Long-term regeneration responses to overstory retention and understory vegetation treatments in the northern Rocky Mountains. Forest Science 63(1): 136-146.

Johnson, MC, Kennedy, MC, and Harrison, S. 2019. Fuel treatments chance forest structure and spatial patterns of fire severity, Arizona, U.S.A. Canadian Journal of Forest Research 49: 1357-1370.

Johnston, JD, Dunn, CJ, and Vernon, MJ. 2019. Tree traits influence response to fire severity in the western Oregon Cascades, USA. Forest Ecology and Management 433: 690-698.

Kalies, EL, and Yocom Kent, LL. 2016. Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management 375: 84-95.

Kennedy, MC, and Johnson, MC. 2014. Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland-urban interface during the Wallow Fire, Arizona, USA. Forest Ecology and Management 318: 122-132.

Knapp, EE, Keeley, JE, Ballenger, EA, and Brenna, TJ. 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 2005: 383-397.

Korb, JE, Stoddard, MT, and Huffman, DW. 2020. Shrubby mixed-conifer forests of the souther Rocky Mountains, USA. Forests 11: 1-20.

Lam, TY, and Maguire, DA. 2011. Thirteen-year height and diameter growth of Douglas-fir seedlings under alternative regeneration cuts in Pacific Northwest. Western Journal of Applied Forestry 26(6): 57- 63.

Latham, P, and Tappeiner, J. 2002. Response of old-growth conifers to reduction in stand density western Oregon forests. Tree Physiology 22: 137-146.

Larson, AJ, and Franklin, JF. 2005. Patterns of conifer tree regeneration following an autumn wildfire event in the western Oregon Cascade Range, USA. Forest Ecology and Management 218: 25-36.

Law, BE, and Waring, RH. 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. Forest Ecology and Management 355: 4-14.

Levine, JI, Collins, BM, York, RA, et al. 2020. Forest stand and site characteristics influence fuel consumption in repeat prescribed burns. International Journal of Wildland Fire 29: 148-159.

Lilles, E, Dhar, A, Coates, KD, and Haussler, S. 2018. Retention level affects dynamics of understory plant community recovery in northern temperate hemlock-cedar forests. Forest Ecology and Management 2018: 3-15.

Littell, JS, Oneil, EE, McKenzie, D, Hicke, JA, and Lutz, JA. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change 102: 129-158.

Littke, KM, Harrington, TB, Slesak, RA, et al. 2020. Impacts of organic matter removal and vegetation control on nutrition and growth of Douglas-fir at three Pacific Northwestern Long-Term Soil Productivity sites. Forest Ecology and Management 468: 118176.

Lyons-Tinsley, C, and Peterson, DL. 2012. Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forests, eastside Cascade Range, Washington, USA. Forest Ecology and Management 270: 117-125. Oregon State University Forest Research Laboratory, Corvallis OR. 165 p.

Maguire, CC, and Chambers, CL. 2005. College of Forestry Integrated Research Project: ecological and socioeconomic responses to alternative silvicultural treatments.

McCaskill, GL. 2018. The Hungry Bob Fire and Fire Surrogate Study: a 20-year evaluation of the treatment effects. Forests 10(15): 1-11.

Means, JE, Cissel, JH, and Swanson, FJ. 1996. Fire history and landscape restoration in Douglas-fir ecosystems of western Oregon. In: Hardy, CC, and Arno, SF. Eds. The use of fire in forest restoration. USDA Forest Service Intermountain Research Station General Technical Report INT-GTR-341. Ogden, UT.

Meigs, GW, Dunn, CJ, Parks, SA, and Krawchuk, MA. 2020. Influence of topography and fuels on fire refugia probability under varying fire weather conditions in forests of the Pacific Northwest, USA. Canadian Journal of Forest Research 50: 636-647.

Miles, PD, Skog, KE, Shepperd, WD, et al. 2005. Broad-scale assessment of fuel treatment opportunities. In: Proceedings of the sixth annual forest inventory and analysis symposium; 2004 September 21-24; Denver, CO. Gen. Tech. Rep. WO-70. Washington, DC: U.S. Department of Agriculture Forest Service. 126p.

Miller, M, and Emmingham, B. 2001. Can selection thinning convert even-aged Douglas-fir stands to uneven-age structures? Western Journal of Applied Forestry 16(1): 35-43.

Mitchell, SR, Harmon, ME, and O'Connell, KEB. 2009. Fire fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19(3): 643-655.

Morris, WG. 1958. Influence of slash burning on regeneration, other plant cover, and fire hazard in the Douglas-fir region. USDA Forest Service Pacific Northwest Forest and Range Experiment Station Paper 29. Portland, OR.

Morrison, PH, and Swanson, FJ. 1990. Fire history and pattern in a Cascade Range landscape. USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-254. Portland, OR.

Nabel, MR, Newton, M, and Cole, EC. 2013. Abundance of natural regeneration and growth comparisons with planted seedlings 10-13 years after commercial thinning in 50-year-old Douglas-fir, Douglas-fir/western hemlock, Oregon Coast Range. Forest Ecology and Management 292: 96-110.

Neill, AR, and Puettmann, KJ. 2013. Managing for adaptive capacity: thinning improves food availability for wildlife and insect pollinators under climate change conditions. Canadian Journal of Forest Research 43: 428-440.

Odion, DC, Frost, EJ, Strittholt, JR, et al. 2004. Patterns of fire severity and forest conditions in the western Klamath Mountains, California. Conservation Biology 18(4): 927-936.

Omi, PN, and Martinson, EJ. 2002. Effect of fuels treatments on wildfire severity. Final report to the Joint Fire Science governing Board. Western Fire Science Research Center, Colorado State University, Fort Collins, CO. 36 p.

Ottmar, RD, and Sandberg, DV. 1985. Calculating moisture content of 1000-hour timelag fuels in western Washington and western Oregon. USDA Forest Service Pacific Northwest Research Station Research Paper PNW-336. Portland, OR.

Peterson, KF, Eskelson, BNI, Monleon, CJ, and Daniels, LD. 2019. Surface fuel loads following a coastal-transitional fire of unprecedented severity: Boulder Creek fire case study. Canadian Journal of Forest Research 49: 925-932.

Pollet, J, and Omi, PN. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire 11: 1-10.

Pook, EW, and Fill, AM. 1993. Variations in live and dead fine fuel moisture in *Pinus radiate* plantations of the Australian Capital Territory. International Journal of Wildland Fire 3(3): 155-168.

Prichard, SJ, and Kennedy, MC. 2012. Fuel treatment effects on tree mortality following wildfire in dry mixed conifer forests, Washington State, USA. International Journal of Wildland Fire 21: 1004-1013.

Prichard, SJ, and Kennedy, MC. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications 24(3): 571-590.

Prichard, SJ, Peterson, DL, and Jacobson, K. 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40: 1615-1626.

Rambo, TR, and North, MP. 2009. Canopy microclimate response to pattern and density of thinning in a Sierra Nevada forest. Forest Ecology and Management 257: 435-442.

Raymond, CL, and Peterson, DL. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research 35: 2981-2995.

Roberts, SD, and Harrington, CA. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. Forest Ecology and Management 255: 2771-2781.

Roberts, SD, Harrington, CA, and Terry, TA. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth. Forest Ecology and Management 205: 333-350.

Rogers, BM, Neilson, RP, Drapek, R, et al. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. Journal of Geophysical Reseach 116: 1-13.

Ruth, RH, and Harris, AS. 1975. Forest residues in hemlock-spruce forests of the Pacific Northwest and Alaska – a state-of-knowledge review with recommendations for residue management. USDA Forest Service Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-29. Portland, OR.

Samran, S, Woodard, PM, Rothwell, RL. 1995. The effect of soil water on ground fuel availability. Forest Science 41(2): 255-267.

Shatford, JPA, Bailey, JD, and Tappeiner, JC. 2009. Understory tree development with repeated stand density treatments in coastal Douglas-fir forests of Oregon. Western Journal of Applied Forestry 24(1): 11-16.

Shaw, JD, Goeking, SA, Menlove, J, and Werstak, CE. 2016. Assessment of fire effects based on forest inventory and analysis data and a long-term fire mapping data set. Journal of Forestry 115(4): 258-269.

Shen, C, Nelson, AS, Jain, TB, et al. Structural and compositional responses to thinning over 50 years in moist forest of the northern Rocky Mountains. Forest Science 65(5): 626-636.

Shonnagel, T, Balch, JK, Brenkert-Smith, H, et al. 2017. Adapt to more wildfire in western North American forests as climate changes. Proceedings of the National Academy of Sciences 114(8): 4582-4590.

Steel, ZL, Safford, HD, Viers, HJ. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6(1): 1-13.

Steen, HK. 1965. Variation in vegetation following slash fires near Oakridge, Oregon. USDA Forest Service Pacific Northwest Forest and Range Experiment Station Research Paper PNW-25. Portland, OR.

Sullivan, TP, Sullivan, DS, and Lindren, PMF. 2001. Influence of variable retention harvests on forest ecosystems. I. Diversity of stand structure. Journal of Applied Ecology 38(6): 1221-1233.

Stephens, SL. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105: 21-35.

Stephens, SL, and Moghaddas, JJ. 2005. Silvicultural and reserve impacts on potential fire behavior and forest conservation: twenty-five years of experience from Sierra Nevada mixed conifer forests. Biological Conservation 125: 369-379.

Stephens, SL, Moghaddas, JJ, Edminster, C, et al. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications 19(2): 305-320.

Tappeiner, JC, Maguire, DA, Harrington, TB, and Bailey, JD. 2015. Silviculture and ecology of western U.S. forests. 2nd Ed. Oregon State University Press, Corvallis, OR.

Teensma, PD. 1996. Integrating fire management into land management planning for westside forests. In: Hardy, CC, and Arno, SF, Eds. The use of fire in forest restoration. USDA Forest Service Intermountain Resarch Station General Technical Report INT-GTR-341. Ogden, UT.

Thompson, JR, and Spies, TA. 2009. Vegetation and weather explain variation in crown damage within a large mixed-severity wildfire. Forest Ecology and Management 258: 1684-1694.

Thompson, JR, Spies, TA, and Olsen, KA. 2011. Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age. Forest Ecology and Management 262: 355-360.

Urgenson, LS, Halpern, CB, and Anderson, PD. 2013. Twelve-year responses of planted and naturally regenerating conifers to variable-retention harvest in the Pacific Northwest, USA.

Van Wagner, CE. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23-34.

Van Wagtendonk, JW. 1996. Use of a deterministic fire growth model to test fuel treatments. In: Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II. Assessments and Scientific Basis for Management Options. Centers for Water and Wildland Resources, UC Davis. Pp. 1155-1165.

Weatherspoon, CP. 1996. Fire-silviculture relationships in Sierra forests. In: Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II, Assessments and Scientific Basis for Management Options. Centers for Water and Wildland Resources, UC Davis. Pp. 1167-1176.

Whitehead, RJ, Russo, GL, Hawkes, BC, et al. 2006. Effect of a spaced thinning in mature lodgepole pine on within-stand microclimate and fine fuel moisture content. In: Andrews, PL, and Butler, BW, Eds. Fuels management – how to measure success: conference proceedings. USDA Forest Service Rocky Mountain Research Station, Proceedings RMRS-P-41. Pp. 523-536.

Wimberly, MC, and Liu, Z. 2014. Interactions of climate, fire, and management in future forests of the Pacific Northwest. Forest Ecology and Management 327: 270-279.

Wimberly, MC, Cochrane, MA, Baer, AD, and Pabst, K. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19(6): 1377-1384.

Williams, N, and Powers, M. 2019. Medium-term effects of active management on the structure of mature Douglas-fir (*Pseudotsuga menziesii*) stands. Ecosphere 10(8): 1-31.

Willis, JL, Roberts, SD, and Harrington, CA. 2018. Variable density thinning promotes variable structural response 14 years after treatment in the Pacific Northwest. Forest Ecology and Management 410: 114-125.

Wilson, DS, and Puettmann, KJ. 2007. Density management and biodiversity in young Douglas-fir forests: challenges of managing across scales. Forest Ecology and Management 246: 123-134.

Youngblood, A, Wright, CS, Ottmar, RD, McIver, JD. 2008. Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, north-eastern Oregon. Forest Ecology and Management 255: 3151-3169.

Zald, HSJ, and Dunn, CJ. 2018. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. Ecological Applications 28(4): 1068-1080.

Zenner, EK, Acker, SA, and Emmingham, WH. 1998. Growth reduction in harvest-age, coniferous forests with residual trees in the western central Cascade Range of Oregon. Forest Ecology and Management 102: 75-88.