THE EFFECTS OF SITE PREPARATION ON THE LONG TERM GROWTH AND PRODUCTIVITY OF INTERIOR DOUGLAS-FIR AND WESTERN WHITE PINE

A Thesis
Presented in Partial Fulfillment of the Requirements for the
Degree of Master of Science
with a
Major in Natural Resources
in the
College of Graduate Studies
University of Idaho

By
Jonathan R. Cherico

Major Professor: Andrew Nelson, Ph.D.

Committee Members: Theresa Jain, Ph.D., Mark Coleman, Ph.D.

Department Administrator: P. Charles Goebel, Ph.D.

August 2018

AUTHORIZATION TO SUBMIT THESIS

The thesis of Jonathan R. Cherico, submitted for the degree of Master of Science with a major in Natural Resources and titled, "THE EFFECTS OF SITE PREPARATION ON THE LONG TERM GROWTH AND PRODUCTIVITY OF INTERIOR DOUGLAS-FIR AND WESTERN WHITE PINE," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ____________________________________ Date: _______________
Andrew Nelson, Ph.D.

Committee Members: ____________________________________ Date: _______________
Theresa Jain, Ph.D.

____________________________________ Date: _______________
Mark Coleman, Ph.D.

Department Administrator: ____________________________________ Date: _______________
P. Charles Goebel, Ph.D.

ABSTRACT

Silvicultural treatments applied prior to regeneration or during early stages of stand development can affect tree and stand productivity throughout the rotation. Most studies rarely extend observations beyond the first decade after treatment, limiting our ability to properly assess long-term treatment efficacy. This is especially true in forests of the Inland Northwest. In 1982, a study was initiated on the Priest River Experimental Forest in northern Idaho to test the effects of different mechanical and chemical site preparation treatments on regeneration performance of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and western white pine (*Pinus monticola* Dougl. ex. D. Don).

The study was replicated at two sites: a high elevation site and a low elevation site. Within each site four treatments were replicated 3 or 4 times, including (1) organic horizon removal and mineral exposure (scalping), (2) mixed organic and mineral soil bedding without competition removal, (3) mixed organic and mineral soil bedding with chemical competition control, and (4) an untreated control. The objective of the study was to examine temporal trends in tree growth and growth efficiency to determine if tree productivity was substantially altered by the type of site preparation. Data collection occurred in the summer of 2017, 35 years after treatment. Seventy-five trees were destructively sampled to reconstruct patterns of stem height, diameter, and volume growth, as well as estimate growth efficiency at age 35. The combined bedding and herbicide treatment consistently increased cumulative stem size over time compared to the three other treatments, while scalping and bedding treatments at times resulted in decreased growth and productivity compared to the untreated control. Site preparation treatments did not significantly impact tree leaf area or growth efficiency for either tree species compared to the untreated control. Results of these studies provide a mechanistic context for the growth and productivity of *P. menziesii* and *P. monticola* in early maturity and provides evidence that chemical vegetation control can shift tree growth trajectories that last well beyond the first decade of development.

ACKNOWLEDGEMENTS

Above all, I must thank Andrew Nelson for his endless support throughout my tenure at the University of Idaho. His guidance and mentoring has opened opportunities that were unimaginable to me before I started at the University of Idaho. All aspects of this thesis would not have been completed without his assistance and vision. My committee members, Terrie Jain and Mark Coleman both have provided me with insight and opportunities to improve this thesis and research. Gus Reely was instrumental in acclimating me to leading my own research and implementing protocols in the field.

The data for this thesis could not be collected and analyzed without the help of many people. Charles Register relocated from southwest Georgia for the summer of 2017 to assist in field data collection, sharing a cabin with me for four days a week. Without his patience and willingness to go far above his job requirements, the field season could have encountered many more difficulties. Field samples were processed and analyzed with the help of Aaron Melville, Josh Mullane, and Casey Danly. Aaron's efficiency and precision in processing foliage samples were essential to the timely completion of my first chapter's analysis. Josh spent countless hours processing over 1500 stem samples and troubleshooting issues with sanding equipment.

Mark Kimsey was instrumental in assisting my data analysis by writing a grant for tree ring analysis software, which dramatically reduced my time processing and analyzing data. Grant Harley provided me with a belt sander that was essential to processing field samples over a three month period. Armando Macdonald provided me with lab space to process samples for seven months, and tolerated the noise and sawdust associated with sample processing. I am incredibly grateful to these professors, researchers, students, coworkers, and friends who facilitated the completion of an otherwise insurmountable task.

DEDICATION

To my friends in Moscow, who embraced me when I moved from Connecticut, and to my friends and family back home who never lost touch.

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CHAPTER I

INTRODUCTION TO MOIST FORESTS OF THE NORTHERN ROCKIES AND SITE PREPARATION

1.1 The maritime influenced forests of the Northern Rocky Mountain Province

The Northern Rocky Mountain Forest-Steppe – Coniferous Forest – Alpine Meadow Province extends from central Washington through western Montana, encompassing the majority of the Inland Northwest region (Bailey 1995). Almost all forested land in the province is mountainous, with rugged terrain reaching greater than 2,700 meters in elevation (Adams 1995; Bailey 1995). Westerly winds spread coastal climate conditions to the western slopes of the northern Rocky mountains, causing atypically mild climate relative to the province's high elevation (Adams 1995). Due to the rain shadow effect, precipitation intensity west of the Continental Divide is much greater than the eastern side. As a result, forests of northern Idaho have a mean precipitation range of 50-1400 mm per year, with some areas receiving greater than 1525 mm of precipitation annually (Cooper et al. 1991; Jurgensen et al. 1997; McGrath et al. 2002). Additionally, higher elevation forests are susceptible to frost conditions in any month of the year, with annual snowfall accumulations commonly exceeding 6500 mm (Jurgensen et al. 1997).

As a result of the region's high annual precipitation, the *Tsuga heterophylla/Clintonia uniflora* series is the most abundant western hemlock habitat type in the Inland Northwest (Cooper et al. 1991). The driest of the hemlock habitat types in the Northern Rocky Mountains, this series has high to very high timber productivity with an understory of moist-site shrubs, grasses, and forbs such as *Clintonia uniflora*, and diverse forest stands including *L. occidentalis*, *P. menziesii*, *P. monticola*, *and P. contorta, T. plicata*, and *T. heterophylla* (Pfister et al. 1977; McGrath et al. 2002). The *Tsuga heterophylla/Clintonia uniflora* habitat type is found on gentle to steep slopes (2-58%) at elevations ranging from 550 to 1585 m (Cooper et al. 1991).

1.1.1 Andisols and their impact on northern Rocky Mountain forests

Prevalent volcanic ash soils contribute to the high productivity of maritime influenced forests of the Northern Rocky Mountain region (Fosberg et al. 1979). These soils are derived from volcanic tephra, and are typically within the Andisol soil order (Nanzyo 2002). Andisols have undisturbed tephra mantles that are at least 36 cm thick, and are most typically found in mid to high elevation forested regions, in which tree canopies and detritus layers reduce surface soil erosion (McDaniel et al. 2005). Andic soils in the northwestern United States are among the most productive soils in the world due to properties such as a high water holding capacity, favorable tilth, and resistance and resilience to compaction (Shoji et al. 1993). Additionally, Andisols have unrestricted deep rooting zones, high resistance to water erosion, high amounts of plant available water, and low soil bulk density, making them favorable forest soils that can be easily altered via site preparation (Shoji et al. 1993).

Andisols of the Inland Northwest formed via the eruption of Mount Mazama (now Crater Lake) in southwestern Oregon approximately 7600 years B.P. (McDaniel et al. 2005). These soils are unique due to their high particle surface areas, aluminum-rich composition, and high cation exchange capacity (Nanzyo 2002). Andisols are able to store twice as much water as basalt derived soils, and as such provide a great benefit to forest productivity in the summer drought-prone Inland Northwest (Geist and Strickland 1978). Increases in Inland Northwest volcanic ash mantle thickness have been shown to increase the site index of forested stands (Kimsey, Moore, and McDaniel 2008). However, timber harvest can compact and reduce ash cap thickness, which in turn reduces soil productivity and future tree growth (Cochran and Brock 1985; Geist and Cochran 1990).

1.2 Western white pine: silvics and management

1.2.1 Silvics of western white pine

Western white pine (*Pinus monticola* Dougl. Ex. D Don), one of the largest growing conifers in the western United States, is among the most commercially valuable trees native to the Inland Empire. The tree can grow as tall as 73 meters, with its diameter at breast height being as large as 200 cm (Graham 1990). It holds high timber value due to its straight growth with minimal taper or bole defects, narrow crown, and overall structural quality (Harvey et al. 2008). In addition to its high quality timber, western white pine's growth rate is rivaled only by western larch in the Inland Northwest (Harvey et al. 2008).

On its coastal range, western white pine can be found from coastal British Columbia to the Sierra Nevada of California (Graham 1990). The interior range of western white pine begins in central British Columbia and extends through the Selkirk Mountains in eastern Washington to the Bitterroot Mountains in western Montana, reaching a southern boundary in northeastern Oregon (Graham 1990). Western white pine has high phenotypic plasticity, with populations in the Northwest varying only slightly from coastal Washington and British Columbia populations (Krugman and Jenkinson 2008). While geographic location has been shown to separate populations of western white pine, altitude does not separate population bands of the species (Rehfeldt 1979). As a generalist species, western white pine is generally differentiated as being located in a northern, transitional, or southern population over its 15° latitudinal and 2500 meter altitudinal range (Rehfeldt et al. 1984).

In the Inland Northwest, western white pine typically grows at elevations between 400 to 1900 meters, with highly productive stands being found in wide river bottoms and less extreme topographies (Mahalovich 2010; Zeglen et al. 2010). Western white pine grows in a wide variety of soils, with depths ranging from 25 to greater than 230 cm (Graham 1990). . The intermediately shade tolerant species performs best on well-drained deep soils, but is found on a variety of soil types, and frequently on sandy soils (Haig et al. 1941; Graham 1990). Climates that typically support western white pine are characterized by short, dry summers and cold winters with heavy snowfall (Haig et al. 1941). Mean annual temperatures range from 5.4 to 10° C, with mean annual precipitation varying from 760 to 2010 mm, and mean annual snowfalls being between 122 and 620 cm. Typically a mid-seral species, western white pine takes advantage of disturbance openings in the forest canopy, playing a minor role in climax stands and old growth forests of the Inland Northwest (Huberman 1935; Jain et al. 2004).

1.2.2 White pine blister rust and management implications

Across its native range, western white populations have been decimated by white pine blister rust, caused by the pathogen *Cronartium ribicola* (Haig et al. 1941). The exotic pathogen was introduced from China to a nursery in Vancouver, British Columbia in 1910, eventually dispersing into the northwest United States and reaching northern Idaho in 1923 (Kinloch 2003). Requiring alternate hosts of five-needled pines and *Ribes* spp. to complete its five-stage life cycle and propagate, *Cronartium ribicola* spores can disperse as far as 150 meters from one host to the next (Kinloch 2003). By 1937, western white pines in the St. Joe National Forest had 15 percent occurrence of infection, and by the mid-1940s, more than 95 percent of white pines in high blister rust hazard areas were infected by the *Cronartium* *ribicola* pathogen (Bingham 1983). Due to a lack of major fires, severe blister rust infections, and intensive salvage harvesting that removed disease-resistant seed sources, western white pine regeneration proportions in north Idaho, eastern Washington, and western Montana decreased from 44 to 5 percent between 1941 and 1979 (Graham 1990).

In an attempt to limit the damage caused by blister rust, more than $150 million was spent by the United States government from 1909 to 1960 on manual and chemical efforts to eradicate *Ribes* spp. and to cure 5-needle pines infected with blister rust (Fins et al. 2002). Despite these massive efforts, and successful damage reduction to eastern white pine (*Pinus strobus*) in the eastern United States, attempts to remove *Cronartium ribicola* from western white pine ecosystems were largely fruitless (Fins et al. 2002, Ketcham et al. 1968). Manual *Ribes* eradication efforts were abandoned in 1969, with funding transitioning to researching genetic solutions to blister rust (Harvey et al. 2008). From 1950 to 1975, research and selection for higher blister rust resistance resulted in the availability of F_2 western white pine seeds that resist the blister rust pathogen at a level of 66% survival (Bingham 1983). The F_2 stock, coupled with tree pruning and thinning has resulted in improved tree survival, with mean mortality percentages of observed western white pine plantations ranging from 7 to 26.3 percent (Schwandt et al. 2013). However, efforts to replant western white pine have been more than halved in the Inland Northwest since 1995, with only 2,000 to 4,000 acres of land being planted annually as opposed to 8,000 to 10,000 acres being planted annually from 1985 to 1995 (Schwandt et al. 2013).

1.3 Interior Douglas-fir: silvics and management

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), is one of the most commercially significant tree species in North America. A 1987 inventory estimated that the species covered a total of 14.3 million hectares of land in the United States alone (Waddell et al. 1989). Douglas-fir is separated by two geographically distinct varieties; coastal (*Pseudotsuga menziesii* var. *menziesii*) and interior or rocky mountain (*Pseudotsuga menziesii* var. *glauca*) (Lavender and Hermann 2014). Interior Douglas-fir has an extensive native range, extending roughly 4500 km from Vancouver Island, British Columbia to central Mexico (Hermann and Lavender 1990). Throughout its native range in the United States, interior Douglas-fir accounted for 6.3 million hectares of land as of 1987 (Waddell et al. 1989). A continuous range exists from northern Idaho through western Montana and northwestern Wyoming, while distribution is discontinuous from southern Idaho through Utah, Nevada, Colorado, New Mexico, Arizona, western Texas, and northern Mexico. Interior Douglas-fir grows at higher elevation than coastal Douglas-fir, and is mainly found on southerly slopes in its northern range and north facing exposures in its southern range (Lavender and Hermann 2014). As latitude of interior Douglas-fir decreases, the elevation at which it grows tends to increase. In its northernmost range, interior Douglas-fir is found from 550 to 2440 meters in elevation, while in the southern Rocky Mountains it grows from 2440 to 2900 meters in elevation (Hermann and Lavender 1990).

Interior Douglas-fir naturally grows under a wide array of climactic conditions, in which mean July temperatures in the Northern Rocky Mountain Province range from 14-20°C, and mean January temperatures vary from -7-3°C (Hermann and Lavender 1990). Moisture conditions for interior Douglas-fir in the northern Rockies can also be highly variable, with mean annual precipitation being between 560 and 1020 mm and average annual snowfall ranging from 40 to 580 cm (Hermann and Lavender 1990). The tree species commonly grows in pure stands, as well as in mixed stands containing western larch, ponderosa pine*,* grand fir*,* and lodgepole pine (Lavender and Hermann 2014). Interior Douglas-fir grows in many soil and parent material types, ranging from gravelly and acidic soils in Wyoming and entisols in the southern Rocky Mountains to volcanic ash in the Inland Northwest (Hermann and Lavender 1990).

Interior Douglas-fir trees grow to an average height of 30 to 37 meters, and an average diameter at breast height of 38 to 102 cm over a 200 to 300 year period (Hermann and Lavender 1990). Under optimal conditions, an interior Douglas-fir tree could grow up 49 meters and have a diameter at breast height of 152 inches over the same 200 to 300 year time frame (Hermann and Lavender 1990). In Idaho, the average diameter at breast height of interior Douglas-fir is 34.5 centimeters, with its mean height being 19.5 meters (Lavender and Hermann 2014). The species is classified as intermediately shade tolerant, being more tolerant of shade than western larch*,* ponderosa pine*,* lodgepole pine*,* and *Populus* spp. (Hermann and Lavender 1990). Adolescent and mature Douglas-fir individuals are well adapted to surviving fires, particularly due to their thick bark and rapid growth (Lavender and Hermann 2014).

1.4 Site preparation

1.4.1 Site preparation and forest response to treatments

Site preparation refers to the suite of soil and vegetation-influencing tools and methods that are used to improve initial forest site conditions. On an industrial level, site preparation is used to improve the germination, establishment, growth, and development of desired regeneration (Wiensczyk et al. 2011). Methods used for site preparation can differ greatly depending on the climate and condition of a site. Heavy soil-altering equipment, manual vegetation removal, and herbicide application are common tools and methods of site preparation that are applied. In the maritime-influenced forests of the Inland Northwest and other cold forest regions, both individual and combined mechanical and chemical site preparation are often applied to promote desired regeneration and reduce competition (Binkley and Fisher 2013). Separate mechanical and chemical site preparation treatments have been shown to improve early lodgepole pine seedling growth in steep, mesic and submesic British Columbia forest sites when compared to untreated controls, while mechanical site preparation also significantly reduced seedling mortality (Simard et al. 2003).

Three potential stand growth responses to site preparation were initially proposed by Morris and Lowery (1988). A Type 1 growth response occurs when an initial growth increase occurs due to site preparation, in which the time required to reach stand maturity is decreased by a static amount. A Type 2 response to site preparation is defined as a continually increasing age shift, which would be indicative of site improvement beyond initial release from competing vegetation. A Type 3 growth response occurs when untreated stands eventually have greater volume production than stands treated with site preparation, or the time required to reach a certain basal area or stand volume increases due to site preparation. Additionally, South et al. (2006) proposed a Type C growth response to site preparation, which occurs when stand volume production initially increases due to site preparation, but later declines to the same total productivity as an untreated stand.

1.4.2 Mechanical site preparation

Methods of mechanical site preparation typically involve disturbing the surface soil to remove or kill competing vegetation, creating microsites favorable for early tree growth and allowing for easier seedling or direct seed planting (Wiensczyk et al. 2011). Mechanical site preparation typically involves affecting the organic soil horizon or altering the composition and structure of the subsoil.

1.4.3 Mechanical Site Preparation Removing the Organic Soil Horizon

Preparation methods that remove the surface organic layer of the soil, such as scalping, provide tree roots with immediate access to mineral soil. Root exposure to the mineral soil results in improved capture of soil surface moisture (MacDonald and Thompson 2003). By removing the organic layer of the soil and subsequent competition present, scalping has been found to increase Douglas-fir, lodgepole pine, and ponderosa pine seedling survival 5 years post-planting in central Idaho (Sloan and Ryker 1986). Greater seedling survival will ultimately help achieve reforestation objectives of well-stocked stands soon after harvest. While scalping provides early enhancements in water availability and greater seedling survival, it has been shown to decrease individual tree height 7 years post-planting and increase the density of non-tree vegetative competition following planting compared to subsoil-influencing site preparation and unscalped treatments (MacDonald and Thompson 2003; Gradowski et al. 2008). This decrease in tree growth is likely due to the reduced levels of organic matter, nitrogen, and cation exchange capacity, as well as increased soil bulk densities noted in scalped soils (Page-Dumroese 1993; Page-Dumroese et al. 1997)

In a study measuring 10th year aboveground planted tree and total stand biomass over 45 treatment installations across the United States and Canada, Ponder et al. (2012) noted that treatments that removed all aboveground biomass, including the organic soil layer often had the lowest individual tree and total stand biomass. A north Idaho study comparing scalping to slash burning preparation and untreated controls noted that 24 years after planting one year old Douglas-fir seedlings, scalping plots resulted in significantly lower diameters at breast height than both burn treatments and the untreated controls (Kimsey and Roché 2012). Additionally, trees in the scarified plots had lower needle mass and levels of needle nutrient content for nitrogen, phosphorus, and potassium than in the untreated control, indicating that the initial benefit of removed vegetative competition and easier outplanting may not translate to increased long term site productivity (Kimsey and Roché 2012). Removal of the organic soil layer results in the loss of essential tree nutrients, which become limiting factors of growth (Ballard 2000).

1.4.4 Subsoil Influencing Mechanical Site Preparation

While scalping removes the forest floor from a planting site to expose the mineral soil, subsoil-influencing methods of mechanical site preparation seek to incorporate soil organic matter with mineral soils or breakup soil impedances such as hardpans. These soil tilling operations are often applied in order to ameliorate undesirable soil compaction, in addition to increasing the amount of readily available nutrients to seedlings (Lowery and Gjerstad 1990). Methods of site preparation that mix soil organic matter and mineral soil have been shown to improve seedling growth, while treatments that reduce soil organic matter and nutrients can hinder seedling development (Jurgensen et al. 1997). Soil organic matter is essential to forest soils, as it increases soil porosity, moisture holding capacity, nutrient exchange, and nutrient retention (Ezell and Arbour 1985). Furthermore, small increases in soil organic matter result in relatively large reductions in soil bulk density (Grigal and Vance 2000). As a result of these factors promoting more conducive root growth and development conditions, soil organic matter is associated with improved long term forest productivity (Grigal and Vance 2000).

Methods of site preparation that involve mixing organic and mineral soils include disk trenching, subsoiling, bedding, and mounding. Bedding involves creating strips of mixed mineral soil, organic soil, and logging debris that usually range from 20-30 cm in height and 1-2m in width (Binkley and Fisher 2013). In high latitude forest sites, bedding is applied in order to raise restrictively low soil temperatures in the rooting zone (Sutton 1993). As a result of reduced soil bulk density, increased soil temperature and nutrient availability, and improved vegetation control, bedding has been shown to improve the growth and initial survival of tree seedlings compared to untreated sites in the Southeastern United States (Miwa et al. 2004). Reduced bulk density caused by bedding improves porosity, aeration, and nutrient concentration in the surface soil, increasing crop tree growth and establishment rates (Harvey et al. 1996; Page-Dumroese et al. 1997). Increasing the surface area and porosity of soil also increases the availability of moisture and soil temperature for crop trees, two often limiting factors of growth during the drought-prone growing seasons with frost potential in the Inland Northwest (Adams 1995; Binkley and Fisher 2013). In the maritime-influenced forests of the Northern Rocky Mountains, bedding has been shown to increase total amounts of nitrogen, phosphorous, and base cations present in the soil, while also having a significantly greater Douglas-fir and western white pine rooting depth than a scalping treatment and untreated control (Page-Dumroese et al. 1997).

In a 20 year study of *Picea glauca* seedling growth and survival in boreal British Columbia, individual stem volumes in bedded treatments were significantly larger than in the untreated plots (Boateng et al. 2009). Additionally, 19 year seedling survival in the bedding treatments was greater than survival with burn windrows, postplanting vegetation control, disk trenching treatments, and the untreated controls (Boateng et al. 2009). 15 year results from the same study plots revealed that subsoil influencing methods of site preparation such as bedding and disk trenching had higher concentrations of exchangeable magnesium, calcium, and potassium than untreated control soils (Macadam and Kabzems 2006). Between years 5 and 15 of the same study, concentrations of nitrogen in the mineral soil were 2-3 times greater in bedding, soil mixing, and disk trenching treatments than in untreated soils (Macadam and Kabzems 2006). Alternate studies on spruce in the region observed daily soil temperatures 23 and 14°C greater at 0.5 and 10 cm subsoil depths in bedded soils compared to untreated soils, thus reducing the threat of damaging surface frost (Draper et al. 1985; Sutton 1993).

1.4.5 Chemical site preparation

While mechanical site preparation can result in easier planting and some improvements in seedling growth, it often does not sufficiently remove, and can even increase postplanting vegetative competition (Page-Dumroese et al. 1997). Chemical site preparation provides an economical option to grow seedlings at a site's potential without altering soil composition or structure (McDonald and Fiddler 1993; Wiensczyk et al. 2011). Employing chemical vegetation control as a form of site preparation has increased in recent decades due to the variety of herbicides available and the low cost of herbicide relative to the costs of labor, machinery and fuel (Lowery and Gjerstad 1990). In addition to its economic advantages, chemical site preparation can be applied in rugged terrains without heavily disturbing soil structure, while also limiting the resprouting of woody vegetation (Lowery and Gjerstad 1990). By not altering the structure of the soil and removing the dominant vegetation, chemical site preparation does not greatly alter species diversity or composition, but instead changes relative species dominance in favor of the planted or desired species (Balandier et al. 2006).

In long term studies of site preparation on white spruce development in British Columbia, chemical site preparation resulted in greater individual stem volumes than mounding, patch scarification, and control treatments (Boateng et al. 2009). Additionally, chemical vegetation control caused a total reduction in overtopped spruce stems, which did not occur in any other treatment (Boateng et al. 2009). Alternate studies comparing chemical and mechanical methods of site preparation have shown chemical site preparation leads to increased stem diameter, height, and volume 5 years after outplanting 1.5 year old *Picea mariana* seedlings (Sutherland and Foreman 2000). A study on the 11 and 20 year growth response of white spruce in British Columbia reported a 6.5 meter increase in site index at age 20 for white spruce sites treated with herbicides compared to untreated sites (Cortini et al. 2010). These results indicate a Morris and Lowery (1988) Type 1 growth response of white spruce to chemical site preparation, in which a treatment reduces the time required for a stand to reach maturity. In a 10 year study of site preparation across North America, Ponder et al. (2012) reported that chemical methods of vegetation control resulted in increased individual tree biomass in nearly every climate, soil condition, and species to which it was applied.

In the western United States, conifer growth, survival, and yield have greatly improved due to chemical site preparation. Vegetation control in both the Pacific and Inland Northwest have improved juvenile conifer growth and outplanting survival, while limiting pest damage and vegetative competition (Newton 1981). Comparisons of chemical site preparation methods to an untreated control on the growth and survival of outplanted Douglas-fir seedlings revealed that herbicide treatments increased seedling survival rates, total height, groundline diameters, and time available for shoot growth 10 years after outplanting (Harper et al. 2005). Site preparation studies performed on Ponderosa pine in three California "Garden of Eden" experiment sites noted that 10 years postplanting, chemical control of competing vegetation resulted in the greatest growth improvements on each site, as it improved moisture and nutrient availability for the seedlings (Powers and Reynolds 1999).

Studies outside of the northwestern United States have also shown the benefits of chemical site preparation. In a southwest Arkansas soil study, 6 clearcut forested watersheds were either prepared chemically or mechanically via shearing and slash windrowing, and 3 forested watersheds were not cut and left as untreated controls (Beasley et al. 1986). Mechanical site preparation treatments resulted in higher mean annual sediment losses one year after treatment and increased stormflows one and three years after treatment when compared to the chemical site preparation treatments (Beasley et al. 1986). Clason (1989) reported a 39-59 m^3/ha increase in volume of *Pinus taeda* 30 years after methyl bromide fumigation treatments compared to non-fumigated treatments at different stocking densities in Louisiana. In eastern Ontario, a study on planted black spruce, white spruce, and natural regeneration growth and survival in different site preparation treatments observed that planted seedlings had larger branch lengths and diameters, as well as greater live crown ratios in post-clearcut herbicide treatments than in nonchemical, partial cutting treatments (Man et al. 2013). Zhao et al. (2009) reported increases in volume up to 80.4 m^3/ha compared to untreated plots over 20 years in *Pinus ellioti* stands in southern Georgia and northern Florida, indicating a Type 2 response, in which maximum growth response to a treatment is attained and remains maximized throughout the rotation.

1.4.6 Combined treatments of mechanical and chemical site preparation

The benefits of site preparation are often maximized through the combination of chemical and mechanical applications. Combinations of bedding and herbicide applications have increased root zone water availability, yearly seedling cumulative biomass, tree nutrient concentration, and rooting depth when compared to bedding, scalping, and control treatments in Douglas-fir and western white pine (Page-Dumroese et al. 1997). In studies that compared various methods of site preparation, growth response of planted conifers were highest when manual and chemical treatments were combined than when only manual treatments were applied (Stewart and Row 1981). In northern California, a 21 year study of chemical and mechanical site preparation impacts on conifer growth noted a 3035 and 1712 percent increase in volume growth for *Pinus ponderosa* and *Abies concolor*, respectively in brushraking treatments with 2 years of herbicide release compared to a rotary mulching treatment and an untreated control (Lanini and Radosevich 2003; Wagner et al. 2006). A site preparation study in northwestern Alabama observed planted loblolly pine basal areas of 40.7 m^2/ha in a stem frilling and herbicide treatment, compared to 1.6 m^2/ha in an untreated control, 27 years after treatment and planting (Glover and Zutter 1993). Miller (2003) reported an 23-121 percent increase in merchantable *Pinus taeda* volume in the southeastern United States 15 years after mechanical site preparation and repeated chemical applications within the first 5 growing years compared to treatments of only mechanical site preparation.

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Chapter II

MULTI-DECADAL EFFECTS OF SITE PREPARATION ON LEAF AREA AND GROWTH EFFICIENCY OF WESTERN WHITE PINE AND INTERIOR DOUGLAS-FIR

2.1 Abstract

Site preparation can improve biotic and abiotic conditions unsuitable to conifer regeneration, but its impacts beyond stand initiation are uncertain. In 1982, interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and western white pine (*Pinus monticola* Dougl. ex. D. Don) seedlings were planted under different site preparation treatments at a low and high elevation site in the Priest River Experimental Forest in northern Idaho. The treatments included: (1) organic horizon removal and mineral exposure (scalping), (2) soil bedding without competition removal, (3) soil bedding with competition chemically removed, and (4) an untreated control. In the summer of 2017, 75 trees were destructively sampled to determine the treatment effects on tree leaf area and five-year growth efficiency (GE). Species-specific mixed-effects allometric models were developed for branch leaf area that account for treatment. While a treatment effect was found in the branch leaf area model, site preparation treatments did not significantly impact tree leaf area or GE for either tree species compared to the untreated control. A monotonically increasing trend in volume increment with increasing tree leaf area was reported for both species, suggesting that both species exhibit plastic responses to growing conditions and have the most rapid wood production when crowns are dominant in the overstory. Interestingly western white pine experienced a monotonically declining pattern of GE with increasing leaf area at the low elevation site suggesting asymptotic wood increment as crown size increased and a stable growth rate across a range of crown sizes. Results show species-specific responses to growing conditions at the two sites.

At sites where western white pine dominates the overstory growth stabilizes with increasing crown size while interior Douglas-fir exhibited increasing growth with increasing crown size regardless of site conditions.

2.2 Introduction

Inland Northwest forests are frequently regenerated with tree planting to meet state mandates and ensure prompt reforestation of desired species composition. In 2014 alone, 3,625 ha of land in Idaho were planted with tree seedlings, and over 4.9 million tree seedlings were produced (Hernández et al. 2015). Competing vegetation such as hardwoods, grasses, shrubs, and forbs compete with conifer seedlings for scarce resources on a site, potentially reducing seedling survival and growth (Löf et al. 2016; Oester and Fitzgerald 2016). Applying treatments prior to planting or during the early stages of stand establishment can improve individual tree and stand productivity throughout the rotation. These treatments, often in the form of site preparation, limit resource competition for planted trees by removing competing vegetation and creating more favorable soil conditions at the seedling microsite (Lowery and Gjerstad 1990). Selection of the proper site preparation technique and intensity is essential, as applying an improper treatment relative to site conditions can have deleterious effects on the growth and survival of the desired tree species (Smith et al. 1997).

Tree productivity and vigor is often measured as growth efficiency (GE), a measurement of a tree's stemwood growth increment per unit of leaf area (Waring et al. 1980). Because trees allocate carbon resources to root growth and height increases before increasing stemwood diameter, GE acts as a strong indicator of individual tree vigor (Waring et al. 1980). Both volume and biomass increment have been used to determine stemwood growth, while leaf area is either determined from crown area estimations, sapwood-foliage relationships or calculating projected leaf area from subsampled leaf area measurements and estimating for the rest of the crown based on spatial or biomass relationships (Gersonde and O'Hara 2005; Stancioiu and O'Hara 2006; Waring, Landsberg, and Linder 2016). Seymour and Kenefic (2002) describe three reported patterns of volume increment relative to tree leaf area: (A) monotonically decreasing, in which growth efficiency declines as crown size increases, (B) sigmoid, in which individual tree growth efficiency is maximized at an intermediate leaf area, then either declines or stagnates, or (C) monotonically increasing, in which growth efficiency increases with increasing crown size (Seymour and Kenefic 2002, Figure 2.1). Both results from Seymour and Kenefic (2002) and DeRose and Seymour (2009) reported Type A growth efficiencies relative to leaf area for *Tsuga canadensis*, *Picea rubens*, and *Abies balsamea* in Maine. Berrill and O'Hara (2007) and Kollenberg and O'Hara (1999), however, predicted monotonically increasing (Type C) growth efficiency of *Sequoia sempervirens* in coastal northern California and *Pinus contorta* Douglas var, *Latifolia* (Engelm.) in Montana as leaf area increases, revealing alternate mechanistic growth trends between the different tree species. A study on *Pinus ponderosa* growth dynamics in western Montana and central Oregon also observed a Type C growth efficiency response to increasing leaf area in older cohorts in the western Montana plots (O'Hara 1996).

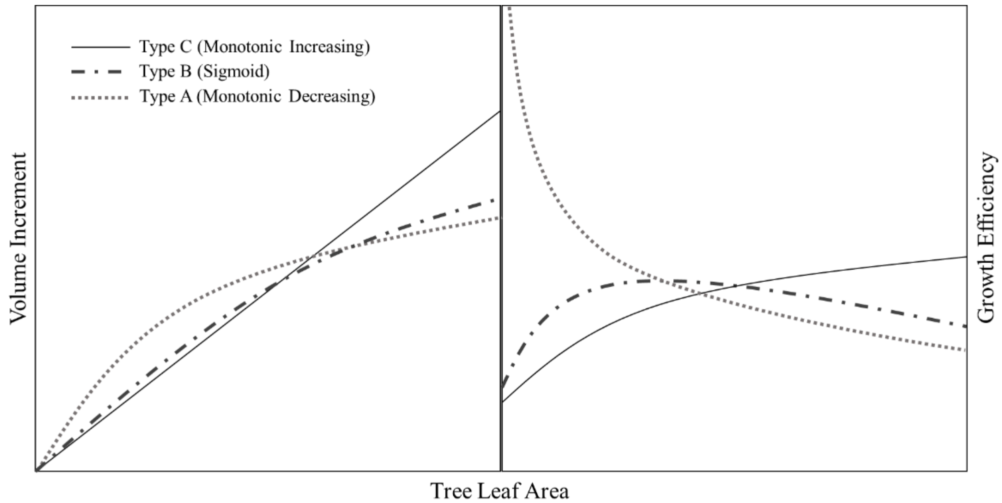

Figure 2.1 *Previously described volume increment and growth efficiency responses to increasing leaf area. Modified from Seymour and Kenefic (2002).*

The pipe model theory, first proposed in Shinozaki et al. (1964), contended that a proportional amount of stem cross sectional tissue exists for a given unit of foliage. Studies following this original paper found that conductive stem tissue, or sapwood at a fixed location had a stronger relationship with leaf area than overall stem tissue (Lehnebach et al. 2018, Monserud and Marshall 1999). Long and Dean (2004) found a direct linear relationship between tree leaf area and sapwood area at the base of the live crown for mature and sapling *Pinus contorta* in northeastern Utah, and also noted the importance of crown length in predicting tree leaf area. A study of four tree species in different European forest types revealed consistent isometric relationships between sapwood area and leaf area, with little variation across a 27° latitude range (Petit et al. 2018). Findings from these and similar studies have allowed sapwood cross sectional area at the crown base to be used as a surrogate for leaf area or leaf biomass.

Growth efficiency not only reflects the photosynthetic capacity of the foliage, but also indicates availability of nutrients in the soil. In stands with trees of similar leaf area and size, fertilization and readily available nutrients have been shown to increase the growth efficiency of *Pinus taeda* trees threefold (Martin and Jokela 2004). Individual tree and stand growth efficiency increase with site preparation and thinning treatments that increase readily available nutrients and site quality (Colbert et al. 1990; Powers et al. 2009). Few studies have examined the effects of site preparation treatments on individual tree productivity beyond the initial years of stand development. The objectives of this study were to (1) develop models relating branch and site traits to leaf area of western white pine (*Pinus monticola* Dougl. ex. D. Don) and interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and (2) determine if site preparation treatments impacted growth and GE of these two tree species 35 years after treatment and planting.

2.3 Materials and methods

2.3.1 Site Description and Experimental Design

The two study sites were established in 1982 on the United States Department of Agriculture, Forest Service Priest River Experimental Forest, 21 km northeast of Priest River, Idaho (Figure 2.2). The low elevation "Fire Weather" site is adjacent to the Priest River, on an approximately 0.405-hectare, flat alluvial bench 715 meters above sea level. This site was burned in a 1922 study, and was afterwards used in forest fuel flammability studies until 1978 (Finklin 1983). Prior to being clearcut in 1982, the site consisted of grasses, forbs, and a low stocking of lodgepole pine (Page 1985). The minimal logging debris from clearcutting were removed at the time of harvest (Harvey et al. 1997). The soil is a mission silt loam within the Inceptisol order, with 2 to 12 percent slopes, and a fragipan at 30 cm depth (Graham et al. 1989; Soil Survey Staff 2017). The mean annual temperature of the site is 6.7 °C, with an average precipitation of 798 mm per year (Tinkham et al. 2015). Fire Weather characterizes a

Tsuga heterophylla/Clintonia uniflora habitat type, and is considered the more harsh of the two growing locations (Harvey et al. 1997).

The second site, “Observatory Point”, formerly consisted of 110-year old western hemlock (*Tsuga heterophylla* (Raf.) Sarg), grand fir (*Abies grandis* (Dougl.) Lindl.), and western white pine (*Pinus monticola* Dougl. ex. D. Don). It was clearcut in 1981 and subsequently cleared via slash piling and burning in 1982. The site is located at a higher elevation and has more rugged terrain than the low elevation site, with an elevation of 1456 meters and slopes ranging from 10-35% (Page 1985). The soil is an Andisol of the subgroup Typic Udivitrands (Soil Survey Staff 2017). The habitat type is represented by *Tsuga heterophylla/Clintonia uniflora*, and is comparable to the higher productivity forests of northern Rocky Mountains (Cooper et al. 1991). The mean annual temperature of the high elevation site is 5.3 °C, while annual precipitation averages 912 mm (Page 1985; Tinkham et al 2015).

A restricted randomized design at Fire Weather, and a randomized complete block design at Observatory Point were in 1982 (Figures 2.3-2.4). Four site preparation treatments were applied in planting rows at both sites. The low elevation site consisted of four blocks planted continuously in one large plot, while the high elevation site consisted of three block replications in different locations of similar slope, habitat type, soil, and aspect (Page-Dumroese et al. 1997). The four row treatments applied to each block include: (1) scalping, which removed the uppermost 10 cm of organic material and mineral topsoil, (2) soil bedding without chemical vegetation control, (3) soil bedding with chemical vegetation control, and (4) an untreated control in which no site preparation occurred. Each treatment row is 30 meters long, 1.5 meters wide, and in the bedding treatments, approximately 46 cm high. The chemical vegetation control treatment consisted of applying 1.68 kg/ha active ingredient of glyphosate (Roundup®) to nonconiferous vegetation in the second and third years of the study, after manually removing competition in the planting year. The study seedlings in the chemical vegetation control treatments were covered during herbicide applications in order to prevent accidental contact (Harvey et al. 1997). The organic horizons and mineral topsoil removed from the scalping treatments were used to construct the bedding treatments (Page 1985). A small crawler tractor was used to perform the scalping treatments and create the soil beds (Page-Dumroese et al. 1997).

In April 1983, 1-0 container stock interior Douglas-fir and western white pine seedlings were planted at both the low and high elevation sites. Each replicate treatment had seedlings planted on 31 x 46 cm spacing, resulting in 218 seedlings per treatment row, and totaling 12208 planted seedlings between the two sites. Each block consisted of the four site preparation treatments for both tree species, resulting in 8 treatment rows. While one genetic source was used for western white pine at both sites, Douglas-fir seedlots from 805 and 1460 meters were planted at the low and high elevation sites, respectively (Page 1985). As a result of post-establishment destructive sampling, seedling mortality, new seedling planting, and site thinning to reduce stocking density, 1066 trees were present in 1990, with between 12 and 55 trees being present in each treatment row (T. Jain, USDA Forest Service, Rocky Mountain Research Station, Moscow ID, Unpublished Data). Prior to this study, no harvesting, maintenance, or sampling had occurred at either site since 1990.

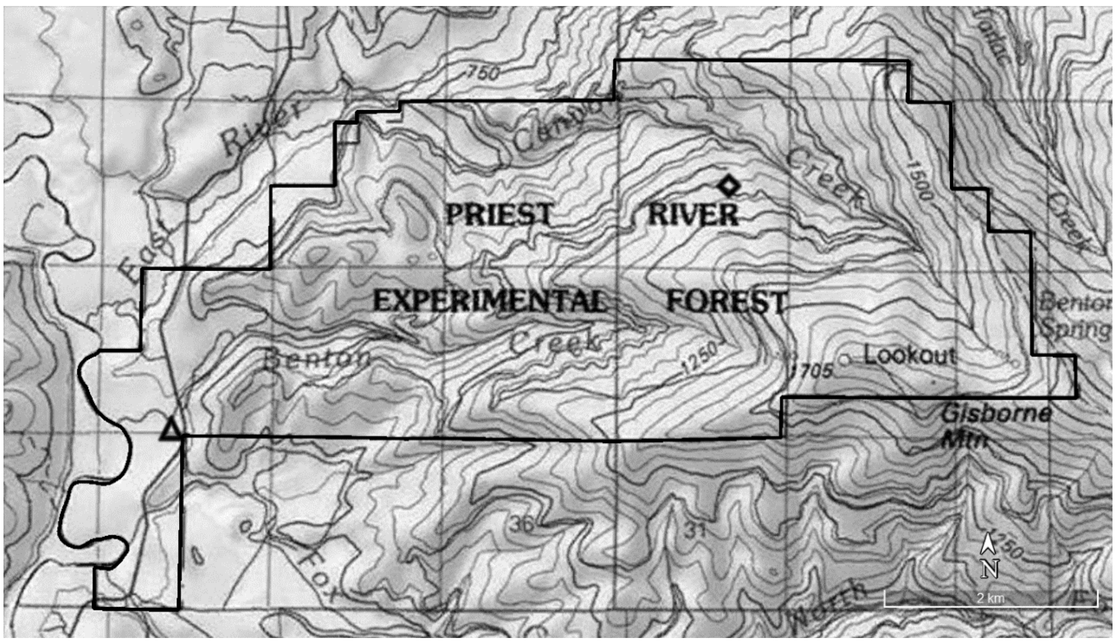

Figure 2.2 *Fire Weather (triangle) and Observatory Point (rhombus) sites within the Priest River Experimental Forest*

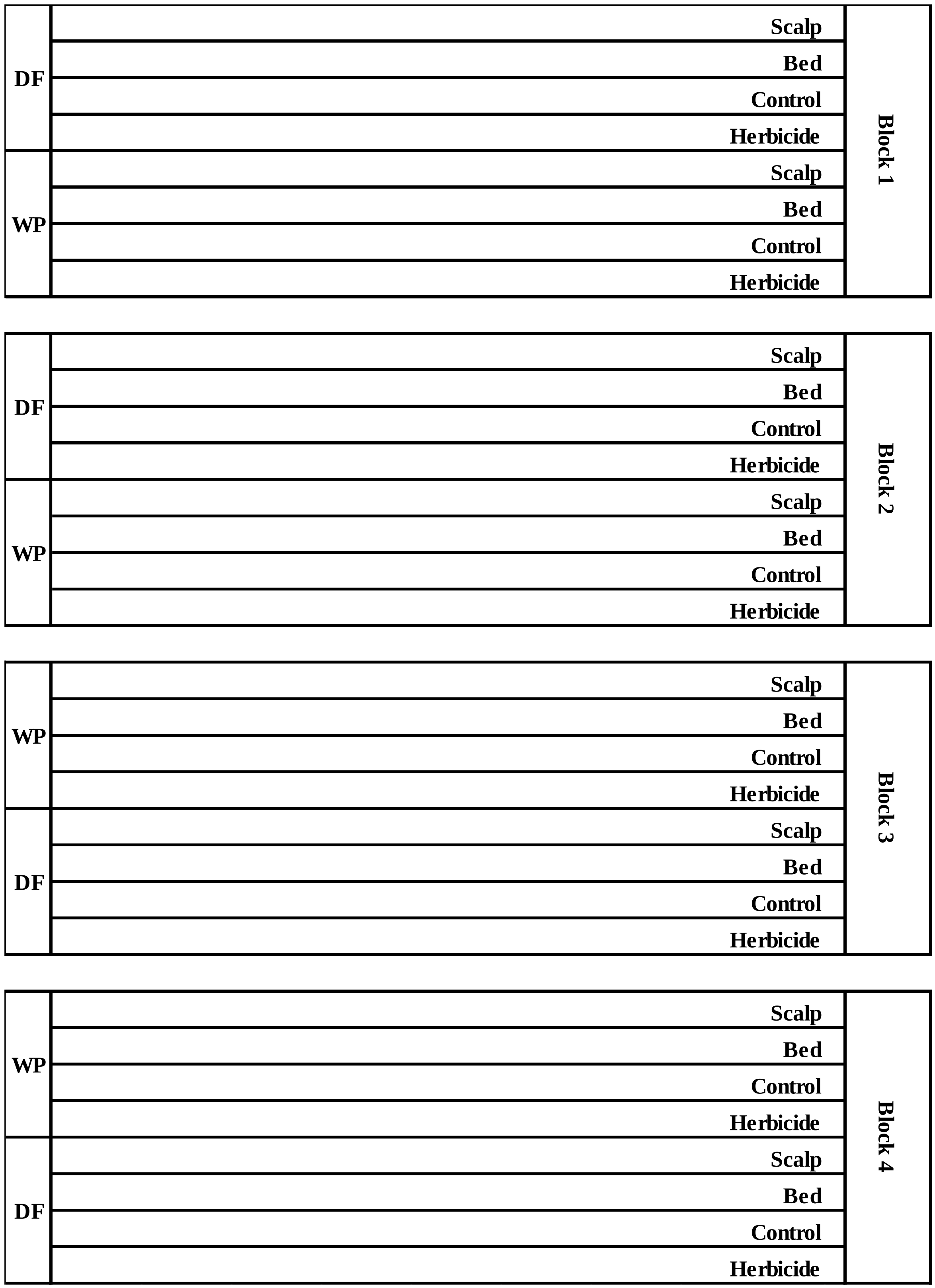

Figure 2.3 *Design of low elevation "Fire Weather" site*

WP	Control	Block 1
WP	Bed	
WP	Scalp	
DF	Herbicide	
DF	Bed	
DF	Scalp	
WP	Herbicide	
DF	Control	
WP	Bed	Block 2
DF	Bed	
WP	Herbicide	
DF	Scalp	
DF	Herbicide	
WP	Scalp	
WP	Control	
DF	Control	
WP	Control	Block 3
DF	Control	
DF	Bed	
WP	Scalp	
DF	Herbicide	
WP	Bed	
DF	Scalp	
WP	Herbicide	

Figure 2.4 *Design of high elevation "Observatory Point" site*

2.3.2 Field data collection

Prior to destructive sampling, both sites were revisited and inventoried to determine the number of remaining trees in each treatment replication (Table A1). Site inventories in 2017 counted 238 study trees at Fire Weather and 141 study trees at Observatory Point. Diameter at breast height (DBH) was recorded for each tree. Trees were separated into DBH quartiles by treatment, site, and species. One to two trees from each diameter quartile by treatment and species were randomly selected for destructive sampling, with an additional tree being chosen if a treatment replication was not represented by the initial randomized selection (Table 2.1). After all neighboring tree measurements were recorded at a site, destructive sampling of the subject trees began. Four to six trees per site, species, and treatment combination were harvested for intensive sampling, ranging from 5.3 to 33.3 cm DBH and 6.4 to 26.31 m in total height (Table 2.1). A lumber crayon was used to mark the north facing side of the subject tree, as well as 0.1524, 0.762, and 1.3716 meters from the ground along the stem. Each subject tree was felled with efforts to minimize branch and stem damage. Once the subject tree was on the ground, a measuring tape was laid out along the stem of the tree, with the 1.37 mark on the measuring tape overlaying the breast height mark already drawn on the stem. Total tree height and height at the base of the live crown were then recorded. The total live crown length was divided into thirds and marked at each section's base with a lumber crayon. Additionally, every 0.914 meters after breast height was marked with a lumber crayon for stem analysis. The total number of branches in each crown section was then counted and recorded.

Based on the branch count in each crown section, two branches per crown section were randomly chosen for leaf area analysis using a random number generator. These branches were measured for vertical position along the stem, cardinal position on the stem, and branch collar diameter before having approximately 100 needles placed in a plastic bag and held inside a cooler. The remainder of the branch foliage was placed inside a paper bag. Both the paper and plastic bag for each subsampled branch were labeled with the appropriate tree and branch code, as well as the date of destructive sampling.

Table 2.1 *Summary of subject trees selected for destructive sampling at Fire Weather (FW) and Observatory Point (OP)*

Site	Trees	DBH (cm)			HT (m)		
	n	min	mean	max	min	mean	max
FW	**43**						
DF	***23***	***5.3***	***14.4***	***22.6***	***6.43***	***12.48***	***18.26***
Bed	6	7.4	13.8	17.5	7.47	12.00	15.46
Control	6	8.9	14.3	18.8	9.33	12.51	14.68
Herbicide	6	14.5	18.6	22.6	12.56	14.99	18.26
Scalp	5	5.3	10.5	22.4	6.43	9.99	16.68
WP	***20***	***13.7***	***22.8***	***33.3***	***14.03***	***21.03***	***26.31***
Bed	6	13.7	19.7	25.7	14.03	18.87	21.43
Control	5	18.5	24.7	32.5	19.12	22.37	26.31
Herbicide	4	22.4	27.5	33.3	20.95	22.91	25.31
Scalp	5	16.0	20.8	24.1	17.47	20.79	23.17
OP	**32**						
DF	***16***	***12.7***	***20.9***	***30.5***	***11.83***	***15.38***	***20.43***
Bed	4	14.5	22.4	27.2	11.92	15.52	19.00
Control	4	12.7	17.8	24.1	11.83	13.56	15.86
Herbicide	4	17.8	24.4	30.5	13.96	17.52	20.43
Scalp	4	14.2	18.9	25.4	14.36	14.91	15.64
WP	***16***	***11.2***	***17.4***	***27.4***	***7.17***	***14.21***	***20.89***
Bed	4	11.2	17.1	20.3	7.17	13.51	17.32
Control	4	11.4	14.4	21.1	8.26	12.12	19.64
Herbicide	4	15.2	22.6	27.4	10.46	17.46	20.89
Scalp	4	12.4	15.4	19.3	10.79	13.75	18.29

The branch foliar subsamples were stored in a freezer at the Priest River Experimental Forest until the end of each week, at which point they were transferred in a cooler to the University of Idaho Center for Forest Nursery and Seedling Research and stored in a freezer until analysis could be performed. A total of 450 branches were collected for leaf area analysis. If either a frozen foliar subsample or its corresponding branch were lost in transfer to the University of Idaho, the branch samples were excluded from the branch models.

After the six branches per trees had been separated and bagged appropriately, the remainder of branches were measured for branch collar diameter, vertical distance from the base of the stem, and branch cardinal position on the stem. Branch collar diameter was measured approximately 5 centimeters away from the branch junction with the stem to avoid swelling using a handheld electronic digital caliper. Branch cardinal position was determined using the previously marked north position on the stem as a reference, and vertical position on the stem was determined by recording the measuring tape reading along the stem at each branch location.

Once all branches had been measured and removed from the subject tree, disks were removed at 0.15, 0.76, and 1.372 meters up the stem, as well as at 0.914 meter increments after breast height, and at the base of each live crown section. Disks were cut to be 1-2 cm thick using either a chainsaw or hand saw depending on stem diameter and to prevent breakage. For each disk, total radius, sapwood radius, most recent 5 year radial increment, and bark thickness were recorded twice, at either a 90 degree increment or at radial extremes. Sapwood-heartwood delineation was determined by holding a disk towards the sun and marking the point at which the wood was no longer translucent. All disks were labeled with their vertical position along the stem, placed in paper bags, and returned to the University of Idaho for further processing and analysis.

2.3.3 Laboratory sample processing for stem analysis

Each stem disk collected in the field was sanded using a Makita 9404 10 × 61 cm variable speed belt sander. 60-80-grit sandpaper was used to remove coarse chainsaw marks, followed by 120-grit paper to fully expose all rings. For disks with finer rings, a Black + Decker BDEMS600 detail sander with 120-150-grit paper was used to reveal rings. An air compressor was used to remove dust after sanding, at which point the disks were strung together sequentially by the height along the stem from which they were harvested.

Once all disks from a subject tree had been sanded and organized, each disk was scanned using WinDendro™ (Regent Instruments Inc., Quebec CA) software and an LA2400 flatbed scanner (Regent Instruments Inc., Quebec CA) at 1200 or 1600 dpi, depending on ring visibility. For each scanned disk, the subject tree ID, subject tree height, disk height, year of harvest, and tree age were manually entered. Radial increment was recorded at two paths, either at a 90° angle or at both the largest and smallest disk radius in order to account for variability in stem growth. Tree rings identified by WinDendro were manually confirmed and adjusted for proper position, angle, missed rings, and false rings. A text file containing the radial increment raw data was produced for each tree. A Microsoft Excel macro, XLStem (Regent Instruments Inc., Quebec CA) was used to produce stem volume annual increment. Stem volume at a given year was calculated using a truncated cone volume formula (Equation [2.1]) in XLStem.

[2.1] $$V_n = \frac{1}{3}\pi(r_1^2 + r_1 r_2 + r_2^2)L$$

where V_n was the inside bark stem volume in year n (dm^3), r_1 was the average inside bark radius of the lower disk (dm), r_2 was the average inside bark radius of the higher disk (dm), and L was the distance between disks (dm). Five year volume increment (VI_5, $dm^3 5year^{-1}$) was calculated by subtracting total volume in year 30 from the total volume in year 34. Growth data from the year of harvest (2017) was excluded, as trees were still growing during the sampling period.

2.3.4 Laboratory data processing for leaf area analysis

For each 100 needle foliar subsample, one sided leaf area (cm^2) was measured using WinSEEDLE™ software (Regent Instruments Inc., Quebec CA). Needles were placed on acrylic trays, while ensuring that no needles were overlapping to prevent inaccurate needle counts and leaf area determinations. The trays were then scanned using an STD 4800 flatbed scanner (Regent Instruments Inc., Quebec CA) at 800 dpi. Once the scan was completed, the foliar subsample was placed in a paper envelope, labeled with its specific identification code, and placed in a forced air oven at 100°C for at least 72 hours, or until constant mass was achieved. Once the needles were dried, the mass of the scanned subsample (g) was recorded using a precision electronic balance to the nearest mg. Specific leaf area (SLA, cm^2g^{-1}) of the scanned foliar subsample was calculated by dividing the one sided leaf area of the subsample by its dry foliar mass.

Branch material that was not processed for SLA analysis was placed in a forced air oven at 100°C for at least 72 hours to ensure no water remained in the foliage. After the samples had dried, foliage was separated from woody material and branch foliar mass (BFM, g) was recorded using a precision electronic balance. Projected branch leaf area (PBLA, cm^2)

was calculated by multiplying BFM by the SLA of the corresponding scanned foliar subsample (Table 2.3).

Table 2.2 *Variables defined in projected tree leaf area and growth efficiency analysis*

Variable	Definition
SLA (cm^2g^{-1})	Branch specific leaf area
PBLA (cm^2)	Projected branch leaf area
BFM (g)	Branch foliar mass
SA_c (cm^2)	Sapwood area at the base of the live crown
PLA (m^2)	Projected tree leaf area
V_n (dm^3)	Total volume in year *n*
VI_5 ($dm^3 5year^{-1}$)	Five year volume increment
GE (dm^3m^{-2})	Growth Efficiency

2.3.5 Projected branch leaf area models, tree leaf area, and growth efficiency

Field measurements of branch collar diameter, site preparation treatment, and branch relative vertical position within the crown were related to projected branch leaf area using a species-specific allometric mixed effects model, modified from Garber and Maguire (2005). Initial parameter estimates were determined using the MODEL procedure in SAS (SAS Institute Inc. 2018). The initial parameter estimates were then used as starting values in nonlinear mixed effects models, which were fit using the “nlme” function in R statistical analysis software (R Core Team 2018). Site was treated as a random effect in the mixed effects model, which determines parameters using a maximum likelihood estimation. Across the 75 destructively sampled subject trees, 420 branches were scanned, weighed, and included in the formation of a branch leaf area model.

The PBLA models were then used to predict the leaf area of all tree branches for which field measurements were recorded. Projected tree leaf area (PLA, m^2), was calculated by taking the sum of all PBLA calculations for each tree using the branch summation method

(Monserud and Marshall 1999). A linear model relating sapwood area at the base of the crown (SA_c, cm^2), species, and site to PLA was fit to confirm PLA projections. A strong simple positive linear relationship between SA_c and PLA was expected if the PLA estimations were accurate (Lehnebach et al. 2018). Five year growth efficiency (GE, dm^3m^{-2}) was then calculated by dividing VI_5 by PLA for each tree. Species specific GE, as well as site and species specific PLA linear models were formed to determine if each site preparation treatment had a significant effect compared to the untreated control.

2.4 Results

2.4.1 Projected branch and tree leaf area

Across all subsampled branches, branch collar diameter ranged from 0.1930 to 4.8743 cm, while branch foliar masses ranged from 0.100 to 807.308 g (Table 2.3). Specific leaf area varied from 24.3461 to 178.6427 cm^2g^{-1}, and PBLA ranged from 0.0005 to 4.2914 m^2 across species and site.

Table 2.3 *Characteristics of branches subsampled for leaf area analysis model fitting*

			Branch collar diameter (cm)			**Branch foliar mass (g)**		
	n trees	**n branches**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
DF	**39**	**220**	**0.1930**	**1.4132**	**3.7719**	**0.100**	**81.775**	**746.388**
FW	23	128	0.2032	1.2655	2.9439	0.187	33.740	192.286
OP	16	92	0.1930	1.6187	3.7719	0.100	148.606	746.388
WP	**36**	**200**	**0.5207**	**1.9393**	**4.8743**	**1.356**	**107.470**	**807.308**
FW	20	110	0.7087	2.2205	4.8743	1.356	116.482	807.308
OP	16	90	0.5207	1.5957	3.7186	1.900	96.458	472.064
			Specific leaf area (cm^2 g^{-1})			**Projected branch leaf area (m^2)**		
		n branches	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
DF	**39**	**220**	**30.3029**	**52.3193**	**114.4114**	**0.0005**	**0.3937**	**3.7627**
FW	23	128	35.7066	55.4656	108.8003	0.0012	0.1819	1.1376
OP	16	92	30.3029	47.9420	114.4114	0.0005	0.6884	3.7627
WP	**36**	**200**	**24.3461**	**56.0188**	**178.6427**	**0.0065**	**0.5798**	**4.2914**
FW	20	110	24.3461	54.1652	89.3485	0.0065	0.6131	4.2914
OP	16	90	36.3465	58.2843	178.6427	0.0097	0.5391	2.5965

Equation [2.2] produced higher generalized and adjusted R^2, lower Akaike information criterion (AIC), root mean squared error (RMSE), and log likelihood values than equations tested from Monserud and Marshall (1999), as well as baseline models from Garber and Maguire (2009) that did not include treatment parameters (Table 2.5). For both species-specific models, all parameters were significant at a significance threshold of p=0.05 (p=0.03 to p <0.001) (Table 2.4). When the untreated control is treated as an intercept instead of indicator variable, scalping and herbicide estimates did not significantly differ from zero in the western white pine model, and bedding did not significantly differ from zero in the interior Douglas-fir model. The control treatment most positively affected PBLA in the western white pine model, while scalping most positively impacted PBLA in the interior Douglas-fir model. In the western white pine model, scalping produced the least positive impact on PBLA, and bedding and control treatments had the least positive impact on PBLA in the interior Douglas-fir model.

[2.2] $$PBLA=\frac{b_0 \varepsilon_i D_b^{\gamma_T} R_v^{b_5-1}}{e^{b_6 R_v^{b_5}}}$$

where ε_i is the random effect of site *i* on branch collar diameter (D_b), R_v is the branch relative vertical position within the crown, and site preparation treatments are defined as:

$$\gamma_T=b_1C+b_2S+b_3B+b_4H$$

where:

$$C=\begin{cases}1, \text{ if treatment=Control} \\ 0, \text{ otherwise}\end{cases}$$

$$S=\begin{cases}1, \text{ if treatment=Scalp} \\ 0, \text{ otherwise}\end{cases}$$

$$B = \begin{cases} 1, \text{ if treatment=Bed} \\ 0, \text{ otherwise} \end{cases}$$

$$H = \begin{cases} 1, \text{ if treatment=Herbicide} \\ 0, \text{ otherwise} \end{cases}$$

Table 2.4 *Parameter estimates for projected branch leaf area equations*

Model	Species	Parameter	Estimate	s.d.	p
[2.1]	WP	b0	0.673342	0.191158	0.003
		b1	2.167930	0.111645	<0.001
		b2	1.908135	0.172916	<0.001
		b3	1.708178	0.166641	<0.001
		b4	1.882994	0.111815	<0.001
		b5	2.000683	0.152268	<0.001
		b6	2.107411	0.275059	<0.001
		ε_i (FW)	-0.187712		
		ε_i (OP)	0.187712		
[2.1]	DF	b0	0.671865	0.224048	0.003
		b1	1.743774	0.161001	<0.001
		b2	2.142064	0.129526	<0.001
		b3	1.755890	0.124047	<0.001
		b4	1.945734	0.115107	<0.001
		b5	1.944431	0.155594	<0.001
		b6	1.970352	0.266636	<0.001
		ε_i (FW)	-0.267393		
		ε_i (OP)	0.267393		

Table 2.5 *Fit statistics for projected branch leaf area equations*

				Generalized R^2	
Species	**LL**	**AIC**	**RMSE**	**Fixed**	**Fixed + Random**
WP	-42.6566	103.3133	0.2920	0.5443	0.7458
DF	81.8217	-143.6435	0.2427	0.6581	0.8219

PBLA estimated for all field-measured branches using Equation 2.2 ranged from <0.001 to 9.499 m^2 for interior Douglas-fir, and from 0.00037 to 7.026 m^2 for western white pine (Table 2.6). When branches were summed for entire trees, PLA ranged between 2.174

and 234.684 m^2 for interior Douglas-fir, and 16.523 and 175.860 m^2 for western white pine. GE was greatest in western white pine and interior Douglas-fir at 4.313 and 1.657 dm^3m^{-2}, respectively. Analysis of variance (ANOVA) revealed that site preparation treatments only impacted PLA of western white pine, though no treatment significantly differed from the untreated control in the western white pine model (Figure 2.5).

Table 2.6 Characteristics *of all branches and trees modelled using Equation [2.2] used to estimate total tree leaf area with branch summation*

	n trees	n branches	Branch collar diameter (cm) Min	Mean	Max	Projected branch leaf area (PBLA, m^2) Min	Mean	Max
DF	**39**	**8032**	**0.0200**	**0.9851**	**9.5631**	**0.001**	**0.271**	**9.499**
FW	23	3611	0.0200	0.9072	4.5794	0.001	0.117	1.334
OP	16	4421	0.0533	1.0488	9.5631	0.001	0.396	9.499
WP	**36**	**4185**	**0.0584**	**1.7624**	**5.8318**	**0.001**	**0.530**	**7.026**
FW	20	2183	0.0787	1.9725	5.4686	0.001	0.531	4.979
OP	16	2002	0.0584	1.5333	5.8318	0.001	0.530	7.026
			Projected tree leaf area (PLA, m^2)			**Growth efficiency (GE, dm^3m^{-2})**		
			Min	**Mean**	**Max**	**Min**	**Mean**	**Max**
DF	**39**	**8032**	**2.174**	**55.838**	**234.684**	**0.632**	**1.015**	**1.657**
FW	23	3611	2.174	18.418	41.904	0.491	1.117	1.657
OP	16	4421	44.463	109.628	234.684	0.632	0.869	1.218
WP	**36**	**4185**	**16.523**	**61.678**	**175.860**	**0.590**	**2.055**	**4.313**
FW	20	2183	16.523	58.007	175.860	1.775	2.823	4.313
OP	16	2002	23.742	66.267	161.297	0.632	1.095	1.495

Sapwood area at the base of the live crown (SA_c, cm^2) displayed a strong positive linear correlation with PLA (Equation [2.3], Figure 2.5). Generalized R^2 for the linear model was greatest in interior Douglas-fir at Observatory Point (R^2=0.975), and lowest in western white pine at Fire Weather (R^2=0.901).

[2.3] $$PLA=b_0 SA_C$$

Table 2.7 *Parameter estimate and correlation of sapwood area at the base of the live crown and projected tree leaf area*

Species	Site	b0 estimate	s.d.	p	Gen R^2
WP	FW	0.32795	0.02488	<0.001	0.9014
WP	OP	0.42333	0.01814	<0.001	0.9732
DF	FW	0.35592	0.01535	<0.001	0.9607
DF	OP	0.63666	0.02652	<0.001	0.9746

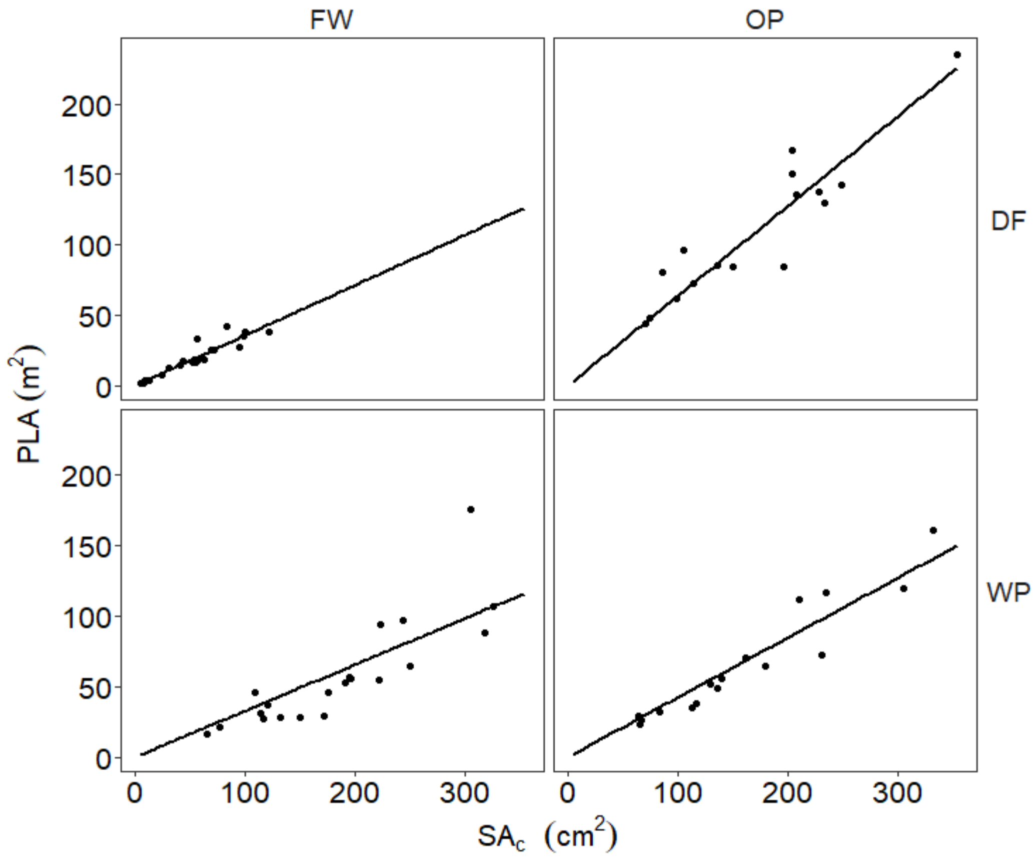

Figure 2.5 *Relationship between sapwood area at the base of the live crown (SA_c) and projected tree leaf area (PLA) by site and tree species*

2.4.2 Treatment and PLA effects on five-year growth efficiency

Analysis of variance revealed that site preparation treatments did not significantly affect GE in trees at Fire Weather or Observatory Point, nor did GE differ between treatments (Table 2.8, Figure 2.6). Site significantly impacted GE and PLA, but species only significantly affected GE (Table 2.8, Table 2.9). Site preparation treatments significantly impacted PLA, but only the bedding treatment for western white pine at Fire Weather significantly differed from the untreated control (Figure 2.7, Table 2.9). The herbicide treatment increased PLA compared to the scalping treatment in interior Douglas-fir at Fire Weather (Figure 2.7).

Table 2.8 *Analysis of variance of treatment, site, and species effect on growth efficiency (GE)*

	SS	***df***	***F***	***p***
Treatment	1.3083	3	1.3846	0.2548
Site	15.6472	1	49.6789	<0.0001
Species	21.2963	1	67.6147	<0.0001
Residuals	21.7327	69		

Table 2.9 *Analysis of variance of treatment, site, and species effect on projected tree leaf area (PLA)*

	SS	***df***	***F***	***P***
Treatment	16331	3	3.3898	0.0228
Site	46946	1	29.2334	<0.0001
Species	546	1	0.3398	0.56185
Residuals	110807	69		

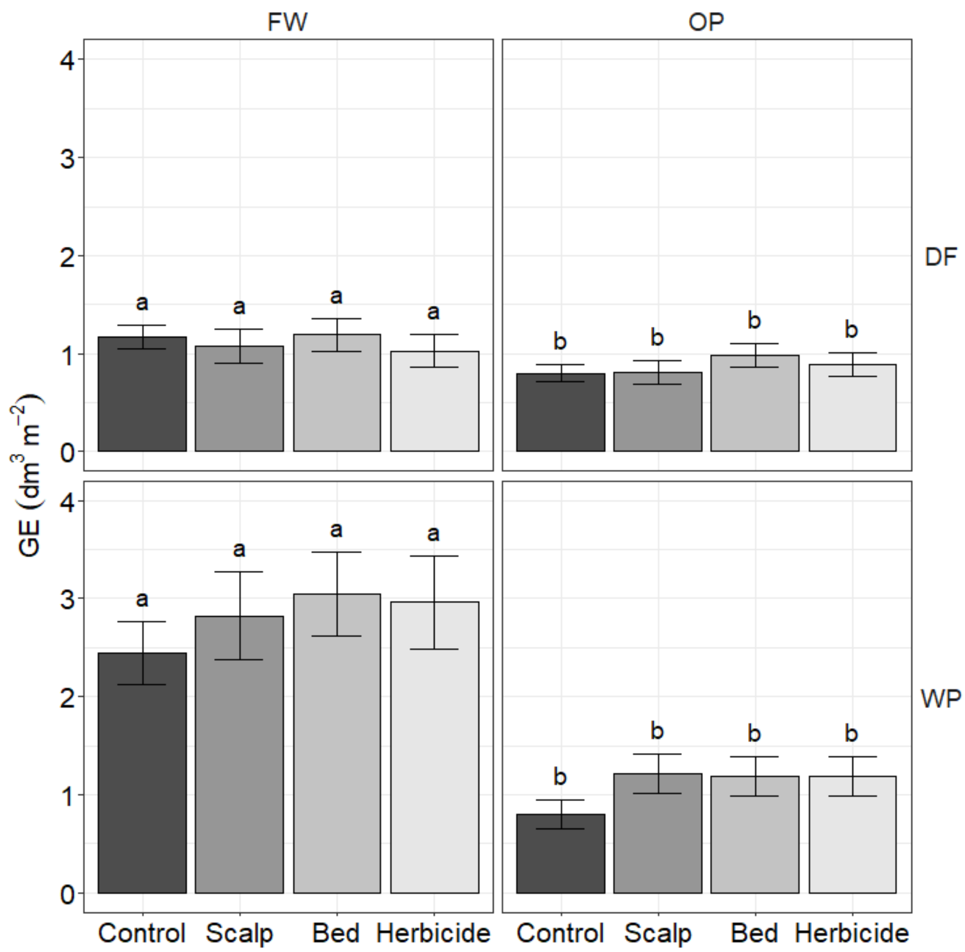

Figure 2.6 *Predicted growth efficiency (GE) by site, species and treatment*

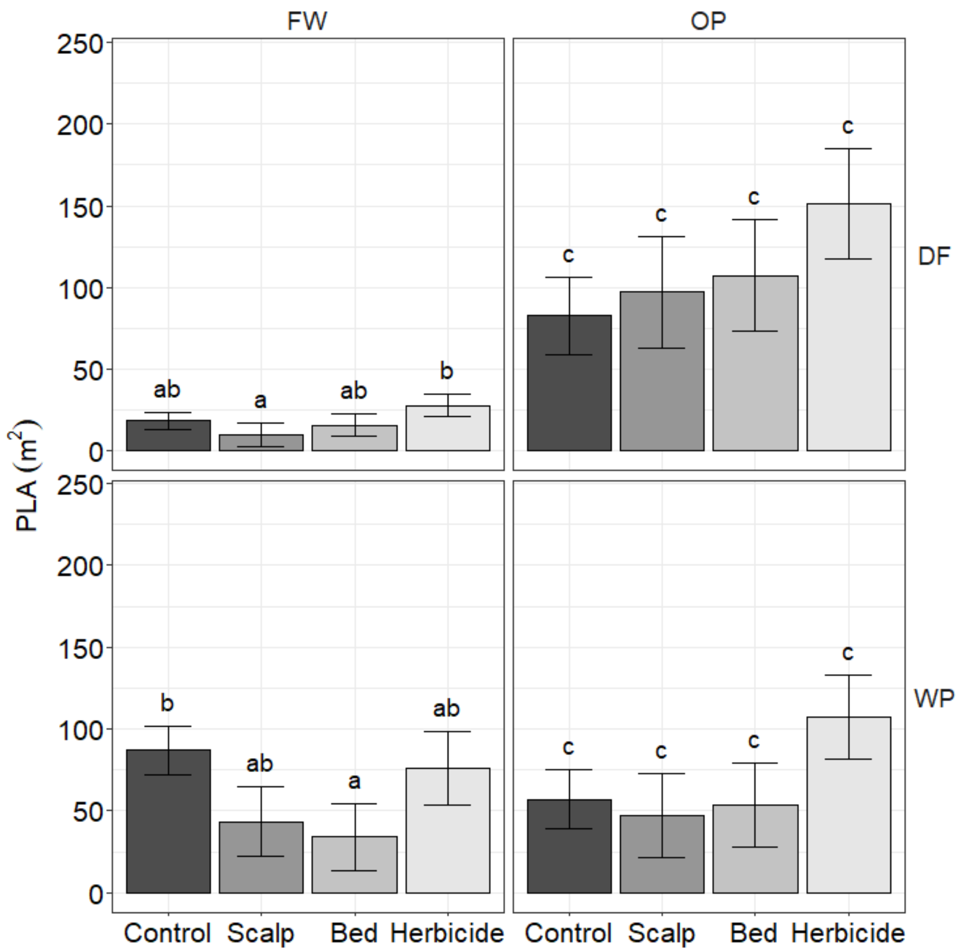

Figure 2.7 *Projected tree leaf area (PLA) by site, species, and treatment*

PLA displayed a strong positive linear correlation with VI_5 across tree species (Figure 2.8). When treated as an allometric power function, parameter estimates for the exponent were 0.94 and 1.12 for interior Douglas-fir and western white pine, respectively, indicating a near-linear relationship between PLA and VI_5. At Observatory point, interior Douglas-fir and western white pine displayed increasing logarithmic trends in GE with increasing PLA (Figure 2.9). A declining logarithmic relationship was found between PLA and GE for western white pine at Fire Weather. No trend between PLA and GE was evident in interior Douglas-fir at Fire Weather.

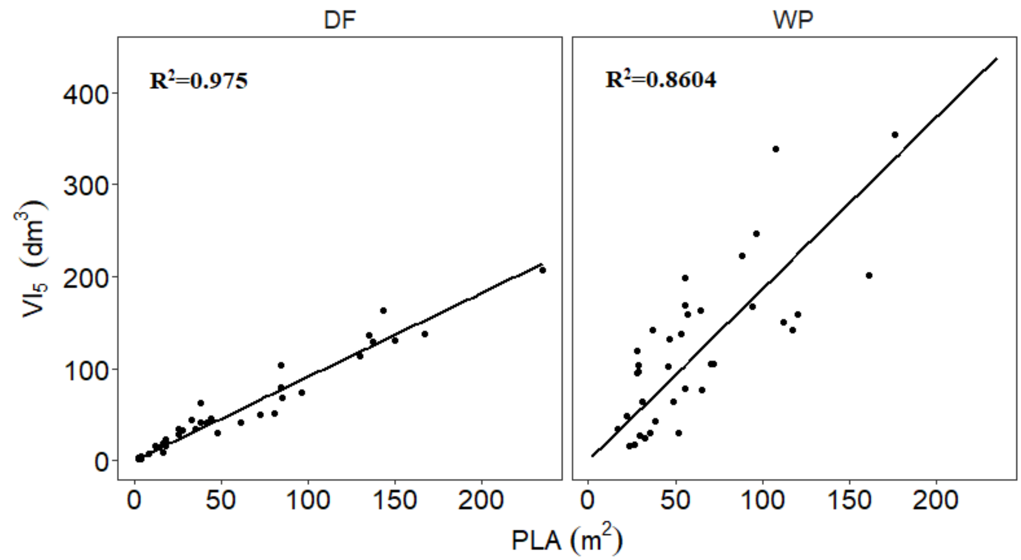

Figure 2.8 *Relationship between projected tree leaf area (PLA) and five-year volume increment (VI_5) by species*

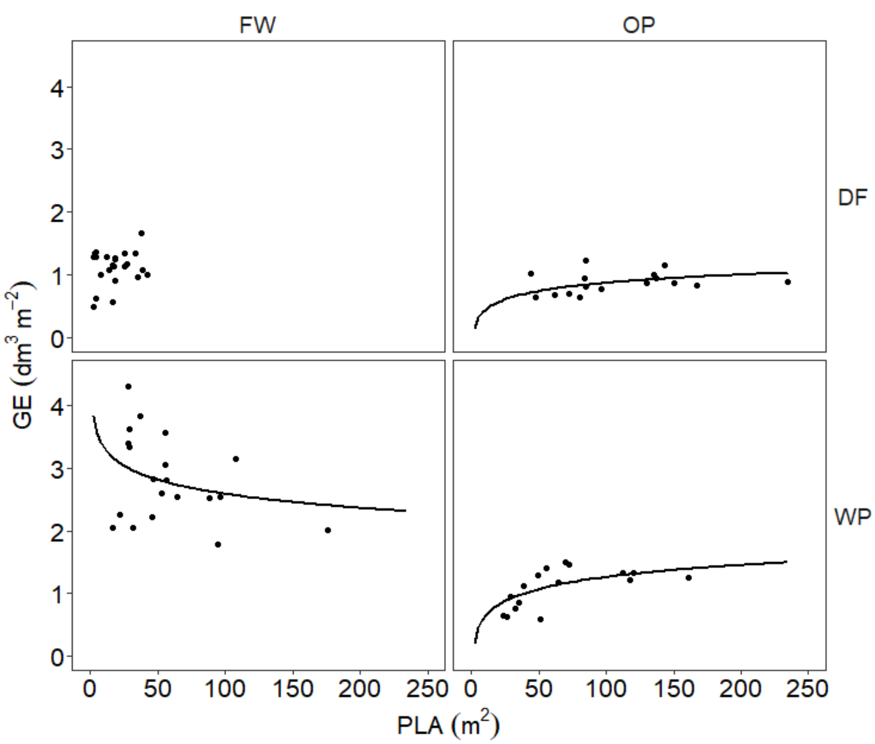

Figure 2.9 *Relationship between projected tree leaf area (PLA) and growth efficiency (GE) by site and species*

2.5 Discussion

2.5.1 Branch and tree leaf area

The displayed simple linear relationship between sapwood area at the base of the live crown and projected leaf area in Figure 2.5 indicates the projected branch leaf area model accurately estimated leaf area. Branch diameter and relative vertical position within the live crown served as the only significant fixed effects in the PBLA model. Both of these parameters are closely related to the amount of conductive tissue that can allocate resources to sustaining foliage on a branch. Prior studies have expanded on the pipe model theory to show that sapwood area at the base of the live crown is directly proportional to tree leaf area (Lehnebach et al. 2018). In finding the expected relationship between these two traits, it can be assumed that the general trend of the PBLA model was accurate. The PBLA model can be used with the branch summation method in future studies to understand site or treatment effects on leaf area of different species and treatments that are not included in this study. Treatment effects on branch leaf area could result in different growth and productivity responses across trees of different shade tolerance, social status, age class distribution, and site quality.

Treatments did not consistently differ from the untreated control in the PBLA model and PLA analyses of variance, nor at all in GE analyses of variance at age 35. However, mean DBH was greatest in the combined bedding and herbicide treatment across site and species (Table A1). The lack of a treatment effect on present productivity despite increased tree yields due to herbicide application indicates an initial growth response to the herbicide treatment that has since diminished. The herbicide treatment likely improved initial site growing conditions until tree roots expanded beyond the treatment rows, and began to interact with neighboring trees. As a result of increased neighboring tree competition for above and below ground resources, growth rates eventually leveled amongst trees of similar size classes within each site and species combination, regardless of initial site preparation treatment.

On a whole tree level, differences may have been difficult to detect due to the relatively small number of trees sampled in each site, species, and treatment combination. Due to intensity of branch measurements and the time required to perform stem and leaf area analysis, each site, species, and treatment combination only had four to six trees sampled. Future studies could accelerate the number of trees sampled in a field season by measuring only branch vertical position along the stem and branch collar diameter, or through using sapwood area at different crown positions as a surrogate for tree leaf area.

2.5.2 Treatment and PLA effects on five-year growth efficiency

Site preparation treatments had no effect on growth efficiency compared to the untreated control. This is likely attributed to design of this experiment, in which silvicultural treatments were performed in rows. While rows are serviceable for seedling studies, as trees increase in size they begin to experience crown overlap between treatments. A competition index can be used to account for present and recent neighboring tree effects on growth, but a static measurement fails to reflect temporal trends of neighboring vegetative competition. In order to reduce the effect of neighboring trees and row-level differences, uniform-shaped plots with substantial buffers are a better option to potentially detect treatment differences.

The positive simple linear relationship between PLA and VI_5, as well as the monotonically increasing relationship between PLA and GE indicates a Type C pattern of growth efficiency for interior Douglas-fir and western white pine at Observatory Point. Similar patterns in GE-PLA relationships were observed in even aged stands of lodgepole pine in central and western Montana (Kollenberg and O'Hara 1999). Eventually, a decline in GE is expected with increasing PLA, but it is likely that trees in these site and species combinations did not reach a size at which resource allocative inefficiencies began to occur.. The monotonic decreasing trend observed for western white pine at Fire Weather is indicative of a Type A pattern of growth efficiency with increasing tree leaf area. White pine trees at Fire Weather had the greatest mean branch diameter across species and site combinations in this study, as well as the greatest mean DBH and heights. Seymour and Kenefic (2002) observed monotonic decreasing trends in GE with increasing PLA of *P. rubens* and *T. canadensis* with fixed leaf area in east-central Maine, noting that trees in the upper strata of closed canopied stands are most likely to experience this trend. The Type A response observed could thus be a result of white pine trees growing faster and larger than interior Douglas-fir at Fire Weather, therefore having greater crown lengths with more large branches. Trees with more large branches must allocate additional resources towards sustaining large branches instead of increasing stemwood volume, while trees with smaller crowns and fewer large branches have not reached the threshold point at which branch sustenance occurs at the cost of stemwood production.

Due to the limited range of PLA for interior Douglas-fir at Fire Weather, no pattern was observed between PLA and GE. In general, interior Douglas-fir trees at Fire Weather were not dominant, consequently having lower total heights, live crown lengths, and therefore PLAs. A wider range of PLAs could be ensured in future studies by using sapwood radius in a fixed location or live crown length instead of diameter at breast height for random sampling selection.

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Chapter III

EFFECTS OF SITE PREPARATION AND COMPETITION ON TEMPORAL TRENDS IN STEM GROWTH OF WESTERN WHITE PINE AND INTERIOR DOUGLAS-FIR

3.1 Abstract

Site preparation is often used to ameliorate biotic and abiotic conditions that otherwise hinder conifer regeneration, but its impacts on periodic trends in tree growth beyond crown closure are uncertain. In 1982, interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and western white pine (*Pinus monticola* Dougl. ex. D. Don) seedlings were planted under different site preparation treatments at two sites in the Priest River Experimental Forest in northern Idaho. The treatments included: (1) organic horizon removal and mineral exposure (scalping), (2) soil bedding without competition removal, (3) soil bedding with competition chemically removed, and (4) an untreated control. In the summer of 2018, 75 trees were destructively sampled to reconstruct cumulative and incremental height, diameter, and volume growth over time and examine if site preparation effects persisted through age 35. Site and species specific nonlinear least squares models were fitted to relate site preparation treatment to temporal trends in cumulative growth. Additionally, trends of neighboring tree competition index (CI) were compared to five year growth increments to observe the influence of competition on recent tree growth. The bedding with herbicide treatment consistently increased cumulative growth over time compared to the untreated control, while scalping and bedding treatment effects varied by tree dimension, species, and site. Increasing CI was negatively correlated with five year growth across species and site. The results of this study reveal the importance of proper site preparation method selection depending on site

conditions, as well as an trend of greater growth with early site preparation and vegetation management treatments that persists beyond crown closure.

3.2 Introduction

Inland Northwest forests are frequently regenerated with tree planting to meet state mandates, promote desired tree species composition, and ensure prompt reforestation. In 2014 across the state of Idaho, more than 4.9 million tree seedlings were grown and 3625 ha of land were planted with trees (Hernández et al. 2015). Competition with hardwood, shrub, grass, and forb natural regeneration limit resource availability for artificially planted conifer seedlings, potentially reducing survival and growth (Löf et al. 2016; Oester and Fitzgerald 2016). Silvicultural treatments prior to planting or during the early stages of stand establishment can be applied to improve individual tree and stand productivity throughout the rotation. Site preparation, which removes competing vegetation and establishes more favorable soil conditions at the seedling microsite, is often implemented to inhibit planted tree resource competition. (Lowery and Gjerstad 1990).

Site preparation refers to the suite of soil and vegetation-influencing tools used to improve initial forest site conditions. On an industrial level, site preparation is applied to improve germination, establishment, growth, and development of favorable regeneration (Wiensczyk et al. 2011). Site preparation can occur as a multitude of treatment types, depending on the climate and condition of a site. Mechanical site preparation can involve using heavy soil-altering equipment or manual vegetation removal, while chemical site preparation often entails fertilizer or herbicide application. In cold forest regions such as the maritime-influenced forests of the Northern Rocky Mountains, mechanical and chemical methods are often used as forms of site preparation, both individually and in tandem (Binkley and Fisher 2013). Proper site preparation method selection and implementation is imperative, as selecting an unfitting treatment relative to site conditions can lower growth and survival of the desired regeneration (Smith et al. 1997).

Morris and Lowery (1988) proposed three potential stand growth responses to site preparation. A Type 1 growth response occurs when an initial growth increase occurs due to site preparation, effectively decreasing the time required to reach stand maturity by a fixed amount. A Type 2 response is quantified as a continually increasing age shift, and would be indicative of site improvement beyond competition release. Type 3 growth responses to site preparation occur when untreated stands eventually have greater volume production than stands treated with site preparation, or the amount of time required to reach stand maturity increases due to site preparation. A Type C growth response to site preparation, as proposed by South et al. (2006), occurs when an initial increase in stand volume production from site preparation later declines, eventually resulting no age shift in growth compared to an untreated stand.

Stem analysis is often performed when a record of past tree growth is desired and temporal height and diameter data is not available for individual trees (Kershaw et al. 2017). This method requires destructive sampling of individual trees, in which disks are removed incrementally along the stem for radial increment analysis (Duff and Nolan 1953). This method of analysis can be used to reconstruct a tree's temporal trends in height, diameter, and volume. Stem analysis is also performed to determine individual tree growth response to silvicultural treatments, historical disturbances, or site conditions (Wilhite and Jones 1984; Heitzman et al. 1997). Data derived from stem analysis is typically used to form temporal growth models.

Multiple model forms have been fitted to describe temporal trends in individual tree growth, often as variations of sigmoid or allometric curves. Fontes et al. (2003) modelled dominant height growth of *P. menziesii* mirb. Franco across 12 sites in Portugal, finding the McDill-Amateis function, to outperform commonly used Chapman-Richards and Schumacher-derived growth equations. A study of coastal Douglas-fir trees across Northern Pacific coastal forests found the Chapman-Richards curve to be unsuitable for predicting tree height growth, as it often under predicted height estimates (Rozenberg 1993). Pödör, Manninger, and Jereb (2014) concluded that logistic, Gompertz, and Chapman-Richards sigmoid growth models all served as strong fitting models for annual diameter growth of beech (*Fagus* spp.) in Northern Hungary, noting that the Gompertz model provided the strongest fit and the most flexibility in parameter estimations.

Indices of competition are often used to account for or describe the impact of surrounding vegetation on individual trees. Generally, a higher competition index value indicates greater levels of competing vegetation, while lower values are representative of less competition for resources. Both distance dependent and independent competition indices have been applied to quantify the composition, structure, and impact of vegetation surrounding subject trees (Weiskittel et al. 2011). Distance independent indices of competition often include the number of trees in a given area, a measurement of basal area within that area, and a site quality metric (Curtis 1970). Distance dependent competition indices are more commonly applied to understand point density and vegetation dynamics, as opposed to stand level vegetation influence, and often include measurements such as distance between trees, crown radius, and neighboring tree size (Clark and Evans 1954, Spurr 1962, Weiskittel 2011).

The objectives of this study were to (1) examine temporal trends in stem growth for western white pine (*Pinus monticola* Dougl. Ex. D. Don) and interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), (2) to determine the growth response of these two tree species to different site preparation treatments throughout a 35 year period, and (3) to understand the impact of neighboring tree competition on present growth trends.

3.3 Materials and methods

3.3.1 Site Description and Experimental Design

In 1982, two study sites were established 21 km northeast of Priest River, Idaho on the United States Department of Agriculture, Forest Service Priest River Experimental Forest. The low elevation "Fire Weather" lies on a flat alluvial bench adjacent to the Priest River, at 715 m in elevation. After initially being burned in a 1922 study the site was used in forest fuel flammability studies until 1978 (Finklin 1983). Prior to being clearcut and study establishment in 1982, Fire Weather contained a low stocking of lodgepole pine, as well as grasses and forbs (Page 1985). All residual slash and debris from clearcutting prior to study establishment (Harvey et al. 1997). Mission silt loams within the Inceptisol order, with 2 to 12 percent slopes, and a fragipan at 30 cm depth are present throughout the site (Graham et al. 1989; Soil Survey Staff 2017). Average annual precipitation at Fire Weather is 79.8 cm per year, with a mean annual temperature of 6.7 °C (Tinkham et al. 2015). This site is characterized by a *Tsuga heterophylla/Clintonia uniflora* habitat type, and is representative of less favorable growing locations within the moist forests of the Northern Rocky Mountains (Harvey et al. 1997).

The midelevation site, "Observatory Point", previously consisted of 110-year old western hemlock (*Tsuga heterophylla* (Raf.) Sarg), grand fir (*Abies grandis* (Dougl.) Lindl.), interior Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca*) and western white pine (*Pinus monticola* Dougl. ex. D. Don). This stand was clearcut in 1981, with all harvesting debris being piled and burned in 1982. The Observatory Point site is located at elevation of 1456 meters, with slopes ranging from 10-35% (Page 1985). Typic Udivitrands soils within the Andisol order are present across the site (Soil Survey Staff 2017). The habitat type is also represented by *Tsuga heterophylla/Clintonia uniflora*, but is subject to less extremes in temperature, and is representative of higher productivity forests of the Northern Rocky Mountain region (Cooper et al. 1991). Mean annual temperature at Observatory Point site is 5.3 °C, with annual precipitation averaging 91.2 cm (Page, 1985; Tinkham, Denner, & Graham, 2015).

A restricted randomized design at Fire Weather, and a randomized complete block design at Observatory Point were in 1982 (Figures 3.2-3.3). Three site preparation treatments and an untreated control were applied in 30m planting rows. The low elevation site consisted of four blocks planted continuously as one plot, whereas the midelevation site consisted of three isolated but nearby replications, each having similar slope, habitat type, soil, and aspect (Page-Dumroese et al. 1997). Treatments applied include: (1) scalping, in which the uppermost 10 cm of organic material and mineral topsoil were removed with a tractor crawler, (2) soil bedding without chemical competition control, (3) soil bedding with chemical vegetation control, and (4) an untreated control in which minimal soil disturbance was applied. Each treatment row is 1.5 meters wide, with beds approximately 46 cm high. The chemical vegetation control treatment consisted of band application of isopropylamine salt of glyphosate (Roundup®) to nonconiferous vegetation in the second and third years of the study at a rate of 1.68 kg per hectare, and manual competition removal in the planting year. Study seedlings in the chemical vegetation control treatments were covered with buckets during herbicide applications in order to prevent accidental herbicide contact (Harvey et al. 1997). Scalped organic material and mineral topsoil were used to create the raised beds (Page 1985). A crawler tractor performed the scalping treatments and constructed the soil beds (Page-Dumroese et al. 1997).

In April 1983, 1-0 container stock seedlings of western white pine and interior Douglas-fir were planted at both sites. Each replicate treatment had seedlings planted on 31 x 46 cm spacing, or 218 seedlings per treatment row, totaling 12218 planted seedlings between the two sites. Each block consisted of the four site preparation treatments for each of the two tree species. One genetic seed source was used for western white pine at both sites, while Douglas-fir seedlots originated from 805 and 1460 meters to match study site elevations (Page 1985). Post-establishment destructive sampling for prior studies, natural mortality, early mortality replanting, and site thinning for density control resulted in 1066 live trees being reported in 1990, with between 12 and 55 trees being present in each treatment row (T. Jain, USDA Forest Service, Rocky Mountain Research Station, Moscow ID, Unpublished Data). No harvesting, maintenance, inventorying, or sampling had occurred between 1990 and May of 2017.

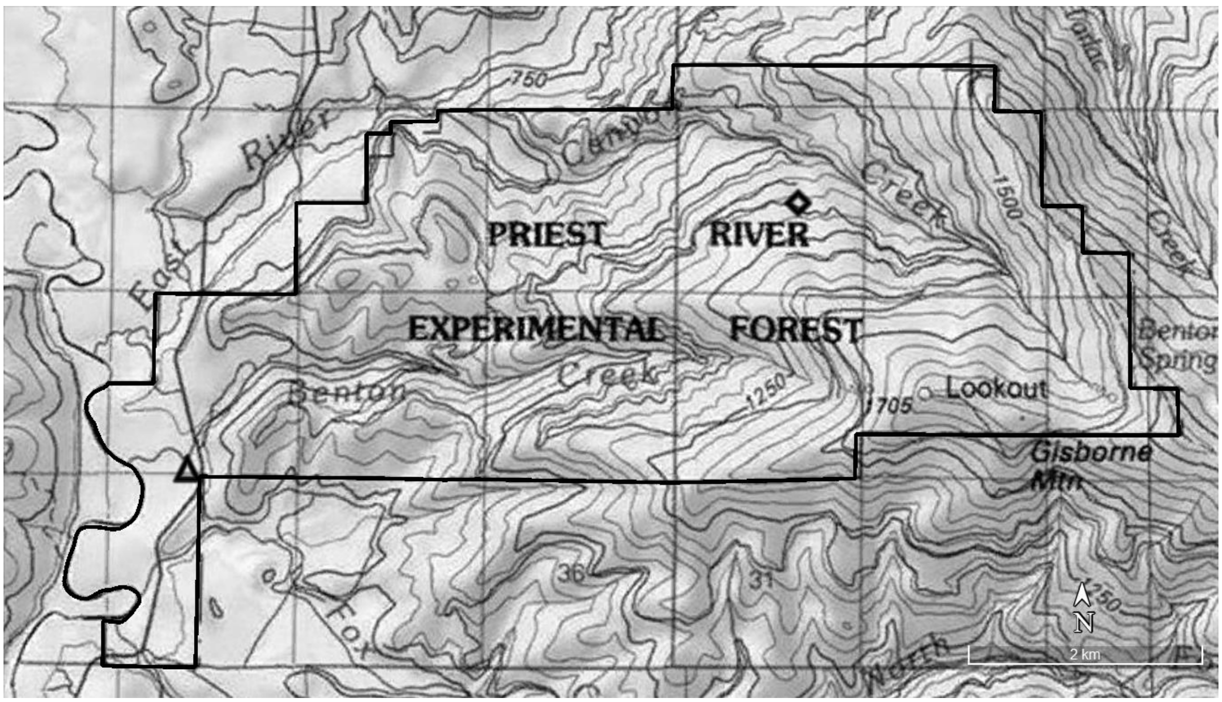

Figure 3.1 *Fire Weather (triangle) and Observatory Point (rhombus) sites within the Priest River Experimental Forest*

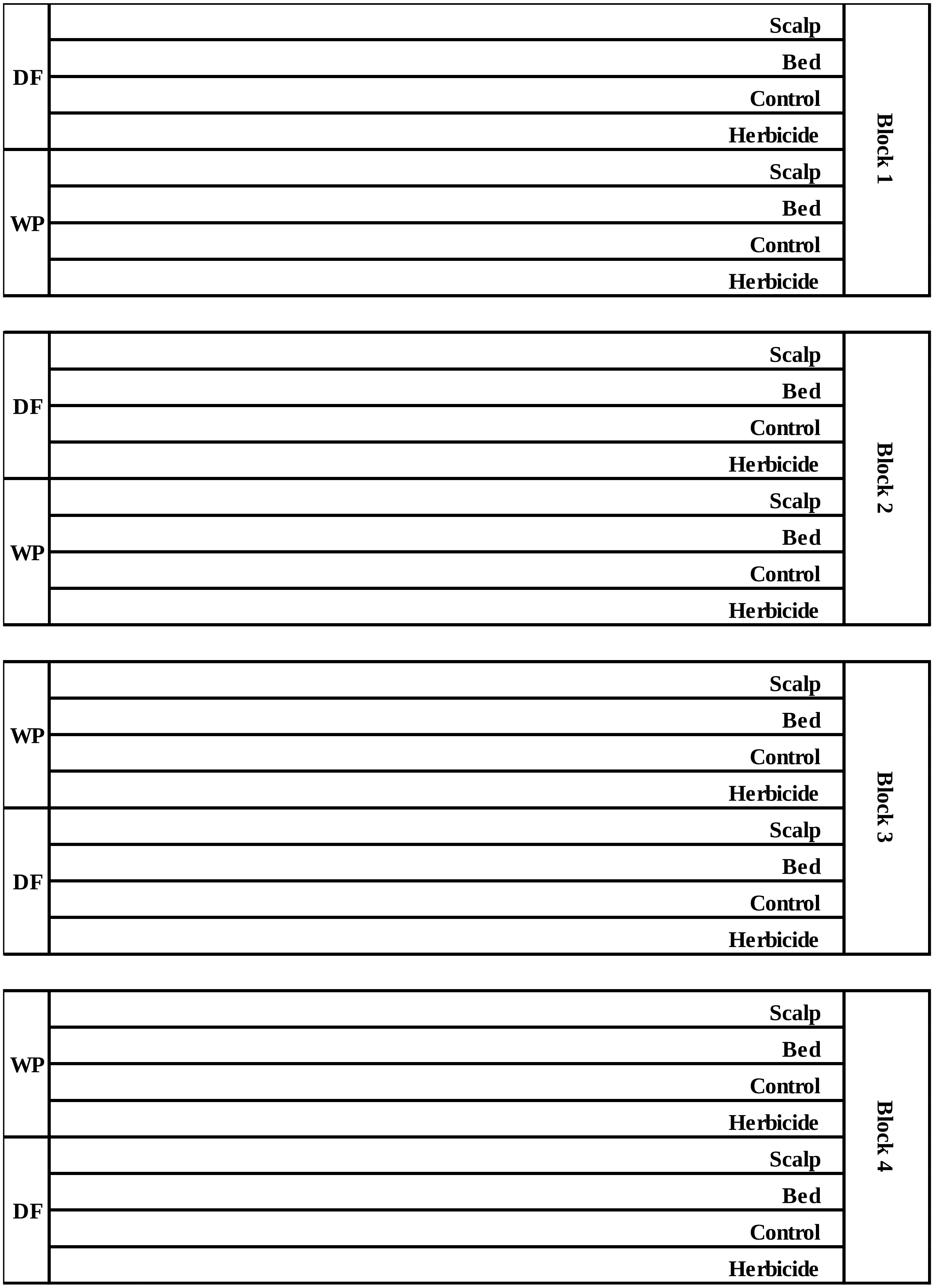

Figure 3.2 *Design of low elevation "Fire Weather" site*

WP	Control	Block 1
WP	Bed	
WP	Scalp	
DF	Herbicide	
DF	Bed	
DF	Scalp	
WP	Herbicide	
DF	Control	

WP	Bed	Block 2
DF	Bed	
WP	Herbicide	
DF	Scalp	
DF	Herbicide	
WP	Scalp	
WP	Control	
DF	Control	

WP	Control	Block 3
DF	Control	
DF	Bed	
WP	Scalp	
DF	Herbicide	
WP	Bed	
DF	Scalp	
WP	Herbicide	

Figure 3.3 *Design of high elevation "Observatory Point" site*

3.3.2 Field data collection

Prior to destructive sampling, both sites were inventoried to determine the number of remaining trees in each treatment replication. Diameter at breast height (DBH), treatment row, and tree count within row were recorded for all trees. Site inventories in 2017 identified 360 study trees, with 219 trees present at Fire Weather and 141 trees at Observatory Point (Table A1). Trees were grouped into DBH quartiles by site, species, and treatment. One to two trees from each site, species and treatment diameter quartile were randomly selected for destructive sampling, with an additional tree being chosen for harvest if a treatment row was not included in the initial random selection.

Each subject tree selected for destructive sampling next had a series of neighboring tree measurements recorded in order to formulate an index of neighboring tree competition. The eight closest neighboring trees in each cardinal direction were selected for these neighborhood measurements. Neighboring tree measurements recorded included distance between neighbor tree and subject tree, neighbor tree crown radius towards and away from the subject tree, neighbor tree height to base of live crown and total height, and cardinal location of the neighbor tree relative to the subject tree. Diameter at breast height, crown radius and stem distance measurements were determined using a Spencer® Logger's tape, while height measurements were recorded with either a Haglöf® Vertex laser hypsometer or a Suunto® PM5/66PC clinometer.

After all neighboring tree measurements were recorded at a site, trees were destructively sampled for stem analysis. A lumber crayon was used to mark 0.152, 0.762, and 1.372 meters from the forest floor along the uphill side of the stem. Each subject tree was felled with efforts to limit stem damage. Once the subject tree was successfully felled, a measuring tape was laid out along the stem, with the 0.15, 0.76, 1.37 mark on the measuring tape overlaying previously marked matching heights on the stem. Total tree height and height at the base of the live crown were then recorded using the measuring tape. Live crown length was next recorded, then divided into three sections of equal length and marked at each section's using a lumber crayon. Stem disks were harvested at 0.15, 0.76, and 1.372 meters up the stem, followed by at 0.914 meter increments after breast height, as well as at the base of each live crown section. Each disk was labeled with its height along the stem, was bagged, and returned to the University of Idaho for further laboratory processing and analysis.

3.3.3 Laboratory sample processing and analysis

A Makita 9404 4x24 inch variable speed belt sander was used to sand each disk. Disks were first sanded with 60-80-grit sandpaper to remove coarse chainsaw marks, and then with 120-grit paper to fully expose all rings. Finer rings were exposed using a Black + Decker BDEMS600 detail sander with 120-150-grit paper. An air compressor was used to remove sanding debris. Disks were strung together sequentially by the vertical position along the stem from which they were harvested for each tree.

Once all disk samples from a subject tree had been processed, scanning was performed using WinDendro™ (Regent Instruments Inc., Quebec CA) software and an LA2400 flatbed scanner (Regent Instruments Inc., Quebec CA) at 1200 or 1600 dpi, depending on ring exposure and visibility. For each disk, the subject tree ID, height, and age, as well as disk height and year of harvest were manually entered. Radial increment was recorded at two paths per disk, either at a 90° angle or at both the largest and smallest radii in order to account for variability in stem growth. All rings identified by WinDendro were manually confirmed and adjusted to ensure proper position and angle, and to identify missed and false rings. A text file containing raw radial increment data was produced for each tree. A Microsoft Excel macro, XLStem (Regent Instruments Inc., Quebec CA), produced temporal stem growth data, including cumulative height, diameter at breast height (DBH), and stem volume, in addition to height, DBH, and stem volume annual increment. Annual height growth was calculated using Carmean's (1972) height interpolation formula in XLStem, while volume was calculated using a truncated cone volume formula (Equation [3.1]). Growth data from the year of harvest (2017) was excluded, as trees were still growing during the sampling period.

[3.1] $$V = \frac{1}{3}\pi({r_1}^2 + r_1 r_2 + {r_2}^2)L$$

Table 3.1 *Variable definitions in truncated cone volume formula*

Variable	Definition
V	Stem Volume Inside Bark (dm^3)
r_1	Average radius of lower disk inside bark(dm)
r_2	Average radius of higher disk inside bark (dm)
L	Distance between disks (dm)

3.3.4 Stem analysis

Cumulative trends in DBH, volume, and height growth under each site preparation treatment were modelled using the “nls” function of the “stats” package of R, and data collected using WinDendro (R Core Team 2018). 2625 data points, or one data point per year per subject tree, were used to fit site and species specific models of each growth trend. Analysis of variance was performed to determine if site, species, age, and treatment had significant effects on cumulative trends in height, DBH, and volume. Trends in the data were compared to base models described in Sit and Poulin-Costello (1994), and initial parameter estimates were obtained using the SAS MODEL procedure (SAS Institute Inc., 2018). In cumulative growth models, treatment and year since planting were substituted into base models to predict annual growth. The SAS Model procedure used the ordinary least squares method for parameter estimation, which were then used as starting parameter estimates for the “nls” function in R. Final parameter estimations in R were determined using the nonweighted least squares estimation method within the “nls” function.

Significance of parameter estimates was determined by setting a significant *p*-value threshold of 0.05. Site preparation treatment parameters deemed insignificant were removed from the model and parameter estimates were re-determined. Treatments removed from the model were considered to have no effect on growth compared to the untreated control. Once a model had only significant explanatory variables remaining, goodness of fit was evaluated using likelihood ratio tests, Akaike information criterion (AIC), root mean squared error, and generalized R^2 values.

Temporal trends in growth increment were observed by plotting data and fitting trendlines using smoothed conditional means with the "geom_smooth" function of the "ggplot2" package in R software (R Core Team 2018, Wickham 2009). The trendlines formed were used to observe temporal trends of height and DBH increment. Local polynomial regression, or LOESS curve fitting was used to display DBH and height increment trends for all site and species combinations. A distance dependent competition index (CI) was modified from O'Neal et al. (1995) to determine the impact of neighboring tree competition on five-year height, and DBH increment across site and species.

The competition index was calculated as:

[3.2]
$$\sum_{i=1}^{n} CI = \frac{R_s + 0.5(R_s + R_a)}{D_{sc}} * \frac{R_s}{0.5(R_s + R_a)} * \frac{HT_c - D_{sc}}{HT_s}$$

n=number of competitor trees, equal to 8 for all subject trees

CI=competition index

R_s=Competitor tree crown radius towards subject tree

R_a=Competitor tree crown radius away from subject tree

D_{sc}=Distance between stems of subject and competitor

HT_c=Total height of the competitor tree

HT_s=Total height of the subject tree

Five year height and DBH growth increment were calculated by subtracting the total growth in year 30 from the cumulative growth in year 34, with growth data being provided from stem analysis performed in XLStem. An analysis of variance test was performed to determine the effects of site and species on CI, as well as 5 year height and DBH increment. Post hoc mean comparisons and Tukey's honestly significant difference test were used to evaluate differences in mean CI, 5 year height increment, and 5 year DBH increment between species and sites within species, at a 95% confidence level.

3.4 Results

3.4.1 Temporal trends in cumulative growth by site preparation treatment

Age, species, site, and treatment all had a significant effect on cumulative height, DBH, and volume growth (Table 3.2). Cumulative height trends across treatment and species were best fit to a modified Gompertz function in the form of Equation [3.3]:

[3.3] $$HT_c = \frac{\gamma_T}{e^{e^{b_4 - b_5 * Age}}}$$

For all height models, treatments were treated as indicator variables in the form of γ_T, where:

$$\gamma_T = b_0 + b_1 S + b_2 B + b_3 H$$

and:

$$S = \begin{cases} 1, \text{ if treatment=Scalp} \\ 0, \text{ otherwise} \end{cases}$$

$$B = \begin{cases} 1, \text{ if treatment=Bed} \\ 0, \text{ otherwise} \end{cases}$$

$$H = \begin{cases} 1, \text{ if treatment=Herbicide} \\ 0, \text{ otherwise} \end{cases}$$

Table 3.2 *Analysis of variance for age, site, species, and treatment effects on temporal trends of height, DBH, and volume cumulative growth*

Height	***SS***	***df***	***F***	***p***
Age	66339	1	11614.362	<0.001
Site	1418	1	248.217	<0.001
Species	1246	1	218.149	<0.001
Treatment	1649	3	96.239	<0.001
Residuals	14953	2618		
DBH				
Age	5891021	1	9505.196	<0.001
Site	50666	1	56.058	<0.001
Species	145330	1	160.794	<0.001
Treatment	325124	3	119.907	<0.001
Residuals	2366210	2618		
Volume				
Age	7308542	1	1728.244	<0.001
Site	242667	1	57.383	<0.001
Species	551520	1	130.417	<0.001
Treatment	568043	3	44.775	<0.001
Residuals	11071216	2618		

All site preparation treatments had a significant effect on cumulative height over time compared to the untreated control (Tables 3.3-3.4, Figure 3.4, Figures A1-A4). Across site and species, the herbicide treatment had the greatest positive effect on temporal trends in cumulative height. For both species at Fire Weather, scalping and bedding treatments significantly reduced cumulative height growth compared to the untreated control and herbicide treatments. However, at Observatory Point, scalping and bedding treatments increased height growth relative to the untreated control.

Table 3.3 *Parameter estimates for models of cumulative tree height growth over time by site preparation treatment*

Model	Species	Site	Parameter	Estimate	s.d.	p
[3.3]	WP	FW	b0	30.052577	0.949158	<0.001
			b1	-1.283417	0.367123	0.001
			b2	-5.659635	0.389540	<0.001
			b3	1.858169	0.391285	<0.001
			b4	1.592957	0.028628	<0.001
			b5	0.080550	0.003019	<0.001
[3.3]	WP	OP	b0	23.30789	3.826260	<0.001
			b1	2.15361	1.039140	0.039
			b2	3.77870	1.153670	0.001
			b3	12.77845	2.283700	<0.001
			b4	1.60629	0.049360	<0.001
			b5	0.05829	0.007340	<0.001
[3.3]	DF	FW	b0	15.714192	0.645180	<0.001
			b1	-2.817855	0.347645	<0.001
			b2	-0.827874	0.316495	0.009
			b3	3.980557	0.350257	<0.001
			b4	1.466873	0.043362	<0.001
			b5	0.085446	0.004754	<0.001
[3.3]	DF	OP	b0	22.669187	1.671609	<0.001
			b1	1.673307	0.517949	0.001
			b2	3.552985	0.565033	<0.001
			b3	7.987153	0.764768	<0.001
			b4	1.475864	0.027550	<0.001
			b5	0.061828	0.004073	<0.001

Table 3.4 *Fit statistics for cumulative height models over time*

Species	Site	LL	AIC	RMSE	Generalized R^2
WP	FW	-1203.34	2420.682	1.356	0.9637
WP	OP	-1195.10	2404.203	2.056	0.8352
DF	FW	-1447.89	2909.785	1.467	0.8966
DF	OP	-939.098	1892.195	1.301	0.9348

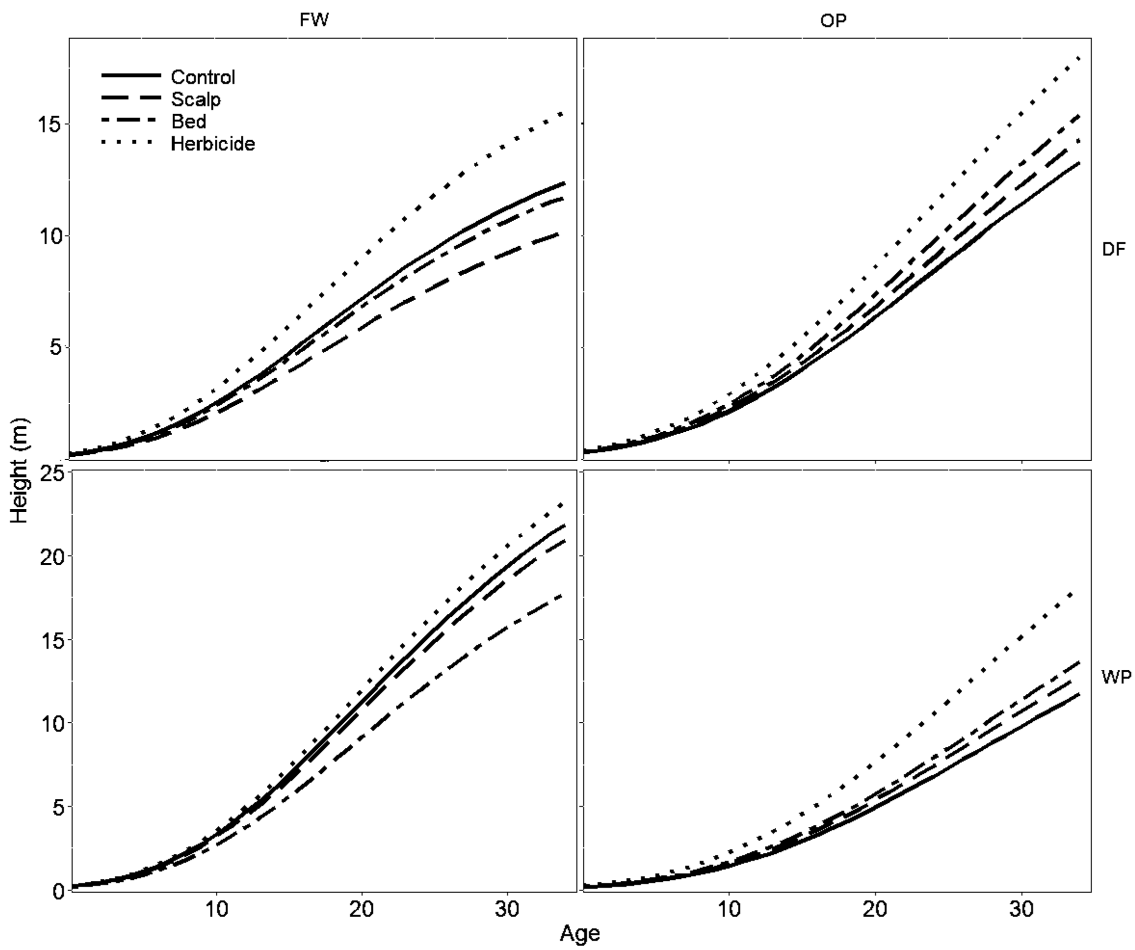

Figure 3.4 *Predicted temporal height growth by site, treatment, and species*

For western white pine, cumulative DBH trends were best fit to a modified Gompertz function in the form of Equation [3.4]. In both site-specific models, all treatment parameters significantly affected temporal trends in DBH growth (Tables 3.5-3.6, Figure 3.5, Figures A5-8). A modified logistic function best fit trends in DBH growth for interior Douglas-fir, in the form of Equation [3.5]:

[3.4] $$DBH_c = \frac{\gamma_T}{e^{e^{b_4 - b_5 * Age}}}$$

[3.5] $$DBH_c = \frac{\gamma_T}{1 + e^{b_4 - b_5 * Age}}$$

The bedding treatment parameter did not significantly affect the DBH growth of interior Douglas-fir at Fire Weather compared to the untreated control (p=0.098), and as such was removed from the model. Interior Douglas-fir DBH growth at Fire Weather was modelled in the form of Equation [3.6]:

[3.6] $$DBH_c = \frac{\gamma_{Ti}}{1 + e^{b_4 - b_5 * Age}}$$

Treatments were treated as indicator variables in the form of γ_{Ti}, where:

$$\gamma_{Ti} = b_0 + b_1 S + b_3 H$$

and:

$$S = \begin{cases} 1, \text{ if treatment=Scalp} \\ 0, \text{ otherwise} \end{cases}$$

$$H = \begin{cases} 1, \text{ if treatment=Herbicide} \\ 0, \text{ otherwise} \end{cases}$$

Temporal volume trends for western white pine at Fire Weather and interior Douglas-fir were best fit to a logistic model in the form of Equation [3.7]:

[3.7] $$V_c = \frac{\gamma_T}{1 + e^{b_4 - b_5 * Age}}$$

Similar logistic models were used to fit trends of volume growth over time for western white pine at Observatory Point (Equation [3.8]) and interior Douglas-fir at Fire Weather (Equation [3.9], Figure 3.6, Figures A9-A12, Tables 3.6-7)). The scalping treatment did not significantly affect volume growth of western white pine at Observatory Point (p=0.350), and bedding did not significantly impact the volume growth of interior Douglas-fir at Fire Weather compared to the untreated control (p=0.18).

Table 3.5 *Parameter estimates for models of cumulative tree DBH growth over time by site preparation treatment*

Model	Species	Site	Parameter	Estimate	s.d.	p
[3.4]	WP	FW	b0	257.084219	7.985851	<0.001
			b1	-34.768665	4.752910	<0.001
			b2	-55.176059	4.721927	<0.001
			b3	33.786650	5.028373	<0.001
			b4	1.980987	0.070334	<0.001
			b5	0.112323	0.005605	<0.001
[3.4]	WP	OP	b0	171.015451	13.066925	<0.001
			b1	19.744502	6.981637	0.005
			b2	43.150848	7.494036	<0.001
			b3	134.038832	11.175650	<0.001
			b4	2.186406	0.116275	<0.001
			b5	0.098055	0.008616	<0.001
[3.6]	DF	FW	b0	263.991308	9.695535	<0.001
			b1	-69.544900	7.502318	<0.001
			b3	108.288547	7.623972	<0.001
			b4	2.075900	0.092741	<0.001
			b5	0.102709	0.007358	<0.001
[3.5]	DF	OP	b0	420.995767	27.492373	<0.001
			b1	59.817150	13.973415	<0.001
			b2	131.383995	15.703222	<0.001
			b3	172.467809	17.129599	<0.001
			b4	1.988609	0.066151	<0.001
			b5	0.072339	0.005443	<0.001

Note: *b2 is excluded from model [3.6] due to the parameter estimate not differing from 0 at a confidence threshold of p>0.05.*

Table 3.6 *Fit statistics for cumulative DBH models over time*

Model	Species	Site	LL	AIC	RMSE	Generalized R^2
DBHc	WP	FW	-3117.07	6248.142	20.87	0.9286
DBHc	WP	OP	-2489.13	4992.260	20.72	0.8898
DBHc	DF	FW	-3568.29	7148.575	20.36	0.8460
DBHc	DF	OP	-2474.54	4963.072	20.19	0.9070

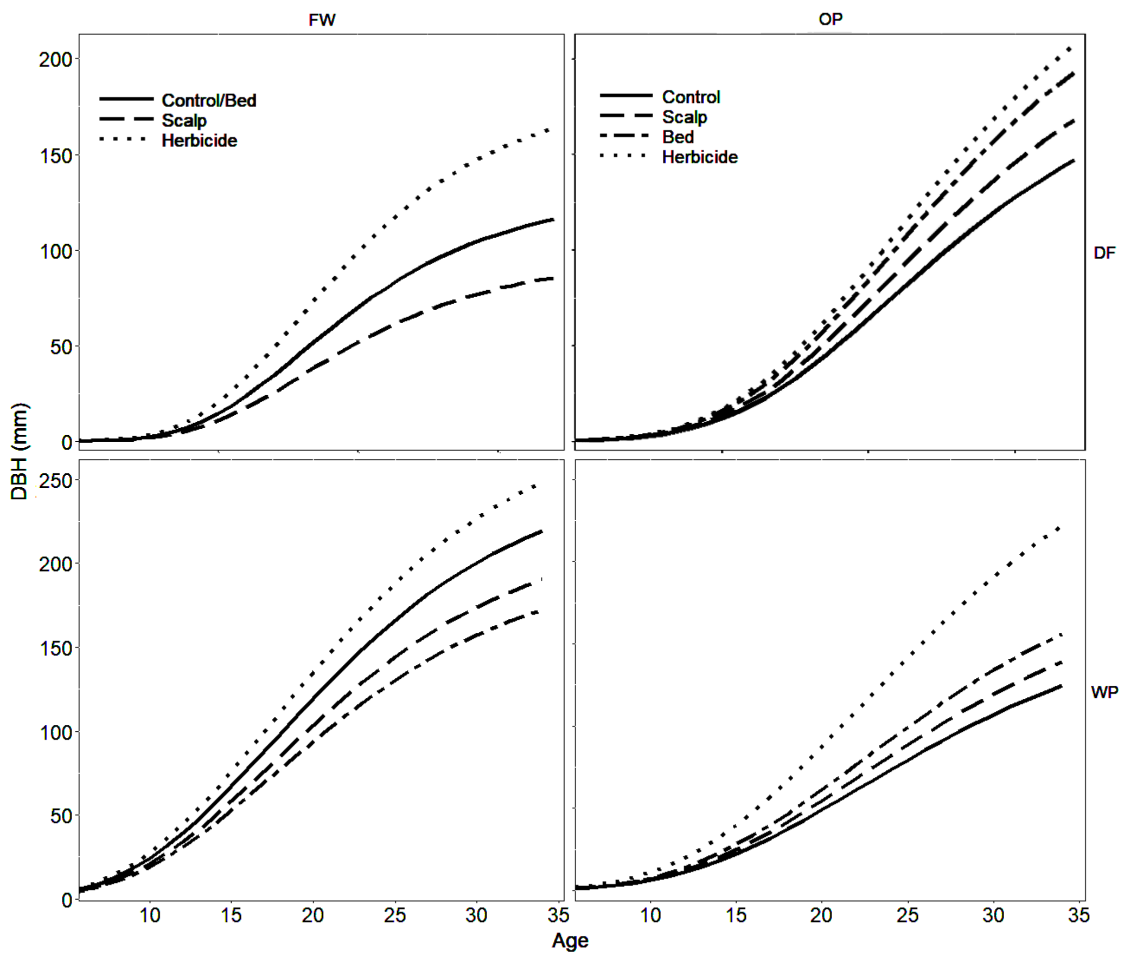

Figure 3.5 *Predicted temporal DBH growth by site, treatment, and species*

[3.8]

$$V_c = \frac{\gamma_{Tj}}{1 + e^{b_4 - b_5 * Age}}$$

$$\gamma_{Tj} = b_0 + b_2 B + b_3 H$$

$$B = \begin{cases} 1, \text{ if treatment=Bed} \\ 0, \text{ otherwise} \end{cases}$$

$$H = \begin{cases} 1, \text{ if treatment=Herbicide} \\ 0, \text{ otherwise} \end{cases}$$

[3.9]

$$V_c = \frac{\gamma_{Ti}}{1 + e^{b_4 - b_5 * Age}}$$

Table 3.7 *Parameter estimates for models of cumulative tree volume growth over time by site preparation treatment*

Model	Species	Site	Parameter	Estimate	s.d.	p
[3.7]	WP	FW	b0	688.47984	88.87645	<0.001
			b1	-232.99333	38.37919	<0.001
			b2	-315.85617	46.38633	<0.001
			b3	170.40061	33.81721	<0.001
			b4	6.59251	0.28838	<0.001
			b5	0.21127	0.01657	<0.001
[3.8]	WP	OP	b0	167.99505	42.61895	<0.001
			b2	61.43726	22.42850	0.006
			b3	337.51365	85.07344	<0.001
			b4	7.37682	0.47998	<0.001
			b5	0.22531	0.02767	<0.001
[3.9]	DF	FW	b0	92.08590	7.35328	<0.001
			b2	-29.61055	6.04678	<0.001
			b3	90.40474	8.44069	<0.001
			b4	6.14224	0.44563	<0.001
			b5	0.23387	0.02275	<0.001
[3.7]	DF	OP	b0	223.50723	43.43603	<0.001
			b1	45.35278	19.70704	0.022
			b2	178.09950	37.60940	<0.001
			b3	276.21833	54.37369	<0.001
			b4	7.32325	0.37145	<0.001
			b5	0.22474	0.02129	<0.001

Note: *b1 is excluded from models [3.8] and [3.9] due to parameter estimates not differing from 0 at a confidence threshold of p>0.05.*

Table 3.8 *Fit statistics for cumulative volume models over time*

Model	Species	Site	LL	AIC	RMSE	Generalized R^2
Vc	WP	FW	-3802.50	7619.00	55.56	0.821
Vc	WP	OP	-2728.14	5468.27	31.73	0.730
Vc	DF	FW	-3696.09	7404.17	23.94	0.694
Vc	DF	OP	-2701.37	5416.73	30.27	0.809

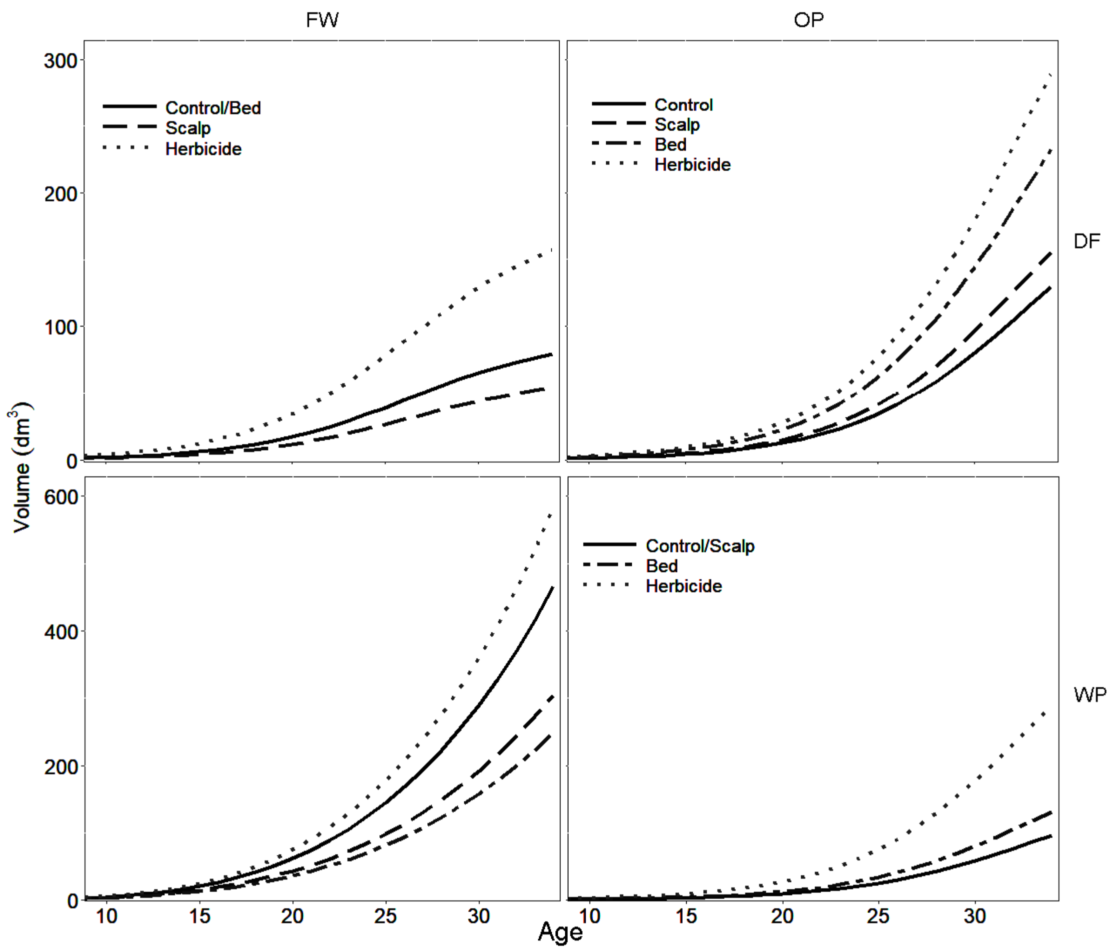

Figure 3.6 *Predicted temporal stemwood volume growth by site, treatment, and species*

3.4.2 Treatment and competition effects on trends in growth increment

Analysis of Variance found site, species, and the interaction of site and species to have significant effects on CI, five year height increment (HT_{i5}, $m^1 5year^{-1}$), and five year DBH increment (DBH_{i5}, $mm^2 5year^{-1}$) (Table 3.9). At Fire Weather, mean CI for interior Douglas-fir was 43.791, while western white pine had a mean CI of 23.184 (Table 3.10). Average CI was significantly greater for Douglas-fir compared to western white pine, and was greatest for interior Douglas-fir at Fire Weather. Mean DBH_{i5} and HT_{i5} of western white pine were greater than interior Douglas-fir at both sites, but did not significantly differ by site within species for western white pine. For interior Douglas-fir, Observatory Point mean HT_{i5} and

DBH_{i5} were greater than at Fire Weather, while mean CI was significantly higher at Fire Weather than at Observatory Point (Table 3.10).

Table 3.9 *Analysis of variance for site and species effects on competition index (CI), 5 year DBH increment and 5 year HT increment*

CI	***SS***	***df***	***F***	***p***
Site	2614.5	1	13.1432	0.001
Species	7.37371466.8	1	7.3737	0.0083
Species:Site	1459.8	1	7.3386	0.008
Residuals	14123.8	71		
DBH_{i5} (mm^1 $5year^{-1}$)				
Site	3513.0	1	65.382	<0.001
Species	2301.0	1	42.824	<0.001
Species:Site	1657.2	1	30.842	<0.001
Residuals	3814.9	71		
HT_{i5} (m^1 $5year^{-1}$)				
Site	4.1641	1	25.348	<0.001
Species	16.7749	1	102.114	<0.001
Species:Site	7.5344	1	45.864	<0.001
Residuals	11.6636	71		

Table 3.10 *Mean competition index, 5 year DBH increment, and 5 year height increment* by species and site within species.

	DF	**WP**
CI	**35.337 (±2.95) *A***	**26.071 (±2.05) *B***
FW	43.791 (±3.94) *a*	27.293 (±1.53) *a*
OP	23.184 (±2.06) *b*	24.544 (±4.25) *a*
DBH_{i5} (mm^1 $5year^{-1}$)	**15.075 (±2.06) *B***	**26.641 (±1.46) *A***
FW	5.608 (±0.50) *b*	24.842 (±1.99) *a*
OP	28.684 (±1.99) *a*	28.890 (±2.06) *a*
HT_{i5} (m^1 $5year^{-1}$)	**1.190 (±0.10) *B***	**2.153 (±0.08) *A***
FW	0.739 (±0.07) *b*	2.235 (±0.07) *a*
OP	1.838 (±0.08) *a*	2.051 (±0.154) *a*

Note: *Uppercase letters indicate differences between species, while lowercase letters indicate differences between sites within a species.*

Table 3.11 *Analysis of variance for age, site, species, and treatment effect on annual DBH and height increment*

HT_i ($m^1 year^{-1}$)	*SS*	*df*	*F*	*p*
Age	38.436	1	515.022	<0.001
Site	1.928	1	25.840	<0.001
Species	10.208	1	136.786	<0.001
Treatment	3.528	3	15.742	<0.001
Residuals	195.380	2618		
DBH_i ($mm^1 year^{-1}$)				
Age	9365.1	1	963.7994	<0.001
Site	40.8	1	4.2011	0.041
Species	1089.9	1	112.1615	<0.001
Treatment	989.4	3	33.9696	<0.001
Residuals	25438.7	2618		

Table 3.12 *Mean annual DBH and height increment by species, site, and treatment*

Species/Site	Treatment	DBH_i ($mm^1 year^{-1}$)	HT_i ($m^1 year^{-1}$)
DF			
FW	Control	3.448 (±0.189) *b*	0.352 (±0.014) *b*
	Scalp	2.520 (±0.212) *c*	0.283 (±0.018) *c*
	Bed	3.328 (±0.205) *b*	0.339 (±0.016) *bc*
	Herbicide	4.450 (±0.225) *a*	0.423 (±0.017) *a*
OP	Control	4.493 (±0.278) *b*	0.380 (±0.019) *b*
	Scalp	4.861 (±0.307) *ab*	0.418 (±0.022) *b*
	Bed	5.601 (±0.328) *ab*	0.433 (±0.021) *ab*
	Herbicide	5.939 (±0.304) *a*	0.491 (± 0.023) *a*
WP			
FW	Control	6.577 (±0.327) *a*	0.625 (±0.027) *a*
	Scalp	5.445 (± 0.273) *b*	0.588 (±0.026) *ab*
	Bed	5.187 (±0.274) *b*	0.529 (±0.0254) *b*
	Herbicide	7.292 (±0.358) *a*	0.642 (±0.029) *a*
OP	Control	3.861 (±0.265) *c*	0.338 (±0.022) *b*
	Scalp	4.168 (±0.268) *bc*	0.383 (±0.024) *b*
	Bed	4.630 (±0.296) *bc*	0.379 (±0.027) *b*
	Herbicide	6.224 (±0.378) *a*	0.489 (±0.032) *a*

Age, site, species, and treatment all had a significant effect on DBH and height increment over time (Table 3.11) Mean annual height increment (HT_i, $m^1 year^{-1}$) across site, treatment, and species displayed a parabolic trend over time (Figure 3.7, Figures A13-A16)

Interior Douglas-fir mean HT_i under the herbicide treatment was greater than all other treatments at Fire Weather, and greater than the control and scalping treatments at Observatory Point (Table 3.12). In western white pine, mean annual height increment for the untreated control and the herbicide treatment at Fire Weather did not significantly differ, but both treatments produced greater mean HT_i than the scalping treatment. White pine mean annual height growth at Observatory Point was greatest in the herbicide treatment while the bedding, scalp, and control treatments did not significantly differ. Across species and site, bedding and scalp treatments did not significantly differ (Table 3.12).

Across site, species, and treatment, annual DBH increment (DBH_i, $mm^1 year^{-1}$) displayed a parabolic trend over time (Figure 3.8, Figures A17-A20). At Fire Weather, interior Douglas-fir mean DBH_i was greatest in the herbicide treatment, while mean DBH_i - was lowest in the scalping treatment (Table 3.12). Mean DBH_i in the herbicide treatment at Observatory Point was greater than the untreated control for interior Douglas-fir, while scalping and bedding treatments did not differ in mean DBH_i from any treatment. Western white pine mean DBH_i did not significantly differ from the untreated control in the herbicide treatment at Fire Weather, but was significantly greater than the scalping and bedding treatments. At Observatory Point, western white pine mean DBH_i under the herbicide treatment was greater than all other treatments, while mean DBH_i was lowest in the untreated control (Table 3.12).

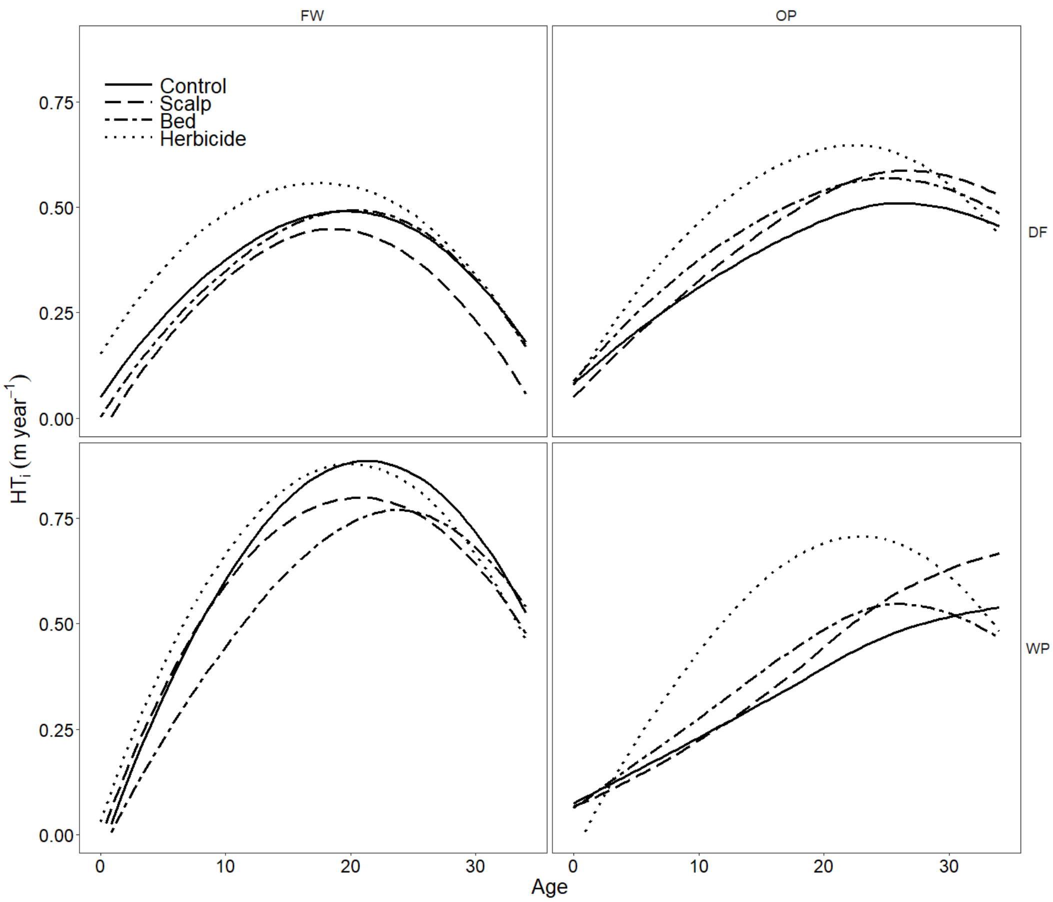

Figure 3.7 *Mean temporal trends in stem height increment by site, treatment, and species*

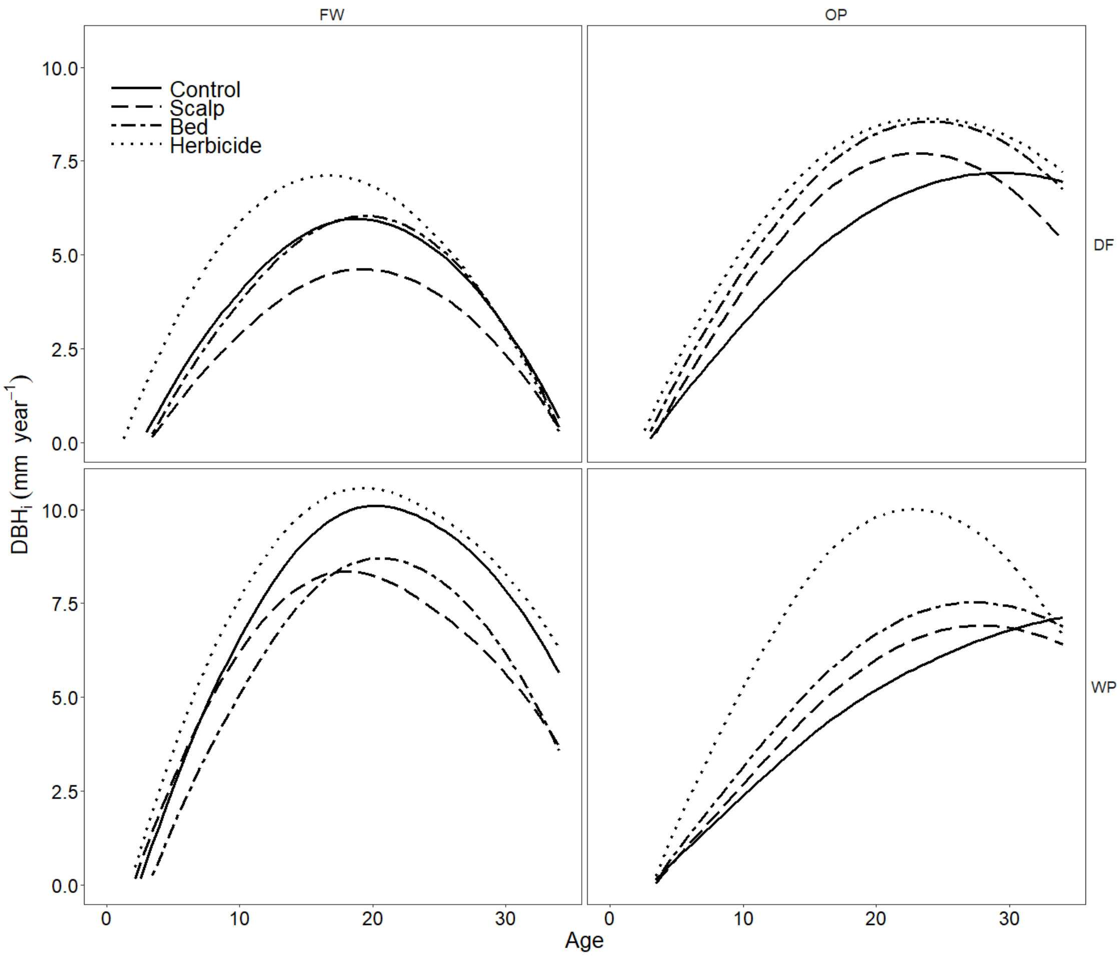

Figure 3.8 *Mean temporal trends in DBH increment by site, treatment, and species*

Similar trends existed between competition index and five year height (HT_{i5}, $m^1 5year^{-1}$) and DBH increment (DBH_{i5}, $mm^1 5year^{-1}$). At Fire Weather, interior Douglas-fir displayed a visible negative trend in 5 year height increment in response to CI (Figure 3.9). No other site and species combination displayed a strong relationship between HT_{i5} and CI. Five year DBH increment response to increase CI was more visible across all treatment and species combinations, with DBH_{i5} generally decreasing with increasing CI (Figure 3.10).

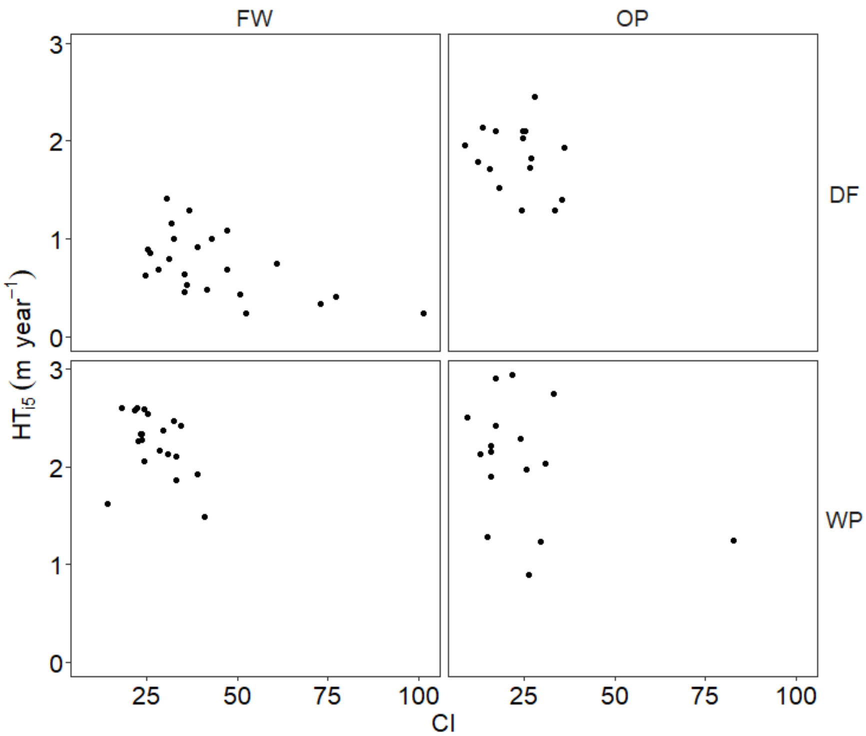

Figure 3.9 *Relationship between neighboring tree competition index (CI) and five year height increment (HT_{i5}) by site and species*

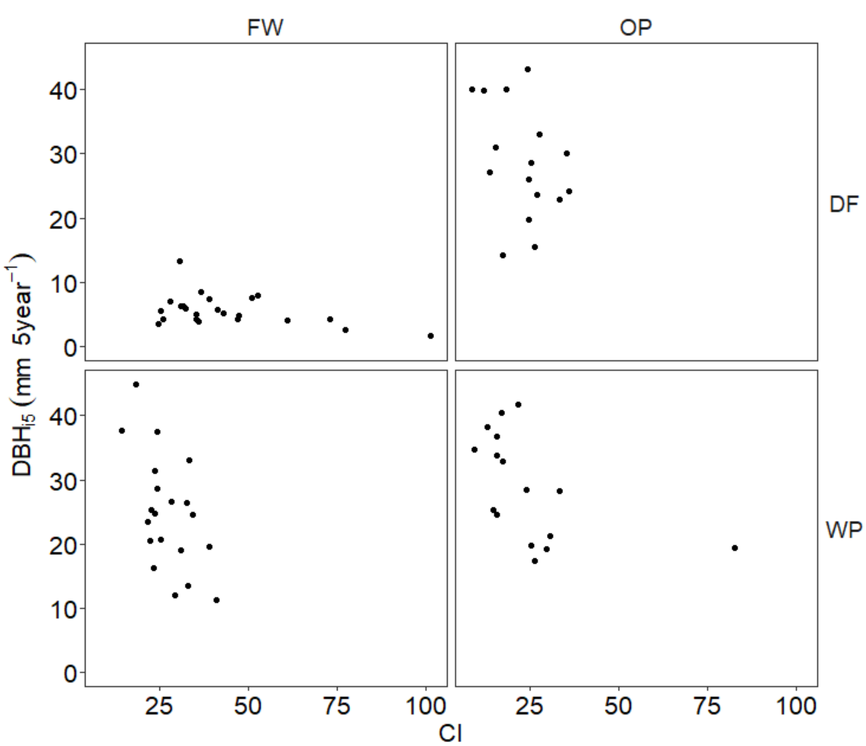

Figure 3.10 *Relationship between neighboring tree competition index (CI) and five year diameter at breast height increment (DBH_{i5}) by site and species*

3.5 Discussion

3.5.1 Temporal trends in cumulative growth by site preparation treatment

Across site, treatment, and species, the combined bedding and herbicide treatment significantly increased cumulative DBH, volume, and height growth over the 35 year growing period. In all models, cumulative height and DBH growth across treatments was declining by age 34, as also noted in parabolic form of mean DBH_i and HT_i curves. This deceleration in height and DBH growth over time implies an initial increase due to the combined bedding and herbicide treatment that will be maintained throughout the growing period, or a fixed age shift in height and DBH growth. A fixed positive age shift across site and species indicates the bedding and herbicide treatment produced a prolonged release from vegetative competition compared to trees in the untreated control. This competition release allowed both species to increase their growth rates until new limiting factors emerged, such as belowground root contact between planted trees and crown interactions. Similar results have been shown by Macadam and Kabzems (2006), in which chemical release from early competition and mechanical improvement in soil conditions set *Picea glauca* [Moench.] Voss on alternate trajectories of development compared to no treatment 15 years after site preparation. Combined with previous research, the results of this study help justify the use of site preparation to improve long-term forest productivity.

In addition to outperforming the untreated control, the combined bedding and herbicide treatment consistently produced equal or greater maximum HT_i and DBH_i and reached maximum HT_i and DBH_i earlier or at the same age as the bedding treatment. This contrast due to follow up application of herbicide stresses the significance of reducing vegetative competition during the initial years of seedling establishment. Without herbicide application, the bedding treatment creates an improved growing microsite for not only the planted tree seedling, but also the seeds that had been dormant in the seedbed. These seeds were able to grow without hindrance, and captured water, sunlight, and belowground space that would otherwise have been available for the planted trees to uptake. Conversely, the combined bedding and herbicide treatment afforded planted trees a lower soil bulk density, increased surface soil temperatures, and release from competition for sunlight and nutrients.

In the combined bedding and herbicide treatment, the predicted rate of cumulative volume growth increased throughout the 35 year study period in western white pine at both sites, and interior Douglas-fir at Observatory Point. A consistently increasing rate of volume growth in the combined bedding and herbicide treatment is indicative of a Type 2 growth response due to treatment. In these three site and species combinations, the addition of applying herbicide to bedded rows for two years after planting effectively improved site quality and produced an increasing age shift throughout the entire observation period. Interior Douglas-fir did not experience a continually increasing rate of cumulative volume increase in any treatment at Fire Weather, a gradual decrease in the rate of annual volume growth. As such, the cumulative volume model for interior Douglas-fir at Fire Weather projects an eventual asymptotic point in which treatment differences in volume over time will remain constant. This pattern of growth is representative of a Type I, or fixed age-shift in volume growth in response to site preparation.

The differing growth patterns expressed between sites indicates the influence of more than site preparation treatment on temporal height, DBH, and volume growth. The experimental design differed between sites, as did plot size. Fire Weather was approximately 0.405 ha in size, while Observatory Point consisted of three separate 0.2025 ha plots. The smaller plot size at Observatory Point, as well as the lack of plot buffers reduced the amount of direct sunlight initially reaching the tree seedlings. Under these conditions, the importance desired regeneration capturing sunlight early in establishment is essential, as light is generally less available. Both the bedding treatment and combined bedding and herbicide treatment raised the initial seedling position 46 cm higher, which likely provided greater initial access to sunlight. At Fire Weather where the initial canopy opening was larger, sunlight was less of an initial limiting factor, while the site is subject to more extremes in temperature. The combined bedding and herbicide treatment provided both release from competition for three years and increased surface soil temperatures, which could be responsible for the increased temporal growth trends under this treatment. These results stress the importance of choosing a site preparation treatment that will most adequately address the limiting factors on the planting site, as noted by Morris and Lowery (1988) and Boateng et al. (2009) The higher tree density and neighboring tree competition at Fire Weather resulted in the study trees requiring greater vertical growth to capture more sunlight, which can be achieved with early competition release with herbicide (Lanini and Radosevich 2003) However, seedling mortality was greater at Observatory Point, which consequently resulted in lower competition between neighboring trees. As the forest floor was still exposed in 2017 due to site understocking, stem exclusion was never reached at Observatory Point. Trees at this site maintained high live crown ratios, experienced greater competition from natural regeneration, and were generally smaller in present height and volume than trees under the same treatment and species combinations at Fire Weather. Had replanting to maintain stocking been performed early in the study at Observatory Point, subject tree cumulative height, DBH, and volume trends could have been more comparable to trees at Fire Weather.

Cumulative and incremental response site preparation treatments had similarities within sites. At Fire Weather, scalping and bedding treatments reduced predicted cumulative height, DBH, and volume growth over time compared to the untreated control, while at Observatory Point, both treatments increased predicted cumulative growth relative to the control. This trend was also noticed in pairwise comparison tests between treatments on annual height and DBH increment. These results emphasize the importance of ensuring proper site preparation selection for a given site. Additionally, these trends indicate that follow-up applications of herbicide can surmount improper mechanical site preparation selection to increase temporal growth compared to trees in untreated sites. The results of this study are supported by findings by Lanini and Radosevich (2003), in which 22 years after planting, greater average height was observed on planted conifers in northern California that underwent two follow-up applications of herbicide on differing site preparation treatments, compared to one or no herbicide applications. Further studies could elaborate on the effects of chemical competition release after mechanical site preparation by comparing multiple mechanical treatments with and without chemical treatments throughout growing rotations at multiple sites.

3.5.2 Effects of competition index on trends in growth increment

Neighboring tree competition proved to have a deleterious effect on the five year growth increment of both tree species. Five-year height increment was not as sensitive to competition as DBH increment, with negative trends being only apparent at Fire Weather for both species. DBH increment displayed negative trends in response to increases in competition, with steep declines in DBH_i being observed with increasing CI across site and species. Future studies could normalize neighboring tree competition by selecting trees under similar levels of neighboring tree competition, or by establishing an experiment in uniformly shaped plots instead of planting rows.

The competition index data also reveals that interior Douglas-fir at Fire Weather experienced far higher competition than any other species and site combination. Tree mortality throughout the growing period was higher at Observatory Point, which resulted in greater spacing between trees than at Fire Weather. When faced with a higher density of study trees and a lack of buffer rows in the initial experimental design, interior Douglas-fir was unable to compete in vertical height growth with western white pine at Fire Weather. However, in the more open grown Observatory Point site, at which greater live crown ratios and more distance between trees existed, temporal trends in growth were similar between species. Maintaining buffered plots at a fixed density across treatment and species would eliminate interspecies competition and allow for more comparable relationships between sites.

3.5.3 Conclusions

Very little research on the long-term effects of site preparation in the northern Rockies has been conducted even though site preparation is a common component of more intensive silvicultural practices. The majority of the research has been conducted in other regions where intensive silvicultural practices are common, such as with Douglas-fir in the Pacific Northwest (Piatek, Harrington and DeBell 2003), radiata pine in New Zealand (Mason and Milne 1999), and loblolly pine in the southeastern US (Clason 1989). Across sites and treatments, combined application of herbicide and soil bedding produced the greatest 35-year growth of western white pine and interior Douglas-fir. With increasing trends of intensive silviculture on productive private forestlands of the Northern Rocky Mountains, the results of this study can help improve management decisions in site preparation selection.

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IV

APPENDIX

Table A1 *Count and DBH statistics of planted interior Douglas-fir and western white pine trees present prior to destructive sampling*

Site	Trees	DBH (cm)		
	n	min	mean	max
FW				
DF	**92**	**5.1**	**15.1**	**25.9**
Bed	20	7.4	14.1	19.3
Control	25	8.1	14.4	22.1
Herbicide	28	11.4	19.0	25.9
Scalp	19	5.1	11.2	22.4
WP	**146**	**10.7**	**23.2**	**34.5**
Bed	29	10.7	20.5	29.0
Control	45	13.0	22.8	33.5
Herbicide	36	17.3	26.6	34.5
Scalp	36	10.9	22.5	32.5
OP				
DF	**82**	**4.8**	**20.5**	**30.7**
Bed	19	14.5	22.4	28.2
Control	21	7.1	17.6	25.1
Herbicide	23	16.5	24.1	30.7
Scalp	19	4.8	17.4	25.4
WP	**59**	**5.8**	**17.6**	**30.2**
Bed	18	13.7	17.9	22.1
Control	16	5.8	12.7	22.1
Herbicide	17	8.9	22.9	30.2
Scalp	8	12.2	15.2	19.3

Table A2 Neighboring tree inventory summary. Includes height (HT), DBH, mean crown radius (MCR, m), and individual tree competition index (ci)

Site	Min HT (m)	Mean HT (m)	Max HT (m)	min DBH (cm)	avg DBH (cm)	max DBH (cm)
FW	4.88	16.60	28.65	4.8	19.9	40.9
OP	1.83	10.40	31.39	1.3	14.3	81.3

Site	Min MCR (m)	Mean MCR (m)	max MCR (m)	Min ci	avg ci	max ci
FW	0.01	1.89	7.62	0.01	4.51	50.64
OP	0.03	1.57	3.92	0.01	2.98	47.12

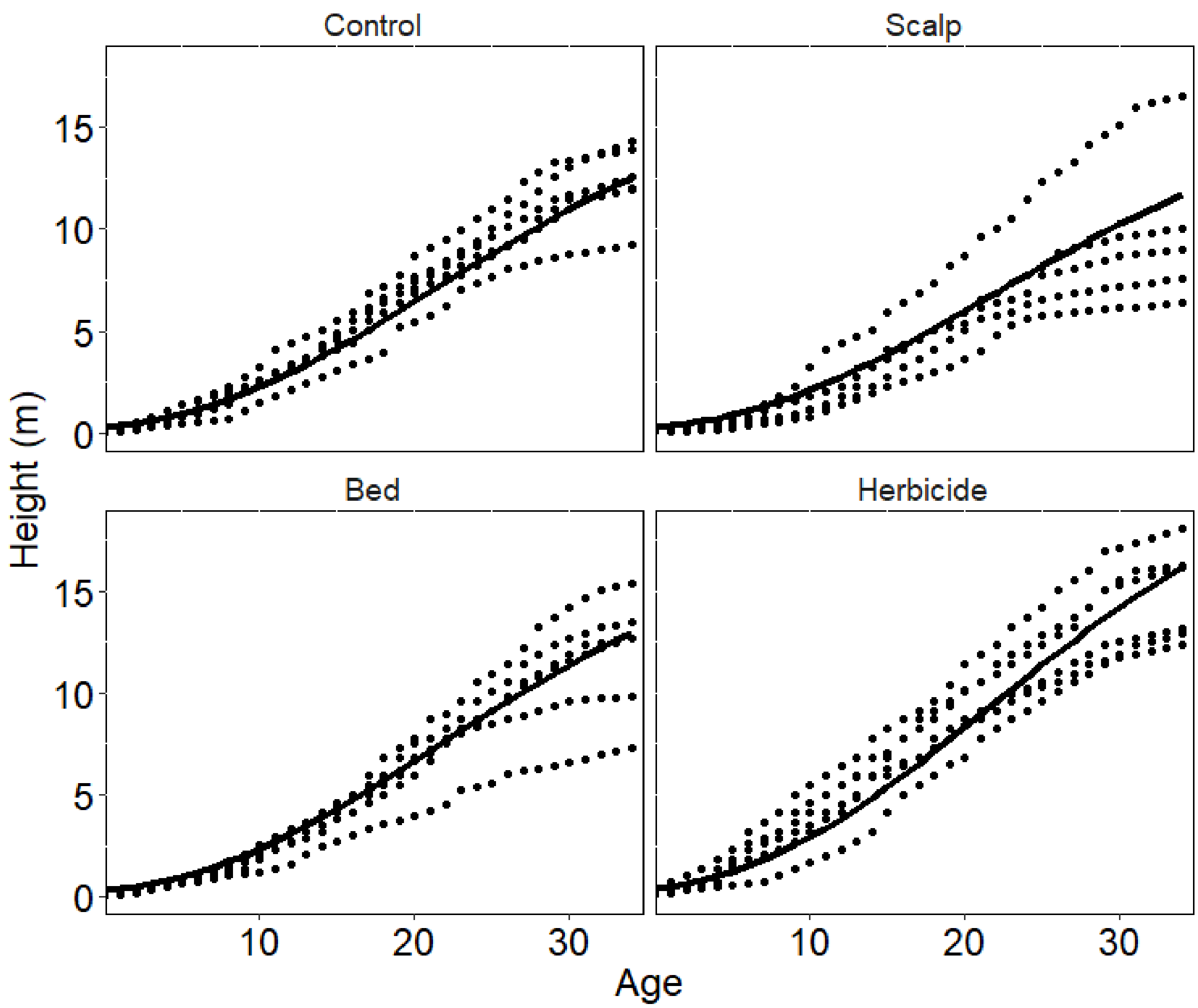

Figure A1 *Observed (dotted line) and predicted (solid line) temporal cumulative height trends of interior Douglas-fir by treatment at Fire Weather*

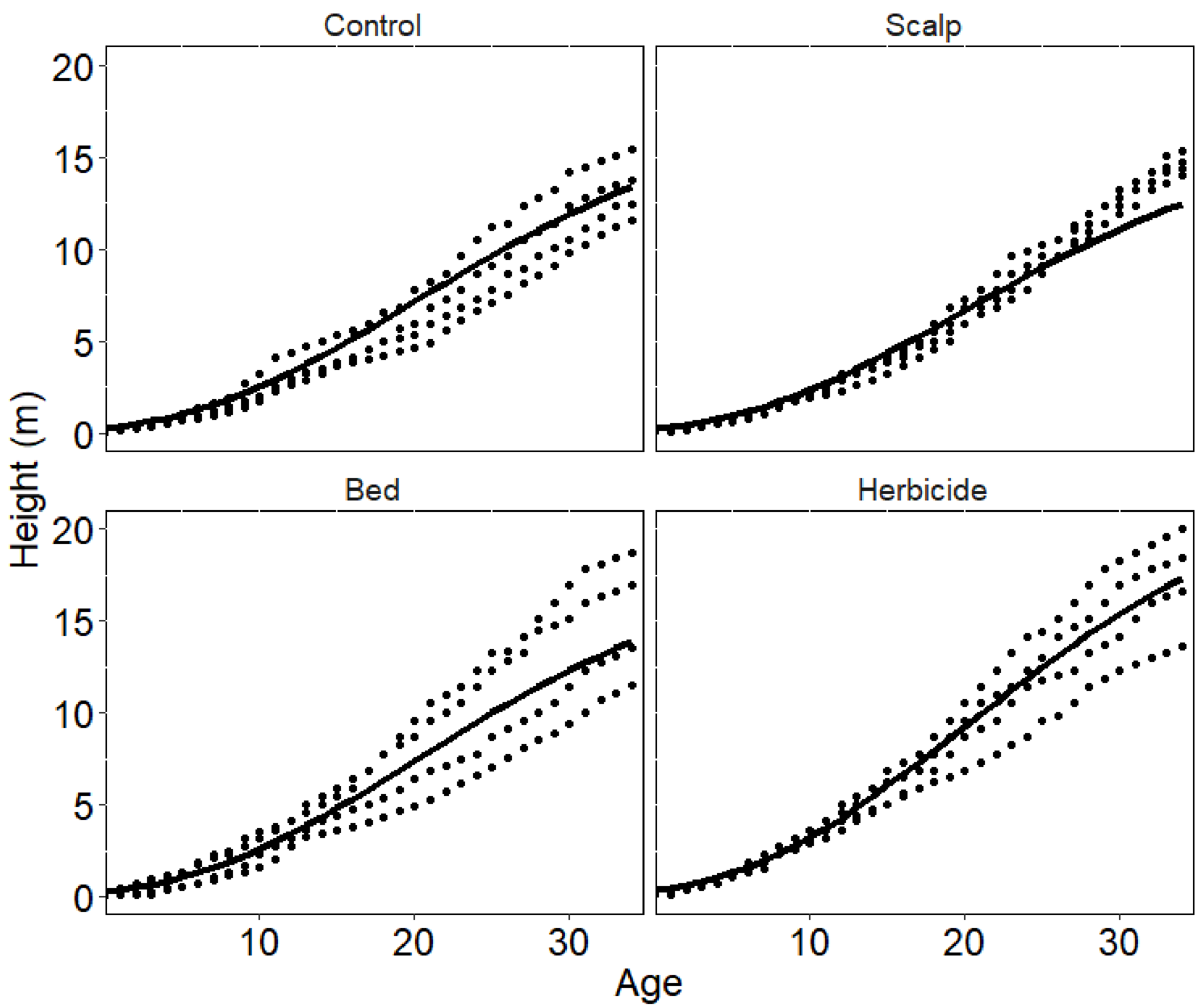

Figure A2 *Observed (dotted line) and predicted (solid line)temporal cumulative height trends of interior Douglas-fir by treatment at Observatory Point*

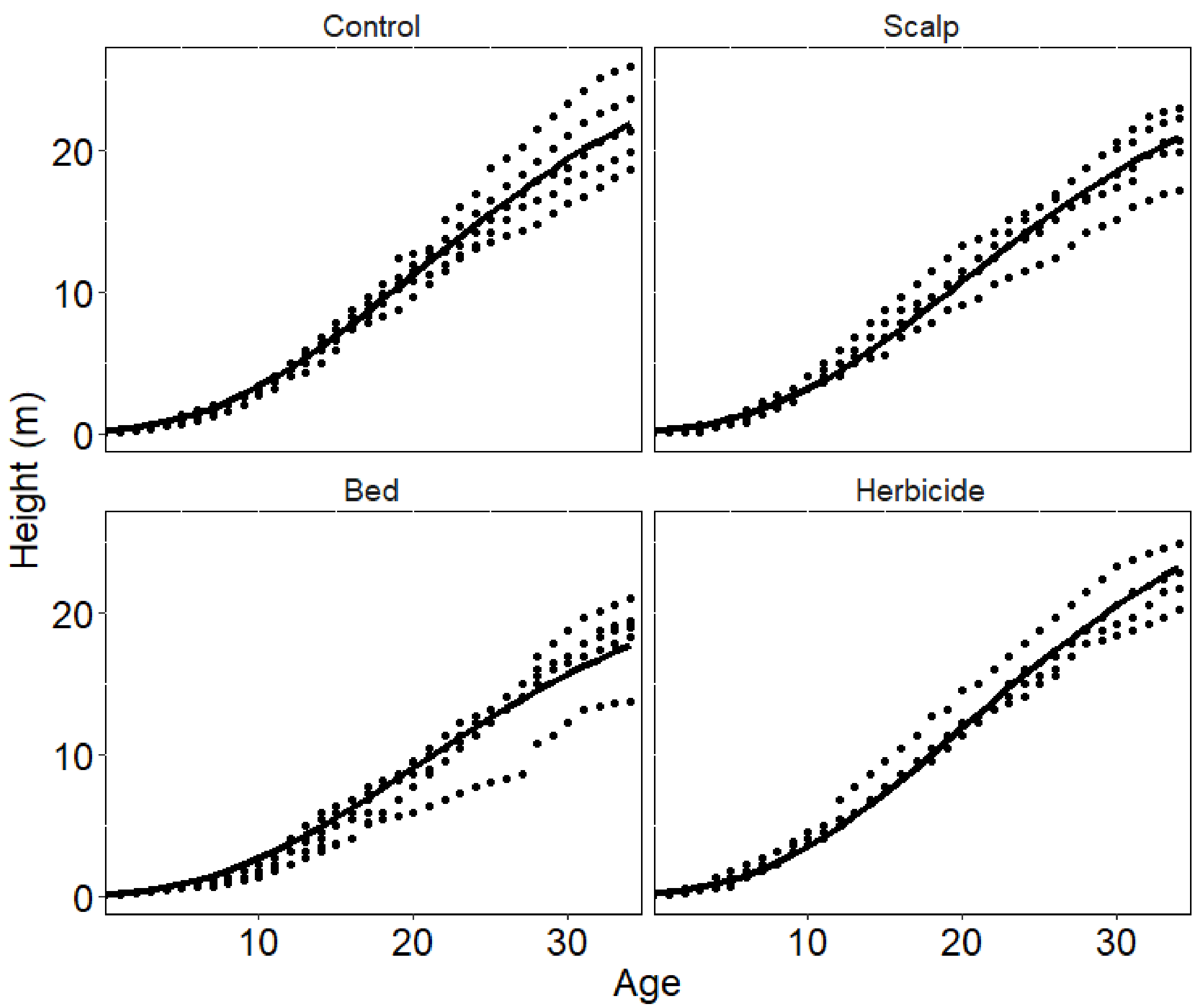

Figure A3 *Observed (dotted line) and predicted (solid line) temporal cumulative height trends of western white pine by treatment at Fire Weather*

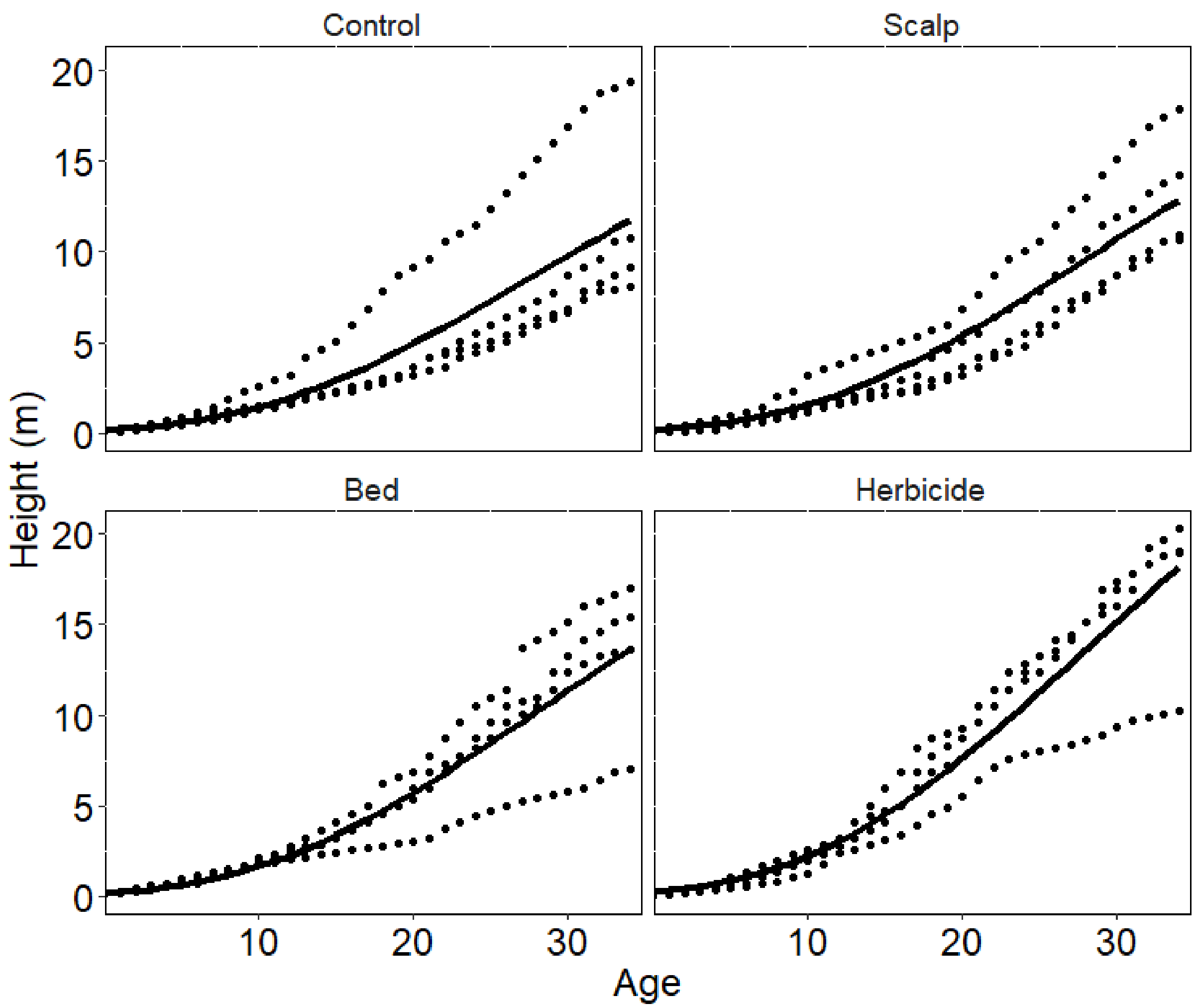

Figure A4 *Observed (dotted line) and predicted (solid line) temporal cumulative height trends of western white pine by treatment at Observatory Point*

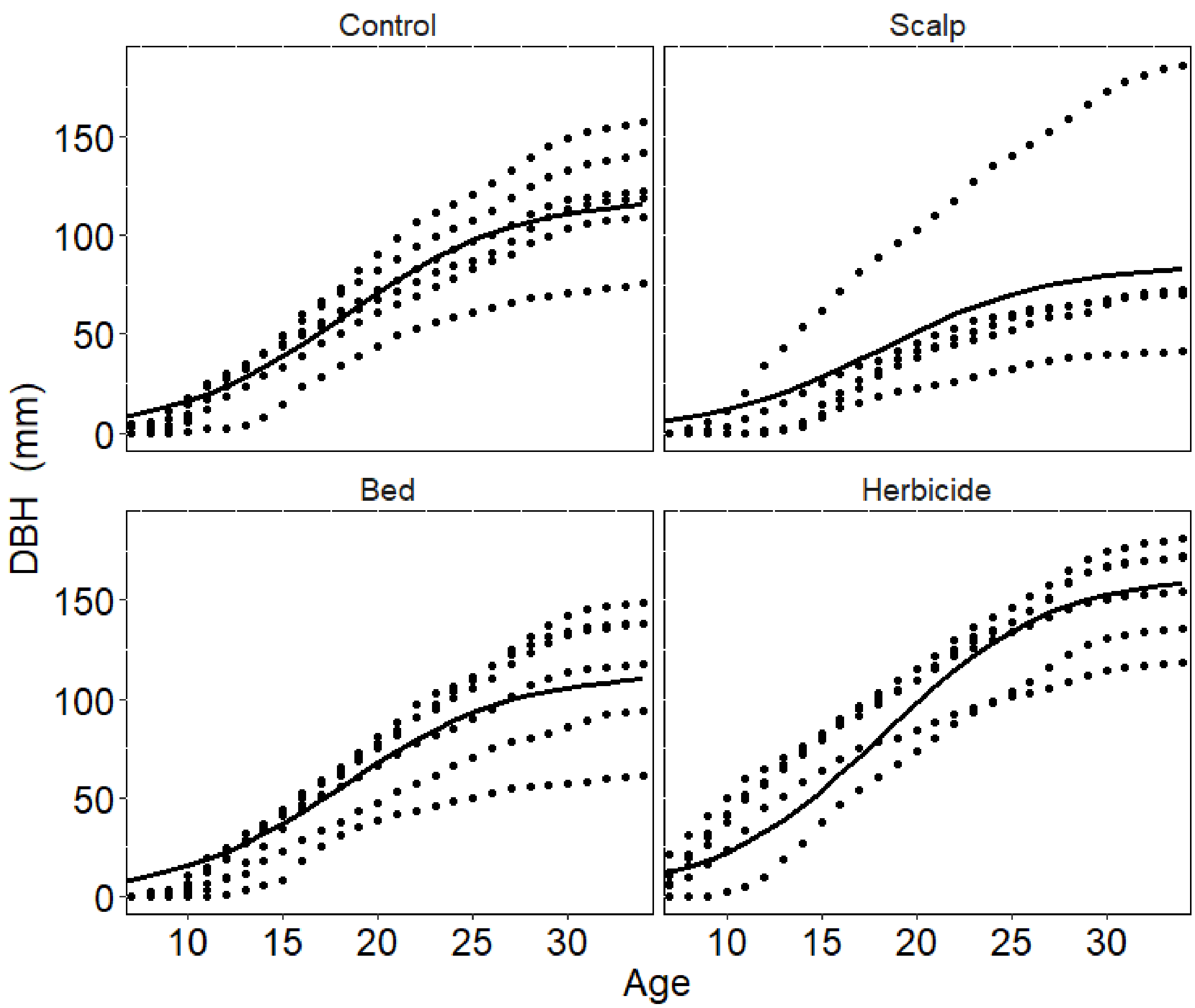

Figure A5 *Observed (dotted line) and predicted (solid line) temporal cumulative DBH trends of interior Douglas-fir by treatment at Fire Weather*

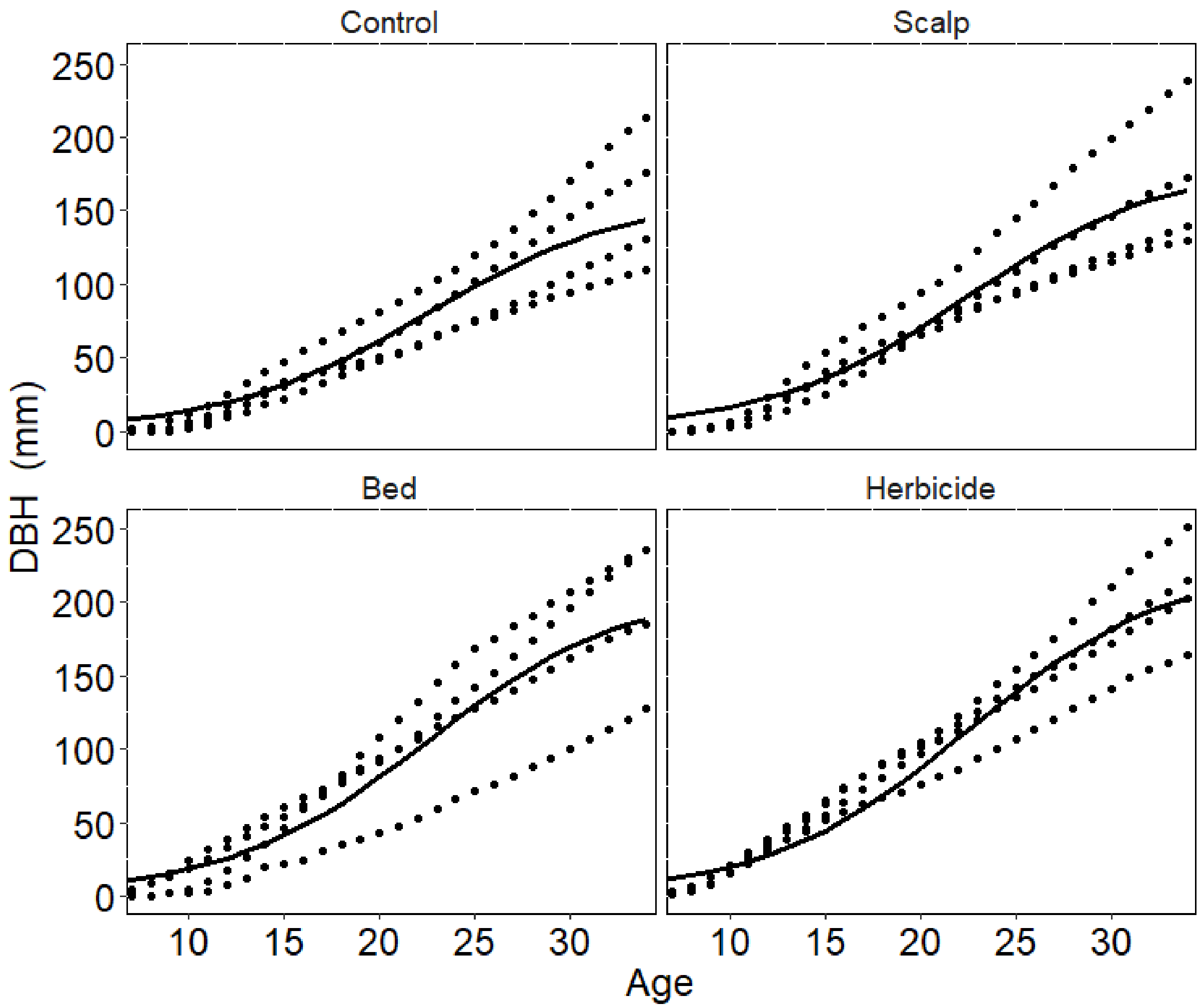

Figure A6 *Observed (dotted line) and predicted (solid line) temporal DBH trends of interior Douglas-fir by treatment at Observatory Point*

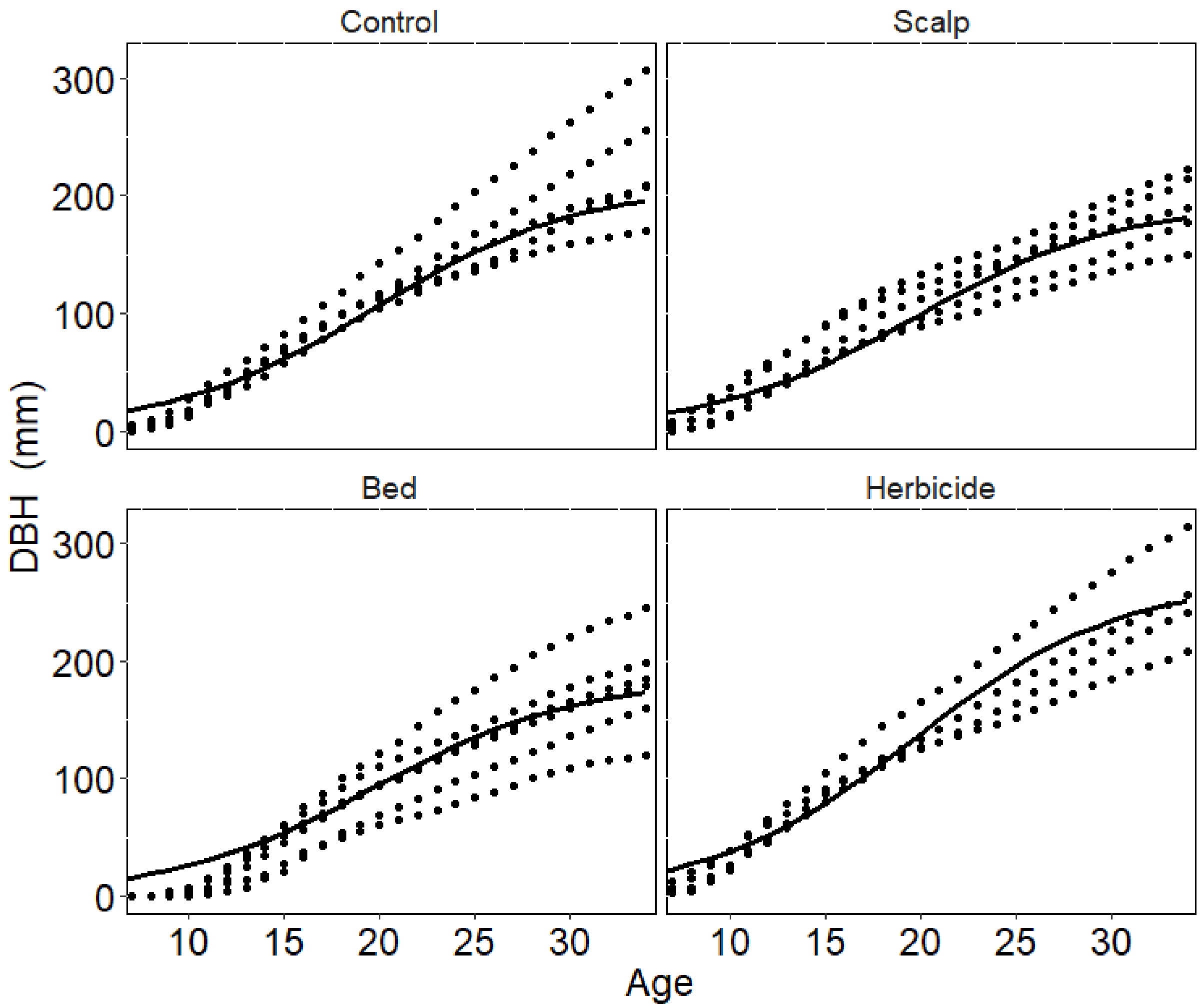

Figure A7 *Observed (dotted line) and predicted (solid line) temporal cumulative DBH trends of western white pine by treatment at Fire Weather*

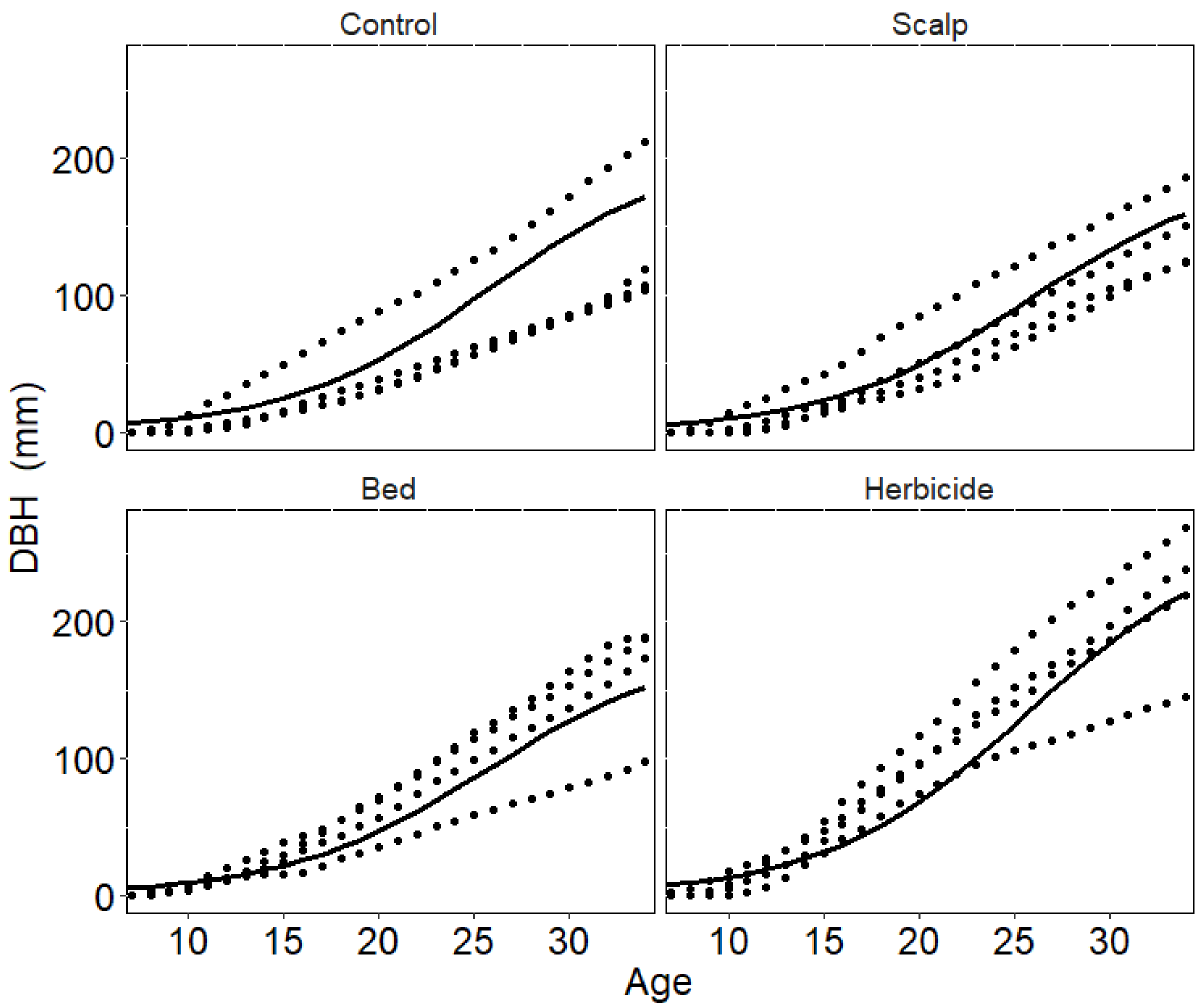

Figure A8 *Observed (dotted line) and predicted (solid line) temporal DBH trends of western white pine by treatment at Observatory Point*

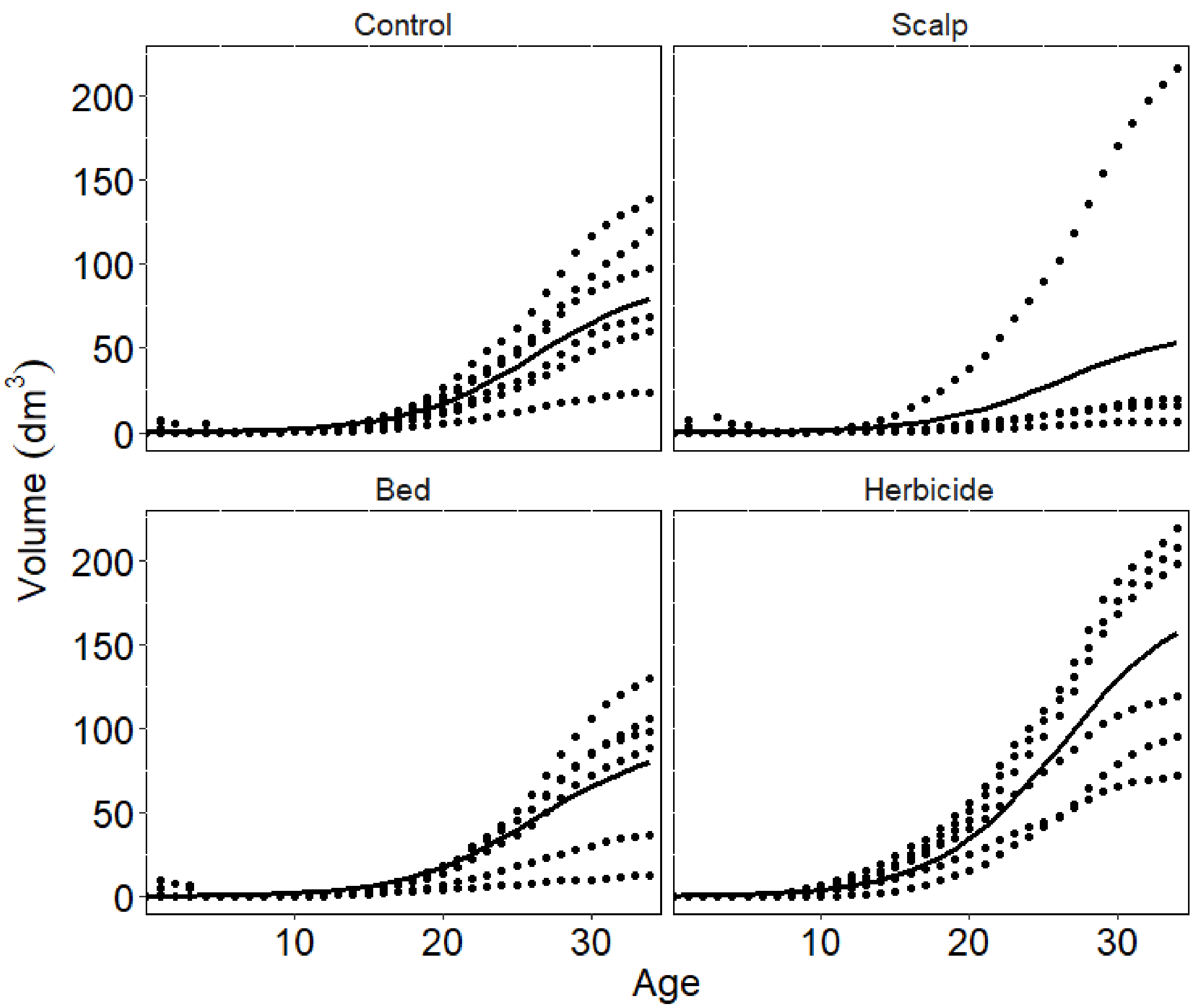

Figure A9 *Observed (dotted line) and predicted (solid line) temporal volume trends of interior Douglas-fir by treatment at Fire Weather*

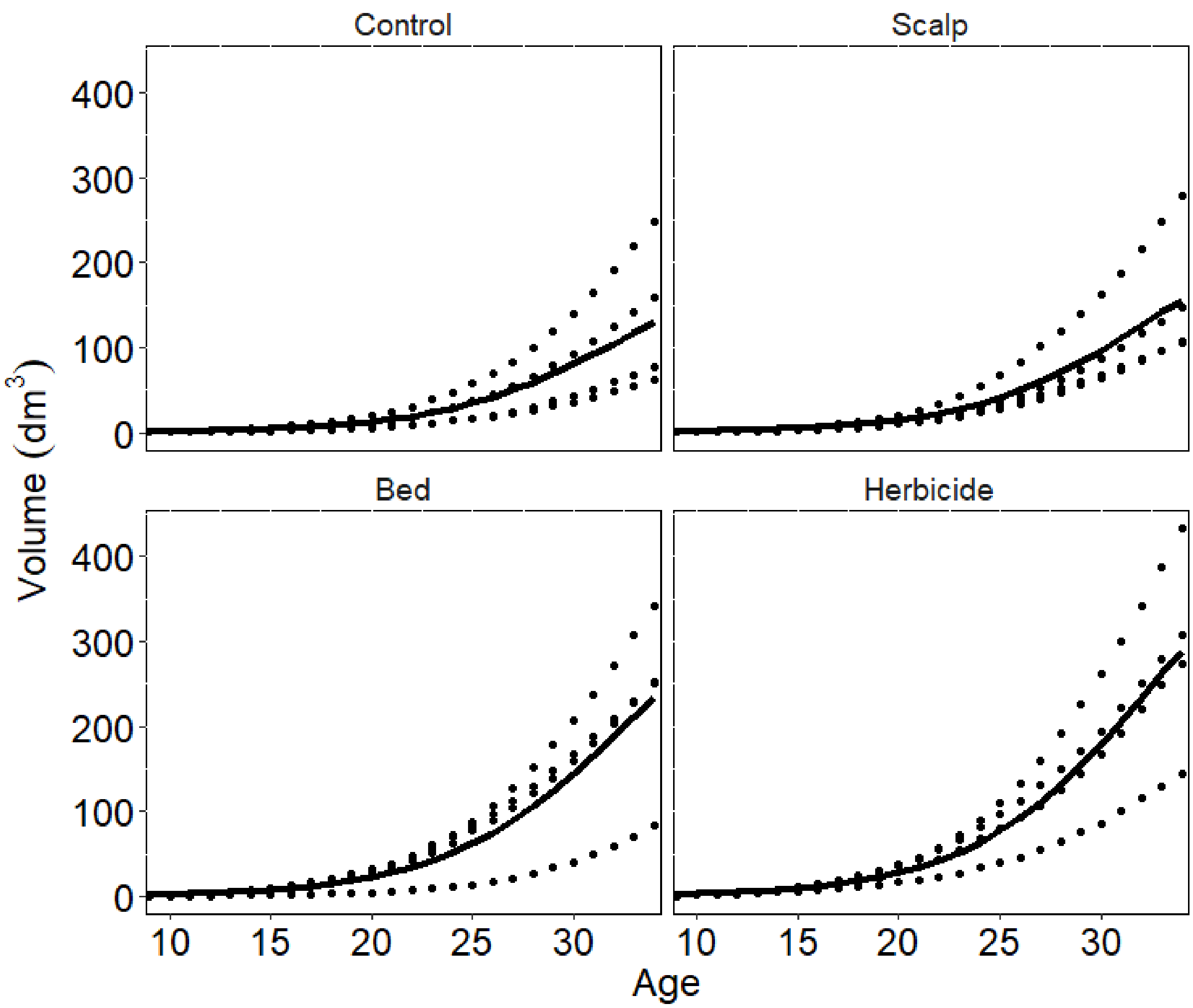

Figure A10 *Observed (dotted line) and predicted (solid line) temporal volume trends of interior Douglas-fir by treatment at Observatory Point*

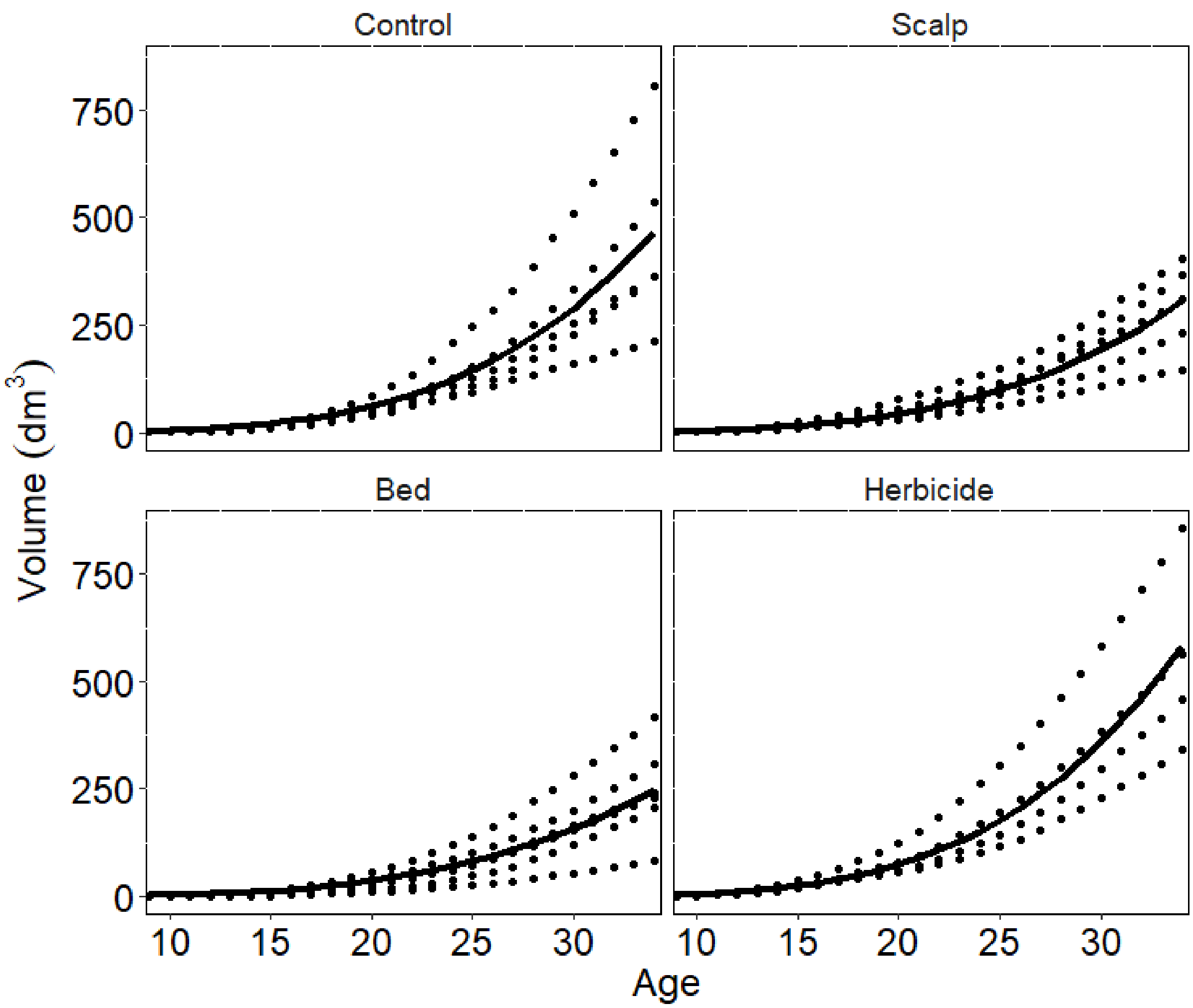

Figure A11 *Observed (dotted line) and predicted (solid line) temporal volume trends of western white pine by treatment at Fire Weather*

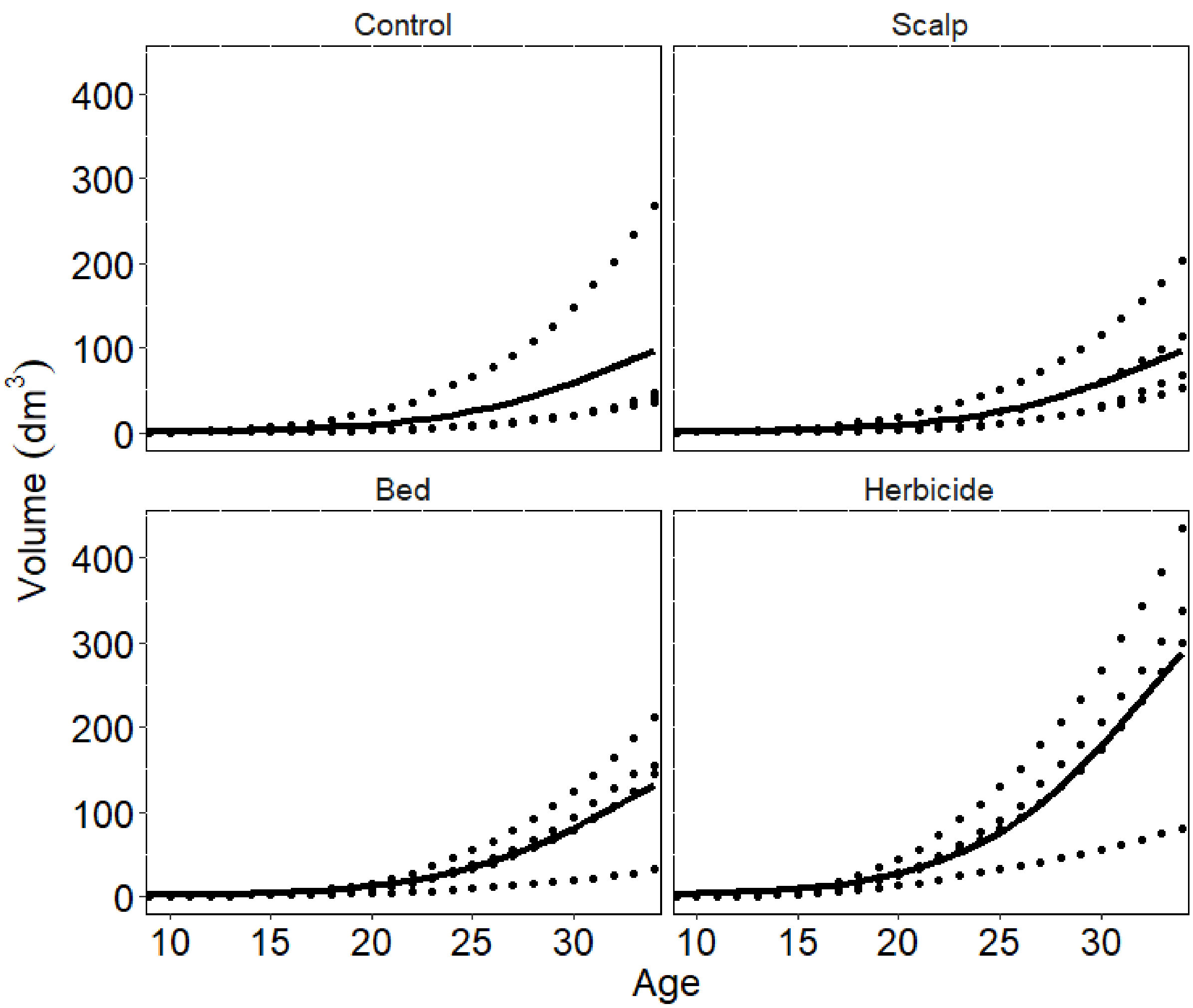

Figure A12 *Observed (dotted line) and predicted (solid line) temporal volume trends of western white pine by treatment at Observatory Point*

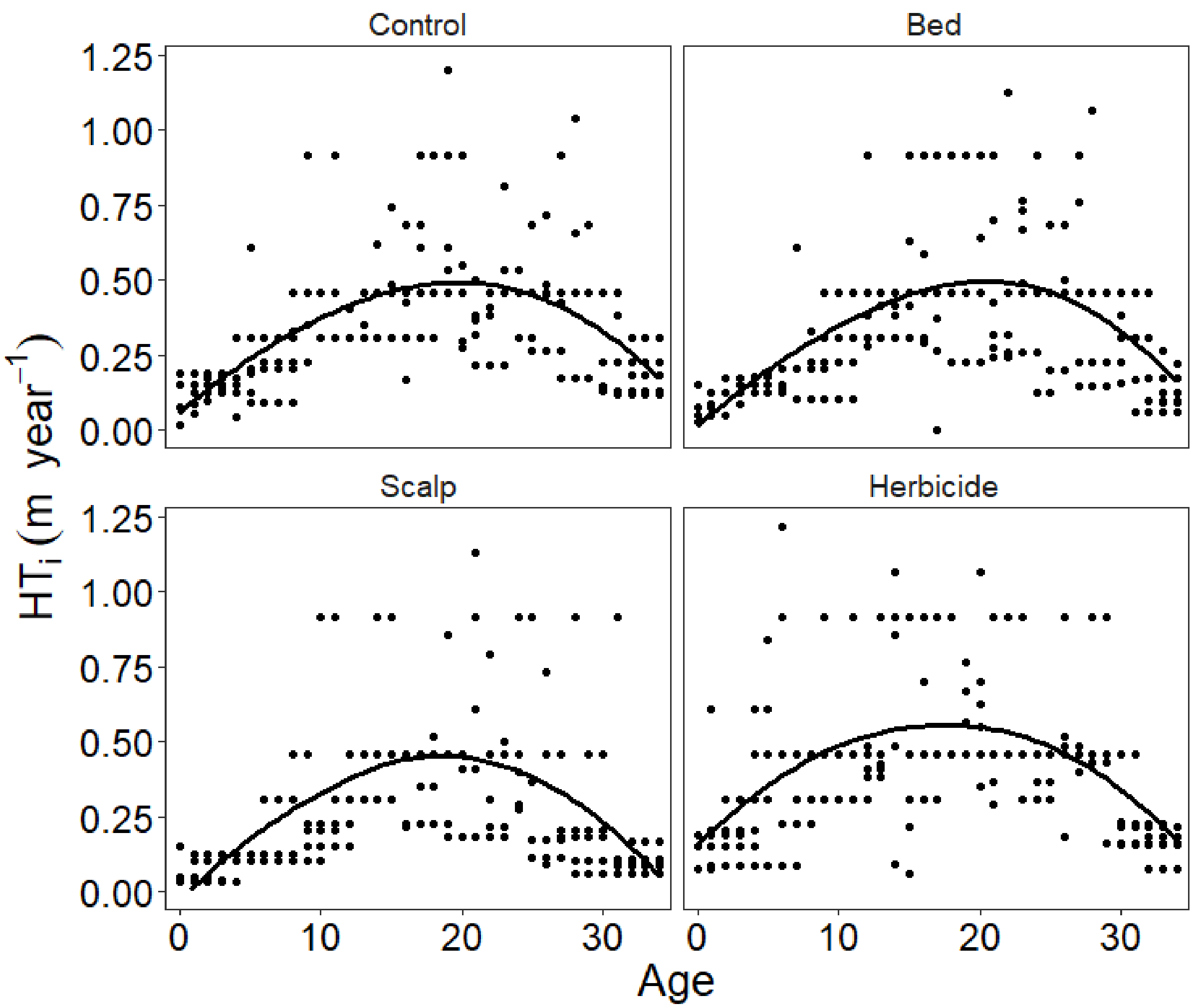

Figure A13 *Smoothed conditional means (solid line) and observed (dots) trends in height increment of interior Douglas-fir at Fire Weather*

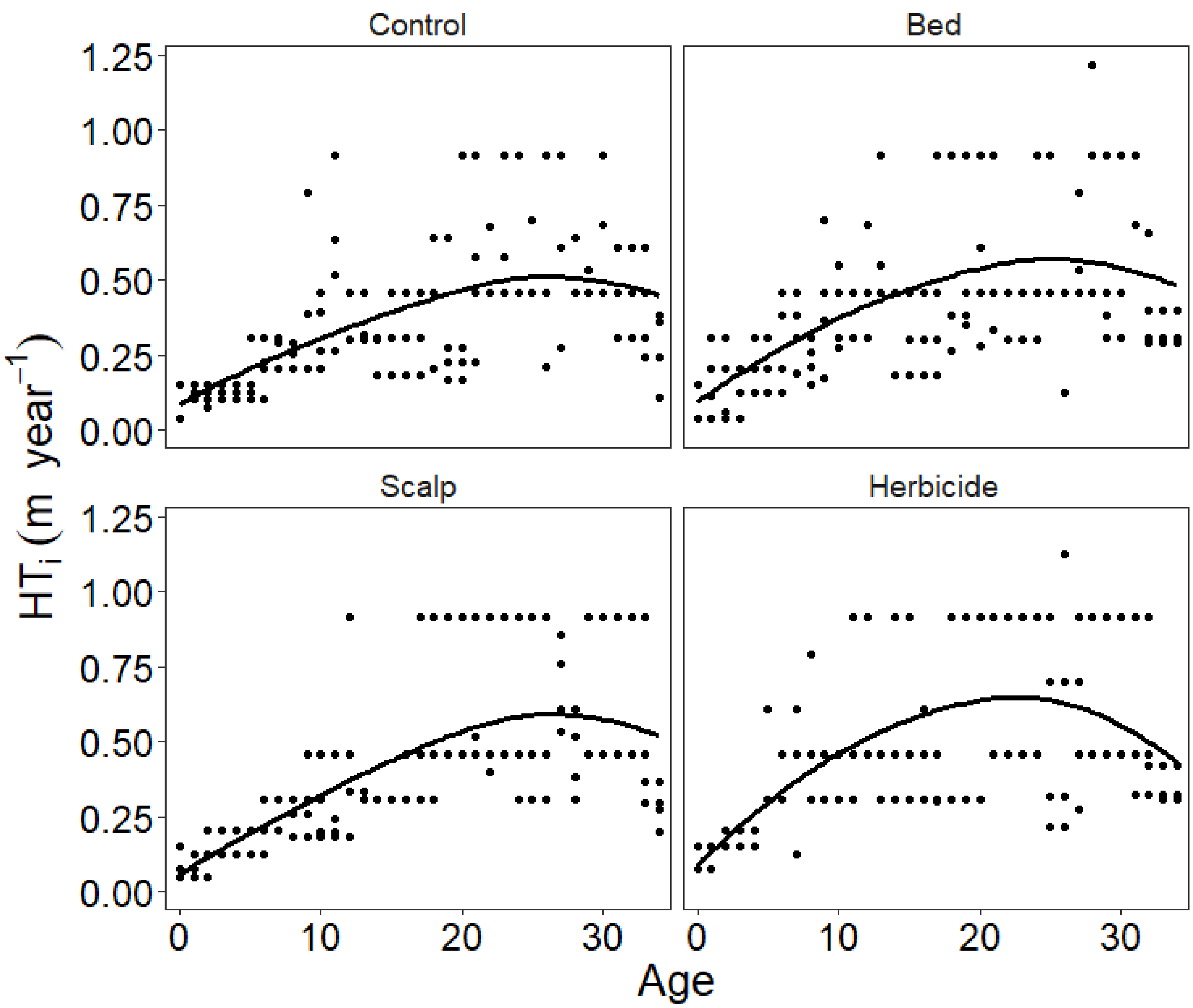

Figure A14 *Smoothed conditional means (solid line) and observed (dots) trends in height increment of interior Douglas-fir at Observatory Point*

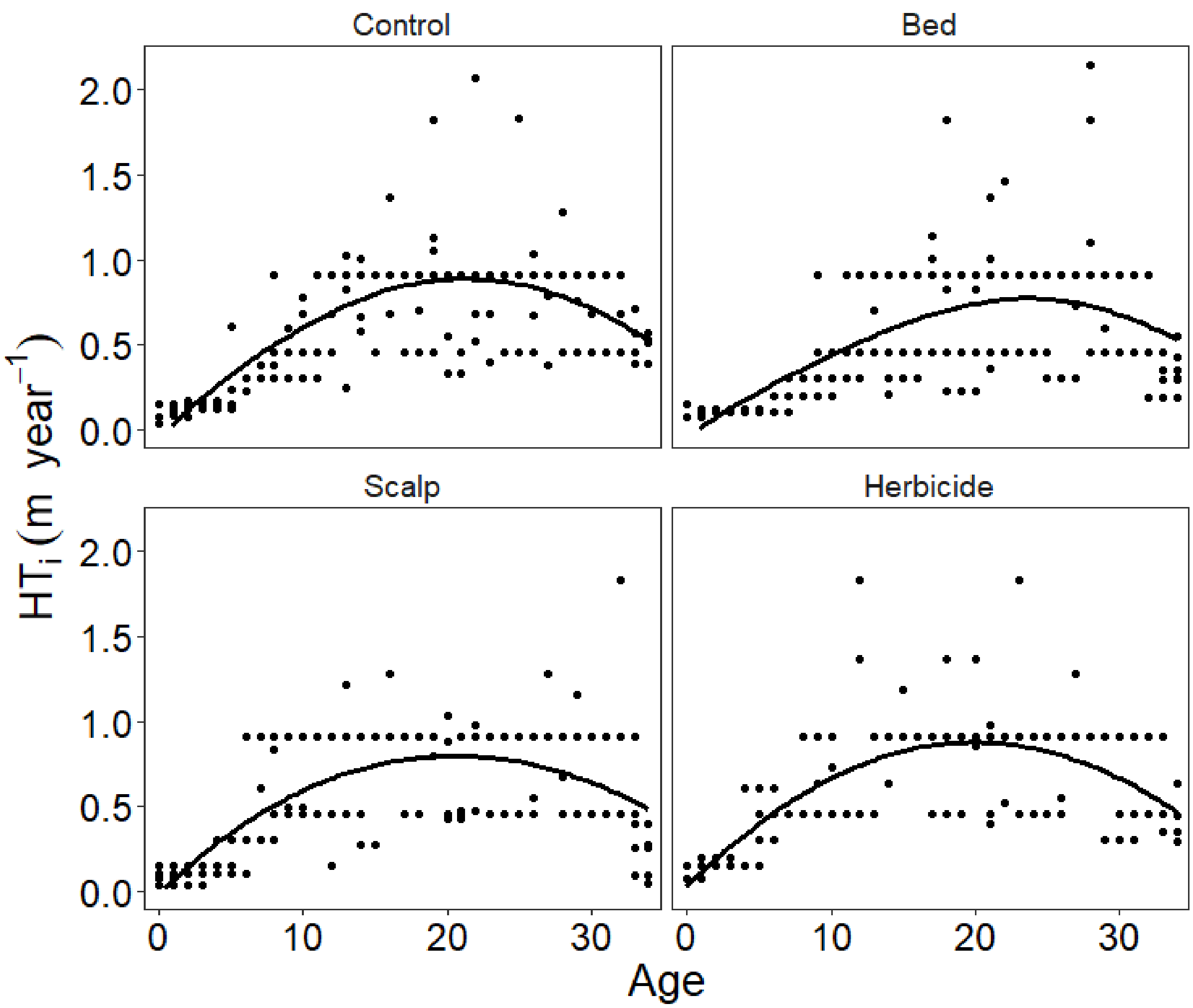

Figure A15 *Smoothed conditional means (solid line) and observed (dots) trends in height increment of western white pine at Fire Weather*

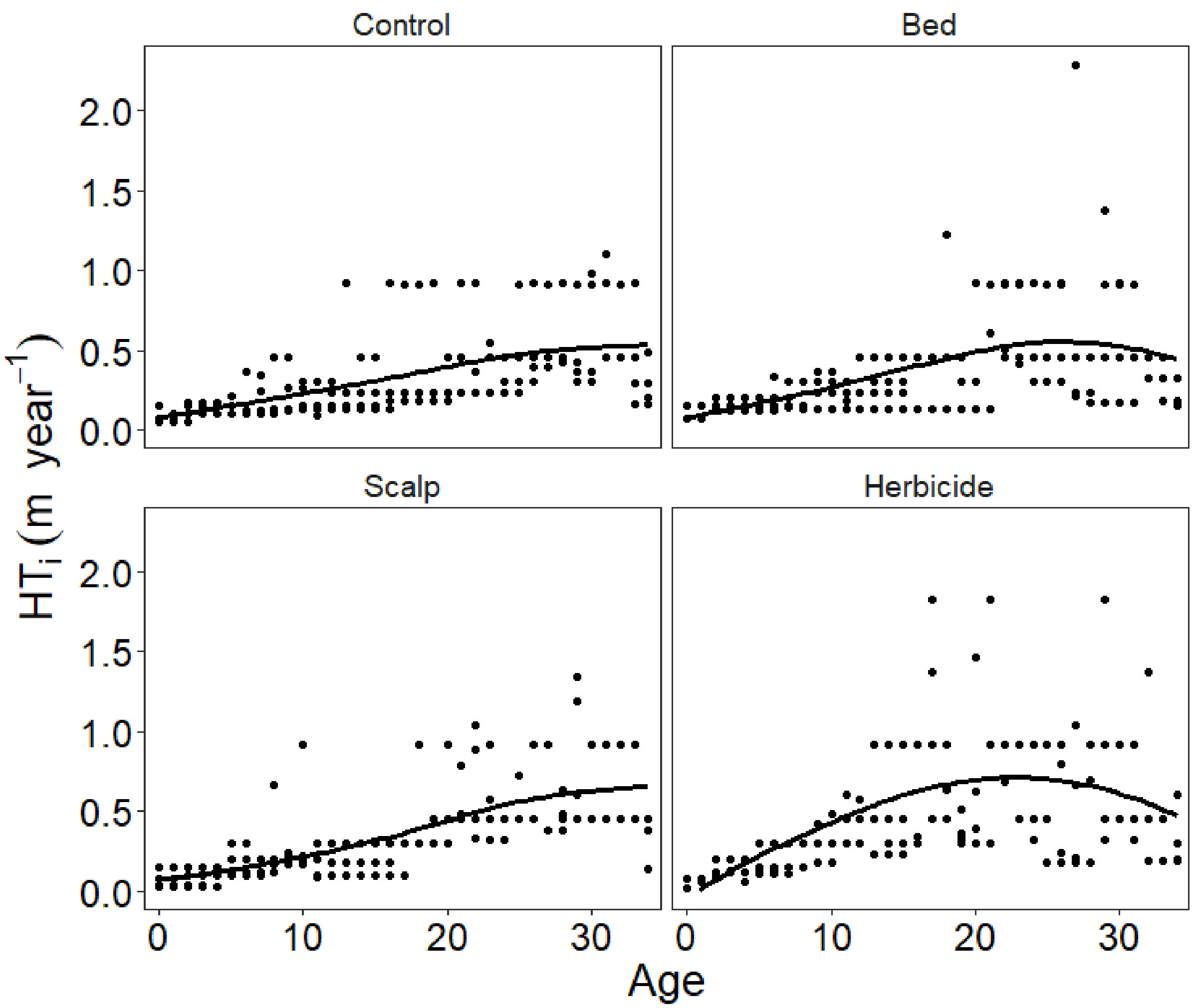

Figure A16 *Smoothed conditional means (solid line) and observed (dots) trends in height increment of western white pine at Observatory Point*

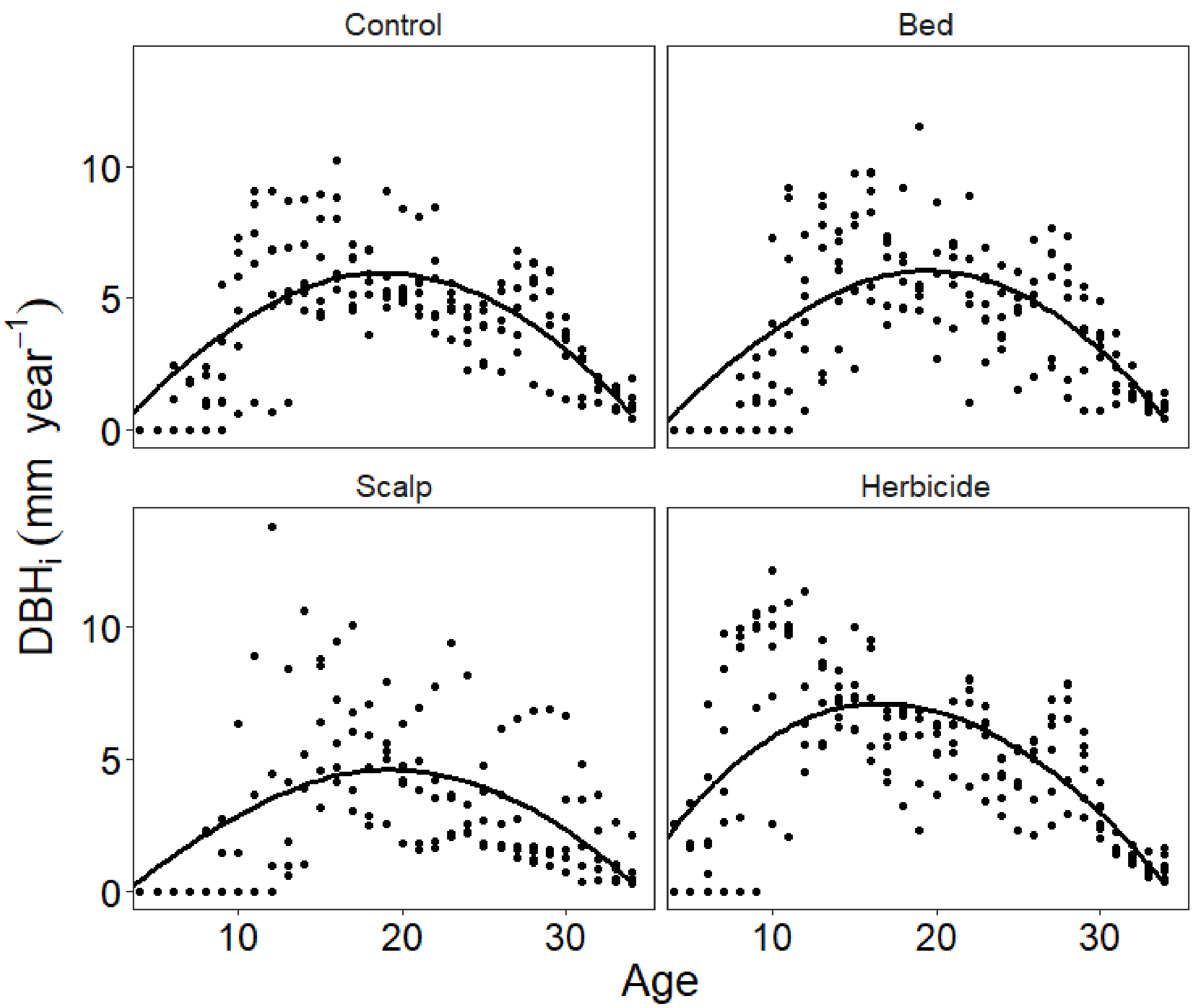

Figure A17 *Smoothed conditional means (solid line) and observed (dots) trends in DBH increment of interior Douglas-fir at Fire Weather*

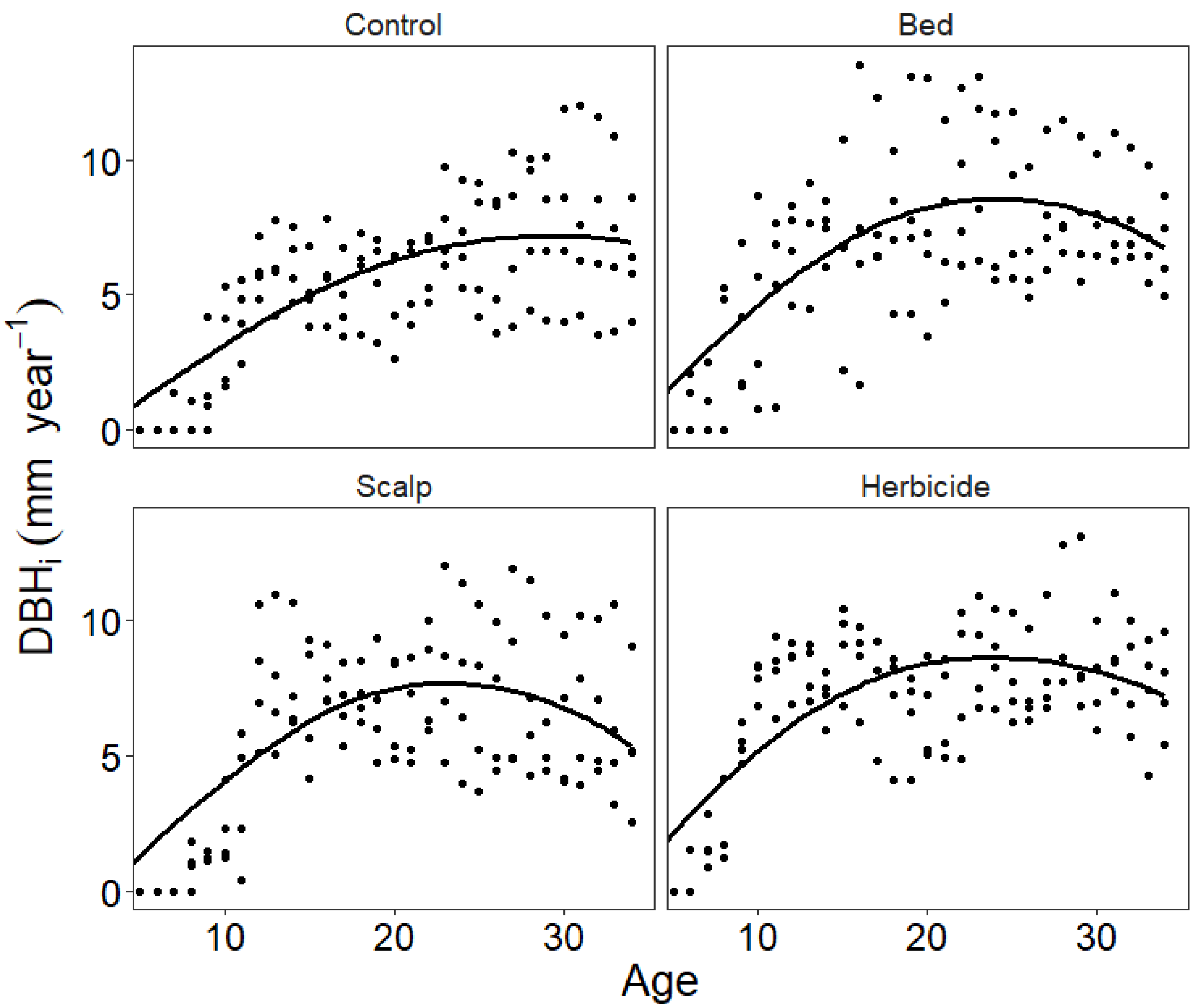

Figure A18 *Smoothed conditional means (solid line) and observed (dots) trends in DBH increment of interior Douglas-fir at Observatory Point*

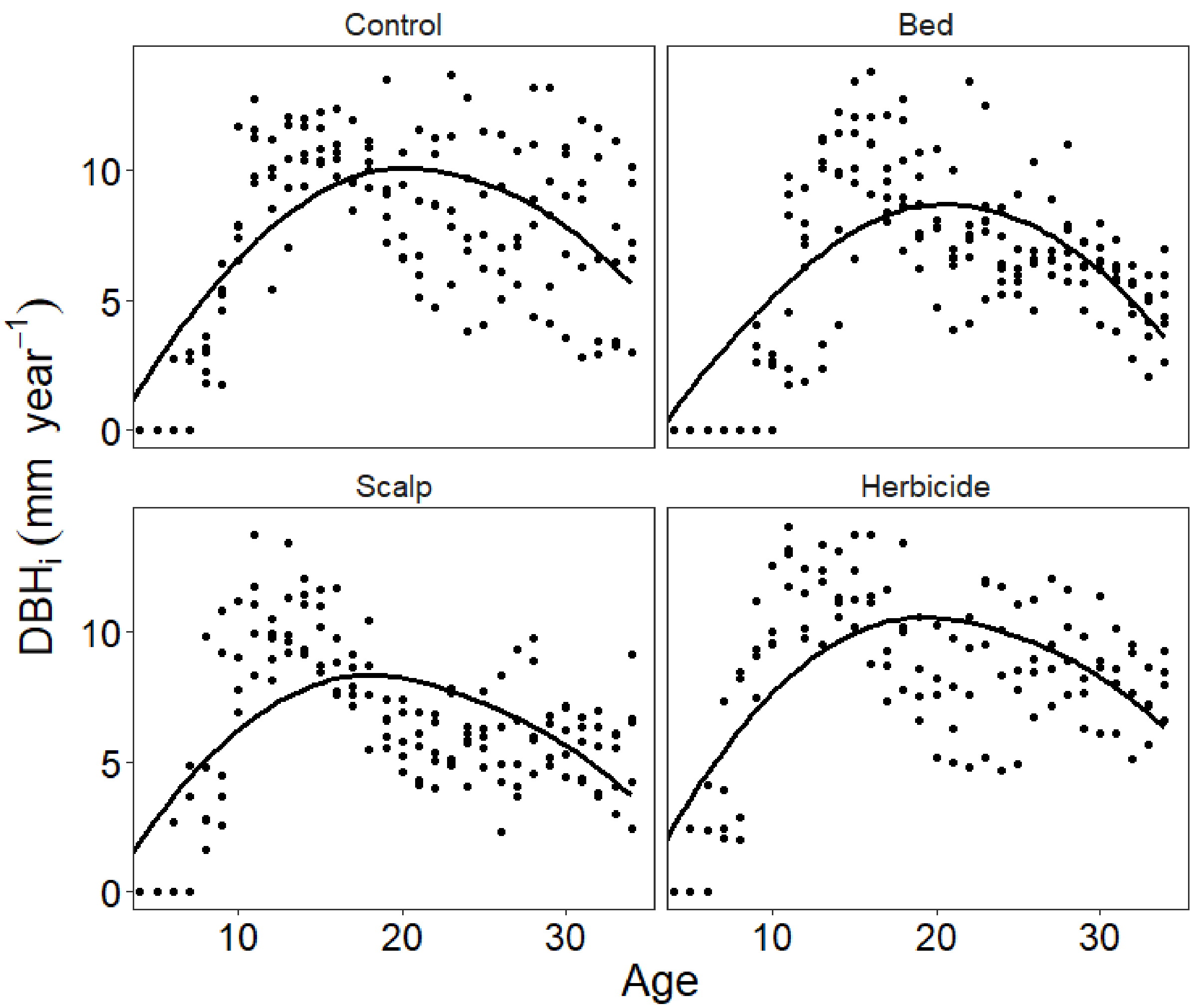

Figure A19 *Smoothed conditional means (solid line) and observed (dots) trends in DBH increment of western white pine at Fire Weather*

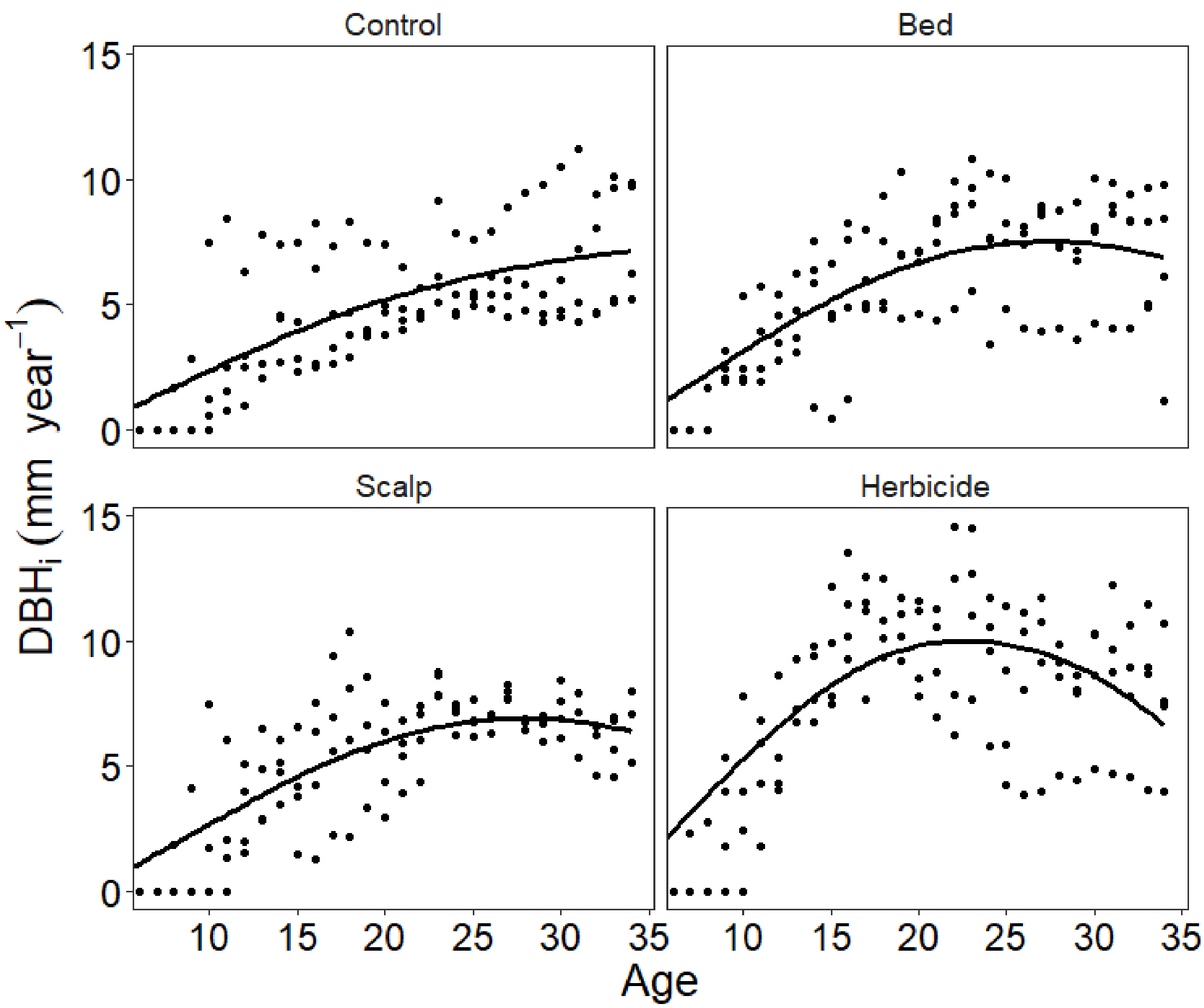

Figure A20 *Smoothed conditional means (solid line) and observed (dots) trends in DBH increment of western white pine at Observatory Point*