Short-term Resource Response to Pre-commercial Thinning Across a Range of Site Conditions in the Inland Pacific Northwest

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Authorization to Submit Thesis

This thesis of Christopher Chase, submitted for the degree of Master of Science with a Major in Natural Resources and titled "Short-term Resource Response to Pre-commercial Thinning Across a Range of Site Conditions in the Inland Pacific Northwest," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Forest stands across the inland Pacific Northwest are overstocked from fire suppression, economic constraints, and a lack of management. Overstocked forests have more competition and stress; causing mortality, susceptibility to insects and disease, and less adaptability to climate change. Reducing the amount of competition in the forest by pre-commercial thinning decreases the amount of stress in the forest and provides more suitable resource conditions for forest growth. This thesis examines the important factors controlling forest resource response to pre-commercial thinning across Northern Idaho and Northeastern Washington. An experiment was done to understand how forest resources respond to thinning across a range in forest productivities and densities. In addition, multiple forests were modeled to determine how different estimates of forest stand carrying capacities impact mortality and fuels.

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Chapter 1. Literature Review

Introduction

Dense mixed conifer forests in the Inland Pacific Northwest compete for limiting resources including light, water, and nutrients. Greater competition for limiting resources causes forests to become stressed. Forests with higher amounts of stress are more prone to attack from insects and disease (Stoszek et al. 1981). Higher amounts of stress in forests also increase the chance of mortality (He and Duncan 2000). Greater amounts of mortality and competition in the forest causes fuel buildup; which increases the stand replacing wildfire hazard (Schoennagel et al. 2004). Therefore, understanding the amount of stress in the forest is critical for improving forest growth and health. How much forests are stressed is largely dependent on the availability of limiting resources, and the amount of competition for those resources.

This review focuses on how the availability of resources and the competition for those resources impacts forest growth and health across the Inland Pacific Northwest. In addition, this report examines how artificially reducing the competition in a forest can alleviate stress and resource limitations. The availability of resources or “site quality” results from numerous factors including the climate, topography (elevation, aspect, and slope), the bedrock or “parent materials”, and the soils (Carmean 1975). Differences in climate, topography, and soils can strongly impact the availability of resources to trees, which dictate how quickly a forest grows (Kimsey et al. 2008). Competition for resources is often determined through measuring the forest density. Forest density is usually defined by both the number of trees per unit area, and the size of those trees (Reineke 1933, Curtis 1982). Reducing the forest density, and thus competition, has been shown to improve forest growth and health (Curtis 2006, Brockley 2005). Artificially reducing the forest density at a relatively young age is commonly done in forestry, and is known as pre-commercial thinning.

Pre-commercial thinning (PCT) is often done to alleviate competition for resources, and promote the growth and vigor of certain species of trees. In the Inland Pacific Northwest, Douglas-fir (*Pseudotsuga menziesii var. glauca*) is a major commercial species commonly favored during PCT operations, and experiences a variety of resource limitations across the region. A seral species in most ecosystems where it occurs, Douglas-fir is limited by light requirements as evidenced by the loss of photosynthetic capability at higher forest densities (Cole and Newton 1986). Annual summer droughts reduce moisture conditions and put stress on Douglas-fir; reducing growth rates (Littell et al. 2008, Chen et al. 2010). Douglas-fir foliar nutrients including nitrogen, sulfur, potassium, boron, and copper are often below critical values across the Inland Pacific Northwest, indicating nutrient limitations (Coleman et al. 2014). Understanding how reducing the competition in Douglas-fir stands through PCT is influenced by the resource availability (site quality), and initial density (competition) will improve the management of forests in the Inland Pacific Northwest.

Douglas-fir Autecology

Douglas-fir is a major commercial timber species which occurs across the North American continent, however, its adaptive traits are specific to a particular place (Rehfeldt 1988). Two distinct varieties of Douglas-fir exist; *P. menziesii var. glauca* (interior or Rocky Mountain) and *P. menziesii var. menziesii* (coastal). Douglas-fir as a species has a large geographical distribution, ranging from British Columbia, Canada, down to Mexico (Chen et al. 2010). The species adaptive traits can be related to environmental conditions (Monserud and Rehfeldt 1990). Local factors also influence the genetics of Douglas-fir, with different adaptive traits occurring with a change in as little as 240m elevation (Rehfeldt 1989).

Although Douglas-fir has a broad gene pool which occurs across three North American countries, it prefers intermediate growing conditions compared to its competitors in the inland

Pacific Northwest. Douglas-fir is less shade-tolerant than grand fir (*Abies grandis*), western red cedar (*Thuja plicata*), or Engelmann spruce (*Picea engelmannii*), but more shade tolerant than lodgepole pine (*Pinus contorta*), western white pine (*Pinus monticola*), ponderosa pine (*Pinus ponderosa*), or western larch (*Larix occidentalis*) (Ferguson et al. 1986). Similarly, Douglas-fir is adapted to warmer mean temperatures than lodgepole pine, western red cedar, and Engelmann spruce, but cooler mean temperatures than ponderosa pine (Minore 1979). In the Inland northwest where annual summer droughts are common; Douglas-fir can tolerate drought better than grand fir, Engelmann spruce, or lodgepole pine, but is less drought tolerant than ponderosa pine (Daubenmire 1968). Nitrogen, P, K, and S are common macronutrients that can be limiting to forests (Coleman et al. 2014). Douglas-fir foliage, wood, bark, and litter has higher N, P, and K concentrations than both western red cedar and Engelmann spruce. However, lodgepole pine and grand fir have higher N concentrations, western larch has higher P concentrations, and ponderosa pine has higher K concentrations in the same tissues (Minore 1979). Many of the factors controlling species adaptation and competition (moisture, temperature) are impacted by climate, and thus needs further consideration.

Climate

Regional variation in climate can drastically influence the resource availability of forests in the Pacific Northwest. For example, the coastal variety of Douglas-fir experiences a different climate than the interior Douglas-fir variety that is reflected through growth rates, stand conditions, and resource availability (Chen et al. 2010). In addition, Douglas-fir radial growth is positively correlated with precipitation across mountainous areas in the Pacific Northwest (Case and Peterson 2005, Coleman et al. 2014). In the Pacific Northwest where growing season droughts are common; the amount and timing of precipitation is important for tree growth. Precipitation in the fall of the previous year, and the spring of the current growing season, had a high number of significant correlations with tree growth (Chen et al. 2010, Bréda et al. 1995). Temperature is another key climatic factor that limits the growth of coniferous species in the inland Pacific Northwest. Colder temperatures decrease the length of the growing season, while warmer growing season temperatures increase moisture stress (Kimsey et al. 2008). Furthermore, drastic changes in climate such as El Niño or La Niña can increase the fire hazard and water stress through the high production (La Niña) and drying (El Niño) of fine fuels (Schoennagel et al. 2004).

Topography

Elevation is a major driver for various components of forest site quality for Douglas-fir. Several studies have demonstrated negative relationships between Douglas-fir site index and elevation (Monserud et al. 1990, Brown and Loewenstein 1978). Elevation also negatively impacts the temperature, which relates to length of growing season and number of frost free days at a given location (Rehfeldt 1989, Chen et al. 2010). Increases in elevation are also associated with similar increases in precipitation (Barry 1973). Anaerobic nitrogen mineralization demonstrates a negative correlation with elevation; particularly as it relates to mean soil temperature (Powers 1990). In contrast, amino acids which represent a portion of soluble organic nitrogen show a positive relationship with elevation (Shan et al. 2014).

Other topographic properties that play a role in site quality are slope and aspect. Depending on slope position, soil fertility and moisture may increase (lower slope) or decrease (upper slope); with similar consequences for plant stress (Stoszek et al. 1981, Carmean 1975). Additionally, steeper slopes generally have more shallow soils, and decrease forest productivity (Stage 1976). Also, Douglas-fir growth is reduced by higher evapotranspiration and sunlight exposure on southerly versus northerly aspects (Kimsey et al. 2008). Optimum aspect for stand volume growth varies with elevation; with more northerly aspects better suited for growth at low elevation from reduced evaporation, but less so at higher elevation because for Douglas-fir because of cooler temperatures

(Stage and Salas 2007). Also, soil development can impact the availability of resources across the landscape.

Parent material/soils

In the inland Northwest, Douglas-fir occurs on soils derived from a variety of parent materials (rock types) including: glacial deposits, sedimentary and meta-sedimentary rocks, extrusive basalts, and granite (Coleman et al. 2014, Shen et al. 2001). Work done by the Intermountain Forest Tree Nutrition Cooperative (IFTNC) shows that basalt and granite rocks have a higher content of cations Fe, Ca, and Mg; impacting soil properties and tree nutrition (Moore et al. 2004). Furthermore, higher K concentrations in Douglas-fir foliage are observed on sedimentary and basalt parent materials than on granite or meta-sedimentary rocks (Shen et al. 2001). Tree growth depends on the parent materials on which they are grown; with extrusive basalts having the highest growth, followed by intrusive parent materials and glacial deposits respectively (Coleman et al. 2014). Mortality is also impacted by geology; both Douglas-fir and western hemlock trees had 1-2% lower annual probability of mortality on sedimentary and basalt parent materials than meta-sedimentary or deep glacial deposits (Moore et al. 2004). Finally, different parent materials have variable responses to fertilizer treatment, indicating unique nutrient limitations and responses to silvicultural practices (Coleman et al. 2014).

Another component of soils in the inland Northwest is the ash deposited from the Mt. Mazama eruption; today known as Crater Lake. The distribution of ash across the landscape is not uniform, generally increasing with elevation (Kimsey et al. 2007). Deeper ash layers improve the site index or forest productivity at a location; just 10 cm of volcanic ash can add roughly 2.5 m of Douglas-fir site index at year 50 (Kimsey et al. 2008). In addition, ash influences the bulk density, porosity, and water holding capacity of the soil (McDaniel and Wilson 2007). Soils which are strongly influenced by Mt. Mazama ash (Andisols) have more extractable Al and Fe, and a better ability to retain P than soils with less ash influence (Vitrandic) (McDaniel et al. 2005). Lastly, as a result of changes in the soil properties from volcanic ash, different plant communities might occur that otherwise would not (Kimsey et al. 2008).

Habitat Types

The potential climax vegetation, known as the habitat type, can provide useful information about the availability of resources of a site (Daubenmire 1952). Habitat types can be used to infer environmental conditions at a location including moisture and temperature regimes, and soil properties (Pfister and Arno 1980). Consequently, habitat types have been useful in predicting forest growth or productivity (Monserud 1984). Thus, forest managers can use habitat type as a tool to understand what species to plant or favor at a particular habitat type, and how those trees will likely grow at that location. For example, white pine had roughly 30% more height growth after 50 years on a western red cedar/ Oregon boxwood habitat type compared to a hemlock / Oregon boxwood habitat type (Stage 1976). While habitat type is useful for understanding the resource conditions at a site, other measures of forest productivity exist.

Forest Productivity (Site Index)

The availability or abundance of resources determines how suitable a site is for forest growth. However, it is difficult and more time consuming to directly measure the availability of resources at a location, so indirect measurements of forest growth prevail. Forest growth can be measured in a variety of ways to understand the availability of resources, or site quality. Biomass, volume, radial, and height growth per unit time are all common metrics used in forestry to determine the site quality. However, height growth is influenced less by competition or stand density, than diameter or volume growth (Martin and Ek 1984, Monserud and Rehfeldt 1990). Consequently, the most common metric of forest site quality is height growth of dominant trees of a given species over a period of 50 or 100 years; called site index.

Site index requires two measurements easily acquired from most forests; the height of a dominant tree of a certain species, and an age of that tree. Site index is a tool that can be used by forest managers to plan harvest rotations, species preferences, and silvicultural treatments. Site index is often difficult to manipulate because it requires changing the availability of resources at a location, which can be costly. Thus, to improve resource availability, the alternative is to reduce the amount of competition for the resources through manipulating the forest stand density. However, there remains uncertainty about the magnitude of resource response after changes in the forest density.

Stand density

Determining the density of a forest is critical for understanding the current stage of forest development, and what management strategies to administer. Forest density often incorporates two things: the number of trees per area of interest, and the size of those trees. In addition, the carrying capacity or the maximum size-density relationship of trees at a particular location is needed to provide a reference for the current stand density (Drew and Flewelling 1979, Curtis 1982). Unfortunately, there is some controversy about the carrying capacity at a specific location. Traditional theory suggests that the carrying capacity is dependent on the species, but independent of site conditions (Reineke 1933). However, recent evidence suggests that the maximum carrying capacity may vary by both the species and the site quality (Pittman and Turnblom 2003). Thus, a need arises for identifying these carrying capacities at various ranges in site quality. Incorrectly diagnosing stand density or development stage could put forests at risk for insect attack and wildfire (Chmura et al. 2011).

The implications of forest stand density on growth and mortality have been well documented and observed (Reineke 1933, Curtis 2006). Denser stands can be less vigorous and more susceptible to predation from insects and disease (Schowalter et al. 1986, Entry et al. 1991). Stands with lower densities have lower mortality rates as they mature (He and Duncan 2000). As density decreases, growth rates of the largest or “dominant” trees increase (particularly volume and diameter), achieving a merchantable size more quickly (Drew and Flewelling 1979). In addition, tree heights, diameters, and crown dimensions are greater in lower density than higher density plantations (Curtis and Reukema 1970). Although the growth of the individual and largest trees increases at lower densities, there is less overall stand volume which can reduce the total value at harvest (Curtis 2006, Basford et al. 1990). While higher density and competition decrease forest growth, resource availability also declines.

Forest density or the amount of competition between trees can also determine the availability of resources. Lower stand densities have higher soil moisture than denser stands throughout the growing season, particularly in the upper soil horizons (Stogsdill et al. 1992). Stand density also impacts light availability both within individual tree crowns and to the forest floor, limiting forest growth and regeneration (Wellner 1948). Similarly, intercepted radiation (the amount of light intercepted by the canopy) shows a strong positive relationship with stand density, and volume growth (Will et al. 2001). Research also indicates that as stand density increases, foliar, fine root, and stem N concentrations decrease; potentially limiting growth (Barron-Gafford et al. 2003). The limitations in forest resources at higher forest densities suggest that reducing the amount of competition will be beneficial.

Manipulating the density of the forest is an effective way to control how growth and resources are distributed throughout a stand (Curtis 2006). There are a variety of ways both natural and artificial in which the density of the forest changes. Natural changes to forest density include wildfire, insects and disease, and severe weather events such as wind or ice storms; and are commonly known as disturbance. Natural disturbance is difficult to control and predict; emphasizing the importance of artificial density management. There are several artificial methods for reducing the density of the stand. Most artificial density reduction practices are mechanical, involving the use of equipment to remove specific undesirable trees. Other methods involve introducing fire, chemicals (herbicides), or insects to control the forest density. Mechanical density reduction is more common because it is easier to predict and usually less expensive than other methods (McRae et al. 2001). Mechanical density reduction costs vary depending on the age and size of the forest being manipulated. Older and larger forests can provide merchantable timber to help pay for the density reduction; this is known as “commercial thinning”. Younger forests may not have merchantable timber, but tend to respond better to the density reduction than older forests because the crowns are still developing (Franklin et al. 2002). Artificial manipulation of the density of the forests at a relatively young or “un-merchantable” age is called “pre-commercial thinning” (PCT); improving the forest resources both above and belowground.

Resource response to Pre-commercial thinning

Thinning improves the resource conditions through manipulating the soil properties, light availability, and understory competition. Soils in thinned stands have higher moisture contents than soils at un-thinned locations (Stogsdill et al. 1992). Thinning allows more light uniformity in the canopy and penetration to the forest floor; improving light available to residual plants (Forrester et al. 2012). As a result of more light reaching the forest floor from thinning practices, soil temperatures increase, improving microsite conditions for microbial activity (Thibodeau et al. 2000). Several nutrients from slash left on site leach into the soils providing more resources for a variety of organisms (Baker et al. 1989). In addition, two essential nutrients for plant growth, N and P, increase after thinning (Vesterdal et al. 1995). Finally, understory vegetation has a variety of responses to thinning depending on forest structure and slash treatments (Ares et al. 2009).

Soil moisture

Higher soil moisture after thinning is likely caused by reduced competition, more precipitation reaching the forest floor (throughfall), and reduced evaporation from the addition of harvest residue (Bréda et al. 1995, Wollum and Schubert 1975). There is an inverse relationship between soil moisture and residual density after thinning; which is most pronounced in the upper horizons of soil where most plant roots are located (Della-bianca et al. 1960). Leaving slash and biomass on site after a pre-commercial thinning shows a significant increase in soil moisture compared to removal (Smethurst and Nambiar 1990). The amount of precipitation reaching the forest floor can increase by as much as 15% over the growing season one year after thinning a loblolly pine plantation from 100 to 25 m^2 ha^{-1} of basal area (Stogsdill et al. 1992). The increased precipitation reaching the forest floor recharges the soils and provides more available moisture to trees.

Light

Thinning removes trees from the canopy, allowing more light into the stand. A change in light availability of only 11% from lower to upper canopy was observed in thinned stands compared to 31% in un-thinned stands (Forrester et al. 2012). Others found 28% to 52% higher photosynthetic photon flux densities in thinned forest canopies compared to un-thinned canopies, with similar increases in photosynthesis (Tang et al. 1999). Besides the forest canopy, more light penetrates to the forest floor after thinning (Pothier 2002). Photosynthetically active radiation at ground level was roughly four times higher at a density of 400 trees per hectare compared to un-thinned controls (Wang et al. 1995). Soil processes can benefit from the warmer conditions after thinning operations.

Soil temperature

Soil temperature changes from more light reaching the forest floor, the addition of organic matter, and removal of the overstory after thinning. Soil temperature increases by up to 2° C during the growing season after PCT compared to soils in un-thinned stands (Selig et al. 2008). This trend however varies throughout the year. Increasing tree spacing (reducing stand density) causes roughly 1-2 °C colder soil temperature in the winter than closer spaced (higher density) stands (Piene 1978). Slash from thinning operations helps stabilize soil temperatures. The separation between soil monthly maximum and minimum temperatures was only about 2°C with slash compared to 10°C when slash was removed (Smethurst and Nambiar 1990). Pre-commercial thinning also creates higher temperature variability among soil microsites; depending on if slash from harvest or vegetation cover is present (Devine and Harrington 2007). In addition, higher soil temperatures and moisture provide more suitable conditions for decomposition of plant matter and mineralization of nutrients (Chmura et al. 2011).

Nutrient cycling

Pre-commercial thinning changes the nutrient status of the soils through improving the microsite for microbial processes and from organic matter inputs. Higher mineralization and organic matter inputs are critical for maintaining nutrient supply and cycling in forests (Coleman et al. 2014). A majority of the nutrients in trees reside in the foliage, which is left on site after PCT (Garrison and Moore 1998). This is evident from leaching of N, P, S, K, Ca, Mg, and B from slash and foliage left on site just one year after a PCT operation (Baker et al. 1989). Inorganic NH_4 increases after pre-commercial thinning, one year post treatment (Thibodeau et al. 2000). Other research indicates both higher mineralization of C and N, as well as microbial biomass C and N (immobilization) when harvest residue is left on site (similar to PCT) compared to when that material is removed (Smolander et al. 2008). Furthermore, research suggests reducing stand density increases the amount of nutrients in the soil available to each tree through reduced competition, without actually changing the nutrient pools of a site (Wollum and Schubert 1975).

Vegetation/understory competition

Another way that PCT impacts the resource availability of a site is through changes in competition from understory vegetation as light becomes more available to the forest floor. Shrub and herbaceous vegetation compete with crop trees for resources, decreasing annual volume growth by as much as 24% (Busse et al. 1996). Shrubs, forbs and ferns may increase in cover after thinning, depending on residual tree density or the amount of available light (Thomas et al. 1999). Species richness demonstrates a positive response to thinning, with up to seven additional species on thinned plots than controls, usually in the form of more early successional species (Ares et al. 2009). However, in the case of pre-commercial thinning where slash is left on site, understory vascular plant cover can be drastically lower (85%) than an un-harvested adjacent control stand one year after treatment (Scherer et al. 2000). Finally, understory response to pre-commercial thinning is not uniform across multiple stands, suggesting influence by the complexity of the forest structure (Ares et al. 2009).

Forest response to Pre-commercial thinning

Forest canopies, foliar nutrients, tree water relations, and stand growth respond to the greater availability of resources after thinning. Thinning allows more sunlight into the tree canopies, creating larger and more robust crowns (Brix 1981). Foliar nutrition of several nutrients increase after thinning suggesting less competition for resources, and more nutrient uptake (Thibodeau et al.

2000). Trees in thinned stands can be more efficient at using water, and less water stressed (Bréda et al. 1995). Lastly, residual trees in thinned stands have higher growth rates, effectively reducing harvest rotation lengths (Brockley 2005).

Canopy characteristics

Crown development and canopy characteristics both respond to increased light availability from pre-commercial thinning. Most commonly observed among these is the increase in percent live crown with increased residual tree spacing. In a post thinning density study, 10% higher proportions of live crown were observed in 600 trees per hectare than 1600 trees per hectare densities after 10 years (Brockley 2005). Higher crown ratio is largely a function of needles lower in the canopy persisting longer than those in un-thinned stands. Seven years after thinning, trees in thinned stands had 25% more live whorls than trees in un-thinned stands (Brix 1981). Another impact of lower branches and needles surviving longer is larger crown widths. Loblolly pine had 22% wider crowns in thinned plots compared to controls (Gillespie et al. 1994). Similarly, ponderosa pine needle lengths were at least 8 mm longer, and needle weights 30 mg heavier in thinned plots than un-thinned plots 8 years after thinning (Wollum and Schubert 1975). All of these factors are coincident with less competition both within the tree and between trees for light, after density reduction practices (Will et al. 2001). However, as the forest develops and the crown closes over time, competition for light will increase (Drew and Flewelling 1979).

Foliar nutrition

Pre-commercial thinning also causes changes in the leaf chemistry of residual trees through reduced competition and greater nutrient availability in the soil. Foliar chemistry response is often measured in the current year needles because the number of needles is fixed the previous season, and foliar nutrition and growth after one season are not confounded by canopy response to treatments (Haase and Rose 1995). The most common foliar chemical response to thinning is an increase in N content, caused by reduced competition for N and more photosynthesis, creating higher needle mass (Hokka et al. 1996, Tang et al. 1999). Nutrient concentrations in needles are less consistent because of simultaneous changes in needle size causing dilution (Brockley 2005). Some studies report an increase in foliar N concentration, while others observe no change (Entry et al. 1991, Velazquez-Martlnez et al. 1992). Other foliar nutrients including K and P demonstrate an increase in concentration after thinning (Thibodeau et al. 2000). In contrast, needle concentrations of Fe and B in Douglas-fir trees decline after thinning (Entry et al. 1991). Finally, more detailed foliar nutrient analyses show content of S, Ca, Mg, and Zn increase after thinning (Wollum and Schubert 1975).

Tree water stress and WUE

Tree water use efficiency (WUE) at the leaf level is the ratio of the amount of carbon assimilated by plants, to the amount of water transpired through the leaves (Seibt et al. 2008). More photosynthesis will increase carbon assimilation and create a higher WUE (Wang et al. 1995). However, water stress will trigger plants to close their stomata; decreasing transpiration, while increasing WUE (Adams and Kolb 2004). Rubisco, the enzyme which catalyzes CO_2 for photosynthesis prefers the lighter ^{12}C isotope. Therefore when the stomata are open (more photosynthesis and transpiration) the difference between ^{12}C and ^{13}C will be less than when stomata are closed. Rubisco in closed stomata (less photosynthesis and transpiration), consumes more of the ^{13}C isotope because relatively more of the ^{12}C is consumed and not rapidly replaced, and the ratio of ^{13}C to ^{12}C increases. Consequently, the ratio of ^{13}C to ^{12}C (known as $\delta^{13}C$) is positively correlated with water use efficiency (Warren et al. 2001). Trees closing their stomata also signify that soil water conditions have been depleted to a point where water supply from the roots and soil cannot adequately sustain the transpiration demand to a point that is too great to maintain current processes. The amount of water stress a plant is experiencing can be measured by leaf water potential (Ψ) (Bréda et al. 1995).

Thinning can impact water use efficiency (WUE) and water stress through changes in soil moisture, tree photosynthesis, and transpiration. In a study of eucalyptus plantations, thinning increased aboveground water use efficiency of residual trees by 23% through greater increases in photosynthesis than transpiration (Forrester et al. 2012). Other research has demonstrated increases in WUE through higher photosynthesis after thinning (Wang et al. 1995). Water stress and transpiration also change with PCT operations (Bréda et al. 1995). Lower density stands (250 stems per hectare) had higher pre-dawn summer water potentials (-1.3 MPa) than higher density (750 stems per hectare) stands (-1.8 MPa) (Warren et al. 2001). While higher pre-dawn water potentials in residual trees after thinning indicate wetter soils, mid-day water potentials can be lower, as a consequence of more transpiration and higher amounts of solar radiation (Brix and Mitchell 1986).

Tree growth

Thinning decreases competition, therefore increasing individual tree growth rates, decreasing harvest rotation lengths, and improving forest health (Sterba 1987, Pothier 2002). The most documented response to pre-commercial thinning is basal area or diameter growth on the individual tree level (Curtis 1982, Drew and Flewelling 1979). For instance, ponderosa pine diameter growth is roughly twice as much after five years as residual tree spacing goes from 5 to 14 feet (Feguson et al. 2011). While diameter growth increases, height growth is unchanged by thinning, resulting in roughly 15% lower height to diameter ratios in lower density (5,000 stems ha^{-1}) than higher density (20,000 stems ha^{-1}) plots (Pothier 2002). Reducing forest density through thinning practices to improve growth efficiency (net growth per unit of leaf area) shows a similar trend to diameter growth; with 56% higher efficiencies at lower densities (Velazquez-Martlnez et al. 1992). As a result of the growth increase from PCT, merchantable timber yield can be 25% higher in thinned than un-thinned stands at a similar rotation (Brodie et al. 1978).

Insects and disease

Research suggests that thinning can decrease the risk of infection from disease and pests. This is likely caused by the amount of stress in a stand as controlled by competition for resources, and the forest structure. More insect herbivory occurs at denser stands because of decreased distances to new hosts, and with more canopy closure because of fewer extremes in environmental conditions (Schowalter et al. 1986). Indeed, lower forest stand densities were modeled to have less defoliation from Douglas-fir tussock moth (Stoszek et al. 1981). Other studies noted that increasing the photosynthetic capability of a stand, such as after thinning, can be an effective way to reduce losses from bark beetle (Waring and Pitman 1985). Besides insects, Armillaria (*Armillaria ostoyae*), a common fungal root pathogen of Douglas-fir, had a 4% lower incidence of infection on trees in a thinned stand compared to an un-thinned stand (Entry et al. 1991). In contrast, other studies suggest that thinning may actually increase the risk of disease in residual trees after selective cutting by approximately 15% compared to an undisturbed forest (Morrison et al. 2001).

Conclusion

Different locations and site conditions impact the way forests respond to disturbance in a number of ways. Most studies focus on a narrow range of site or forest stand conditions, limiting the applicability of the research across the landscape. In addition, a majority of the research focuses only on specific resources, ignoring or discrediting relationships between resources. Pre-commercial thinning improves the availability of light, moisture, and nutrients; which limit forest growth and health. However the degree of change in resource availability after thinning is dependent on site quality and forest density. Understanding how forests respond to PCT across a range of resource and competitive conditions will improve forest management decisions in the Inland Pacific Northwest. Finally, while the long term forest resource response to thinning is critical, short term responses will provide useful information on how trees and resources initially respond to disturbance.

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Chapter 2: Resource response one year after pre-commercial thinning in dry inland forests

Abstract

Many forests across the United States are overstocked from fire suppression and inadequate forest management. Overstocked stands have higher competition for limiting resources which causes stress. The amount of stress a forest is experiencing is related to the current availability of resources (productivity), and the competition for those resources (stand density). Forests that are stressed are more susceptible to insects and disease, and mortality, which causes fuel buildup and increases the wildfire hazard. Stress can be alleviated by decreasing the amount of competition through silvicultural techniques, such as pre-commercial thinning. Pre-commercial thinning (PCT) reduces the density (amount of trees per area) of a stand to certain specifications; alleviating competition and stress. The objectives of this study were to determine how reducing the competition in a stand through PCT might improve resource availability at a range of initial productivities and densities. A triplet-plot approach was used to understand how forest resources responded to different PCT regimes across ranges in density and productivity throughout Northern Idaho and Northeastern Washington. Light levels were negatively correlated with initial density, and thinning created from 33% to 58% less light interception than controls depending on tree spacing. Soil water in the spring was positively correlated with productivity; and higher in thinned plots for both the spring and summer. Soil temperature was positively correlated with productivity in both the spring and summer, and increased by roughly 0.5°C in the spring and 1°C in the summer after thinning. Douglas-fir foliar nutrients decreased (N, Ca, Zn), increased (P, B) and were un-changed (S, Cu, K) after thinning. As a result of decreased competition, light and water resources were consistently more available. Nutrient resources had more complex responses to PCT depending on

the stand productivity, density, and other factors. PCT had the greatest relative impact on soil N availability, followed by soil moisture in the summer and light interception.

Introduction

As a result of fire suppression and a lack of forest management in the Pacific Northwest, many forest stands are overstocked. Overstocked forests have greater competition for resources limiting growth including light, water, and nutrients; causing stress among trees (Cole and Newton 1986, Nambiar and Sands 1993). In addition to greater competition, changing climatic conditions are putting further stress on forests (Chmura et al. 2011). Stress reduces the ability of forests to resist insects and disease; increasing the likelihood of tree mortality (Stoszek et al. 1981, Louda and Collinge 1992). Overstocking and greater amounts of mortality lead to fuel buildup; creating a higher stand replacing wildfire hazard (Schoennagel et al. 2004). Thus, understanding or estimating the amount of stress or competition a stand is experiencing is critical for prioritizing forest management decisions.

How much stress a stand is experiencing is largely a function of two things: the availability of the resources that are essential for tree growth and development (light, water, nutrients), and the amount of competition for those resources (Dobbertin 2005, He and Duncan 2000). However, it is easier to measure and quantify the forest growth or productivity than it is to directly measure the resource availability. A common indirect measure for the availability of resources or “site quality” at a location is the productivity or site index. Site index is the amount of height growth over a given amount of time for the largest or “dominant” trees of a certain species (Monserud 1984). Higher site index at one location indicates a better site quality than lower site index at a different location. The uncertainty of resource availability at a location makes manipulating the site quality difficult. As a result, options for manipulating the availability of resources (fertilizer, irrigation) are often costly, and in some circumstances, damaging (Coleman et al. 2014). Consequently, most forest managers commonly focus their efforts on competition for limiting resources.

The amount of competition in a stand can be characterized by the density of the forest. The most common metrics of density combine the number of trees per area, and the size of those trees (Reineke 1933, Curtis 1982). Higher densities suggest greater competition for resources and as a consequence, more stress. Higher stress in dense stands is accentuated in trees with the lowest competitive advantage (suppressed) and will likely die without relief from competition (Dobbertin 2005). The density needs to be reduced in order to relieve the competition and stress, and improve the resource availability in a forest. A common silvicultural practice which reduces the density of forest is pre-commercial thinning.

Pre-commercial thinning (PCT) is a forest management practice that reduces the density of a forest to a specific criteria or target set by the land manager or silviculturalist. This practice is called "pre-commercial" because the forest is at a relatively young age and the removed trees are un-merchantable. PCT reduces the amount of competition between trees; alleviating stress and providing benefits to residual trees. Lower competition after PCT provides residual trees a better chance to cope with changing climatic conditions (Chmura et al. 2011). Less competition allows for better crown development and growth on residual or "crop" trees (Ferguson et al. 2011). Faster growing and more vigorous crop trees decrease harvest rotation lengths, and provide better product dimensions at harvest (Curtis 2006). Decreased stress in forests after PCT create resiliency to insect attack (Waring and Pitman 1985). In addition, thinning allows more space between tree crowns, reducing the risk of stand replacing wildfire (Moghaddas and Stephens 2007). The amount of competition or stress relief depends on both the pre-thinning stand conditions (mentioned previously), and the post-thinning stand conditions. As a result of lower competition post-thinning, resources limiting forest and tree growth become more available (Thibodeau et al. 2000, Sterba 1988). Due to the reliance on indirect measures of resource availability after thinning (productivity or site index), direct measures are less available. Understanding how the resources controlling the indirect tree growth respond to thinning will improve both forest management and research decisions.

Perhaps the most obvious resources responding to PCT are the physical resources; light, water, and temperature. Reducing inter-crown competition through PCT allows for more light throughout tree crowns; resulting in more photosynthesis (Brockley 2005, Ferguson et al. 2011). PCT increases soil moisture conditions by increased precipitation throughfall, less stand water use, and decreased evaporation from higher slash loads (Stogsdill et al. 1992; Smethurst and Nambiar 1990). In addition, higher soil and pre-dawn shoot water potentials occur after thinning; indicating lower water stress (Brix and Mitchell 1986, Laurent et al. 2003). Furthermore, post-thinning soil temperatures may increase by as much as 2° C (Thibodeau et al. 2000). Increased soil temperature is thought to provide a more suitable environment for soil biota and nutrient mineralization processes (Powers 1990). While just as important for tree growth as physical resources, chemical or nutrient resources are more difficult to measure and therefore less understood.

Several essential nutrients limit forest growth in the inland Northwest (Webster and Dobkowski 1983). Douglas-fir foliage has been identified as nutrient deficient for nitrogen, sulfur, potassium, and boron throughout several regional locations. Nitrogen is most frequently beneath critical levels for Douglas-fir, ponderosa pine, and grand fir across a majority of stands in the Inland Northwest (Moore et al. 2004). Thinning can help alleviate competition for these limiting nutrients. A majority of the nutrients acquired by trees reside in the foliage, which is left on site during PCT operations (Garrison and Moore 1998). Nutrients and organic matter from trees felled after PCT incorporate into the soils, providing greater availability and retention of nutrients (Sterba 1988). Supporting this, research shows positive correlations with foliar N, P, and K concentrations after PCT (Thibodeau et al. 2000). However, changes in foliar nutrient concentration will likely dissipate as the canopy responds to changes in nutrient availability (Hokka et al. 1996, Gower et al. 1992). As a result, changes in nutrient pools due to thinning are difficult to measure because of their dynamic nature and relationships with other resources (water, temperature) (Sands and Mulligan 1990). Furthermore, how well residual trees are able to seek out and immobilize these nutrients is less certain. There is little information about how resources respond to thinning at various initial site conditions and competition regimes. The objectives of this experiment were to determine how reducing competition through PCT impacted relative resource availability at a range of initial stand productivities and densities. In addition, this study sought to determine the tree growth response to PCT treatment across a range of even aged Douglas-fir (*Pseudotsuga menziesii (Mirb.) Franco var glauca*) plantations.

Methods

Study design

Fourteen sites were selected across Northern Idaho and Northeastern Washington to capture the range of forest productivity and density in the region (Figure 1). Productivity was determined by measuring dominant Douglas-fir height growth over the past ten years (Table 1). Ten year growth was measured from distinguished whorls, if whorls were not well distinguished; five year growth was measured and doubled for comparing to ten year growth measurements. All measurements were taken post-treatment, therefore control plot total basal area during year 0 (2013) defined pre-thinning initial stand density.

At each location, three comparable 0.04 hectare (tenth acre) measurement plots were established. Each 0.04 hectare measurement plot was located within a 0.2 hectare (half acre) treatment plot acting as a buffer. Treatments were conducted during the summer of 2013; including a control (no thinning), 544 trees per hectare (4.3 m spacing), and 321 trees per hectare (5.5 m spacing) randomly assigned to each plot. The 4.3 m spacing treatment was selected to represent the "operational" spacing, and the 5.5 m spacing was selected to determine how the additional removal of competition impacted resource availability. Thinning favored dominant, healthy, well-formed Douglas-fir trees at proper spacing intervals. Douglas-fir was chosen as the major species for study with initial basal area ranging from 48% to 98% of the measurement plot (Table 1).

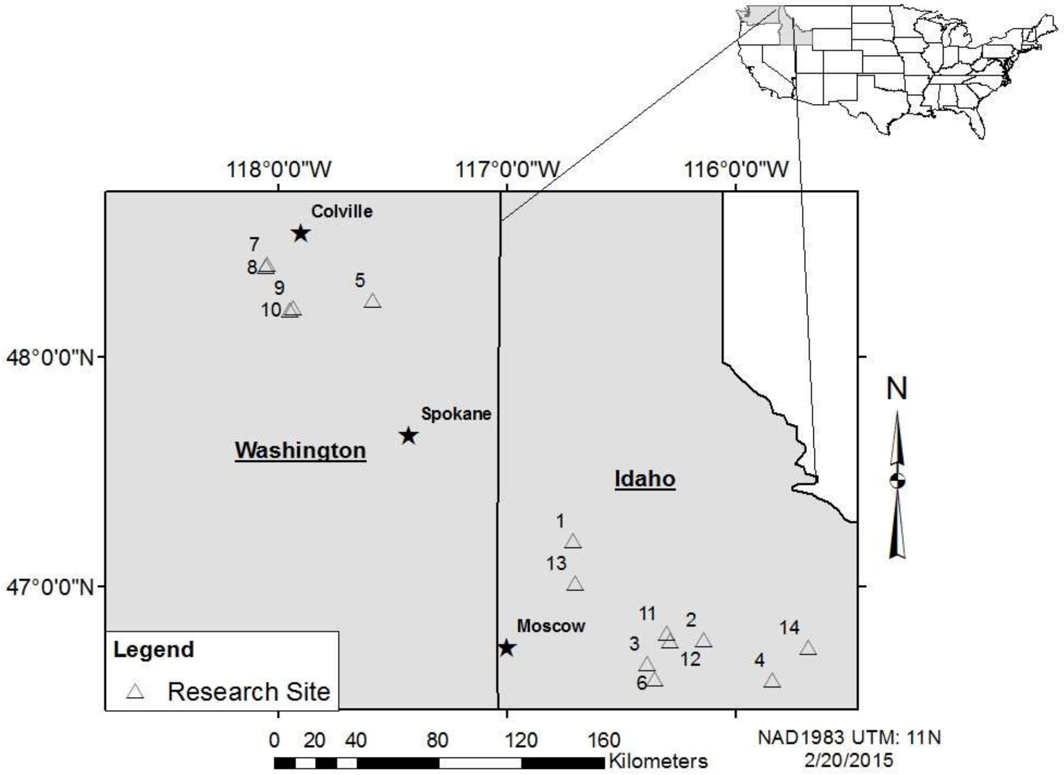

Figure 1. *Map of research locations*

Table 1. Initial stand characteristics for the fourteen research locations ordered from lowest to highest basal area. Bold and underlined stands had data loggers and ion exchange resins installed.

Stand	Basal area (m^2 ha^{-1})	Productivity (m $decade^{-1}$)	Stand age (years)	Trees ha^{-1}	QMD (cm)	SDI	Volume (m^3/ha)	Proportion Douglas-fir (%)
3	9.12	7.28	15	1730	11.01	142	17.97	67
12	9.62	6.46	14	3558	9.44	106	10.52	84
13	11.85	6.86	18	3682	13.73	193	27.78	85
4	13.61	7.41	16	2323	12.73	171	24.45	92
8	14.54	5.49	30	3385	11.37	156	21.16	69
2	18.49	7.74	19	2471	17.20	291	57.97	91
14	19.66	6.89	16	4547	13.00	211	31.11	74
7	20.50	5.24	30	7636	11.17	146	24.76	81
9	22.01	5.12	29	2076	13.71	211	35.87	98
11	23.50	7.28	20	8624	13.68	202	32.93	49
5	25.62	5.76	26	3064	16.27	266	55.93	66
10	25.95	5.24	29	6054	13.40	195	40.99	48
1	26.03	7.74	28	1112	17.66	304	57.37	93
6	28.37	6.83	20	8303	12.18	167	24.32	68

Site characteristics

Site characteristics were determined using a combination of topographic, soil, and climate variables. Soil properties were measured at three random locations in each plot using a bulk density sampler, and soil auger. Measurements included bulk density, ash depth, duff layer depth, and soil classification. Parent materials and soil classification were determined through site observations and verified using United States Geological Survey (USGS) maps (NRCS 2014). Parent materials were separated into weathering potential (low, medium, high) based on previous chemical and mineralogical analyses (Garrison et al. 2003, Kimsey et al. 2008). Climate data including mean annual precipitation (MAP) and mean annual temperature (MAT) was acquired from the ClimateWNA model using the latitude, longitude, and elevation of plot locations (Wang et al. 2012) (Table 2).

Table 2. Site characteristics for the fourteen research locations ordered from lowest to highest basal area. Bold and underlined sites had data loggers and ion exchange resins installed.

Stand	MAT (°C)	MAP (mm)	Elevation (m)	Habitat type *	Ash depth (cm)	Soil bulk density (g/cm^3)	parent material	Rock weathering
3	6.5	1043	1035.25	THPL/ASCA	51.67	0.73	gneiss	Medium
12	6.9	1024	932.71	THPL/CLUN	52.80	0.65	Tertiary sediments	High
13	7.4	876	900.66	TSHE/ASCA	57.60	0.80	quartzite	Low
4	6.3	1232	1169.15	THPL/ASCA	49.77	0.72	mica schist	Medium
8	5.8	646	1185.02	THPL/CLUN	37.23	0.76	glacial	Low
2	6.3	1115	1036.48	THPL/ASCA	56.40	0.84	schist	Medium
14	6.6	1343	1075.41	THPL/ASCA	72.77	0.58	granitic	Medium
7	5.7	641	1233.18	ABGR/LIBO	41.37	0.90	glacial	Low
9	6.4	787	1097.25	THPL/CLUN	36.97	0.77	glacial	Low
11	6.2	1098	1045.95	THPL/CLUN	58.53	0.78	gneiss	Medium
5	6.3	733	983.20	TSHE/CLUN	40.97	0.90	quartzite	Low
10	5.9	822	1162.51	ABGR/CLUN	42.37	0.73	glacial	Low
1	7.3	793	1006.92	THPL/ASCA	41.13	0.92	siltite-argillite	Medium
6	7.1	885	1027.16	THPL/CLUN	80.57	0.54	Schist	Medium

*Note: THPL: Western red cedar (*Thuja Placata),* TSHE: Western hemlock (*Tsuga heterophylla)*, ABGR: Grand fir (*Abies Grandis*), ASCA: wild ginger (*Asarum caudatum*), CLUN: queencup beadlily (*Clintonia uniflora*), LIBO: twinflower (*Linnaea borealis*).

Tree growth

Tree diameters and species were recorded on all trees above breast height (1.37 m) in every plot after dormancy, during the fall of both 2013 and 2014. A stratified random subsample of five trees per one inch diameter class was chosen to make more detailed tree measurements on control plots. All trees in thinned plots received detailed measurements. Detailed measurements included total height, measured using a TruPulse^{TM} 200B (Laser Technology Inc., Centennial Colorado), and crown class assignments, one year after PCT (2014). Crown classes (dominant, co-dominant, intermediate, and suppressed) were assigned to un-measured trees also using height to diameter regression equations and observed crown class thresholds (smallest tree in each crown class). Height to diameter regressions were built from subsampled trees for each plot, and applied to the remaining trees in each plot. The ten largest trees in each plot (247 trees ha^{-1}) defined the “crop” trees at a location. Height to base of live crown was also measured on crop trees for crown ratio calculations. Crown ratios were determined by subtracting the height to base of live crown from the total height, then dividing by the total height. Volume was calculated for each species using the United States Forest Service volume equations (Wykoff et al. 1982).

Physical resources

Physical resource measurements included light, water, and temperature. Photosynthetically active radiation (PAR) was measured on all plots during peak sunlight hours in mid-summer after PCT treatments. PAR readings were taken every meter on four random transects through each plot using a SunScan SS1 ceptometer (Delta-T Devices Ltd., Cambridge U. K.). Ceptometer measurements were referenced to a BF3 beam fraction sensor simultaneously measuring total PAR at a nearby opening receiving full sunlight. Six locations had Em5b data loggers, with two EC5 soil volumetric water content (VWC) sensors and either two RT-1 temperature sensors wired to the logger (Decagon Devices Inc., Pullman WA), or two self-logging temperature sensors (DS1921G Thermocron iButton, Maxim Integrated Products Inc., San Jose CA). Moisture and temperature sensors were installed 15 cm below the soil surface, recording measurements every three hours at each plot. The remaining eight sites only had two self-logging temperature sensors at 15 cm depth at each plot (DS1921G Thermocron iButton, Maxim Integrated Products Inc., San Jose CA). At the eight sites without moisture sensors, three to five randomly distributed spot soil VWC readings were taken fifteen centimeters below the soil surface using a TRIME-FM3 (IMKO GMBH, Ettlingen Germany) or a Hydrosense$^{\text{TM}}$ (Cambell Scientific Inc., Logan UT) time domain reflectometers. Spot soil moisture readings were taken during the fall, spring, and summer after treatment; research sites were inaccessible during the winter.

Chemical Resources

Soil chemical resources included extractable soil nutrients, and nutrients in the soil solution. At all locations, soil samples were collected using a bulk density sampler during the summer of 2014 and air dried for three to four weeks. Soil samples were analyzed for pH using an electrode, extractable K with a flame photometer, extractable SO_4 using ion chromatography, and extractable P, organic matter, NO_3, NH_4, and B measured colorometrically using a spectrometer (University of Idaho Analytical Sciences Laboratory, Moscow ID). Soil nutrient concentrations (µg/g) were converted to a content (µg/cm^3) using average bulk density values (g/cm^3) for each plot. The six sites with data loggers had five ion exchange resin capsules installed in each plot measuring available nutrients in solution (Unibest Inc., Walla Walla WA). Ion exchange resins were installed at a depth of 15 cm during the late summer of 2013, and removed during mid-summer in 2014. Resin capsule nutrients were extracted using a drip of 50mL HCl acid, and measured using flow injection (NO_3 and NH_4), or Inductively coupled plasma optical emission spectroscopy (all other nutrients) by Unibest. Ion exchange resin capsule values were converted to µg cm^{-2} using the surface area of each capsule to represent the total amount of nutrients captured by each capsule. Resin capsule analytes included: total N, NO_3, NH_4, Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, and Zn.

Foliar nutrient characteristics were determined from foliage collected in the field, and processed in the laboratory. Four sunlit branches from the top third of the crown were sampled from five randomly selected dominant Douglas-fir trees in each plot using a pruning poll for a total of 20 branches per plot. After collection, foliage was placed in coolers with ice for transport, and then frozen in the lab to minimize water loss during processing. A composite sample of one hundred current-year needles from each tree was analyzed for leaf area using a digital camera (PowerShot SX40 HS, Canon U.S.A. Inc., Melville NY) and Image J software (Abràmoff et al. 2004). Needles were dried at a temperature of 65 °C for 48 hours, then ground. Ground foliage was analyzed for macro

(N, P, K, Mg, Ca, and S) and micro (Zn, Mn, Cu, Fe, B, and Al) nutrients (Harris Laboratories, Lincoln NE). Foliar nutrients were vector analyzed to simultaneously compare concentration, content, and needle weights (Timmer and Stone 1978).

Statistical Analysis:

An Analysis of Covariance was done for each response variable (tree growth, physical, and chemical resources). Tree growth was defined by either the total basal area growth on a plot after one year, or the mean basal area growth of the largest 10 trees per plot. Soil moisture and temperature data from both spot measurements and data loggers were averaged by plot and season when the measurement was taken. Soil and resin capsule nutrients, and foliar micro nutrients were logarithmically transformed to normalize the data. Logarithmically transformed data was back transformed using the “lsmeans” package in R for presentation purposes (Lenth and Hervã 2015). Initial stand basal area (density) and productivity were first added as covariates to determine their impact on thinning response. To control for additional variation, climate, site, and stand covariates were added using correlation matrices and stepwise Bayesian Information Criterion (BIC) selection. Interactions were tested using type III sums of squares and main effects with type II sums of squares using the “car” package in R (Fox and Weisburg 2011). For models with no interactions with thinning treatment, adjusted means and standard errors were obtained using Tukey’s multiple comparisons of means with the “multcomp” package (Hothorn et al. 2008). Interactions between covariates and treatments were tested at the first and third quartile of the covariate using the “effects” package in R (Fox 2003). Data was analyzed using R studio (version 0.98.942, R Core Team 2013).

Results

Tree growth

Tree and plot growth responded to thinning and initial stand conditions. Total plot basal area growth decreased 27% in the 4.3, and 43% in the 5.5 m spacing relative to the control (Figure 2a). Total plot basal area growth was also influenced by initial plot basal area (basal area 0), and the interaction between initial basal area and stand productivity (Table 3). Plot growth on lower initial basal area plots (10 m^2 ha^{-1}) increased only 71%, while plot growth on higher initial basal area plots (20 m^2 ha^{-1}) increased 119% as productivity improved from 5.5 to 7.5 m $decade^{-1}$. Crop tree growth increased by 23% in the 4.3 m, and 56% in the 5.5 m spacing compared to controls (Figure 2b). Some of the variation in dominant tree growth was explained by productivity (Table 3). Crown ratio was 3% higher in the 4.3 m spacing and 6% higher in the 5.5 m spacing than the control. Crown ratio increased with stand productivity, but decreased at higher initial stand basal areas (Table 3).

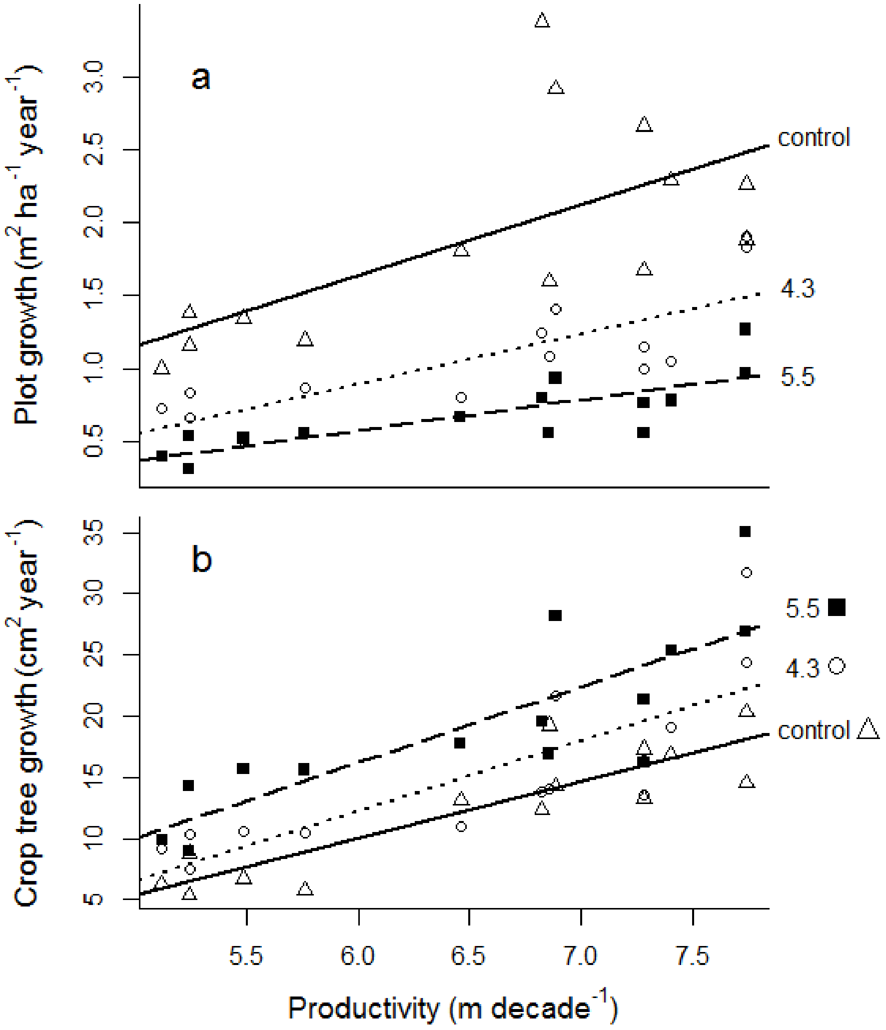

Figure 2. *Plot basal area growth (a), and crop tree growth (b) one year after thinning across a range in stand productivity*

Table 3. Statistical analysis of Productivity (P), Density (D), and Thinning (T) on plot and crop tree growth. Bold text indicates significant differences at α = 0.1. Means and standard errors (in parenthesis) for each treatment are presented below.

Source	**Plot growth (m^2 ha^{-1} $year^{-1}$)**		**Crop tree growth (cm^2 $year^{-1}$)**		**Crown Ratio**	
	r	**p**	**r**	**P**	**r**	**p**
P	0.463	0.380	0.747	**< 0.001**	0.468	0.138
D	0.113	0.598	-0.071	0.417	-0.645	**0.005**
T		**0.006**		**< 0.001**		**0.180**
P x D		0.686		0.812		**0.023**
P X T		0.698		0.668		0.949
D X T		0.397		0.696		0.701
P X D X T		0.452		0.723		0.739
basal area 0	0.722	**0.018**				
P X basal area 0		**0.002**				
R^2	0.8133		0.713		0.629	
Control	1.586 a		12.434 a		0.815 a	
4.3	1.159 b		15.253 a		0.839 a	
5.5	0.904 c		19.397 b		0.862 b	

Note: Pearson correlation coefficient (r), p value from the ANCOVA (p), and the R squared value of the linear model (R^2). Treatments means followed by the same letter are not significantly different at α = 0.1.

Physical Resource Response

Intercepted photosynthetically active radiation decreased after thinning and increased with initial stand basal area (Table 4). There was a 33% iPAR decrease in the 4.3 meter spacing, and a 58% decrease in the 5.5 meter spacing compared to the control (Figure 3). While it appeared that differences in iPAR due to thinning increased with initial basal area, the interaction was not significant (Table 4). Soil VWC during the spring was 13% higher in the 4.3 and 18% higher 5.5 m spacing than the controls (Table 4), and increased by 18% as stand productivity increased from 5.5 to 7.5 m decade^{-1}. Soil VWC in the summer was 51% higher in the 4.3 m spacing and 74% higher in the 5.5 m spacing relative to the control without any covariate correction. Soil temperature at 15cm depth during both the spring and summer increased in thinned plots compared to controls (Table 4). Soil temperatures increased with productivity in both the spring and summer, but spring temperature was also influenced by elevation and aspect. Spring soil temperatures were warmer on more easterly aspects (sine of aspect > 0, Table 4), with little difference in north-south aspects (cosine of aspect p = 0.670).

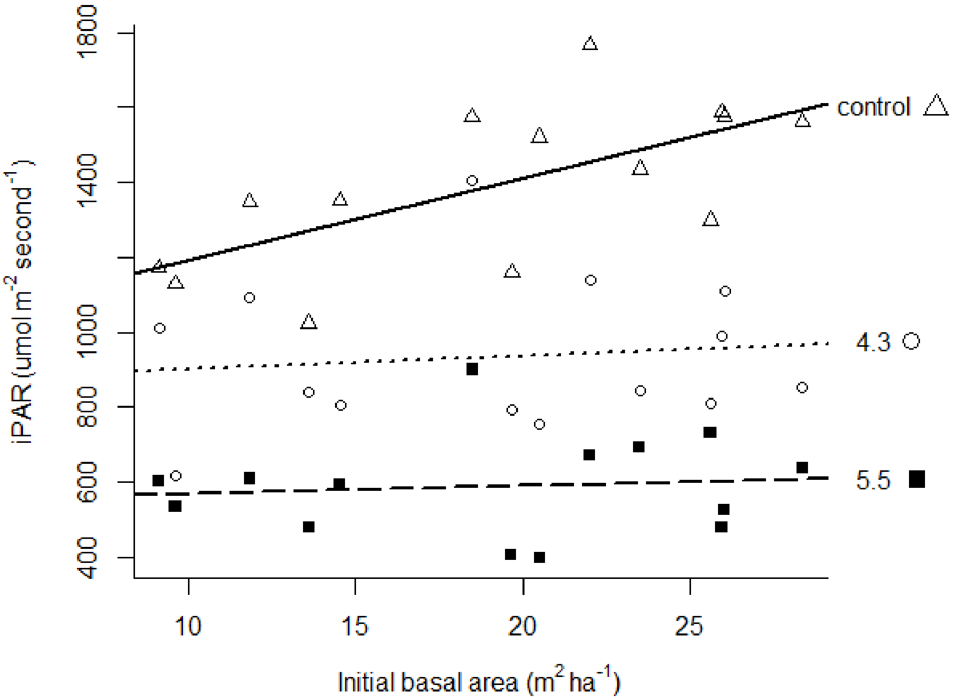

Figure 3. *Intercepted photosynthetically active radiation (iPAR) by treatment and initial stand basal area.*

Table 4. Effects of Productivity (P), Density (D), and Thinning (T) on soil moisture and temperature. Bold text indicates significant differences at α = 0.1. Means and standard errors (in parenthesis) for each treatment are presented below.

Source	**Spring VWC (cm^3 cm^{-3})**		**Spring temp (°C)**		**Summer VWC (cm^3 cm^{-3})**		**Summer temp (°C)**		**iPAR (µmol m^{-2} s^{-1})**	
	r	**p**	**R**	**P**	**r**	**p**	**r**	**p**	**r**	**p**
P	0.386	**0.009**	0.467	**0.016**	0.127	0.219	0.460	**0.001**	0.022	0.500
D	0.052	0.379	-0.088	0.164	0.202	0.142	0.029	0.370	0.152	**0.048**
T		**0.092**		**0.055**		**0.002**		**0.011**		**< 0.001**
P x D		0.986		0.154		0.445		0.646		0.293
P X T		0.982		0.360		0.853		0.708		0.386
D X T		0.509		0.263		0.869		0.604		0.128
P X D X T		0.972		0.258		0.899		0.574		0.558
Elevation			-0.516	**0.009**						
Sine (aspect)			0.348	**0.009**						
R²	0.1897		0.4499		0.2334		0.3304		0.765	
Control	0.379 a		5.224 a		0.157 a		12.869 a		1389.684 a	
4.3	0.428 ab		5.716 ab		0.237 b		13.613 b		929.341 b	
5.5	0.447 b		5.883 b		0.273 b		13.775 b		585.134 c	

Note: Pearson correlation coefficient (r), p value from the ANCOVA (p), and the R squared value of the linear model (R^2). Treatments means followed by the same letter are not significantly different at α = 0.1.

Chemical Resource Response

Both the soil and foliar chemical nutrients showed response to stand conditions and PCT. Total extractable inorganic soil N (NO_3 + NH_4) was 62% higher in the 4.3 m spacing and 36% higher in the 5.5 m spacing than the control, and increased with both initial basal area and stand productivity (Table 5). A majority of total N was in the form of NH_4 which increased with both initial basal area and stand productivity, but not thinning treatment (Table 5). Soil NO_3 however, was 157% higher in the 4.3 m spacing and 171% higher in the 5.5 m spacing compared to the control (Figure 4). Soil NO_3 showed no significant relationship to productivity or density (p = 0.104 and 0.294 respectively), but increased with both precipitation (r = 0.089, p = 0.008) and soil bulk density (r = 0.134, p = 0.010). Soil S was 20% higher in the 4.3 m spacing treatment than either the 5.5 or control and increased by 23% as stand productivity went from 5.5 to 7.5 m decade^{-1} (Table 5). Resin capsule B and S were highest in the control plots, then declined with increasing tree spacing (Table 5). Resin capsule B was 8% lower in the 4.3 m spacing and 20% lower in the 5.5 m spacing than the control. Resin capsule B was positively correlated with ash depth and initial basal area (Table 5). Resin S was 3.2 ug cm^{-2} lower than the control in the 4.3 m spacing, and 4.4 ug cm^{-2} lower in the5.5 m spacing (Table 5).

Table 5. Effects of Productivity (P), Density (D), and Thinning (T) on soil chemical resources. Bold text indicates significant differences at α = 0.1. Means and Tukey's multiple comparisons of means for each treatment are presented below.

Source	**Total N (ug cm^{-3})**		**NH_4 (ug cm^{-3})**		**Soil S (ug cm^{-3})**		**Resin B (ug cm^{-2})**		**Resin S (ug cm^{-2})**	
	R	**P**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**
P	0.312	**0.003**	0.229	**0.020**	0.268	**0.070**	-0.268	0.383	0.315	0.135
D	0.389	**0.001**	0.249	**0.040**	0.057	0.553	0.607	**0.030**	0.060	0.600
T		**0.015**		0.172		**0.076**		**0.046**		**0.054**
P x D		0.610		0.403		0.367		0.404		0.189
P X T		0.865		0.745		0.781		0.881		0.674
D X T		0.828		0.733		0.673		0.893		0.653
P X D X T		0.915		0.705		0.653		0.934		0.660
Rock weathering							-0.138	**0.007**		
Ash depth							0.319	**0.001**	0.716	**< 0.001**
Duff depth									0.152	**0.061**
R^2	0.347		0.173		0.128		0.624		0.661	
Control	10.357 a		8.366 a		1.999 ab		0.143 a		14.636 a	
4.3	16.807 b		11.049 a		2.388 b		0.130 ab		11.482 ab	
5.5	14.035 a		8.897 a		1.961 a		0.113 b		10.199 b	

Note: Pearson correlation coefficient (r), p value from the ANCOVA (p), and the R squared value of the linear model (R^2). Treatments means followed by the same letter are not significantly different at α = 0.1.

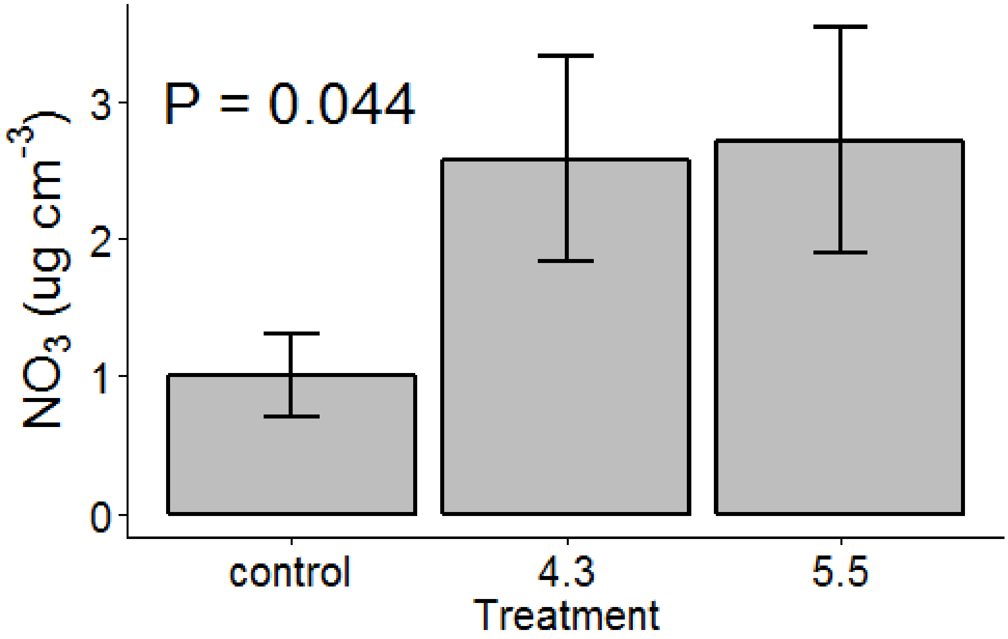

Figure 4. *Adjusted means and standard errors for soil NO_3 by treatment*

Pre-commercial thinning influenced Douglas-fir needles weights and foliar nutrients in a variety of fashions. Douglas-fir foliar nutrients were not deficient for K, Ca, B, or Cu but were deficient in P, N, and S when compared with critical nutrient concentrations (Webster and Dobkowski 1983). Thinned stands were more N deficient, no longer P deficient, and more deficient in S for the 5.5 m spacing but less S deficient in the 4.3 m spacing than controls. Dominant Douglas-fir needle weight increased by 15% in the 4.3 and 12% in the 5.5 m spacing treatments when compared to the control; and was positively correlated with stand productivity ($r = 0.337$, $p = 0.016$). Foliar N decreased by 5% in concentration, but increased by 5% in content on thinned plots (Figure 5). Foliar N concentration was positively correlated with stand productivity (Table 6). Other nutrients had little or no change in concentration (S, K, Cu; $p \geq 0.446$) but increased in content after thinning treatment (Figure 5; $p < 0.1$). Foliar Cu content was positively correlated with initial stand density (Table 6), and foliar S content had no relationship with productivity or density ($p \geq 0.642$). The 4.3 m spacing had

13% more foliar K content than the 5.5 m spacing, and 22% more than the control at low productivity locations (5.5 m decade^{-1}), but only 4% difference between treatments at higher productivity sites (7.5 m decade^{-1}) (P X T p = 0.095).

Other foliar nutrients either increased or decreased in both nutrient concentration and content as a result of PCT. Foliar Ca, and Zn contents and concentrations declined in thinned plots compared to controls (Figure 5), which indicates excess based on vector analysis (Haase and Rose 1995). While both foliar Ca and Zn concentrations were negatively influenced by stand productivity, foliar Zn was also influenced by elevation (Table 6). In contrast, foliar concentrations and contents of P, B, and Al were positively influenced by thinning, suggesting deficiencies according to vector analysis. At lower productivity sites (5.5 m decade^{-1}), foliar P content declined 27% with increasing density (10 to 25 m^2 ha^{-1}) but at higher productivity sites (7.5 m decade^{-1}), foliar P content increased by 13% from low to high density (P X D p = 0.029). Both foliar B and Al contents were positively influenced by elevation, but B declined with higher precipitation while Al decreased with increasing soil bulk density (Table 6).

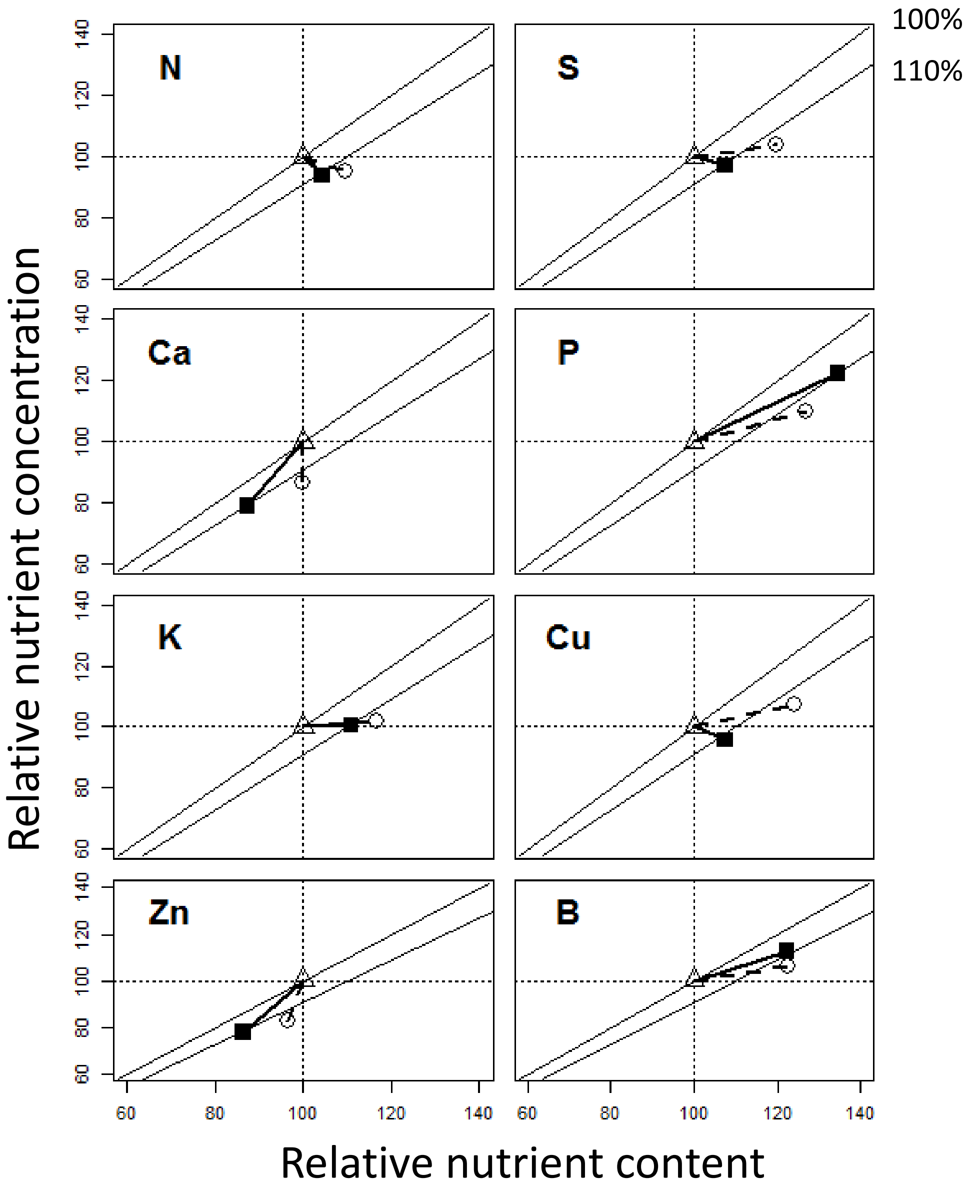

Figure 5. *Vector analysis for foliar nutrients by treatment, all units are relative to control (100). Treatments include a control* (△)*, 4.3 m spacing* (○) *and 5.5 m spacing* (■)*. Diagonal lines represent no change (100%) or a 10% increase (110%) in needle weights relative to controls.*

Table 6. Statistical analysis of Productivity (P), Density (D), and Thinning (T) on foliar nutrient concentrations and content. Nutrient presented had significant main effects of thinning treatment. Means and Tukey's multiple comparisons of means for each treatment are presented below. Bold text indicates significant differences at α = 0.1.

	[N] (g kg^{-1})		**[P] (g kg^{-1})**		**[Ca] (g kg^{-1})**		**[Zn] (mg kg^{-1})**		**Cu content (µg 100 needles^{-1})**		**B content (µg 100 needles^{-1})**		**Al content (µg 100 needles^{-1})**	
Source	**r**	**P**	**r**	**P**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**
P	0.233	**< 0.001**	-0.574	**< 0.001**	-0.432	**0.002**	-0.432	**0.076**	0.108	0.209	-0.233	0.179	-0.079	0.553
D	-0.174	0.377	-0.083	**0.095**	0.206	0.324	0.097	0.900	0.367	**0.014**	0.198	0.287	-0.057	0.632
T		**0.020**		**0.003**		**0.006**		**0.053**		**0.085**		**0.029**		**0.035**
P x D		0.948		0.135		0.260		0.117		0.141		0.391		0.542
P X T		0.343		0.193		0.678		0.244		0.552		0.119		0.319
D X T		0.340		0.303		0.777		0.254		0.692		0.313		0.483
P X D X T		0.290		0.264		0.810		0.231		0.566		0.202		0.417
Elevation	0.459	**< 0.001**					0.590	**< 0.001**			0.341	**0.030**	0.159	**0.046**
MAP											-0.384	**0.013**		
Bulk Density													-0.396	**0.002**
R^2	0.475		0.484		0.329		0.426		0.180		0.298		0.288	
Control	10.03 a		1.50 a		4.82 a		2.914 a		2.281 a		16.904 a		97.455 a	
4.3	9.60 ab		1.65 ab		4.17 b		2.773 ab		2.730 b		20.595 b		127.938 b	
5.5	9.40 b		1.84 b		3.80 b		2.696 b		2.426 ab		20.570 b		112.722 ab	

Note: Pearson correlation coefficient (r), p value from the ANCOVA (p), and the R squared value of the linear model (R^2). Treatments means followed by the same letter are not significantly different at α = 0.1.

Discussion

Tree growth

The difference between plot basal area growth on control plots and thinned plots was greatest at higher productivity (Figure 2a). This relationship is not surprising because more productive forests grow faster. However, the knowledge that thinned stands at higher productivities respond better to thinning than stands at lower productivities is useful. Forest managers whose objective is to maximize stand basal area growth should prioritize high productivity locations for thinning. Other research shows similar basal area growth responses to both fertilization and thinning, but this experiment is unique in looking at inherent site quality or productivity (Brockley 2005). Similarly, dominant tree growth increased slightly more on thinned plots at high productivities than thinned plots at low productivities compared to controls (Figure 2b). This suggests that over time, thinning high productivity stands could potentially improve the overall productivity of the site (Pothier 2002, Brisette et al. 1999). Changes in crop tree crown ratios were observed just one year after thinning, even though the changes were relatively small. Previous research has demonstrated that higher crown ratios in response to thinning are common; although generally over longer time scales (Brix 1981, Brockley 2005). However, changes in the crown ratio could be influenced by measurement error because it is harder to see branches in denser control plots.

Physical resources

Intercepted photosynthetically active radiation (iPAR) showed another interesting pattern. At higher initial densities, one would expect less iPAR after thinning because of lower crown ratios and more narrow crowns. However, the relationship between iPAR and initial stand density was not negative in the thinning treatments, suggesting that thinning denser stands will not lower iPAR in the residual stand (Figure 3). Supporting this finding, strong correlations have been shown between intercepted radiation and stand volume growth, and higher specific leaf areas at higher forest densities (Will et al. 2001). However, the considerable variability about iPAR across plots may misrepresent the direction of the relationship between iPAR and initial density after thinning. In addition, as the forest canopy develops over time, iPAR in thinned plots will likely approach that of the controls (Drew and Flewelling 1979). Surprisingly, relative iPAR response to PCT was fairly low compared to the other resources suggesting that other variables may have a stronger influence on tree growth.

Pre-commercial thinning drastically increased summer soil water conditions (Table 4). However, because slash was left on all plots and no measurements of water use were made, it is difficult to distinguish if the increased soil moisture was caused by less water use from plants (Stogsdill et al. 1992) or increased slash loading (Smethurst and Nambiar 1990). To separate the effects of slash and competition on soil moisture, transpiration, and precipitation through-fall would need to be measured. Regardless, residual trees on thinned plots are likely less water stressed than those in control plots. Soil VWC in spring was positively correlated with productivity, and increased by thinning (Table 4). In other words, higher productivity stands received a greater soil moisture benefit from PCT in the spring than lower productivity stands. Higher soil moisture in the spring has been shown to be an important predictor of Douglas-fir growth (Littell et al. 2008). Interestingly, soil VWC in the summer was independent of both initial density and productivity. From the higher soil VWC in the summer after thinning, summer drought conditions were lower in thinned plots, reducing water stress (Bréda et al. 1995).

Higher temperatures in thinned plots during both the spring and summer could produce longer growing seasons. Spring soil temperatures were warmer on more easterly aspects, with little difference in north-south aspects. Warmer easterly slopes could result from faster warming of the soils in the morning when the sun is in the east. Soil temperatures were positively correlated with productivity, suggesting that more productive sites have warmer soil temperatures throughout the spring and summer (Table 4). Research has demonstrated higher site index or productivity values on warmer, more easterly slopes than other aspects depending on the elevation (Kimsey et al. 2008). Furthermore, at higher soil temperatures, N mineralization will likely increase unless limited by other factors such as moisture (Powers 1990, Chmura et al. 2011).

Chemical resources

Extractable N in the soil increased after thinning, but declined in foliar concentration. A majority of N mineralization and mobility in the soil occurs when the soil is moist and warm, such as after thinning (Powers 1990). Other research has observed an increase in inorganic soil N (NO_3 and NH_4) after PCT; improving forest growth (Brix 1981, Forrester et al. 2012), and insect resistance (Stoszek et al. 1981). Our results agree with these findings, particularly for the 4.3 m spacing (Figure 4, Table 5). Contrary to what others have found, no significant changes were detected in foliar N content, but foliar N concentration decreased after thinning (Hokka et al. 1996). The decrease in foliar N concentrations was most likely due to a dilution effect because of heavier needles on residual trees in thinned plots (Figure 5). Lower productivity sites were more deficient in N (7-8 g kg^{-1}) than high productivity sites (9-10 g kg $foliage^{-1}$), and thinning could exacerbate these deficiencies. It is possible that the trees were not yet able to acquire the N in the soil, or were out-competed by other organisms (Thibodeau et al. 2000). A precaution, soil N was measured at one point in time, yet N pools are in constant flux suggesting that the amount of inorganic N may be different in actuality (Davidson et al. 2000).

Boron declined in the soil solution, but increased in the foliage. The amount of available B determined through resin capsule analysis decreased with increased tree spacing. However, foliar B was elevated in thinned plots, suggesting that residual trees are better able to seek out and acquire B after PCT operations. Potential explanations for the B decrease in solution but increased in the foliage are that plant roots acquired B before it reached the resin capsule at 15 cm depth, or that trees are better able to acquire B than the resin capsules. Although the stands studied in this experiment were not B deficient, B uptake still increased after thinning (Figure 5). If this pattern remains true, thinning could help alleviate B deficiencies which occur in roughly 20% of Douglas-fir stands throughout the Inland Northwest (Moore et al. 2004). Relieving the B deficiency in trees could provide better drought and cold tolerance (Lehto et al. 2010). Boron deficiency in trees can degrade stem form and wood quality (Coleman et al. 2014).

Sulfur in the soil and foliage had an interesting response to the different thinning treatments. Both the control and the 5.5 meter spacing had lower sulfur values than the 4.3 meter spacing (Table 5). Although not significant, a similar pattern as the soil S existed for the S concentration in the foliage. In contrast, resin S was higher in the control than either the 4.3 or 5.5 m spacing. However, resin capsules should be scrutinized because of the lower sample size than the soils, or foliage. Douglas-fir was S deficient across all of the study sites, and increasing the S deficiency from thinning to 5.5 m spacing could have consequences for nutrient cycling processes and tree growth (Coleman et al. 2014). The mechanisms behind why the 4.3 m spacing had more S are unclear. One possible explanation could be the specific microsite created by the 4.3 meter spacing (intermediate light levels, moisture, and temperature) provide better conditions for S mineralization than the other two treatments (Chmura et al. 2011). Another reason could be more living root biomass in the 4.3 m spacing than the 5.5 m spacing facilitating microbial processes (Broeckling et al. 2007). Differences between thinning treatments are likely caused by a combination of microsite and microbial processes. The relationship between S and thinning intensity needs further research to understand the mechanisms controlling the response.

Phosphorous had the strongest response in the foliage compared to all other nutrients analyzed, with no significant differences in the soil ($p \geq 0.132$). Other research has demonstrated an increase in foliar P after pre-commercial thinning (Thibodeau et al. 2000, Hokka et al. 1996). One suggestion for this relationship is that leaching of P from slash left after PCT replaced the P immobilized by the trees (Sterba 1988). Another speculation is that a majority of the P acquired by trees was in the organic horizon of the soil, which was not sampled in this experiment (Johnson et al. 2003). Although others have reported that P is not regionally deficient (Coleman et al. 2014), foliar P concentration was below critical levels at 10 out of the 14 locations in this study (Webster and Dobkowski 1983). On average, thinning alleviated the P deficiency across all research locations. Alleviating P deficiency in Douglas-fir can improve growth rates, photosynthetic efficiency, and root hydraulic conductance (Marschner and Rimmington 1988).

Research Implications

Many studies focus on the availability of light throughout the canopy after thinning as the primary resource controlling photosynthetic or growth response of trees (Will et al. 2002, Tang et al. 1999). While iPAR had strong relative responses to thinning, relative soil moisture in the summer had the strongest response (figure 6). In addition, the relative response of extractable soil N (NO_3 and NH_4) was also comparable to light and moisture. Intercepted photosynthetically active radiation was greatest at stands with higher initial densities for control plots, but not for thinned plots (Figure 3). Higher relative soil moisture in the summer happened regardless of the initial stand conditions (productivity or density). The relative response in extractable N was greatest at both more productive and denser stands (Table 5). The influence of initial site and stand conditions on resource response to pre-commercial thinning, and the magnitude of relative soil moisture and soil N emphasize the need for considering multiple resources and locations when studying the forest response to density manipulations.

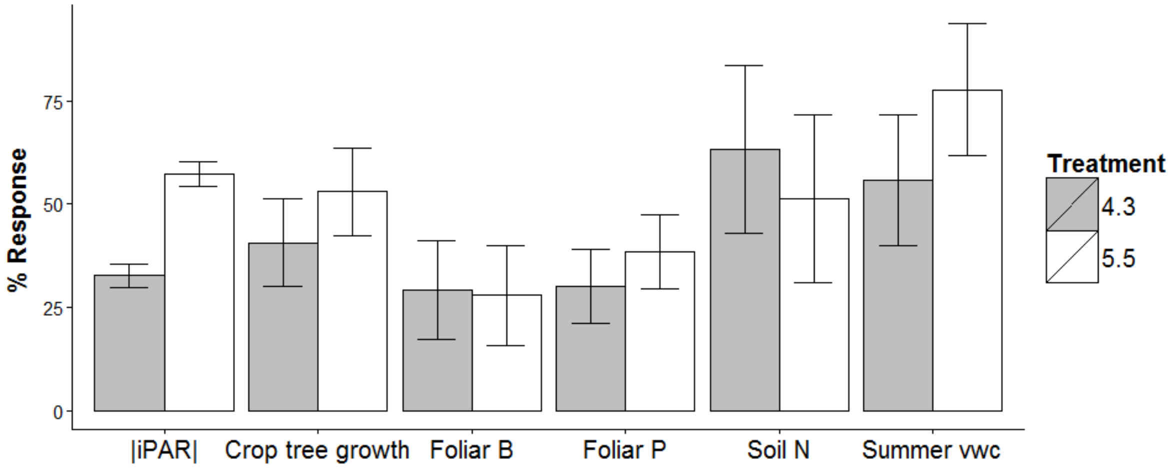

Figure 6. *Resource response to pre-commercial thinning relative to un-thinned controls. The absolute value of iPAR is presented for meaningful comparison between resources.*

Conclusion

The results of this paper suggest intricate relationships between resource availability, PCT, site, and stand characteristics. Thinning consistently provides greater light availability and soil moisture after thinning. The availability of soil nutrients N, and S improve, but B and S in the soil solution decrease. Foliar nutrient contents respond to thinning negatively (Ca, Zn) and positively (P, B), while heavier needles dilute other nutrients (N, K, S). Improved light, moisture, and nutrients after thinning will reduce a suite of resource limitations and relieve multiple stresses in forests, and improve growth. More productive forests had greater tree growth, crown ratios, soil moisture, temperature, extractable soil N, and foliar N response after thinning; but lower foliar P, K, Ca, and Zn. Denser stands had greater post-thinning light, extractable soil N, resin capsule B, and foliar Cu; but lower crown ratios and foliar P. Thinning high density stands at low productivities will provide the greatest stress relief because resources are more limiting and competition is high. Future research should monitor how the responses in light, water, and nutrients continue to develop over time, and seek to expand the scope of forest productivity and density.

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Chapter 3. Validating Forest Vegetation Simulator SDImax values for mortality and fuels across the Inland Pacific Northwest.

Abstract

Fire suppression over the last century has led to fuel accumulation in many forests. This has emphasized a need for better modeling of fuels and tree mortality across forests in the United States to understand potential wildfire hazard. Four scenarios of the maximum stand density index in the forest vegetation simulator were modeled to determine potential errors in estimates of the maximum stand density index and the consequences for mortality and fuels. While none of the models were perfect, some sites did experience drastically different mortality and fuel accumulation based on the maximum stand density index. The discrepancy between maximum stand density index estimates of the different models suggest that better estimates of the maximum stand density index and mortality need to be obtained for useful fire prevention and fuels management efforts using the forest vegetation simulator.

Introduction

Catastrophic and high severity fires have been increasing in recent years as a result of fire suppression, fuel buildup, and excessive recruitment of shade tolerant species (Westerling et al. 2006). In addition, fire suppression in overstocked stands creates vulnerability to infestation of disease and insects, adding even more fuels (Jenkins et al. 1998). This issue is compounded when warmer temperatures and longer fire seasons are predicted under various climate change scenarios (Dale et al. 2001). Therefore, it is crucial to identify forests and stands which have or will imminently experience fuel buildup as a result of density dependent mortality. Furthermore, accurate model predictions of mortality and fuel dynamics are critical for informing forest managers and decision makers in the present.

Understanding the carrying capacity at a location is essential for understanding the stage of forest stand development. Mortality, stochastic weather events (wind storms, fires, ice damage), human activity (logging, thinning), wildlife browse, insects, and disease all inhibit efforts to determine a stand or site's carrying capacity (Drew and Flewelling 1979). Therefore, the amount and size of trees in a stand, fire records, and plant species composition are often used to determine the carrying capacity of a given site (Geist et al. 1994). The stand density index is one way to quantify the density of the forest; using the amount of trees on a site and the size of those trees (Reineke 1933). While knowing the density of the forest is useful, it is just as necessary to know the carrying capacity of that site. Correct determination of the carrying capacity of the site represented by the maximum stand density index (SDIMAX) is essential for estimating when density dependent mortality will occur and the magnitude. The SDIMAX is a measure of the species-specific maximum number of trees of a particular size a site can carry per unit area (Reineke 1933). While current stand stocking levels and densities are readily measured or observed, the SDIMAX is less so. Although SDIMAX values are determined for pure even aged plantations, multiple or mixed species stands lack equivalent SDIMAX estimates (Woodall et al. 2005). As a result, models that use SDIMAX might be providing forest managers with inaccurate information.

The Forest Vegetation Simulator (FVS) is a management tool used by the United States Forest Service and other private and public agencies for modeling growth and yield of forest resources across the United States. FVS uses SDIMAX to identify the particular stage of forest stand development, which is critical for predictions of mortality, growth, and fuels (Drew and Flewelling 1979, Dixon 2002). Recent analysis of the default SDIMAX values in FVS has identified possible over-predictions of SDIMAX in FVS from outdated information in the model (Intermountain Forest Tree Nutrition Cooperative (IFTNC), unpublished data, 2013). This could have serious repercussions for managers using FVS for fuels and fire prevention management under the Fire and Fuels Extension

(Rebain et al. 2002). This paper attempts to identify and analyze the impact of FVS default SDIMAX and IFTNC estimated SDIMAX on mortality and fuels and validate predicted mortality against measured estimates.

Methods

Ten years of data were compiled and organized for 90 sites with observed mortality and growth measurements. The 90 sites encompassed a large region of the Pacific Northwest represented by four FVS variants: Blue Mountains (BM), Central Idaho (CI), East Cascades (EC), and the Inland Empire (IE) (Figure 1). Species, diameter outside bark at breast height, mortality, and total tree heights were recorded in 0.04 hectare (1/10th acre) plots every two years for ten years. Diameters were used to calculate the amount of basal area (m^2 ha^{-1}) and SDI for each site. The amount of basal area was similar between variants, with 34 m^2ha^{-1} mean basal area in the BM variant, 32 in the CI variant, 33 in the EC variant, and 34 in the IE variant (Appendix A). In addition, site characteristics including elevation, aspect, slope, and habitat types were obtained from digital elevation models and site observations. Habitat types were mostly in the Douglas-fir (PSME) and grand fir (ABGR) series, with few sites in the hemlock (TSHE) and western red cedar series (THPL) (Appendix A). The nearest national forest code was assigned to each site for model calibration within FVS. The measurement period was between 1981 and 1992 depending on year of plot establishment. IFTNC predicted SDIMAX came from a model in development using site specific parameters such as parent material, annual dryness index, species composition, elevation, and aspect (Intermountain Forest Tree Nutrition Cooperative, unpublished data, 2013). All applicable data were entered into FVS and modeled under several different SDIMAX scenarios.

The first scenario used the default SDIMAX values for each site (FVS), calculated as follows (Dixon 2002).

$$MaximumSDI = \left(\frac{S_1SDI\ *\ S_1BA\ +\ S_2SDI\ *\ S_2BA + \ldots\ + S_nSDI\ * S_nBA}{Total\_Stand\_BA}\right)$$

Where:

S_1SDI is maximum SDI for the first species in the stand
S_1BA is total basal area of the first species in the stand
S_2SDI is maximum SDI for the second species in the stand
S_2BA is total basal area of the second species in the stand
S_nSDI is maximum SDI for the nth species in the stand
S_nBA is total basal area of the nth species in the stand

FVS selects SDIMAX based on location code (national forest) and habitat code, for each variant and species. Certain variants use a maximum basal area which is converted to a SDIMAX value using the equation SDIMAX = maximum basal area * 0.54542^{-1}. Note if current stand SDI is greater than 85% of SDIMAX, then SDIMAX is recalculated by FVS to be 85% of stand SDI (Dixon 2002). Mortality and accretion were reported for the ten year projection period from FVS outputs. Accretion is the change in volume (m^3 ha^{-1} $year^{-1}$) during the 10 year period. FVS calculates volume from initial and final tree diameter and height measurements using allometric equations specific to site (habitat type, elevation, aspect, etc.) and stand characteristics (basal area, crown ration) FVS (Dixon 2002). Total dead surface and standing fuels were obtained at the end of the measurement periods (years 1991 and 1992). Fuels were not measured at the study sites, so reported fuel outputs were only predicted by the Fire and Fuels Extension of FVS.

Additional runs included the following IFTNC predicted SDIMAX scenarios. SDIMAX was also re-calculated if current stand SDI was above 85% of the maximum for IFTNC scenarios. Mortality and accretion were assigned to IFTNC models the same as the FVS default model. The first run was done with a specific SDIMAX unique to each site based on the variables described above, and is referred as “Site”. The second run used the average IFTNC predicted SDIMAX by variant and habitat code, called “Mean”. The third and final model run used the highest IFTNC predicted SDIMAX value, also by variant and habitat code (similar to how default FVS SDIMAX is determined) is represented by “Max”.

Outputs including growth, mortality, and fuels data were obtained the same throughout all model runs.

Statistical Analysis

This study was a completely randomized block design with each variant representing a block, each model scenario was a treatment, and study locations were replicates within blocks. All growth, mortality, and fuels estimates were converted from English units to metric. Data was analyzed using R studio (version 0.98.942, R Core Team 2013).

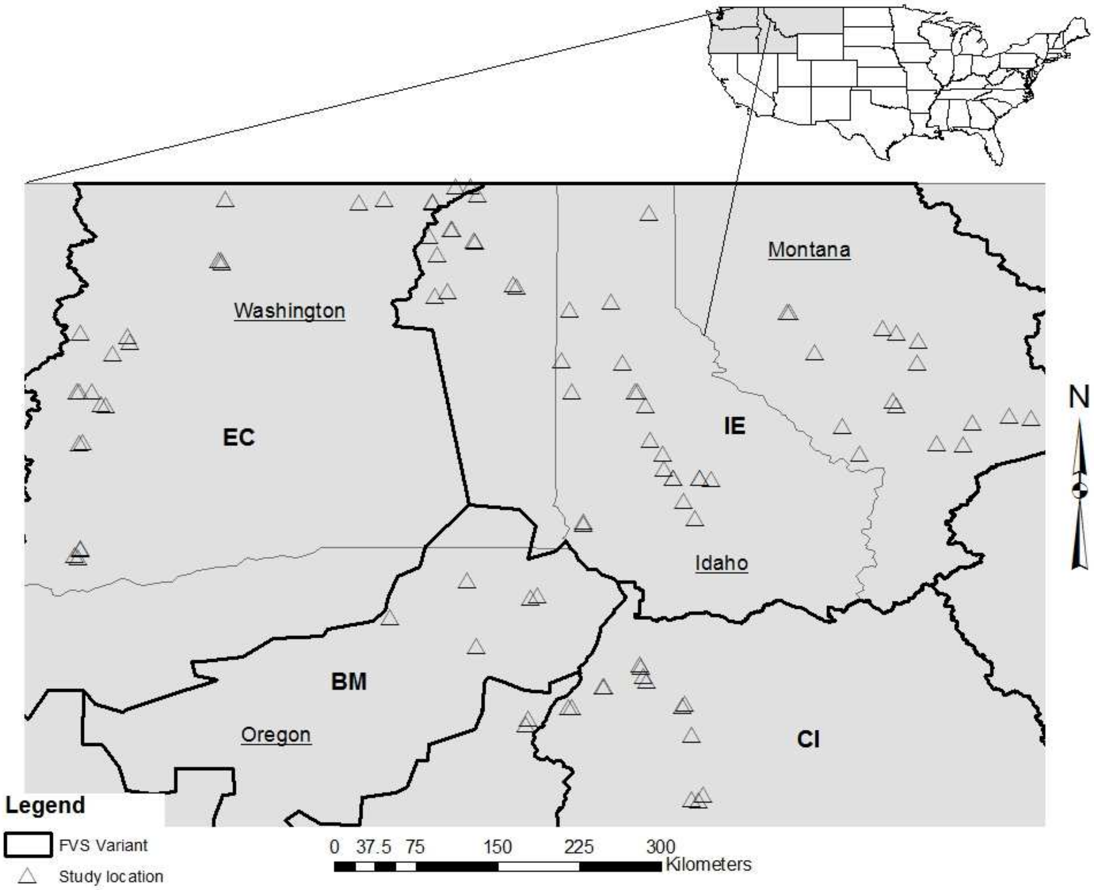

Figure 1. *Map of research plots across four FVS variants and four states*

Results

Average SDIMAX, and the percent of SDIMAX varied greatly among scenarios and especially by variant (Figure 2). SDIMAX was recalculated by FVS for 3% of sites for the FVS scenario, 22% for the “Site”, 26% for “Mean”, and 18% for the “Max” scenarios so that stand SDI was 85% of the maximum. The BM variant had the most comparable SDIMAX and percent of SDIMAX values between all model scenarios. In the remaining three variants, average FVS default SDIMAX was higher than the mean IFTNC predicted SDIMAX. Consequently, percent of SDIMAX in the CI, EC, and IE variants were lower using FVS default SDIMAX than percent of SDIMAX using the IFTNC models (Figure 2). The differences between model scenarios for SDIMAX and percent of SDIMAX was most pronounced in the EC and IE variants (Figure 2). The IE variant had the highest FVS default SDIMAX of 384 (Habitat code 545), while the BM variant had the highest SDIMAX of the IFTNC scenarios with 316 (Site 213). In contrast, the BM variant had the lowest FVS default SDIMAX of 114 (Site 239), while the lowest SDIMAX predicted by IFTNC was 103 (Site 236) in the IE variant (Appendix A).

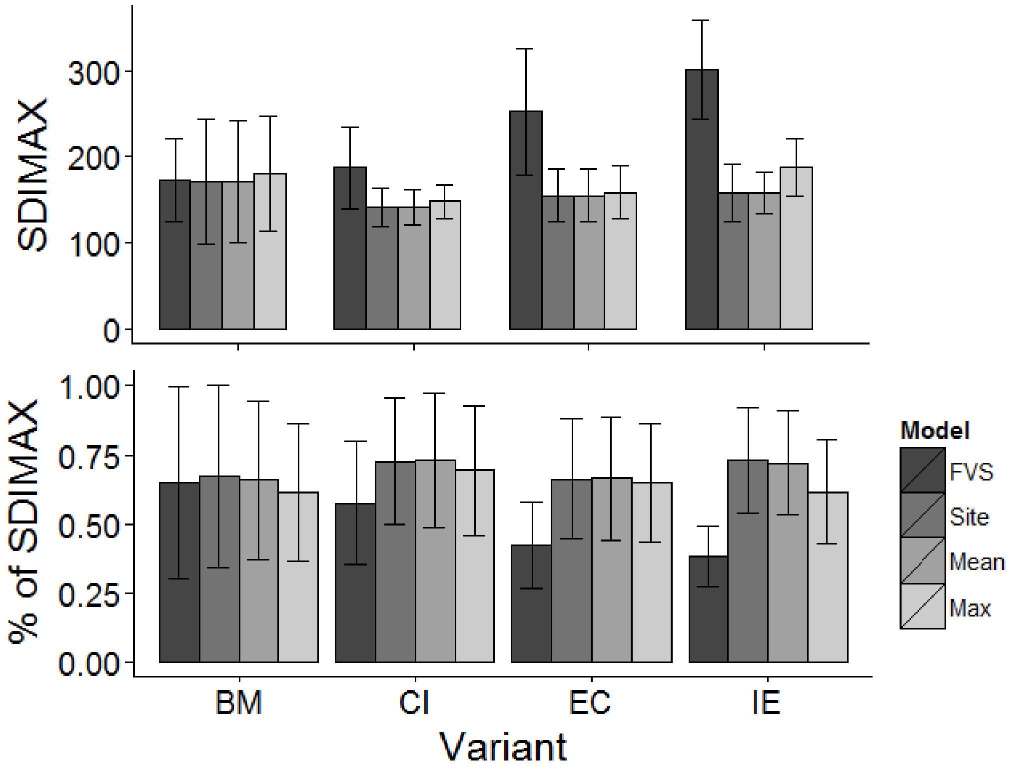

Figure 2. *SDIMAX and percent of SDIMAX means and standard deviations by variant and SDIMAX model scenario for 90 sites across the Pacific Northwest.*

Average measured mortality was highest in the Blue Mountain (BM) region, followed by the Inland Empire (IE), East Cascades (EC), and Central Idaho (CI). All models had poor predictions of mortality in relation to measured values at all variants and regions (Figure 3). Model predictions of mortality were least accurate in the BM and CI variants as indicated by negative correlations between predicted and observed mortality (Figure 3). The FVS default SDIMAX scenario had the best predictions of mortality out of all SDIMAX scenarios, followed by “Mean”, “Max”, and “Site” (Table 1). In addition to the best mortality predictions across all variants, FVS was superior to IFTNC SDIMAX scenarios for the BM and CI variants. The “Mean” and “Max” SDIMAX scenarios had the best predictions of mortality in the EC and IE variants. Of the IFTNC SDIMAX model scenarios, the “Mean” had the highest model R^2 in the IE variant (Table 1). While FVS default SDIMAX had the best model predictions of mortality overall, there were some sites which both models poorly predicted mortality when compared to observations (Sites 210, 239, 244 258) (Appendix B).

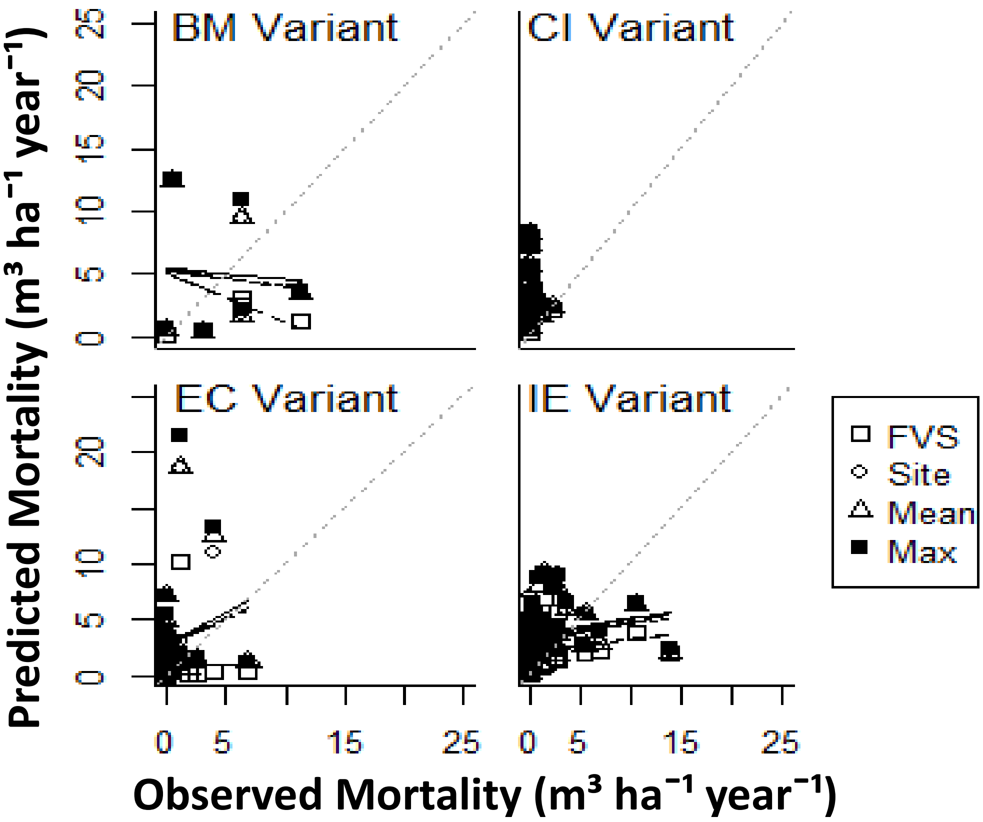

Figure 3. *Observed and FVS predicted mortality over a ten year period by variant for 90 sites in the Pacific Northwest. The fine gray dotted represents a 1:1 relationship and all other lines are regressions from model predictions.*

Table 1. Predicted versus observed mortality R^2 values for each variant and mean R^2 across four variants and SDIMAX scenarios

	BM	CI	EC	IE	Mean
FVS	**0.121**	0.041	0.001	0.040	0.051
Site	0.008	0.033	0.031	0.014	0.021
Mean	0.012	0.038	0.037	**0.055**	0.035
Max	0.004	0.038	0.036	0.038	0.029

Note: Bold values indicate the highest R^2 value for the FVS and IFTNC scenarios

Model predictions of accretion aligned much more closely with observed values than mortality (Figure 4). However on average, all models explained less than half of the variation in accretion across all variants. The "Site" SDIMAX scenario produced the closest overall model predictions of accretion compared to observed values, followed by "Max", FVS, and "Mean" (Table 2). However, the FVS scenario predictions had the highest R^2 values out of all the SDIMAX scenarios in the EC variant. The "Site" had the best R^2 in the CI variant, and the "Max" scenario had the highest model R^2 in both the BM and IE variants (Table 2). On an individual basis, some sites had strong deviations in observed accretion depending on model scenario (210, 256, 258, 290) (Appendix B).

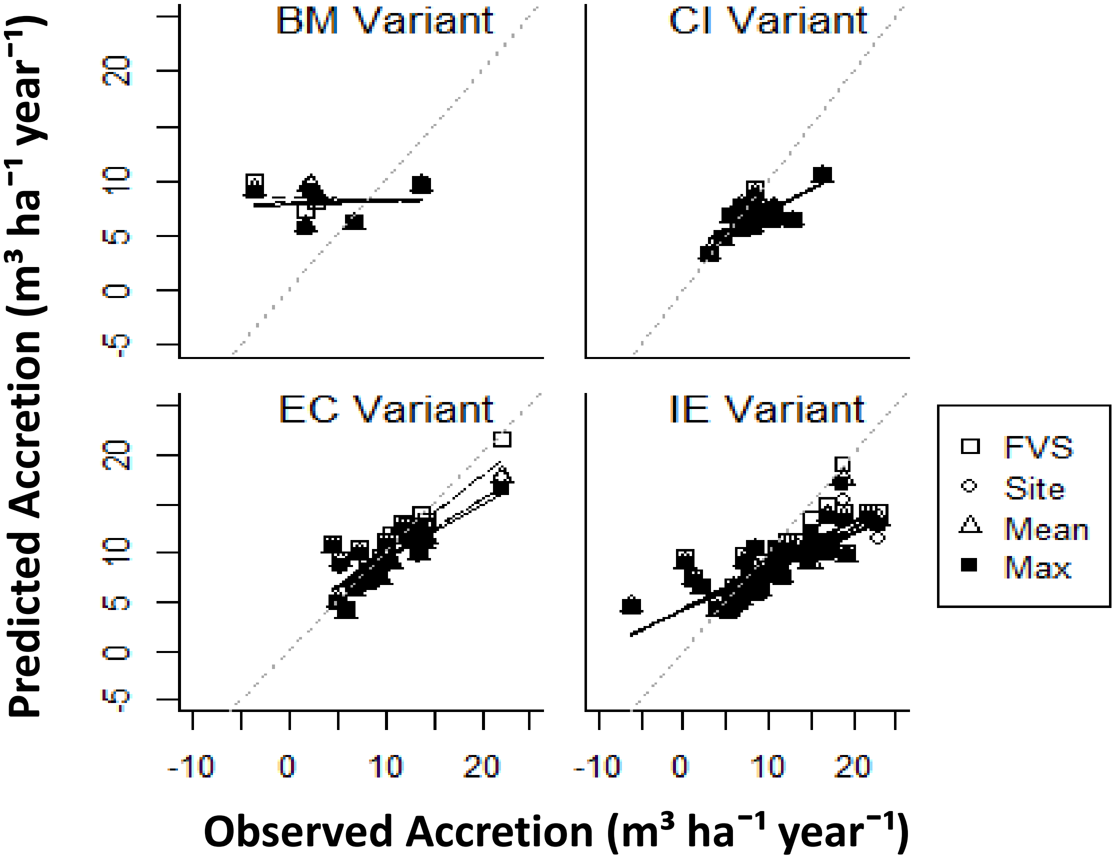

Figure 4. *Observed and FVS predicted accretion over a ten year period by variant for 90 sites in the Pacific Northwest. The fine gray dotted represents a 1:1 relationship and all other lines are regressions from model predictions.*

Table 2. Predicted versus observed accretion R^2 values for each variant and mean R^2 across four variants and SDIMAX scenarios

	BM	CI	EC	IE	Mean
FVS	0.009	0.525	**0.747**	0.626	0.477
Site	0.007	0.600	**0.698**	0.631	0.484
Mean	0.007	0.587	0.682	0.633	0.477
Max	0.017	0.596	0.669	0.642	0.481

Note: Bold values indicate the highest R^2 value for the FVS and IFTNC scenarios

Average dead surface fuels showed the smallest amount of variation between models (Figure 5). The BM and CI variants consistently had the highest amount of surface fuels per hectare. The EC variant had the lowest amount of dead surface fuels, and the IE variant was intermediate (Figure 5). However, there were some cases where there was considerable variation in dead surface fuels. Sites 204, 218, 228, and 255 had dead surface fuel estimates differing from 0.6 to 1.9 metric tons per hectare from FVS default SDIMAX to IFTNC SDIMAX (Appendix B).

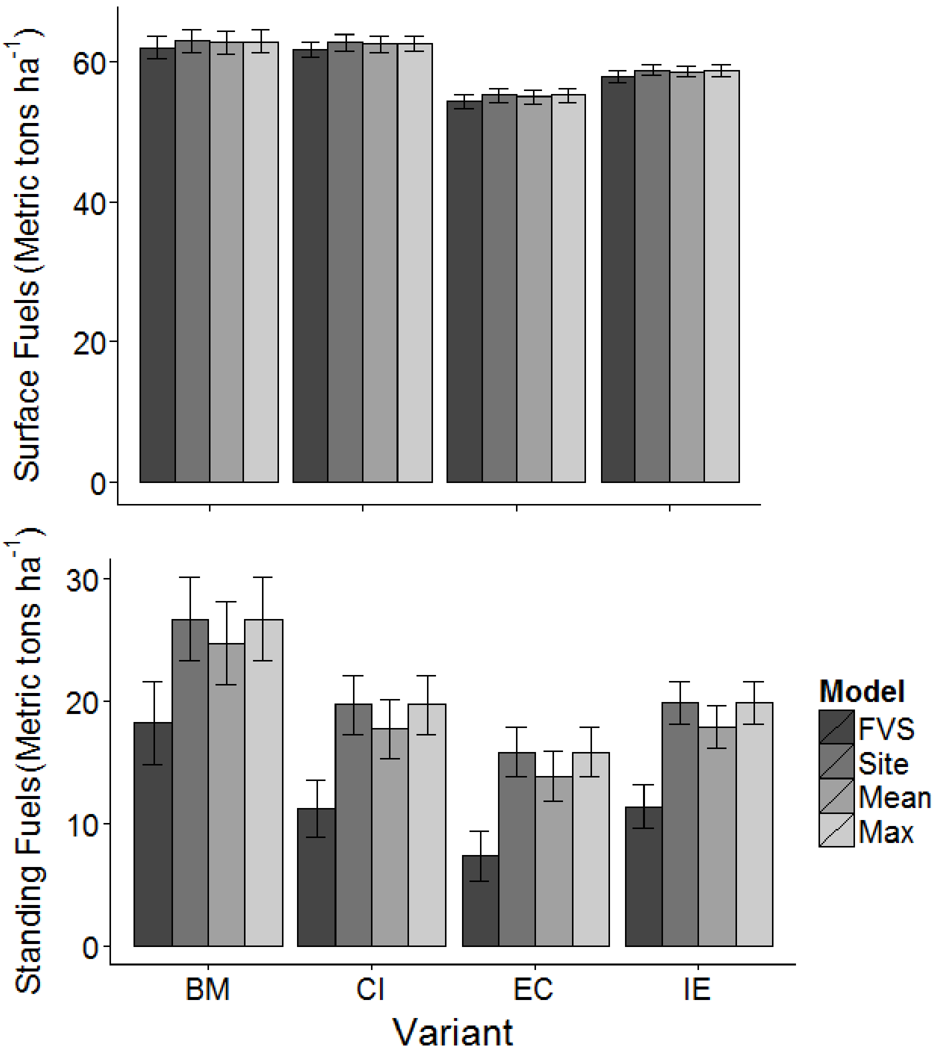

Figure 5. *FVS modeled surface and standing fuel means and standard errors at the end of a ten year period by variant and SDIMAX scenario for 90 sites in the Pacific Northwest.*

Average dead standing fuels demonstrated more drastic differences between the SDIMAX inputs. In all scenarios, the BM variant had the most dead standing fuels at the end of the ten year model period (Figure 5). However, dead standing fuels were drastically higher (greater than 7 metric tons per hectare) using the IFTNC SDIMAX scenarios for the BM variant. In contrast, the EC variant consistently had the lowest amount of dead standing fuels on average between scenarios. The FVS default SDIMAX scenario had much lower predictions of dead standing fuels (11 metric tons per hectare) than the IFTNC scenarios for the EC variant. Both the IE and CI variants showed a similar pattern as the EC variant, although to a lesser degree respectively (Figure 5). Sites 204, 218, and 255 had drastic differences in dead standing fuels by scenario including FVS default SDIMAX predicting 15 metric tons per hectare less than IFTNC scenarios (Appendix B).

Discussion

There are several important points that can be made from this model validation exercise. The first and foremost of which is that SDIMAX is a critical reference point for understanding and predicting a stands stage of growth and how it will behave in the near future (Reineke 1933). In addition, SDIMAX is variable and identifying the correct SDIMAX can drastically improve FVS model predictions of mortality, growth, and fuel loading (Dixon 2002). However if an incorrect SDIMAX is assigned to a stand, then model predictions quickly become inaccurate and meaningless.

This model validation demonstrates that FVS estimates of both mortality and growth need to be improved (Figures 3 and 4). Unfortunately, IFTNC estimates of SDIMAX do not improve FVS predictions of mortality and need further development. However, IFTNC SDIMAX scenarios did produce better predictions of accretion than FVS default SDIMAX (Table 2). While the FVS scenario had the highest model R^2 for predicting mortality in the BM variant, IFTNC R^2 were lower than the other variants, likely because of the smaller sample size in the BM variant. The CI variant had the most similar predictions of mortality across all model scenarios which is surprising because the BM variant had the most similar SDIMAX values (Figure 2). The EC and IE variants had consistently higher model predictions of accretion than the BM or CI variant. This is likely from the larger amount of research sites located in the EC and IE variants (24 and 45 respectively). Another explanation could be the allometric equations which calculate accretion in the EC and IE variants are more accurate than the BM or CI variants. Poor model fits for mortality resulted from FVS modeling background mortality on locations which experienced no mortality over the 10 year period. Finally, more research locations in the BM and CI variants could help alleviate uncertainties in FVS predictions of accretion.

It is important to reiterate that in cases where current stand SDI was greater than 85% of the SDIMAX; FVS automatically readjusted SDIMAX so that SDI is at 85% of SDIMAX (Dixon 2002). This could have several consequences for model validations of SDIMAX. The first is that because SDIMAX is adjusted, current model estimates of SDIMAX are inaccurate, and the actual forest conditions are misrepresented in the model. The second is that model predictions of mortality, accretion, and fuels would likely be worse if SDIMAX wasn't adjusted. For example, if current SDI was greater than 85% of the maximum, FVS would kill off trees so that current stand SDI was at the upper limit of density related mortality (85%) (Dixon 2002). Finally, where SDI was more than 85% of SDIMAX for all model scenarios, comparisons between models will be less meaningful because of the SDIMAX adjustment. The SDIMAX was adjusted on only 3% of sites for the FVS scenario, but from 18% to 26% for the IFTNC SDIMAX scenarios; further emphasizing inaccuracies in IFTNC SDIMAX estimates. This asserts the need for model improvement in these cases because the SDIMAX is likely much too low for that specific site or habitat type.

In addition to mortality and accretion, standing fuels can be drastically changed by SDIMAX (Figure 5). This is of particular value to those using the Fire and Fuels Extension and FVS to model fuels and identify areas which are or will be prone to wildfires (Rebain et al. 2002). Fuels predictions unfortunately were not validated with field measurements and observations. However, where mortality estimates vary between model scenarios, fuels (particularly dead standing fuels) will likewise show variation. Indeed, there is a strong correlation between modeled mortality and the amount of standing fuels in FVS (Figure 6). Using site 255 as an example, modeled total dead surface and standing fuels changed from 64.4 to 66.3 for FVS default SDIMAX to 15.3 to 30.4 Mg ha^{-1} for

IFTNC SDIMAX scenarios (Appendix B). The additional roughly two metric tons per hectare of surface fuels and fifteen metric tons per hectare of standing fuels could drastically change fire behavior if the stand were to experience a fire (Schoennagel et al. 2004). Also, these differences could potentially determine if a site is fuel limited or in need of fuels treatment by land managers. However, fuels measurements at each location would be most useful to compare model estimates.

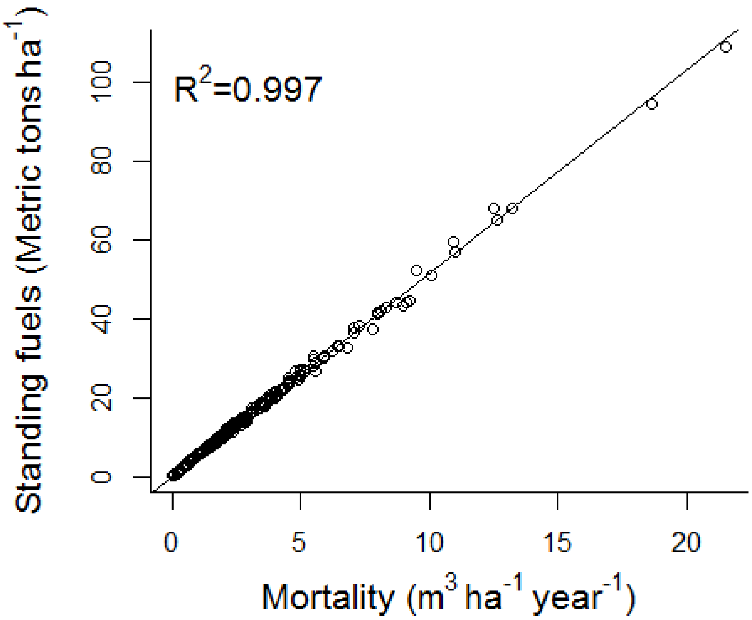

Figure 6. *FVS modeled mortality and standing fuels for all SDIMAX scenarios and variants*

The general trends of the SDIMAX scenarios produced a pattern; FVS overestimates mortality and accretion when observations were relatively low (0-5 m^3 ha^{-1} $year^{-1}$), but underestimates when observed mortality and accretion were relatively high (15-20 m^3 ha^{-1} $year^{-1}$, Figures 3 and 4). Noting the limitations of the data and models is necessary to contextualize the results of this experiment. First, it is evident in some sites that other factors besides density dependent mortality were influencing mortality. Stochastic phenomena such beetle damage, wind events, and disease are much more difficult to predict; so naturally the model will prove inaccurate in these circumstances.

Another limitation in the dataset is the measurement period. Although ten years of data on a plot is enough to capture some mortality and growth, certainly longer time spans are preferable for better understanding the relationship between SDIMAX and mortality. Similarly, this model trial used data from 90 sites which may be considered inadequate to accurately model mortality and growth given the amount of variability in climatic factors, site conditions, etc. Finally, some variants had more sites than others which could be improved with a larger sample size (Tables 1 and 2).

Conclusion

FVS is constantly being used, analyzed, and developed to better provide for researchers and managers using the model. Likewise, the IFTNC model of SDIMAX is still in the early stages of development and needs more validation before it can be applied to management and used to inform other models with confidence. The model testing done in this paper shows preliminary results of an ongoing project intended to inform FVS predictions of mortality and fuels based on SDIMAX. The existing inaccuracies and potential consequences that proper estimates of SDIMAX have for FVS modeling and applications creates the need for further research and development. Locating data sets that include plots with a range of mortality rates and measured surface and standing fuels is a critical step in further model development

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Appendix A

Table A. Basal area, SDI, SDIMAX, and percent of SDIMAX by site, variant, scenario, and habitat type for all 90 sites in the Pacific Northwest.

						FVS		Site		Mean		Max	
		Habitat		BA			% of		% of		% of		% of
Site	**Variant**	**Code**	**Habitat**	**(m^2ha^{-1})**	**SDI**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**
207	BM	11	PSME/PHMA-BLUE	28.0	90	121	74%	155	58%	137	66%	155	58%
239	BM	11	PSME/PHMA-BLUE	52.2	144	114	127%	119	121%	137	105%	155	93%
213	BM	70	ABGR/LIBO2	24.4	74	242	31%	316	23%	316	23%	316	23%
257	BM	83	ABGR/SPBE	45.1	126	185	68%	152	83%	145	87%	152	83%
258	BM	83	ABGR/SPBE	34.2	94	185	51%	138	68%	145	65%	152	62%
212	BM	85	ABGR/AGGL-PHMA	22.4	73	192	38%	147	49%	147	49%	147	49%
			Mean	**34**	**100**	**173**	**65%**	**171**	**67%**	**171**	**66%**	**179**	**61%**
			Standard deviation	**12.0**	**29.0**	**48.2**	**35%**	**72.1**	**33%**	**71.1**	**29%**	**67.0**	**25%**

						FVS		Site		Mean		Max	
		Habitat		BA			% of		% of		% of		% of
Site	**Variant**	**Code**	**Habitat**	**(m^2ha^{-1})**	**SDI**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**	**SDIMAX**
222	CI	260	PSME/PHMA5	27.2	98	192	51%	152	65%	152	65%	152	65%
202	CI	290	PSME/LIBO3	16.3	59	218	27%	118	51%	118	51%	118	51%
223	CI	310	PSME/SYAL	24.8	84	166	51%	148	57%	148	57%	148	57%
280	CI	320	PSME/CARU	37.8	116	122	95%	123	94%	123	94%	123	94%
276	CI	340	PSME/SPBE2	33.3	106	140	76%	146	73%	136	78%	155	69%
277	CI	340	PSME/SPBE2	41.7	132	140	94%	155	85%	136	97%	155	85%
278	CI	340	PSME/SPBE2	23.7	77	140	55%	119	65%	136	57%	155	49%
279	CI	340	PSME/SPBE2	35.9	109	140	78%	122	89%	136	80%	155	70%
244	CI	375	PSME/OSBE	61.0	162	196	82%	122	133%	119	136%	122	133%
245	CI	375	PSME/OSBE	32.7	111	196	56%	117	94%	119	93%	122	91%
203	CI	505	ABGR/SPBE2	24.4	78	299	26%	165	47%	165	47%	165	47%
221	CI	525	ABGR/ACGL	34.4	107	244	44%	194	55%	194	55%	194	55%
201	CI	590	ABGR/LIBO3	33.5	108	211	51%	150	72%	141	77%	150	72%
220	CI	590	ABGR/LIBO3	23.9	81	211	38%	132	61%	141	57%	150	54%
			Mean	**32**	**102**	**187**	**59%**	**140**	**74%**	**140**	**75%**	**147**	**71%**
			Standard deviation	**10.8**	**25.9**	**49.4**	**23%**	**22.5**	**23%**	**20.4**	**24%**	**20.5**	**23%**

Table A. Continued

						FVS		Site		Mean		Max	
Site	Variant	Habitat Code	Habitat	BA (m^2ha^{-1})	SDI	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX
268	EC	5	THPL/CLUN	44.5	148	340	43%	151	98%	149	99%	151	98%
242	EC	11	PSME/CARU-O&C	36.0	124	214	58%	116	107%	119	104%	122	101%
282	EC	11	PSME/CARU-O&C	24.0	85	211	40%	122	70%	119	72%	122	70%
225	EC	20	PSME/ACCI/FEOC	20.9	67	291	23%	149	45%	150	45%	151	44%
248	EC	20	PSME/ACCI/FEOC	26.9	85	291	29%	151	56%	150	57%	151	56%
259	EC	25	PSME/SYAL	40.8	132	192	69%	141	94%	141	94%	141	94%
227	EC	30	PSME/SPBEL	16.7	52	225	23%	164	32%	163	32%	164	32%
228	EC	30	PSME/SPBEL	30.2	96	217	44%	162	59%	163	59%	164	58%
226	EC	38	PSME/PUTR/CARU	23.4	70	150	47%	154	46%	154	46%	154	46%
218	EC	39	PSME/PHMA-O&C	21.1	68	190	36%	120	57%	136	50%	153	45%
289	EC	39	PSME/PHMA-O&C	40.4	139	190	73%	153	91%	136	102%	153	91%
241	EC	41	PSME/VACCI	16.9	61	159	38%	116	52%	117	52%	118	52%
283	EC	41	PSME/VACCI	24.3	86	161	53%	118	73%	117	73%	118	73%
217	EC	44	PSME/VACA	28.0	93	144	65%	143	65%	143	65%	143	65%
262	EC	91	TSHE/PAMY/CLUN	39.8	131	346	38%	247	53%	247	53%	247	53%
229	EC	117	ABGR/ARCO	29.7	81	318	26%	142	57%	142	57%	142	57%
260	EC	124	ABGR/CARU	54.9	158	364	43%	174	91%	177	89%	180	88%
263	EC	124	ABGR/CARU	44.5	131	364	36%	180	73%	177	74%	180	73%
261	EC	132	ABGR/BENE	48.6	148	342	43%	152	97%	153	97%	153	97%
224	EC	137	ABGR/SYAL/CARU	57.2	154	235	66%	191	80%	177	87%	191	80%
249	EC	137	ABGR/SYAL/CARU	39.4	122	235	52%	163	75%	177	69%	191	64%
215	EC	140	ABGR/PHMA	15.3	57	233	24%	151	38%	151	38%	151	38%
230	EC	149	ABGR/ACCI-WEN	27.3	82	295	28%	212	39%	212	39%	212	39%
			Mean	**33**	**103**	**248**	**43%**	**155**	**67%**	**155**	**67%**	**159**	**66%**
			Standard deviation	**12.2**	**34.5**	**72.3**	**15%**	**31.3**	**22%**	**30.5**	**22%**	**30.8**	**21%**

Table A. Continued

						FVS			IFTNC 1			IFTNC 2			IFTNC 3	
Site	**Variant**	**Habitat Code**	**Habitat**	**BA (m^{2}ha^{-1})**	**SDI**	**SDIMAX**	**% of SDIMAX**		**SDIMAX**	**% of SDIMAX**		**SDIMAX**	**% of SDIMAX**		**SDIMAX**	**% of SDIMAX**
266	IE	250	PSME/VACA	25.4	86	218	40%		138	62%		145	60%		161	54%
267	IE	250	PSME/VACA	28.6	90	218	41%		136	66%		145	62%		161	56%
209	IE	260	PSME/PHMA	34.6	108	271	40%		140	77%		141	77%		164	66%
210	IE	260	PSME/PHMA	30.5	101	271	37%		164	61%		141	71%		164	61%
216	IE	260	PSME/PHMA	36.1	117	271	43%		148	79%		141	83%		164	71%
233	IE	260	PSME/PHMA	31.4	92	271	34%		118	78%		141	65%		164	56%
235	IE	260	PSME/PHMA	19.9	69	271	25%		120	57%		141	49%		164	42%
236	IE	260	PSME/PHMA	33.7	112	271	41%		103	108%		141	79%		164	68%
243	IE	260	PSME/PHMA	32.9	104	271	38%		162	64%		141	74%		164	63%
247	IE	260	PSME/PHMA	27.8	88	271	32%		153	57%		141	62%		164	54%
275	IE	260	PSME/PHMA	36.3	120	271	44%		160	75%		141	85%		164	73%
290	IE	260	PSME/PHMA	44.6	149	271	55%		141	106%		141	106%		164	91%
232	IE	310	PSME/SYAL	32.4	100	271	37%		138	73%		145	69%		218	46%
234	IE	310	PSME/SYAL	32.2	100	271	37%		131	76%		145	69%		218	46%
238	IE	310	PSME/SYAL	12.9	50	271	18%		181	28%		145	34%		218	23%
246	IE	310	PSME/SYAL	23.1	87	271	32%		146	59%		145	60%		218	40%
251	IE	310	PSME/SYAL	38.0	130	271	48%		128	102%		145	89%		218	60%
269	IE	310	PSME/SYAL	36.9	118	271	44%		143	83%		145	81%		218	54%
271	IE	310	PSME/SYAL	39.9	143	271	53%		218	65%		145	98%		218	66%
284	IE	310	PSME/SYAL	25.5	81	271	30%		110	73%		145	55%		218	37%
285	IE	310	PSME/SYAL	31.2	95	271	35%		115	83%		145	65%		218	43%
270	IE	320	PSME/CARU	24.0	80	271	30%		132	61%		132	61%		132	61%
237	IE	330	PSME/CAGE	40.0	123	174	71%		115	108%		115	108%		115	108%
231	IE	340	PSME/SPBE	20.8	67	271	25%		105	64%		105	64%		105	64%
208	IE	506	ABGR/PHMA	40.3	117	288	41%		155	76%		147	80%		155	76%
211	IE	506	ABGR/PHMA	38.1	134	288	46%		137	98%		147	91%		155	86%
288	IE	506	ABGR/PHMA	60.9	179	288	62%		149	120%		147	121%		155	115%

Table A. Continued

						FVS		IFTNC 1		IFTNC 2		IFTNC 3	
Site	Variant	Habitat Code	Habitat	BA (m^2ha^{-1})	SDI	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX	SDIMAX	% of SDIMAX
255	IE	520	ABGR/CLUN	43.7	160	332	48%	177	90%	153	104%	177	90%
274	IE	520	ABGR/CLUN	31.6	97	332	29%	142	68%	153	63%	177	55%
286	IE	520	ABGR/CLUN	49.7	144	332	43%	141	103%	153	94%	177	81%
264	IE	530	THPL/CLUN	50.1	169	384	44%	224	76%	187	90%	223	76%
265	IE	530	THPL/CLUN	38.4	127	384	33%	151	84%	187	68%	223	57%
204	IE	545	THPL/ASCA	27.2	90	384	24%	174	52%	195	46%	220	41%
205	IE	545	THPL/ASCA	24.5	79	384	20%	187	42%	195	40%	220	36%
206	IE	545	THPL/ASCA	27.4	88	384	23%	178	49%	195	45%	220	40%
240	IE	545	THPL/ASCA	34.4	112	384	29%	195	57%	195	57%	220	51%
250	IE	545	THPL/ASCA	29.7	104	384	27%	156	66%	195	53%	220	47%
253	IE	545	THPL/ASCA	49.8	146	384	38%	193	75%	195	75%	220	66%
254	IE	545	THPL/ASCA	20.5	86	384	22%	218	39%	195	44%	220	39%
256	IE	545	THPL/ASCA	43.3	152	384	39%	220	69%	195	78%	220	69%
273	IE	545	THPL/ASCA	32.9	113	384	29%	219	51%	195	58%	220	51%
281	IE	545	THPL/ASCA	47.8	161	384	42%	206	78%	195	83%	220	73%
272	IE	590	ABGR/LIBO	33.4	127	288	44%	189	67%	186	69%	189	67%
287	IE	590	ABGR/LIBO	40.1	139	288	48%	182	76%	186	75%	189	73%
			Mean	**34**	**112**	**303**	**38%**	**158**	**73%**	**158**	**72%**	**188**	**61%**
			Standard deviation	**9.5**	**29.44198406**	**56.1**	**11%**	**33.7**	**19%**	**25.2**	**19%**	**33.0**	**19%**

Appendix B

Table B. Observed and modeled mortality and accretion ($m^3 ha^{-1} year^{-1}$), and total dead surface and standing fuels ($Mg\ ha^{-1}$) by site, variant, scenario, and habitat type for all 90 sites in the Pacific Northwest.

				Observed		FVS				Site				Mean				Max			
Site	Variant	Habitat Code	Habitat	Mort	Acc	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels
239	BM	11	PSME/PHMA-BLUE	0.4	13.8	12.5	9.6	62.6	68.2	12.5	9.6	63.9	68.1	12.5	9.7	64.0	67.9	12.5	9.7	64.0	67.9
207	BM	11	PSME/PHMA-BLUE	6.3	2.1	2.4	9.1	53.0	13.2	1.7	9.7	53.3	9.0	2.2	9.2	53.3	12.2	1.7	9.7	53.3	9.0
213	BM	70	ABGR/LIBO2	2.9	2.9	0.4	8.1	96.4	2.1	0.4	8.3	96.9	2.1	0.4	8.3	96.9	2.1	0.4	8.3	96.9	2.1
257	BM	83	ABGR/SPBE	6.4	1.6	3.1	7.3	58.1	17.2	9.5	5.9	60.0	52.1	10.9	5.7	60.4	59.6	9.5	5.9	60.0	52.1
258	BM	83	ABGR/SPBE	11.4	-3.6	1.2	9.9	55.0	6.5	3.7	9.0	55.2	19.8	3.6	9.0	55.3	18.8	3.4	9.1	55.4	18.1
212	BM	85	ABGR/AGGL-PHMA	0.0	6.7	0.1	6.2	47.1	0.5	0.6	6.0	47.0	3.0	0.6	6.0	47.0	3.0	0.6	6.0	47.0	3.0
			Variant Average	**4.6**	**3.9**	**3.3**	**8.4**	**62.0**	**17.9**	**4.7**	**8.1**	**62.7**	**25.7**	**5.0**	**8.0**	**62.8**	**27.3**	**4.7**	**8.1**	**62.8**	**25.4**
			Variant St. Dev.	**4.4**	**5.9**	**4.7**	**1.4**	**17.6**	**25.4**	**5.1**	**1.7**	**17.7**	**27.9**	**5.3**	**1.7**	**17.7**	**29.0**	**5.1**	**1.7**	**17.7**	**27.9**

				Observed		FVS				IFTNC 1				IFTNC 2				IFTNC 3			
Site	Variant	Habitat Code	Habitat	Mort	Acc	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels
222	CI	260	PSME/PHMA5	0.0	8.0	2.2	5.9	59.1	12.3	2.4	5.8	59.2	13.4	2.4	5.8	59.2	13.4	2.4	5.8	59.2	13.4
219	CI	260	PSME/PHMA5	0.0	6.6	1.3	5.5	55.4	6.8	1.4	5.4	55.5	7.8	1.4	5.4	55.5	7.8	1.4	5.4	55.5	7.8
202	CI	290	PSME/LIBO3	0.0	4.6	0.3	4.8	51.9	1.7	0.7	4.6	52.2	4.1	0.7	4.6	52.2	4.1	0.7	4.6	52.2	4.1
223	CI	310	PSME/SYAL	0.0	9.1	1.5	7.3	62.5	8.0	1.7	7.1	62.7	9.6	1.7	7.1	62.7	9.6	1.7	7.1	62.7	9.6
280	CI	320	PSME/CARU	0.0	10.7	5.6	7.5	67.3	28.8	5.6	7.5	67.3	28.8	5.6	7.5	67.3	28.8	5.6	7.5	67.3	28.8
277	CI	340	PSME/SPBE2	0.0	16.4	7.3	10.5	70.0	38.1	7.3	10.5	70.0	38.4	7.3	10.5	70.0	38.1	7.3	10.5	70.0	38.4
279	CI	340	PSME/SPBE2	0.0	10.6	4.5	7.1	66.8	23.6	5.9	6.7	67.6	30.6	4.8	7.1	67.0	25.0	3.8	7.3	66.4	19.4
276	CI	340	PSME/SPBE2	0.0	10.2	3.5	6.5	65.6	18.8	3.2	6.6	65.4	17.5	3.6	6.4	65.7	19.6	3.0	6.7	65.3	16.2
278	CI	340	PSME/SPBE2	1.3	6.9	2.0	7.6	60.3	10.3	2.7	7.3	60.8	14.1	2.1	7.6	60.4	10.9	1.7	7.8	60.1	8.5
244	CI	375	PSME/OSBE	0.0	12.7	8.0	6.4	71.9	41.5	8.3	6.4	72.0	42.7	8.3	6.4	72.0	42.7	8.3	6.4	72.0	42.7
245	CI	375	PSME/OSBE	2.2	3.1	2.1	3.3	65.0	12.3	2.3	3.3	65.1	13.2	2.3	3.3	65.1	13.2	2.3	3.3	65.1	13.2
203	CI	505	ABGR/SPBE2	0.0	7.4	0.6	7.0	60.1	3.1	1.4	6.7	60.6	7.0	1.4	6.7	60.6	7.0	1.4	6.7	60.6	7.0
221	CI	525	ABGR/ACGL	0.6	8.0	2.5	6.5	60.1	13.0	2.7	6.5	60.3	14.2	2.7	6.5	60.3	14.2	2.7	6.5	60.3	14.2
220	CI	590	ABGR/LIBO3	0.0	5.7	1.5	6.9	57.4	8.0	2.1	6.6	57.8	11.3	2.0	6.7	57.7	10.5	1.8	6.7	57.6	9.9
201	CI	590	ABGR/LIBO3	0.7	8.3	1.9	9.3	59.7	10.3	3.4	8.7	60.6	18.5	3.8	8.5	60.9	20.7	3.4	8.7	60.6	18.5
			Variant Average	**0.3**	**8.5**	**3.0**	**6.8**	**62.2**	**15.8**	**3.4**	**6.7**	**62.5**	**18.1**	**3.4**	**6.7**	**62.4**	**17.7**	**3.2**	**6.7**	**62.3**	**16.8**
			Variant St. Dev.	**0.7**	**3.3**	**2.4**	**1.7**	**5.5**	**12.1**	**2.3**	**1.7**	**5.4**	**11.7**	**2.2**	**1.6**	**5.4**	**11.5**	**2.2**	**1.7**	**5.4**	**11.4**

Table B. Continued

				Observed		FVS				IFTNC 1				IFTNC 2				IFTNC 3			
Site	Variant	Habitat_ Code	Habitat	Mort	Acc	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels
268	EC	5	THPL/CLUN	0.0	13.9	0.1	12.5	57.2	0.4	3.6	11.1	59.8	17.9	3.6	11.1	59.8	17.8	3.6	11.1	59.8	17.9
214	EC	5	THPL/CLUN	0.0	11.6	0.1	13.1	47.1	0.3	1.0	12.2	47.5	5.4	0.9	12.3	47.4	4.9	0.8	12.4	47.4	4.4
242	EC	11	PSME/CARU-O&C	0.4	6.0	0.5	4.3	58.4	2.7	1.7	4.0	59.2	9.2	1.7	4.0	59.2	9.2	1.7	4.0	59.2	9.2
282	EC	11	PSME/CARU-O&C	0.0	8.3	0.1	8.3	55.9	0.3	1.4	7.6	57.1	7.4	1.3	7.6	57.0	7.1	1.4	7.6	57.1	7.4
248	EC	20	PSME/ACCI/FEOC	0.0	13.6	0.1	13.9	56.0	0.3	2.4	12.4	57.6	12.8	2.4	12.5	57.6	12.5	2.4	12.4	57.6	12.8
225	EC	20	PSME/ACCI/FEOC	0.0	9.5	0.1	9.6	51.2	0.2	0.6	9.2	51.4	3.5	0.6	9.2	51.3	3.1	0.6	9.3	51.3	2.9
259	EC	25	PSME/SYAL	0.0	8.0	1.6	8.7	57.6	8.6	4.0	8.0	59.4	21.4	4.0	8.0	59.4	21.4	4.0	8.0	59.4	21.4
227	EC	30	PSME/SPBEL	0.0	5.1	0.1	5.0	42.2	0.2	0.1	5.0	42.1	0.2	0.1	5.0	42.1	0.2	0.1	5.0	42.1	0.2
228	EC	30	PSME/SPBEL	2.5	7.2	0.1	10.5	52.7	0.6	1.5	9.8	53.6	7.9	1.5	9.8	53.6	7.6	1.4	9.9	53.6	7.3
226	EC	38	PSME/PUTR/CARU	0.0	7.0	0.2	6.7	49.5	1.1	0.1	6.8	49.4	0.3	0.1	6.8	49.2	0.3	0.1	6.8	49.4	0.3
289	EC	39	PSME/PHMA-O&C	0.0	14.0	1.4	12.7	61.4	7.4	3.5	11.8	63.2	18.2	3.5	11.7	63.2	18.1	3.5	11.8	63.2	18.2
218	EC	39	PSME/PHMA-O&C	1.7	5.3	0.1	9.4	50.6	0.2	1.4	8.5	51.3	7.4	1.3	8.6	51.3	6.6	0.5	9.1	50.8	2.7
283	EC	41	PSME/VACCI	0.0	8.1	1.2	7.1	54.1	6.5	1.3	7.1	54.2	6.9	1.3	7.1	54.2	6.9	1.3	7.1	54.2	6.9
241	EC	41	PSME/VACCI	0.0	6.6	0.0	6.6	46.7	0.2	0.9	6.1	47.2	5.0	0.9	6.1	47.1	4.9	0.8	6.1	47.1	4.7
217	EC	44	PSME/VACA	0.0	9.3	1.7	8.7	55.0	8.6	1.6	8.7	55.0	8.5	1.6	8.7	55.0	8.5	1.6	8.7	55.0	8.5
262	EC	91	TSHE/PAMY/CLUN	6.9	4.6	0.3	10.9	55.7	1.3	1.2	10.6	56.4	6.1	1.2	10.6	56.4	6.1	1.2	10.6	56.4	6.1
229	EC	117	ABGR/ARCO	0.0	12.4	0.1	12.7	47.9	0.5	2.7	11.6	48.4	14.5	2.7	11.6	48.4	14.5	2.7	11.6	48.4	14.5
263	EC	124	ABGR/CARU	0.0	14.2	0.1	13.3	59.7	0.6	5.0	11.5	61.7	26.9	5.5	11.3	61.9	29.6	5.0	11.5	61.7	26.9
260	EC	124	ABGR/CARU	3.9	10.6	0.3	12.0	61.4	1.4	11.0	9.4	66.1	56.8	13.2	8.9	67.1	68.2	12.6	9.0	66.8	64.8
261	EC	132	ABGR/BENE	0.0	9.6	0.1	8.8	57.2	0.7	7.1	7.4	61.0	36.4	7.1	7.4	61.0	36.4	7.1	7.4	61.0	36.4
224	EC	137	ABGR/SYAL/CARU	1.1	22.0	10.1	21.6	63.5	51.1	18.6	17.7	67.2	94.2	21.5	16.4	68.4	108.8	18.6	17.7	67.2	94.2
249	EC	137	ABGR/SYAL/CARU	1.2	13.3	1.1	10.4	55.8	5.7	2.9	9.6	56.8	15.0	2.0	9.9	56.3	10.0	2.0	9.9	56.3	10.5
215	EC	140	ABGR/PHMA	0.0	10.0	0.0	11.1	49.6	0.2	0.3	10.8	49.6	1.7	0.3	10.8	49.6	1.7	0.3	10.8	49.6	1.7
230	EC	149	ABGR/ACCI-WEN	0.0	12.6	0.1	11.1	49.1	0.5	0.1	11.1	48.9	0.5	0.1	11.1	48.9	0.5	0.1	11.1	48.9	0.5
			Variant Average	**0.7**	**10.1**	**0.8**	**10.4**	**54.0**	**4.2**	**3.1**	**9.5**	**55.2**	**16.0**	**3.3**	**9.4**	**55.2**	**16.9**	**3.1**	**9.5**	**55.2**	**15.8**
			Variant St. Dev.	**1.6**	**4.0**	**2.0**	**3.6**	**5.4**	**10.4**	**4.1**	**2.9**	**6.4**	**21.1**	**4.8**	**2.7**	**6.6**	**24.6**	**4.3**	**2.9**	**6.5**	**22.0**

Table B. Continued

				Observed		FVS				IFTNC 1				IFTNC 2				IFTNC 3			
Site	Variant	Habitat_ Code	Habitat	Mort	Acc	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels
267	IE	250	PSME/VACA	0.0	9.0	1.5	7.9	52.2	8.2	3.3	7.3	53.1	17.1	2.9	7.5	52.9	15.3	2.4	7.6	52.7	12.9
252	IE	250	PSME/VACA	0.9	4.5	2.4	4.2	59.5	11.5	2.7	4.1	59.7	13.1	2.9	4.1	59.8	14.0	2.7	4.1	59.7	13.1
266	IE	250	PSME/VACA	0.0	6.3	1.3	5.1	53.7	7.1	1.9	5.0	54.1	10.2	1.8	5.0	54.0	9.7	1.6	5.0	53.9	8.7
275	IE	260	PSME/PHMA	0.0	9.0	2.6	6.3	60.0	13.7	3.4	6.1	60.4	17.5	3.8	5.9	60.7	20.0	3.3	6.1	60.4	17.1
236	IE	260	PSME/PHMA	0.2	5.1	1.7	4.1	59.3	9.2	2.5	4.0	59.8	13.6	2.4	4.0	59.7	12.7	2.0	4.1	59.5	11.0
233	IE	260	PSME/PHMA	0.0	8.5	1.3	7.3	52.2	6.8	4.5	6.4	53.8	23.3	3.3	6.8	53.2	17.1	2.5	7.0	52.8	13.3
247	IE	260	PSME/PHMA	0.3	8.0	1.5	5.9	51.8	7.5	2.2	5.8	52.2	11.5	2.5	5.7	52.4	12.9	2.1	5.8	52.2	10.7
209	IE	260	PSME/PHMA	1.3	9.9	2.0	8.5	58.1	10.6	5.0	7.7	59.8	25.9	5.0	7.7	59.7	25.7	3.9	8.0	59.1	20.1
235	IE	260	PSME/PHMA	0.1	3.9	0.6	4.2	49.2	3.2	1.1	4.1	49.6	6.1	0.9	4.1	49.4	5.0	0.8	4.1	49.3	4.3
216	IE	260	PSME/PHMA	2.2	8.2	2.4	6.9	59.8	12.1	4.1	6.5	60.8	20.8	4.3	6.4	60.9	22.2	3.6	6.6	60.5	18.1
243	IE	260	PSME/PHMA	2.8	7.9	1.9	8.7	56.9	10.0	3.6	8.1	57.9	18.7	4.5	7.8	58.4	23.4	3.6	8.1	57.8	18.4
290	IE	260	PSME/PHMA	10.7	0.3	3.8	9.7	63.4	20.1	6.4	9.0	64.8	33.1	6.4	9.0	64.8	33.1	6.4	9.0	64.8	33.1
210	IE	260	PSME/PHMA	13.8	-6.2	2.0	4.6	55.9	10.5	2.1	4.5	56.0	11.3	2.3	4.5	56.1	12.3	2.1	4.5	56.0	11.3
251	IE	310	PSME/SYAL	0.0	5.6	1.5	4.6	60.2	8.0	2.7	4.4	60.9	14.1	2.9	4.4	61.1	15.2	1.7	4.6	60.4	9.4
232	IE	310	PSME/SYAL	0.0	11.3	1.4	10.3	54.9	7.2	4.6	9.0	56.6	24.2	4.2	9.1	56.4	22.1	2.0	10.0	55.2	10.5
234	IE	310	PSME/SYAL	0.0	12.3	1.3	11.1	53.1	6.7	4.9	9.4	55.0	24.6	4.1	9.9	54.6	20.3	2.0	10.8	53.4	9.7
269	IE	310	PSME/SYAL	0.1	6.2	1.3	4.9	59.4	6.7	2.8	4.5	60.4	15.2	2.7	4.5	60.3	14.8	1.5	4.8	59.6	8.4
285	IE	310	PSME/SYAL	0.0	6.7	0.9	5.4	52.3	5.0	3.4	4.8	53.7	18.4	2.3	5.1	53.0	12.1	1.2	5.3	52.5	6.5
284	IE	310	PSME/SYAL	0.0	5.9	0.5	6.6	50.3	2.8	2.7	5.7	51.7	14.6	1.5	6.1	51.0	8.6	0.8	6.4	50.5	4.1
238	IE	310	PSME/SYAL	0.0	5.9	0.2	5.4	43.5	0.9	0.3	5.3	43.5	1.4	0.3	5.2	43.6	1.8	0.2	5.4	43.5	1.1
246	IE	310	PSME/SYAL	1.1	8.5	0.7	7.5	54.8	3.9	1.6	7.0	55.4	8.8	1.6	7.0	55.4	8.8	0.9	7.3	55.0	5.0
271	IE	310	PSME/SYAL	7.1	1.0	2.2	7.6	62.3	11.1	2.8	7.4	62.7	14.0	4.0	7.1	63.3	19.9	2.8	7.4	62.7	14.0
270	IE	320	PSME/CARU	0.0	5.8	0.5	5.6	51.7	2.6	1.4	5.2	52.3	7.8	1.4	5.2	52.3	7.8	1.4	5.2	52.3	7.8
237	IE	330	PSME/CAGE	0.0	8.5	3.8	6.9	61.1	19.5	5.1	6.6	61.9	26.4	5.1	6.6	61.9	26.4	5.1	6.6	61.9	26.4
231	IE	340	PSME/SPBE	0.0	5.5	0.5	5.3	46.4	2.5	1.6	4.9	47.1	8.8	1.6	4.9	47.1	8.8	1.6	4.9	47.1	8.8
288	IE	506	ABGR/PHMA	1.6	17.2	6.8	11.1	64.3	32.8	9.2	10.6	65.4	44.4	9.2	10.6	65.4	44.4	9.2	10.6	65.4	44.4
211	IE	506	ABGR/PHMA	0.6	14.9	2.2	10.4	61.8	12.3	4.8	9.1	63.6	26.6	4.8	9.1	63.6	26.6	5.0	9.0	63.6	27.2
208	IE	506	ABGR/PHMA	3.8	7.0	3.1	9.9	59.6	16.2	5.9	9.1	60.9	30.1	6.4	9.0	61.2	33.1	5.9	9.1	60.9	30.1

Table B. Continued

				Observed		FVS				IFTNC 1				IFTNC 2				IFTNC 3			
Site	Variant	Habitat_ Code	Habitat	Mort	Acc	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels	Mort	Acc	Surface fuels	Standing fuels
286	IE	520	ABGR/CLUN	0.9	13.6	4.1	11.3	63.0	20.9	8.7	10.1	65.2	44.3	8.7	10.1	65.2	44.3	8.0	10.3	64.9	41.2
274	IE	520	ABGR/CLUN	0.5	10.8	1.5	10.5	54.3	7.5	4.3	9.3	55.9	22.6	3.8	9.5	55.6	20.0	3.0	9.9	55.2	15.9
255	IE	520	ABGR/CLUN	5.6	15.0	2.8	13.4	64.4	15.3	5.5	11.8	66.3	30.4	5.5	11.8	66.3	30.4	5.5	11.8	66.3	30.4
264	IE	530	THPL/CLUN	2.3	11.4	8.0	8.6	68.1	41.1	8.0	8.5	68.2	41.5	8.1	8.5	68.3	42.0	8.0	8.5	68.2	41.5
265	IE	530	THPL/CLUN	0.0	22.9	2.4	14.2	61.7	12.6	7.1	11.5	64.6	37.7	5.1	12.7	63.3	27.0	4.0	13.3	62.7	21.1
281	IE	545	THPL/ASCA	0.3	17.1	5.2	10.4	65.2	26.6	6.2	10.1	65.8	31.8	6.5	9.9	65.9	33.3	5.9	10.1	65.6	30.4
256	IE	545	THPL/ASCA	0.8	19.1	4.1	10.0	64.4	21.7	5.0	9.7	64.9	25.6	5.5	9.5	65.1	28.0	5.0	9.7	64.9	25.6
253	IE	545	THPL/ASCA	2.9	21.8	5.6	14.3	64.3	26.9	9.1	13.3	65.9	44.0	9.0	13.4	65.8	43.5	7.8	13.7	65.3	37.5
240	IE	545	THPL/ASCA	0.0	19.0	2.2	14.3	60.8	11.5	4.1	13.2	61.9	21.7	4.2	13.2	61.9	21.9	3.6	13.6	61.6	18.6
206	IE	545	THPL/ASCA	0.0	14.5	1.4	9.9	55.5	7.4	2.4	9.4	56.1	12.5	2.2	9.6	55.9	11.3	1.9	9.7	55.8	10.0
205	IE	545	THPL/ASCA	0.0	15.8	0.9	11.1	53.1	4.9	1.8	10.6	53.6	9.5	1.7	10.6	53.6	9.0	1.5	10.8	53.4	7.7
254	IE	545	THPL/ASCA	0.0	15.1	0.8	10.1	58.9	4.5	1.0	9.9	59.0	5.8	1.1	9.7	59.1	6.4	1.0	9.9	59.0	5.8
250	IE	545	THPL/ASCA	1.7	18.7	1.1	19.0	60.0	6.0	4.5	15.3	62.1	24.8	3.1	16.9	61.2	16.7	2.5	17.5	60.8	13.6
273	IE	545	THPL/ASCA	2.6	17.1	1.6	14.9	60.4	8.4	2.9	13.9	61.3	15.3	3.5	13.5	61.6	18.1	2.9	13.9	61.3	15.2
204	IE	545	THPL/ASCA	2.8	8.4	1.3	10.6	57.3	7.1	2.4	10.0	57.9	13.1	2.1	10.2	57.7	11.4	1.9	10.4	57.6	10.0
287	IE	590	ABGR/LIBO	0.2	11.6	4.1	7.6	63.2	21.7	4.5	7.4	63.5	24.0	4.5	7.4	63.5	23.8	4.5	7.5	63.4	23.7
272	IE	590	ABGR/LIBO	5.5	2.1	2.0	6.6	60.0	9.9	2.7	6.4	60.4	13.1	2.7	6.4	60.4	13.3	2.7	6.4	60.4	13.1
			Variant Average	**1.6**	**10.0**	**2.2**	**8.7**	**57.8**	**11.6**	**3.9**	**8.1**	**58.8**	**20.4**	**3.8**	**8.1**	**58.7**	**19.9**	**3.3**	**8.3**	**58.4**	**17.0**
			Variant St. Dev.	**2.9**	**6.0**	**1.7**	**3.4**	**5.4**	**8.4**	**2.2**	**2.9**	**5.5**	**10.9**	**2.2**	**3.0**	**5.6**	**10.8**	**2.2**	**3.1**	**5.6**	**11.0**