

**The Effects of Biomass Removal and Vegetation  
Control on Douglas-fir Foliar Nitrogen and Phosphorus in  
the Pacific Northwest, USA.**

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A thesis  
submitted in partial fulfillment of the  
requirements for the degree of  
Master of Science

University of Washington  
2017

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Program Authorized to Offer Degree:  
School of Environmental and Forest Sciences

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**Abstract**

The Effects of Biomass Removal and Competing Vegetation Control on Douglas-fir Foliar Nitrogen and Phosphorus in the Pacific Northwest, USA.

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As the demand for forest products increases, there is concern about the long-term impacts on site productivity. This study examines the foliar nitrogen (N) and phosphorus (P) of Douglas-fir (*Pseudotsuga menziesii*) trees in three sites – Fall River, Matlock, and Molalla – in the Pacific Northwest to determine the impacts of competing vegetation control and increased biomass removal. Needles samples were collected from randomly selected Douglas-fir trees in the winter of 2016. We analyzed the samples for nitrogen and phosphorus. Standard mixed-model ANOVA tests were run on the final linear models, followed by Tukey’s multiple comparison test to determine whether the treatments had an impact on the foliar nutrients. The impacts of increased biomass removal and vegetation control on foliar N and the N:P ratio were only significant in Matlock, the least productive site. There was no impact of increased biomass removal and vegetation control on foliar P within any of the sites. However, for each foliar nutrient, site was the most significant factor, indicating that the determination of the impact of each treatment must be site specific. Foliar nutrients were correlated with soil nutrient pools. The sites with larger soil N and P pools had higher foliar N and P concentrations, respectively. Fall River was the most productive site, and had the highest foliar N and P concentrations. Molalla had a smaller soil P concentrations, and had a slight foliar P deficiency (although not below critical deficiency

levels). Matlock had a smaller N pool, and had the lowest foliar N values (although not below critical deficiency levels). Because the foliar N and P concentrations were not below critical deficiency levels at any of the sites, there was no immediate concern about the impacts of increased biomass removal. However, smaller soil and foliar nutrient pools at Matlock and Molalla suggested that these sites should be monitored to assure that there are no long-term impacts on soil productivity following intensive biomass removal.

Our analysis of foliar nutrients at Matlock was complicated by the presence of scotch broom (*Cytisus scoparius*), an aggressive invasive species. Scotch broom is the dominant woody competitor at Matlock and out-competed the Douglas-fir saplings. Scotch broom fixes N, which enables it to outcompete Douglas-fir on N limited sites. Our data showed that scotch broom cover had a significant impact on foliar N. The plots with increased biomass removal had significantly higher scotch broom cover. Increased scotch broom cover led to increased foliar N, and although higher foliar N typically indicates growth, increased foliar N was associated with lower diameter at base height (DBH). The negative correlation indicates that although the trees were getting more N, they were also struggling to compete against the scotch broom. The Douglas-fir trees could not grow tall enough to shade out the scotch broom. The data suggested that productivity and commercial viability of the Matlock site requires the removal of invasive scotch broom.

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## 1. Introduction

Commercial silviculture has increasingly focused on removal of as much of the residual harvest material as possible, beyond just the bole of the tree. Although the Pacific Northwest has some of the most productive forests in the United States (Smith et al. 2004), increased biomass removal has implications for both short- and long-term forest health and productivity. Vital to the continued output of industrial forest stands is the long-term soil productivity (LTSP) network. The LTSP network was founded to examine the long-term effects of intensive forest management practices on the soil quality and productivity of forest stands across the United States and Canada (Ares et al. 2007b). Research at the LTSP sites has primarily focused on the effects of practical forestry and management techniques – such as increased biomass removal and vegetative control.

Traditionally in the commercial logging industry, only the more valuable bole wood is removed, while the slash is left on site (Favre and Napper 2009). Harvesting the bole wood removes some nutrients from ecosystems while the slash is often left behind as a soil nutrient source once it decomposes (Favre and Napper 2009). Increasing harvest intensity and the removal of competing vegetation has the potential to remove a large source of nutrients needed to support the productive growth of future planting rotations. To better understand the impact of intensive biomass removal, we compared foliar N and P concentrations (a common indicator of ecosystem N and P status) to two different treatments, biomass removal and competing vegetation control.

Nitrogen (N) is the primary nutrient limiting productivity of Douglas-fir (*Pseudotsuga menziesii*) in the Pacific Northwest (Gessel et al. 1990, Beldin and Perakis 2009). As a native tree species to the Pacific Northwest, Douglas-fir productivity is relatively high due to the

species' efficient use of limited soil N pools (Radwan and Brix 1986). In the Pacific Northwest, Douglas-fir trees can be found in N-deficient soils (Gessel et al. 1990), especially in actively logged forests, where nutrients are constantly removed with each harvest.

Secondary to N limitations, phosphorus (P), another essential plant nutrient, can limit productivity in the Pacific Northwest (Favre and Napper 2009, Radwan and Brix 1986). Weathering of soil primary minerals is the dominant flux of new P into an ecosystem (Favre and Napper 2009, Johnson et al. 1982). Decomposition of soil organic matter has been found to account for as much as 65% of total P in the soil (Bauer and Black 1994). Deficiencies of P for stand trees tends to only happen in soils where the parent materials were P deficient (Radwan and Brix 1986). Both P and N are essential for good tree growth and foliar P and N have been shown to be significantly correlated with height and diameter growth in White Spruce (Wang and Klinka 1997). Determining foliar N and P is also a cheaper and easier method to determine stand productivity than soil sampling (Wang and Klinka 1997).

The effects of biomass removal on nutrient budgets and the productivity of subsequent stands are important for stand sustainability, especially as whole-tree removal becomes more common. Biomass removal, through logging, removes nutrients that would have been recycled back into the soil if left on site (Powers et al. 1990, Switzer et al. 1981). Johnson et al. (1982) found that generally twice as much N was lost after whole-tree harvest (WT), rather than bole-only removal (BO). The loss of N is generally attributed to secondary losses after logging due to increased leaching, erosion, and runoff (Radwan and Brix 1986, Strahm et al. 2005). P pools within the soil have a linear relationship with harvest intensity, the higher the intensity, the larger the P loss (Scott et al. 2004). WT treatments remove relatively more of the total site P than N, and reduce productivity more in lower P sites (Scott et al. 2004). However, many of the studies

have only been in place for a short amount of time; the long-term impacts of nutrient loss through increased biomass removal have been inconclusive, with different studies reporting differing results. The constant in these studies is that nutrient-poor sites tend to react more strongly to increased biomass removal than more productive sites. (Bigger and Cole 1983, Slesak et al. 2011, Slesak et al. 2016).

While increased biomass removal takes nutrients from the system, herbicides have been used to allow planted trees to have greater access to soil nutrients by controlling competing vegetation (Slesak et al. 2016). Vegetation control (WC) increases the availability of essential plant resources, like nutrients, water, and light to stand trees (Wagner et al. 2004). In conjunction with other treatments, vegetation control has also been found to increase net N mineralization in loblolly pine (*Pinus taeda*) stands (Gurlevik et al. 2004, Rifai et al. 2010). By increasing soil water content (by decreasing plant consumption), WC treatments have been shown to increase P and N mineralization (Devine and Harrington 2007, DeBruler 2014). WC treatments can also influence soil pools of P. Plant-available P can be affected by presence of N-fixing plants, like Scotch broom (*Cytisus scoparius*), which are important for phosphatase activity within the rhizosphere, and are often targeted by WC treatments (DeBruler 2014). The impact of WC on trees as they grow older is still unclear. It has been found that the effects of WC treatment are reduced after the full crown closure because the trees can then shade out competing vegetation (Harrington et al. 2013). Although the early growth gains by the trees remain, the trees are no longer benefiting from WC treatments (Snowdon and Waring 1984). The long-term effects of WC treatments are unclear, such treatments tend to reduce vegetative cover and increase soil nitrogen and carbon pools for stand trees by limiting competition, which can be linked to higher productivity (Ares et al. 2007b, Devine et al. 2011, Knight et al. 2014).

For this research, we studied three sites in the Pacific Northwest: Fall River (Brooklyn, WA), Molalla (Molalla, OR), and Matlock (Matlock, WA). These three sites represented a range of productivity, from high productivity (Fall River) to low productivity (Matlock). The effects of biomass removal and WC treatments on N in Fall River, Matlock, and Molalla have been varied (Ares et al. 2007b, Slesak et al. 2016). The degree to which these treatments alter the nutrient pools of a site depends on whether the study looks at above- or belowground pools. Increased biomass removal treatments at Fall River removed 33-70% of the aboveground N pool (Ares et al. 2007b). The WT harvest removed approximately twice the amount of N than the bole-only harvest (BO) treatment (Ares et al. 2007b). Despite high N removal, there was not a severe impact on the total N at Fall River, because the site has such a large reservoir of N within the mineral soil (13,143 kg/ha) (Ares et al. 2007b). Fall River has the largest N pool of the three sites in this study; Matlock has the lowest soil N pool (3,300 kg/ha), and Molalla has a moderately-sized N pool (7,220 kg/ha) (Slesak et al. 2016). As a high productivity site with a large soil N reservoir, the WT treatment at Fall River only reduced soil N stocks by 6% (Ares et al. 2007b). Matlock and Molalla are lower productivity sites where plant-available N and P, respectively, are more limiting for the Douglas-fir trees. At these lower productivity sites, the effects of biomass removal treatments (WT and BO) on N were found to be limited, and were usually seen only as interactions with WC treatments (Slesak et al. 2016).

Additionally, biomass removal led to reductions in soil P, while soil N pools were not significantly altered (Slesak et al. 2016). Matlock has more soil P than Molalla, 1,500 mg/kg and 970 mg/kg, respectively (DeBruler 2014). DeBruler (2014) found that P concentrations were the only soil nutrients to decline after 10 years of stand growth. The loss of P is attributed to its removal in the harvested biomass. In contrast, soil N concentrations were sustained because the

Douglas-fir slash left on site is relatively rich in N (and low in P). When the debris decomposes, the soil N is replenished, while the P is not (DeBruler 2014).

WC treatments had significant impacts at all three sites. WC treatments increased water availability at Fall River, leading to increased tree growth, although the effect diminished after year 10 (Holub et al. 2013). At Matlock and Molalla, WC treatments increased the survivability of Douglas-fir trees (Slesak et al. 2016). At Molalla, Harrington and Schoenholtz (2010) credit the WC treatments with increasing soil nutrient pools by killing the invasive plants. WC treatments also led to increases in soil N concentration at Matlock and Molalla sites (Slesak et al. 2016). The responses to WC treatments suggests that total plant community is a key factor in determining and maintaining soil productivity (DeBruler 2014).

A major difference among the three sites is the presence of extensive scotch broom at Matlock, which is the primary woody competitor of the Douglas-fir trees (Harrington and Schoenholtz 2010). Scotch broom is a nitrogen-fixing invasive plant in Washington (Haubensak et al. 2004). Initially it was introduced in the Pacific Northwest because scotch broom was believed to be beneficial due to its ability to fix N in N-poor sites (Caldwell 2006). However, it has become clear that scotch broom can have significant negative impacts on the ecosystem and plant communities (Caldwell 2006). At sites invaded by scotch broom, net mineralization of N and available N is far greater than in non-invaded sites, although there is a small overall change in the total N pool (Haubensak et al. 2004). In the Pacific Northwest, scotch broom tends to invade well-drained soils in disturbed sites and spreads aggressively to form pure broom stands, often at the expense of the original plant community (Parker et al. 1994). The competition between the invasive scotch broom and native plants can be fierce; the predicted survival of Douglas-fir trees decreased by 30% when Scotch broom cover increased to 40% (Harrington and

Schoenholtz 2010). The survivability of Douglas-fir increased in more nutrient-rich sites, with higher nutrient- and water-holding capacities (Harrington and Schoenholtz 2010).

In Pacific Northwest, scotch broom has been found to affect all aspects of the ecosystem. Scotch broom acidifies the soil, and leads to greater soil organic matter accumulation, soil carbon, and soil nitrogen (Caldwell 2006). Soil organic matter increases under scotch broom because scotch broom litter is more lignified and harder to decompose (Singh and Narang 1991). Scotch broom litter also has more tannins, which can limit decomposition (Frutos et al. 2002). Scotch broom increases net N-mineralization due to its ability to fix N (Caldwell 2006, Liao et al. 2008). Although the N-fixation and increased soil organic matter increase both soil C and N, the increase between the two is comparable, so there is often no net change in soil C:N (Caldwell 2006). Scotch broom impacts C and N more readily, but it can impact soil P as well. N-fixing systems have been found to have greater P demands and there is a greater P acquisition under scotch broom, indicating the shrub may be preferentially removing P (Crews 1993, Caldwell 2006). Beyond changing the soil N and P ratio, scotch broom can be problematic. Scotch broom produces high concentrations of alkaloids, specifically sparteine, which is thought to reduce herbivory and inhibit competing seed germination (Wink et al. 1983, Wink et al. 1982). Scotch broom can also inhibit ectomycorrhizal fungi (EMF) colonization (Grove et al. 2012). EMF colonization is critical for initial nutrient acquisition by conifers, including Douglas-fir trees (Grove et al. 2012, Read et al. 2004, Teste et al. 2009). Although N-fixation by scotch broom could be helpful for a Douglas-fir stand, scotch broom will more likely be aggressive and problematic in a timber stand.

Although many of the studies mentioned refer to changes in soil nutrient pools and tree productivity in relation to management treatments, foliar nutrient status serves as a proxy for soil

nutrient pools as they are highly correlated. Foliar analysis has been shown to be representative of soil nutrient pools, especially in the case of severe nutrient deficiency (Van de Driessche and Rieche 1974). The reverse has also been shown to be true: soil nutrient pools can be indicative of foliar nutrient concentrations, as soil nutrient pools grow, foliar nutrients increased (Wang and Klinka 1997). However, despite this correlation, soil and tree nutrients should be used together to better understand the condition of the stand.

To better understand the interactions of WT and WC treatments in the Pacific Northwest and the impacts of the treatments on Douglas-fir stands, we analyzed the foliar nutrients from Fall River, Matlock, and Molalla in Washington and Oregon. Examining foliar nutrition is a cheaper and simpler method for determining the nutrient status of a stand (Wang and Klinka 1997). Foliar nutrition comparisons can help to diagnose nutrient deficiency, as well as inform managers of the implications of intensive forest management for tree growth. If more and more companies decide to utilize harvest slash, instead of allowing it to decompose, there may be serious long-term effects on the productivity and longevity of forest stands. To prevent these issues, the impact of these intensive management treatments should be consistently studied to provide as much data about the status of the stand over time as possible. The objectives of this study were to: 1) assess the nutrient status of trees within the WT, WC, and BO treatments at Matlock, Molalla, Fall River; 2) use foliar nutrients to assess the effectiveness of plot treatments and to develop future treatments.

## **2. Materials and Methods**

### **2.1 Site selection**

The research was conducted on three sites in the Pacific Northwest, all of which are affiliated with the North American Long-Term Soil Productivity study: Fall River, Matlock, and Molalla (Table 1) (Ares et al. 2007b, Slesak et al. 2016). We selected these three sites as representative of Douglas-fir stands in the Pacific Northwest. They represent a range of productivity and ages (Table 1). The Fall River site is in the Willapa Hills south of the Olympic Peninsula in coastal Washington. The soil formed from weathered Miocene basalt and contains volcanic ash in the upper horizons (Ares et al. 2007b). The soil is classified as a medial over clayey, ferrihydritic over parasequic, mesic Typic Fulvudand (Ares et al. 2007b, Soil Survey Staff, USDA-NRCS 1999). The Matlock site is in the Olympic Peninsula, Washington. Matlock's soil formed in deep glacial outwash classified as a sandy-skeletal, mixed, mesic, Dystric Xerorthents (Slesak et al. 2016, Soil Survey Staff, USDA-NRCS 2015). The Molalla site is in Oregon within the Cascade Range. The soil formed in basic agglomerate residuum and is classified as fine-loamy, isotic, mesic, Andic Dystrudepts (Slesak et al. 2016, Soil Survey Staff, USDA-NRCS 2015). Fall River and Molalla have much higher soil-water holding capacity, and Matlock and Molalla have differing pool sizes for nitrogen and other essential nutrients (Devine et al. 2011).

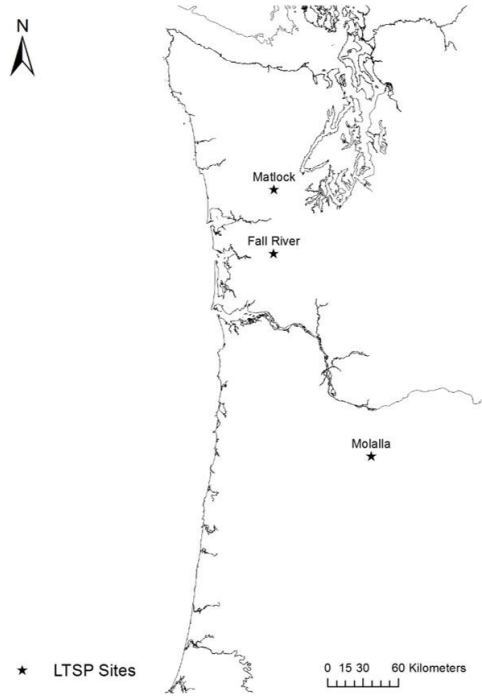


Figure 1: Geographic locations of Fall River, Molalla, and Matlock installations in the Pacific Northwest (Credit: Dr. Kim Littke).

Table 1: Site characteristics for Matlock, Molalla, and Fall River (Harrington et al. 2013, Slesak et al. 2016, Ares et al. 2007b, Holub et al. 2013).

<b>Characteristic</b>	<b>Matlock (WA)</b>	<b>Molalla (OR)</b>	<b>Fall River (WA)</b>
<b>Latitude, longitude</b>	47.2068N, 123.4428W	45.1968N, 122.2858W	46.72N, 123.41W
<b>Elevation (m above sea level)</b>	35	549	334
<b>Aspect, slope</b>	Flat, 0%	NW to SW, 0% to 30%	W, 9%-16%
<b>Soil series, texture</b>	Grove, very gravelly loamy sand	Kinney, cobbly loam	Boistfort, silt loam
<b>Douglas-fir 50-year site index (m)</b>	36	36	41-43
<b>Mean annual temperature (°C)</b>	10.7	11.2	9.8
<b>Mean annual precipitation (cm)</b>	240	160	170

The three study sites have a xeric climate with cool, wet winters, and dry, hot summers. The sites are all in the western hemlock vegetation zone. The predominate vegetation association at Fall River is western hemlock (*Tsuga heterophylla*), western sword fern (*Polystichum munitum*), and oxalis (*Oxalis oregana*) (Ares et al. 2007b). Matlock is dominated by western hemlock and salal (*Gaultheria shallon*). Scotch broom has also invaded Matlock, becoming the primary woody competitor for the site (Harrington and Schoenholtz 2010). Molalla is predominantly western hemlock, Oregon grape (*Mahonia nervosa*), and western sword fern (Slesak et al. 2016).

## 2.2 Experimental design and treatments

This study examined 2 factors, with two levels each. Factor 1 was biomass removal level (whole tree or bole-only), and factor 2 was vegetation control (initial site preparation or annual vegetation control for five years), designated by vegetation control (WC) or non-vegetation

control (NWC). Whole tree (WT) removed the logging debris (or slash), as well as the merchantable bole. Bole-only (BO) removed only the merchantable bole. Fall River contains four replications of 12 treatments in a randomized complete block factorial design that were implemented in 1999 (Terry et al. 2001). This study included three treatment levels from Fall River: WT+WC, BO+WC, BO+NWC. At Fall River, the WC treatment indicates herbicides were applied through year 3. Each treatment plot is 0.25ha (Appendix A).

Matlock and Molalla were harvested in April and May of 2003, respectively (Harrington and Schoenholtz 2010). A 2 x 2 randomized complete block factorial design was installed at both sites (Harrington and Schoenholtz 2010). All the plots were initially treated with herbicide in the summer of 2003 to reduce competing woody vegetation, and the WC plots were then treated with herbicide each year for five years (Harrington and Schoenholtz 2010). Each factorial combination was replicated four times with 0.3ha plots (Appendix B and C). The sites were then planted with Douglas-fir seedlings in February (Molalla) and March (Matlock), 2004.

### **2.3 Foliage collection**

The foliage was collected over the course of two months in 2016 using Ballard and Carter (1986) protocol. Specifically, Fall River foliage was sampled in January, while Molalla and Matlock foliage were sampled in February. Using the tree numbers assigned at planting, the sampled trees were systematically selected from every other north-south row in Matlock and Molalla, and at random within the Fall River plots. The selection was restricted to dominant and codominant trees. Dominance and codominance was determined using tree height data measured for previous studies. Five trees per plot were selected at Fall River due to the size of the trees. Ten trees per plot were selected at Matlock and Molalla.

A minimum of two branches were collected from the current year's foliage, from the 3<sup>rd</sup> whorl (ranging from ¼- ½ the size of the tree from the live crown of the tree) on the southern side of each tree. From each branch, three shoots were collected: the central and two lateral shoots, and the lammas growth was discarded. The samples were then stored at 4°C in a cold room at the University of Washington, before the samples were thoroughly air-dried. One hundred air-dried needles from each sample were then placed into an oven to dry for another 12 hours at 75°C, before being weighed to determine dry biomass. The remaining portions of the foliage were ground by hand using a mortar and pestle and then redried at 70°C for 24 hours.

## **2.4 Chemical Analysis**

N concentrations were measured following method EPA 29-2.2. To determine the P content, we analyzed the samples using Inductively Coupled Plasma Mass Spectrometry (ICP) analysis using method EPA 200.7. All chemical analysis was performed at the University of Washington School of Environmental and Forest Sciences Analytical Service Center.

## **2.5 Data Analysis**

We examined the response of foliar N and P concentration to the treatments in three Douglas-fir stands. The analysis considered four biomass removal and vegetation control combinations: BO-WC, BO-NWC, WT-WC, WT-NWC. Matlock and Molalla were tested for all combinations.

For statistical comparison, the measurements of the N and P concentration, as well as the diameter at base height (DBH) were averaged by plot. The DBH and scotch broom cover data for Matlock were provided by Dr. Tim Harrington (United States Forest Service) and both were collected in 2013. Linear regression analyses were used to test foliar N, P, and N:P for each site,

as well as all sites combined. All the statistical analyses were computed in R (R Core Team, 2017). For the combined model, “site” was used as a blocking factor, and for all the models, the blocks within each site were treated as random effects. The linear models were then determined to be hetero- or homoscedastic, and transformations were performed on the explanatory variables as needed, updating the linear models with those transformations. Standard mixed-model ANOVA tests were run on the final linear models and performed Tukey’s multiple comparison test to determine differences using an  $\alpha = 0.10$  based on previous foliar nutrient studies (Ponder et al. 2012).

### **3. Results and Discussion**

#### **3.1 Nitrogen**

While there are significant differences between foliar N at each site ( $F = 14.76$ ,  $p < 0.1$ ), there were no significant treatment effects across all sites. Foliar N at Matlock was significantly lower than at either Fall River or Molalla (Fig. 2). Our results were supported by N pool levels, with Fall River as the highest foliar N values and Matlock as the lowest. Despite the relatively low foliar N values at Matlock, none of the sites were deficient.

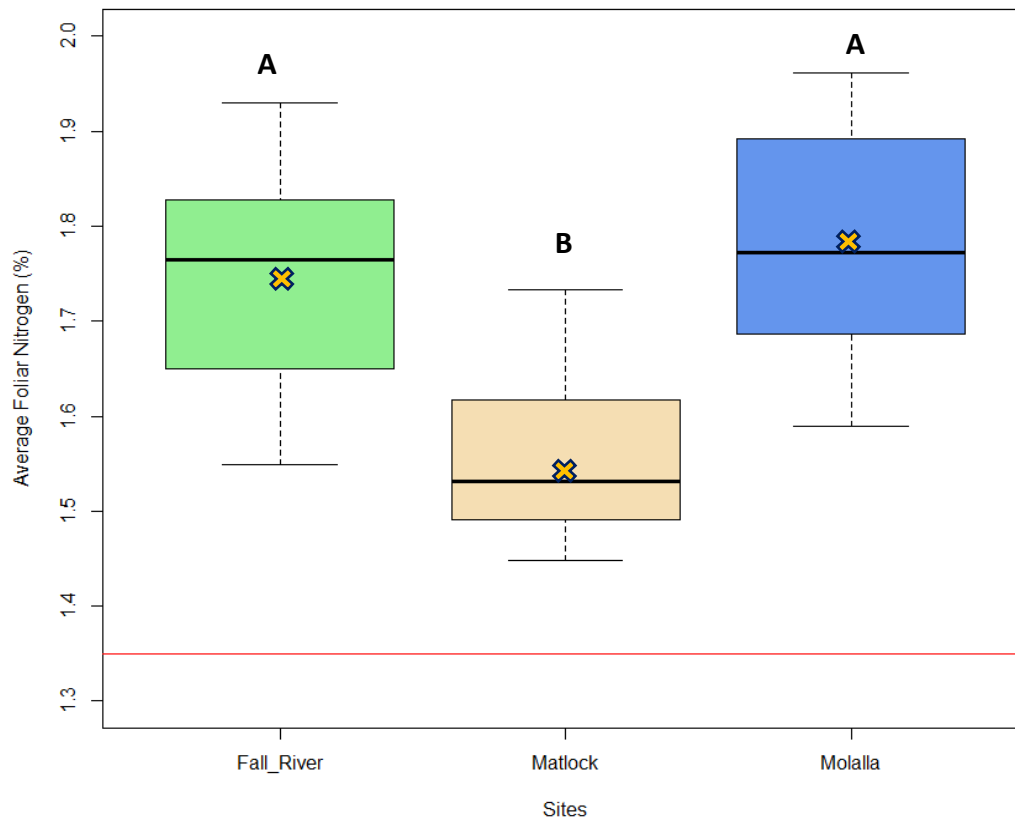


Figure 2: Box plot of average foliar nitrogen as compared by site. Letters represent Tukey's HSD test results. Foliar N at Fall River and Molalla were found to be statistically similar, while Matlock was significantly lower. The red line represents adequate N% (1.35%). The "x" represents the site average foliar N.

The soil N pool size is due to the soil characteristics at each site. Fall River's soil is clay loam to silty clay loam and a soil N pool of 14,672 kg N/ha (Ares et al. 2007b). Despite having lower allophane and imogolite concentrations than most Andisols, it is a productive soil, with low bulk density, and high water- and nutrient-holding capacity (Ares et al. 2007b). The clay portion of Fall River's soil is made up primarily of hydroxyl-interlayered vermiculite, which is not as expansive as vermiculite, but does expand, increasing retention and CEC/AEC sites (Ares et al. 2007b). Molalla is a cobbly loam, with a higher water- and nutrient-holding capacity and has a soil N pool of 4338 kg N/ha (Harrington and Schoenholtz 2010). Matlock is very gravelly loamy sand with a lower retention capacity and has a soil N pool of 2246 kg N/ha (Harrington and Schoenholtz 2010). Our data suggested that foliar N is positively related to the soil N pools.

A larger soil pool will have higher foliar N values. Fall River and Molalla had higher overall values of foliar N than Matlock (Fig. 2). The estimated values for average foliar N was 1.74% at Fall River, 1.78% at Molalla, and 1.55% at Matlock. The estimate at Molalla was higher than Fall River due to lower C:N ratio and higher annual temperature at Molalla (Table 1). Molalla has the lowest forest floor C:N ratio of all three sites (Slesak et al. 2016, Ares et al. 2007b), indicating higher net N mineralization. Net N mineralization also increases as temperature increases, especially in forested ecosystems, partially because of increased decomposition rates (Rustad et al. 2001). With more available N, the trees at Molalla will have increased N uptake.

Supporting previous conclusions from Bigger and Cole (1983), Slesak et al. (2011), Slesak et al. (2016), organic matter removal and vegetation control treatments were only significantly related to foliar N at the least productive site, Matlock ( $F = 16.20, p < 0.1$ ) (Fig. 3). Because Matlock has lower nutrient-retention in the soil and a smaller N pool, removal of organic matter reduces the amount of N available for uptake by the trees. Lower soil N availability yields lower foliar N concentrations. Despite the lower soil N pool and the impacts of the treatments on foliar N, Matlock's N levels have not fallen below the critical threshold of 1%, as defined by Carter (1992). A foliar N above 1.35% is considered to be adequate for Douglas-fir growth and even the most extreme foliar N values at Matlock did not fall below 1.4 % (Fig. 3). However, there still should be concern about long-term impacts of these intensive management techniques on foliar N at Matlock, considering the small N pool at Matlock and its lower quality soil.

The results were complicated by the presence of scotch broom, a nitrogen-fixer. The BO treatment at Matlock was determined to have lower foliar N than the WT treatment (Fig. 3), due to scotch broom. The WT treatment removed all the remaining slash after harvest, slash that

when dispersed across the site can reduce scotch broom growth (Harrington and Schoenholtz 2010). As Fig. 4 shows, scotch broom cover was significantly higher in the WT treatments, fixing N within the soil, increasing the plot N soil pool, and increasing the availability of N for Douglas-fir trees within those plots. Scotch broom cover was statistically significant for foliar N ( $F = 8.14, p < 0.1$ ), and affected it positively.

Although vegetation control did not significantly decrease scotch broom cover, the vegetation control still significantly affected foliar N ( $F = 8.19, p < 0.1$ ). Fig. 3 shows that NWC treatment has significantly higher foliar N. The WC treatment most likely reduced the Scotch broom cover, reducing the soil N available for the Douglas-fir trees and leading to less N being taken into the foliage. This supported previous research at Matlock, in which DeBruler (2014) theorized that Scotch broom could also be adding C and N to the soil at Matlock at higher rates. Matlock was N-poor enough that scotch broom would be and was very successful and the addition of N to the soil by scotch broom could be seen as a positive impact on the site. The scotch broom could increase soil N without the need for fertilization or amendments.

The benefits of N-fixation do not outweigh the fact that young Douglas-fir seedlings could not compete early on with scotch broom. Scotch broom has been found to interfere with the re-establishment of conifer seedlings on harvested lands (Parker et al. 1994). Harrington and Schoenholtz (2010) have shown increases in scotch broom reduce Douglas-fir survivability, and Watt et al. (2003) showed that scotch broom outcompeted *Pinus radiata* to the point where the stand could not be successful. At Matlock, the scotch broom has reduced Douglas-fir growth (Harrington and Schoenholtz 2010). The 2013 diameter at base height (DBH) and foliar N concentrations were negatively correlated at Matlock ( $F = 8.94, p < 0.1$ ) (Fig. 5). Matlock was the only site to have a negative correlation between DBH and foliar N (Fig. 6). The negative

relationship suggested that the site productivity is not increasing despite the presence of N fixing scotch broom and elevated foliar N concentrations. The scotch broom likely outcompeted the Douglas-fir trees for water and nutrients, resulting in lower tree productivity (as indicated by DBH) than the foliar N concentrations would otherwise suggest. Although scotch broom increases soil organic matter accumulation, as well as soil C and N – which could be positive in a low N site like Matlock – a large presence of Scotch broom affects the economic viability of the site, especially at the beginning stage of stand development. The scotch broom will continue to outcompete the Douglas-fir trees and reduce yield.

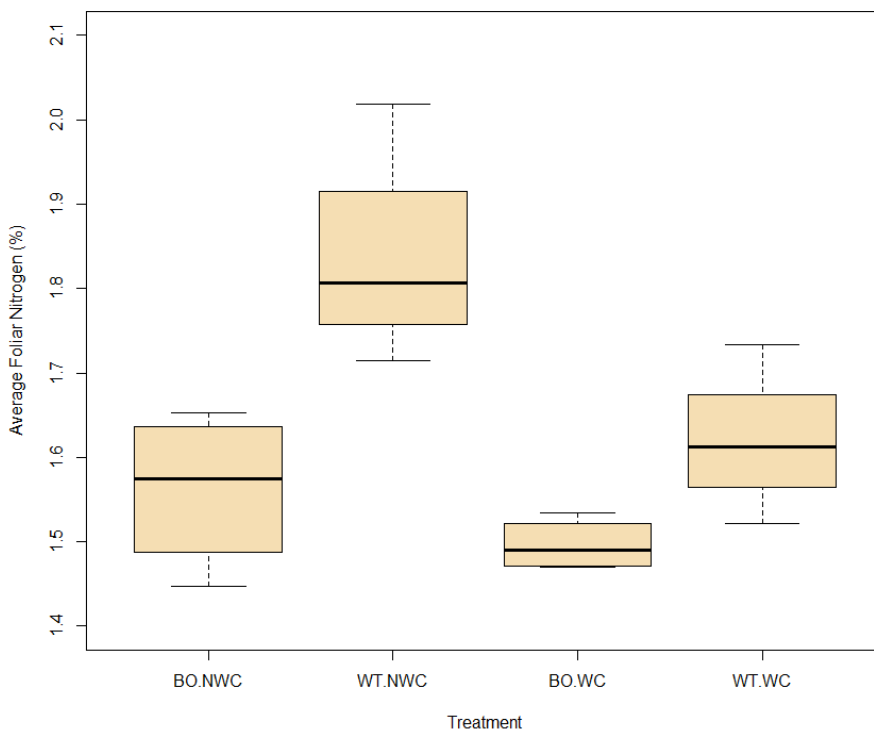


Figure 3: Box plot of average foliar nitrogen (%) at Matlock as compared by both biomass removal and vegetation control treatment. The interaction effects were not found to be significant. However, it is clear how much more foliar N is present in the WT and NWC treatments due to Scotch broom.

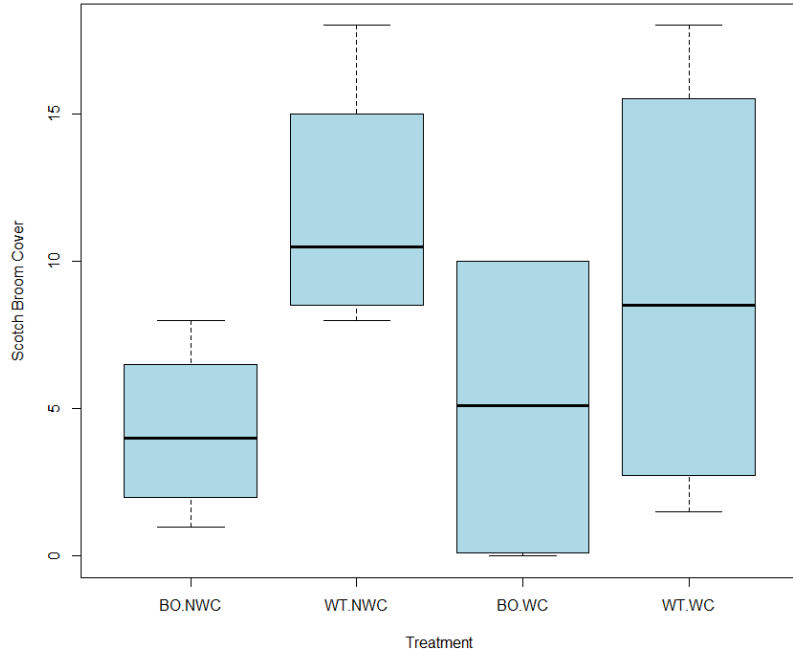


Figure 4: Box plot of scotch broom cover at Matlock as compared by both biomass removal and vegetation control treatment. Scotch broom cover was significantly impacted by biomass removal treatments.

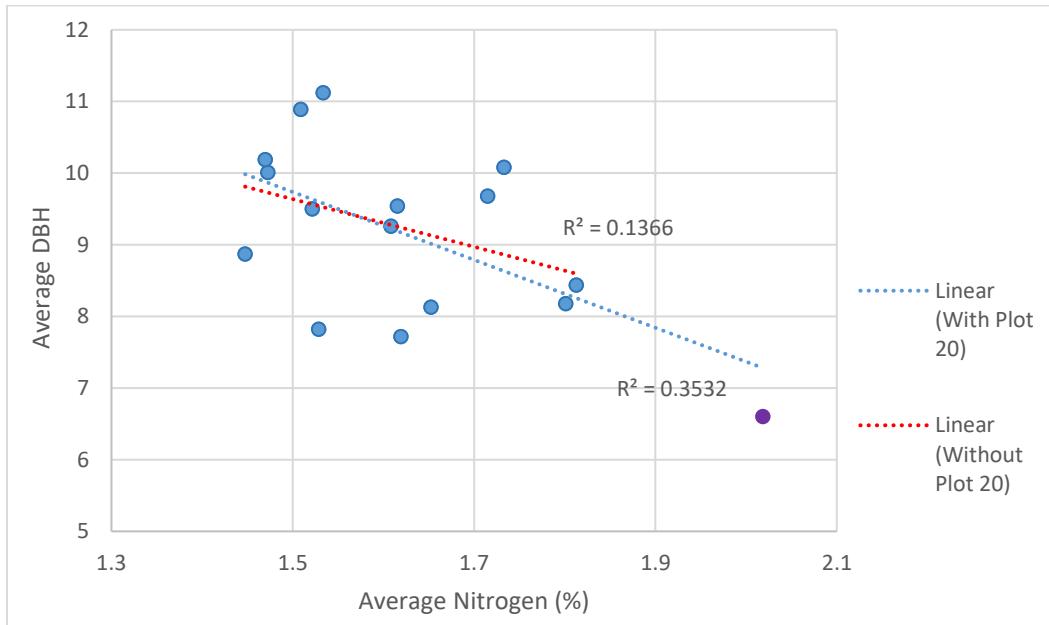


Figure 5: Plot of average Douglas-fir tree DBH plotted against average foliar nitrogen at Matlock. As foliar N increased, the DBH decreased, leading to a negative relationship. The downward trend was driven by the lower right point (colored purple), which represented Plot 20, a WT-NWC plot. Without the outlier, the downward trend was not as strong, leading to the conclusion that plot 20 strongly affected the analysis.

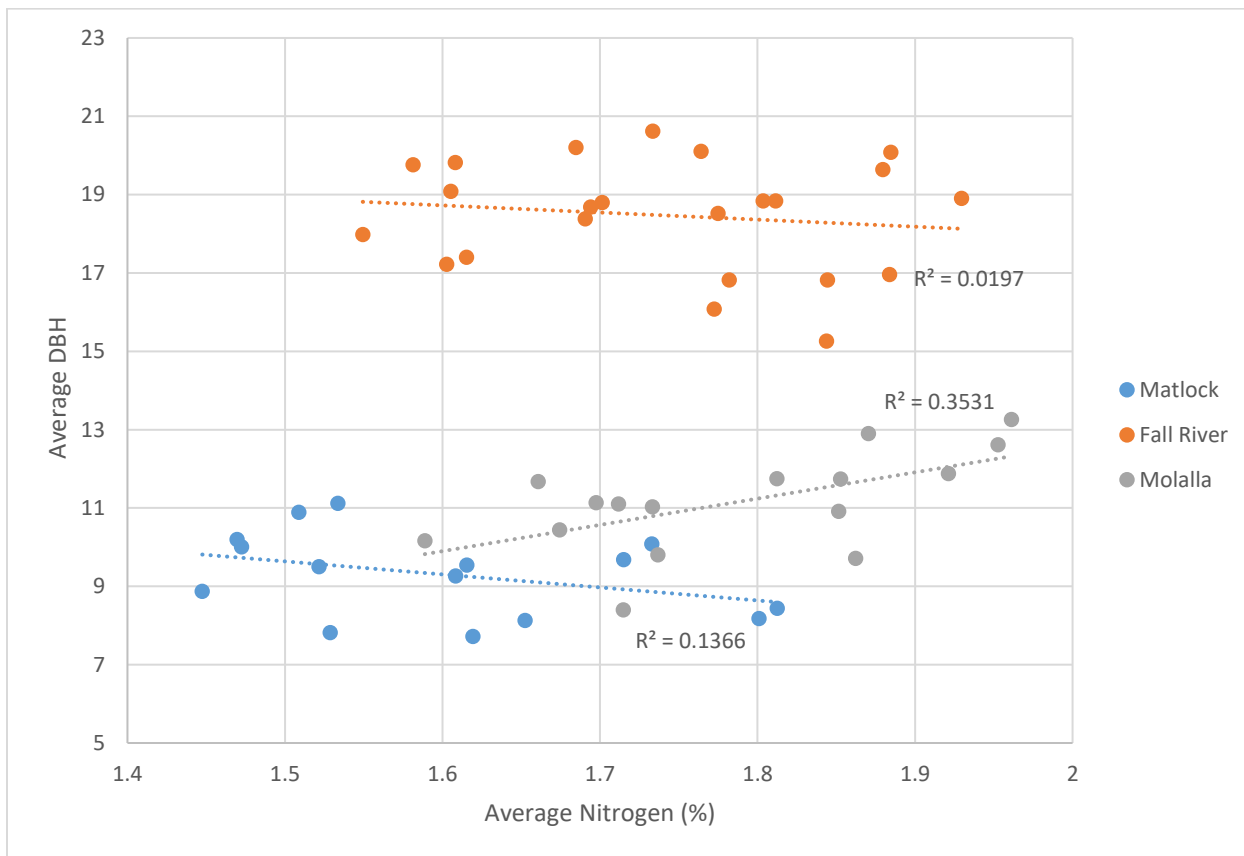


Figure 6: Plot of average Douglas-fir tree DBH plotted against average foliar nitrogen at Fall River, Matlock (without plot 20), and Molalla. The downward trend is only present at Matlock, due to the presence of scotch broom affecting Douglas-fir tree size.

At both Fall River and Molalla, there was no significant difference in foliar N between BO and WT, or the WC and NWC treatments – most likely due to the productive soil at both sites. There are large enough nutrient pools within Fall River’s and Molalla’s soils that the increased organic matter removal treatment did not have a statistically significant impact on the foliar N of the Douglas-fir trees, supporting previous research (Roberts et al. 2005, Holub et al. 2013, Ares et al. 2007a). The productivity of both sites may also explain why the vegetation control treatments had no significant impact. The soil N pools are large enough that the Douglas-fir trees are not outcompeted for nutrients by other vegetation at the site. The lack of impact of the vegetation control treatments at Fall River is supported by previous research at Fall River,

which found no statistical significance in foliar N between vegetation control treatments (Ares et al. 2007a, Devine et al. 2013). N availability was not a limiting factor at either of these sites, and the most intensive practices do not appear to have had a serious impact on the foliar N of the Douglas-fir trees.

Our data supported that site was the most important determinant in the effect of increased biomass removal and vegetation control on foliar N. When managers are evaluating whether to apply these treatments, they must consider the site characteristics, and not apply generalities. Fall River and Molalla have productive soils and soil N pools large enough that increased biomass removal or lack of vegetation control did not lead to lowered foliar N. These sites may be ones that can support more intensive treatments without immediate issue. Matlock, however, is a less productive site with a smaller N pool, leading to greater treatment impact. Even at Matlock, the impacts of the treatments are complicated by the site-specific vegetative community. The scotch broom is most likely increasing net N mineralization on WT and NWC plots, which then allows the Douglas-fir trees to take up more foliar N. However, the competition from the scotch broom is reducing Douglas-fir height and survivability (Harrington and Schoenholtz 2010). Due to both the lower soil N and the dominance of scotch broom, Matlock is a site that cannot support more intensive biomass removal.

### **3.2 Phosphorus**

As with foliar N, foliar P significantly differed among sites ( $F=4.82$ ,  $p<0.01$ ), but did not significantly respond to either treatment across all sites. Molalla contained significantly less P in the foliage compared to Fall River and Matlock (Fig. 7). Using Carter's critical thresholds (1992), Molalla's foliar P might have been slightly deficient, with a median value below the threshold of 0.15% P (Fig. 7). Foliar P at Fall River and Matlock was above the adequate

threshold of 0.15% (Fig. 7) (Carter 1992). Although organic P is important, most of the P found in soil is due to weathering from parent material (Johnson et al. 1982, Favre and Napper 2009), and typically the older the soil, the fewer primary nutrients such as P are available to be weathered out into the soil (Walker and Adams 1958).

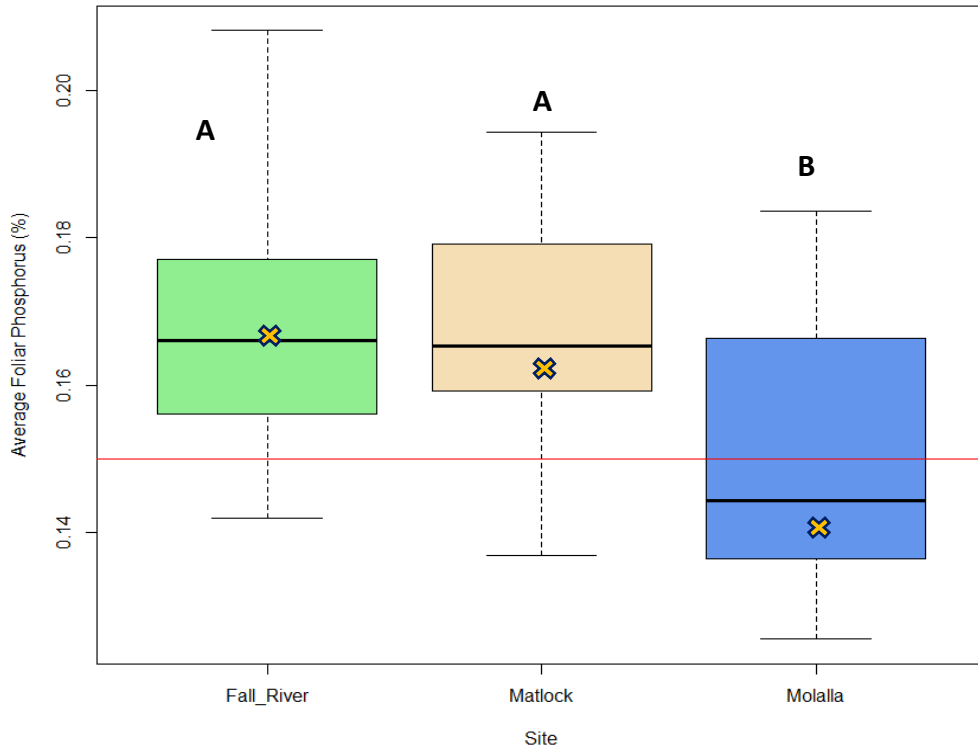


Figure 7: Box plot of average foliar phosphorus (%) as compared by site. Letters represent Tukey's HSD test results ( $p < 0.1$ ). Foliar P at Fall River and Molalla are not significantly different, while Molalla was significantly reduced. The red line represents adequate P% (0.15%). The "x" represents the site average foliar P.

Molalla is most likely the oldest soil of the three sites, which is why it has the lowest soil P pool. Molalla's soil developed from Miocene volcanic rocks, including Andesite (Sherrod and Smith 2000). The soil has very developed horizons and is very deep, meaning it has had more time to develop (Soil Survey Staff, USDA-NRCS 2015). Fall River developed from Miocene basalt, but has been influenced by ash from eruptions, as recently as approximately 6,800 years ago (Ares et al. 2007b). The newer volcanic material would have refreshed the soil nutrient

pools. Fall River also has weaker horizon differentiation, meaning it has undergone less development (Soil Survey Staff, USDA-NRCS 1999). Matlock soil is an Entisol that developed on glacial outwash from the last glaciation (10,000 to 14,000 years ago) (Soil Survey Staff, USDA-NRCS 2015).

Neither biomass matter removal nor vegetation control treatments were found to be significantly correlated with foliar P at any of the individual sites. The lack of treatment effect at Matlock is interesting. Studies have shown N-fixing systems tend to have greater P demands, because the species have enough N, they preferentially remove P (Caldwell 2006, Crews 1993). Our results also did not support a decrease in P uptake due to greater reductions in soil P from more intensive management techniques at Matlock (DeBruler 2014, Slesak et al. 2016). The different results may be due to the difference between foliar P and soil P.

The P data supported site as the most important determinant in the effect of increased biomass removal and vegetation control on foliar P. The treatments did not have significant impact on the foliar P within the sites. Fall River and Matlock have large enough soil P pools that the increased biomass removal did not impact the foliar P. However, previous research at Matlock has shown that soil P tends to be removed with more intensive management techniques, which is something a manager must consider. Our data supported that Molalla has a low soil P pool, which can be seen in the low foliar P. Molalla had foliar P values that indicate the site may react well to additions of P. Although there were no treatment effects at Molalla, the low P must be considered. If more intensive management techniques remove P, and the site is already low in P, there may be long-term issues with site productivity.

### **3.3 N:P Ratios**

As with foliar N and P, the N:P ratio significantly differs between sites ( $F=15.12$ ,  $p<0.01$ ), and neither treatment had an effect when all the sites were compared, supporting once again site as the most important determinant for impacts on foliar nutrients. All the sites were determined to be different than one another, although Matlock and Fall River are more similar (Fig. 8). Because of the importance of N and P for plant growth, foliar N:P ratios have been used to both determine N and P deficiencies, but also to determine if there have been shifts from N limitation to P limitation (Gusewell 2004, Koerselman and Meuleman 1996). However, although N:P ratios reflect the availability of N and P, the correlation is not exact because variation in N:P supply ratio does not have an equal effect on foliar N:P (Gusewell 2004). N:P ratios tend to best be used to examine whether the trees or the community are under N or P limitations and what can be done to address the issue (Ballard and Carter 1986).

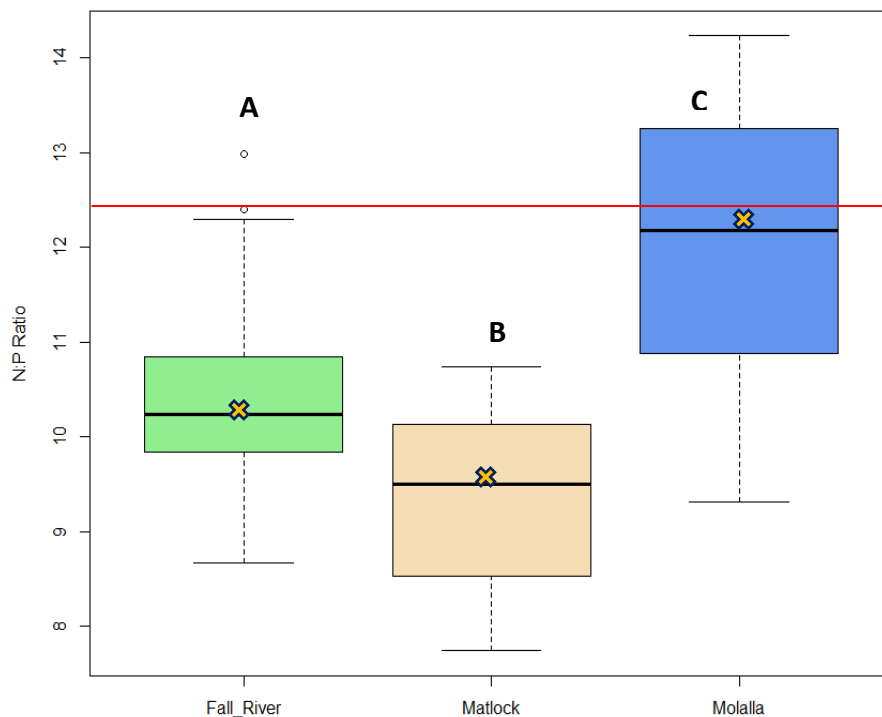


Figure 8: Box plot of foliar N:P as compared by site. Letters represent Tukey's HSD test results ( $p<0.01$ ). Foliar N:P ratios were significantly different at each site. The red line is the threshold of P deficiency (above 12.5 is considered a slight P deficiency). The "x" represents the site average foliar N:P ratio.

Molalla had a higher N:P ratio (Fig. 8), which tends to mean that the site is more deficient in P (Fig. 8) (Ballard and Carter 1986). However, none of the N:P ratios fell into critical P or N deficiency. Above a ratio of 16, the site is severely P deficient (Ballard and Carter 1986). The most extreme of Molalla's values fell close to 16, but not above it (Fig. 8). Molalla can be considered to be slightly P deficient, however, as the upper quartiles fall above 12.5 (Fig. 8), which Ballard and Carter (1986) consider to be a threshold for P deficiency. Therefore, at Molalla, P is a limiting nutrient for the Douglas-fir trees. Management at this site may want to consider adding P to increase P uptake by the Douglas-fir trees.

Matlock was the only site where N:P ratios were significantly different for biomass removal and vegetation control. WT and NWC treatments had higher N:P ratios, indicating higher N values (Fig. 9). The higher N:P ratio was due to two reasons, the WT treatments at Matlock removed more soil P than the BO treatments (Slesak et al. 2016), and WT and NWC treatments allowed for more scotch broom cover, increasing the soil N pool, decreasing the soil P pool, and increasing phosphatase activity (DeBruler 2014, Caldwell 2006). The increased scotch broom cover increased soil N faster than P was being removed, lowering the N:P ratio. Although the overall effect of these two treatments was not enough to raise the ratio to the critical threshold N:P ratio value of 16, it should still be something to consider. Despite having a larger soil P pool than Molalla and no significant impact of the treatments on foliar P, the treatments significantly affected the N:P ratio, supporting the view that less productive sites are more affected by increased biomass removal. It also supported that the presence of Scotch broom is significantly negatively affecting the foliar nutrient response of the Douglas-fir trees.

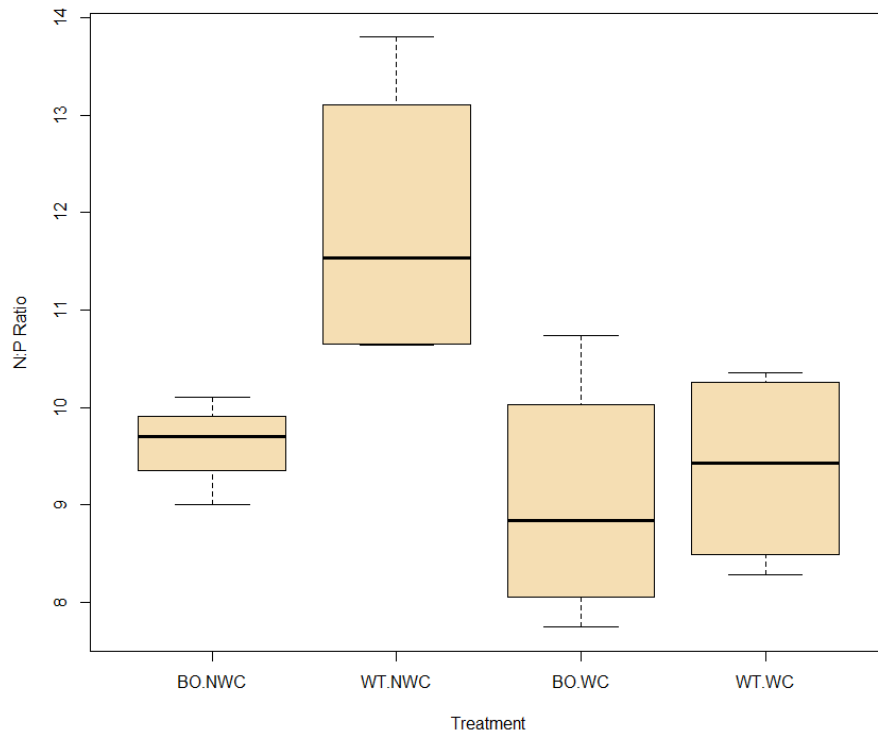


Figure 9s: Box plot of foliar N:P at Matlock as compared by biomass removal and vegetation control treatment. The WT-NWC plots had significantly higher N:P ratio.

Fall River is the only site where there is no concern about either foliar N or P. Increased biomass removal did not affect the foliar N or P, as can be seen by the lack of significance in the N:P ratios. Apart from outliers, all the ratios fall below 12.5, which Ballard and Carter (1986) define as the threshold for the start of slight P deficiencies. The foliar N:P ratios show that Fall River has large enough N and P soil pools that neither nutrient is limiting for Douglas-fir growth. The foliar values at Fall River are high enough that the intensive management is not causing significant negative effects.

### 3.4 Needle weight

There was no significant difference in needle weights across all the sites, as well as between the treatments within each of these sites (Fig. 10). Although many factors contribute to

needle morphology, including light exposure, age, and climate, dry needle weight is highly correlated with plant dimensions and nutrient availability (Niinemets and Kull 1995, Hager and Sterba 1985). Because of the differences between the sites, we could not make statistical conclusions comparing the foliage size between sites, limiting our analysis to within each site. 10-year measurements at Matlock and Molalla determined that Molalla had taller trees and a greater percentage of canopy cover (Slesak et al. 2016), which, considering previous research, indicate Molalla should have heavier needles. And if needles grow larger due to higher nutrient availability, Fall River should have larger needles as well. However, we did not see a correlation between the needle weight and nutrient availability in our results, despite the differences in foliar and soil N and P at Fall River, Molalla, and Matlock. This may indicate that the nutrient availability for N and P is high enough for all the sites, including Matlock, that there were no significant effects on needle weight. It also could mean that Fall River has another limiting nutrient, other than N or P, that is reducing needle size. Fall River has low soil calcium (Ca), similar to a nearby site, Weikswood, that has high soil N, but low soil Ca. The needle size at Weikswood was also smaller than expected (Dr. Kim Littke, personal communication, April 2017). The lower Ca may be reducing needle size at Fall River, as well. However, considering the previous results at the three sites, the needle weight data and its implications should be used with more variables to determine whether it is a sufficient enough indicator of tree growth and nutrient availability.

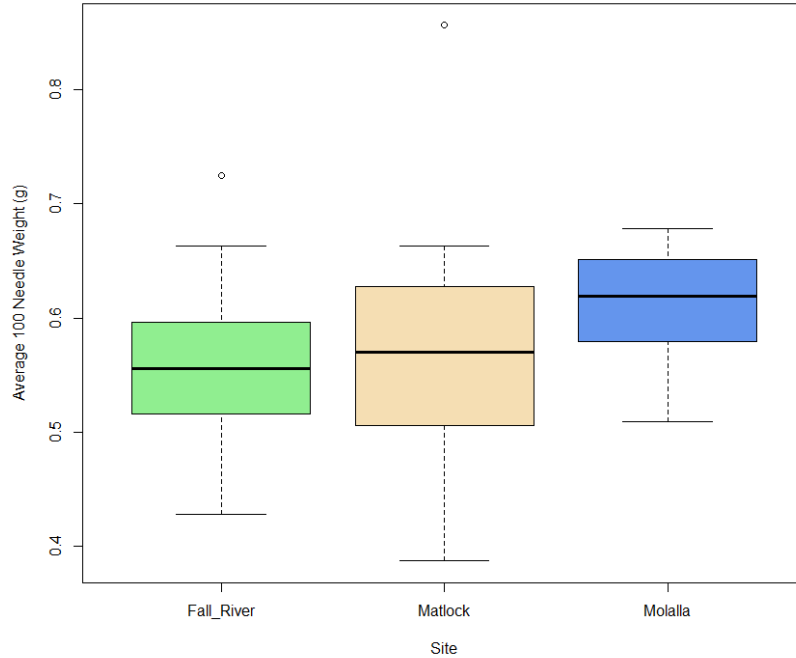


Figure 10: Box plot of average dry needle weight as compared by site. There were no significant differences within each the sites.

#### 4. Conclusions

1. Site is the most important determinant for treatment effect. The effectiveness of vegetation control and the ability of a site to withstand the impact of increased biomass removal can only be determined on a site by site basis.
2. However, some generalities can be applied. The more productive the site, the less likely treatments will have a negative effect. Increased biomass removal only had a significant impact on foliar N and N:P at Matlock, the least productive site.
3. None of the sites foliar N or P fell below critical levels, meaning there is no immediate concern about the effects of increased biomass removal. However, the lower foliar N at Matlock and foliar P at Molalla were concerning. The smaller soil and foliar nutrient pools indicated that these sites should be monitored to assure that there are no long-term impacts on soil productivity.

4. Scotch broom complicates management at Matlock. Despite its ability to fix N, scotch broom is an aggressive invasive species that has severely affected Douglas-fir tree growth at Matlock. Scotch broom cover at Matlock was greater in WT and NWC plots, leading to higher foliar N, but also lower DBH. The scotch broom must be removed if Matlock is to be a successful timber stand.

## References:

- Ares, A., Terry, T.A., Harrington, C.A., Devine, W., Peter, D., Bailey, J., 2007a. Biomass removal, soil compaction, and vegetation control effects on five-year growth of Douglas-fir in coastal Washington. *For. Sci.* 53, 600–610
- Ares, A., Terry, T.A., Piatek, K.B., Harrison, R.B., Miller, R.E., Flaming, B.L., Licata, C.W., Strahm, B.D., Harrington, C.A., Meade, R., Anderson, H.W., Brodie, L.C., Kraft, J.M., 2007b. The Fall River Long-Term Site Productivity Study in Coastal Washington: Site Characteristics, Methods, and Biomass and Carbon and Nitrogen Stores Before and After Harvest. Gen. Tech. Rep. PNW-GTR-691. 85p.
- Ballard, T.M., and Carter, R.E., 1986. Evaluating forest stand nutrient status. Ministry of Forests, British Columbia Land Management Report 20. ISSN: 0702-9861.
- Bauer, A., and Black, A.L. 1994. Quantification of the effect of soil organic matter content on soil productivity. *Soil Science Society of America Journal.* 58: 185-193
- Beldin, S.I., and Perakis, S.S., 2009. Unearthing the secrets of the forest: U.S. Geological Survey Fact Sheet. FS 2009-3078, 4 p.
- Bigger, C., and Cole, D., 1983. Effects of harvesting intensity on nutrient losses and future productivity in high and low productivity red alder and Douglas-fir stands. Pages 167-178 in R. Ballard and S. Gessel, editors. IUFRO symposium on forest site and continuous productivity. United States Forest Service General Technical Report PNW-163.
- Caldwell, B.A., 2006. Effects of invasive scotch broom on soil properties in a Pacific coastal prairie soil. *Applied Soil Ecology.* 32: 149-152.
- Carter, R., 1992. Diagnosis and interpretation of forest stand nutrient status. In: Chappell, H.N., Weetman, G.F. & Miller, R.E. (Eds.), *Forest fertilization: sustaining and improving nutrition and growth of western forests.* College of Forest Resources Contribution #73, University of Washington, Seattle. p. 90–97
- Crews, T.E., 1993. Phosphorus regulation of nitrogen fixation in a traditional Mexican agroecosystem. *Biogeochemistry* 21:141–166
- Debruler, D. G., 2014. Soil Carbon, Nutrients, and Phosphorus Fractions: Responses to Weed Control and Harvest Residual Retention in two 10-Year-Old Douglas-fir (*Pseudotsuga menziesii*) Stands of the Pacific Northwest (Master's Thesis). Virginia Polytechnic Institute and State University.
- Devine, W.D., Footen, P.W., Harrison, R.B., Terry, T.A., Harrington, C.A., Holub, S.M., Gould, P.J., 2013. Estimating Tree Biomass, Carbon, and Nitrogen in an 11-Year-old Douglas-fir Plantation on a Highly Productive Site. USFS Research Paper PNW-RP-591.
- Devine, W.D., Harrington, C.A., 2007. Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. *Agric. For. Meteorol.* 145, 125–138.
- Devine, W.D., Harrington, T.B., Terry, T.A., Harrison, R.B., Slesak, R.A., Peter, D.H., Harrington, C.A., Shilling, C.J., Schoenholtz, S.H., 2011. Five-year vegetation control effects on aboveground biomass and nitrogen content and allocation in Douglas-fir plantations on three contrasting sites. *Forest Ecology Management.* 262: 2187-1298.
- Favre, R. and C. Napper. 2009. Biomass fuels and whole tree harvesting impacts on soil productivity- Review of literature. National Technology and Development Program. The United States Department of Agriculture Forest Service. Web. Available: [http://www.fs.fed.us/t-d/pubs/pdf/hi\\_res/09201803hi.pdf](http://www.fs.fed.us/t-d/pubs/pdf/hi_res/09201803hi.pdf)  
Accessed: 20 November 2016.

- Frutos, P., Hervás, G., Ramos, G., Giraldez, F.J., Mantecon, A.R., 2002. Condensed tannin content of several shrub species from a mountain area in northern Spain, and its relationship to various indicators of nutritive value. *Anim. Feed Sci. Technol.* 95: 215–226
- Gessel, S.P., Miller, R.E., D.W. Cole, 1990. Relative importance of water and nutrients on the growth of coast Douglas-fir in the Pacific Northwest. *Forest Ecology and Management.* 30: 327-340.
- Grove, S., Haubensak, K.A., Parker, I.M., 2012. Direct and indirect effects of allelopathy in the soil legacy of an exotic plant invasion. *Plant Ecology.* 213: 1869-1882
- Gurlevik, N., Kelting, D.L., and Allen, H.L., 2004. Nitrogen mineralization following vegetation control and fertilization in a 14-year-old loblolly pine plantation. *Soil Science Society of America Journal.* 68.1: 272-281.
- Gusewell, S., 2004. N:P ratios in terrestrial plants: variation and functional significance. *The New Phytologist.* 164: 243-266.
- Hager, H., Sterba, H., 1985. Specific leaf area and needle weight of Norway Spruce (*Picea abies*) in stands of different densities. *Canadian Journal of Forest Research.* 15: 389-392.
- Harrington, T.B., and Schoenholtz, S.H., 2010. Effects of logging debris treatments on five-year development of competing vegetation and planted Douglas-fir. *Can. J. For. Res.* 40: 500–510.
- Harrington, T.B., Slesak, R.A., Schoeholtz, S.H., 2013. Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir. *Forest Ecology and Management.* 296: 41-52.
- Haubensak, K., Antonio, C.D., Alexander, J., 2004. Symposium effects of nitrogen-fixing shrubs in Washington and coastal California. *Weed Technology.* 18:1475-1479.
- Holub, S.M., Terry, T.A., Harrington, C.A., Harrison, R.B., Meade, R., 2013. Tree growth ten years after residual biomass removal, soil compaction, tillage, and competing vegetation control in a highly-productive Douglas-fir plantation. *For. Ecol. Manage.* 305: 60–66.
- Johnson, D.W., Cole, D.W., Bledsoe, C.S., Cromack, K., Edmonds, R.L., Gessel, S.P., Grier, C.C., Richards, B.N., Vogt, K.A., 1982. Nutrient cycling in forests of the Pacific Northwest. In R.L. Edmonds (ed.) *Analysis of coniferous forest ecosystems in the western United States*, pp. 186-232. Hutchinson Ross Publishing Co., Stroudsburg Pennsylvania.
- Knight, E., Footen, P., Harrison, R., Terry, T., Holub, S., 2014. Competing vegetation effects on soil carbon and nitrogen in a Douglas-fir plantation. *Soil Science Society of America Journal.* 78: 146-151.
- Koerselman, W., Meuleman, A.F.M, 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. *Journal of Applied Ecology.* 33:1441-1450.
- Lavender, D.P., and Walker, R.B., 1979. Nitrogen and related elements in nutrition of forest trees. *Proc. Forest fertilization conf.* S.P. Gessel, R.M. Kenady, and W.A. Atkinson eds. College of Forest Resources, Institute of Forest Resources. University of Forest Resources. University of Washington, Seattle. Contribution no. 40: 15-22. Ha
- Liao, C.Z., Peng, R.H., Luo, Y.Q., Zhou, X.H., Wu, X.W., Fang, C.M., Chen, J.K., Li, B., 2008. Altered ecosystem carbon and nitrogen cycles by plant invasion: a meta-analysis. *New Phytologist.* 177: 706-714.

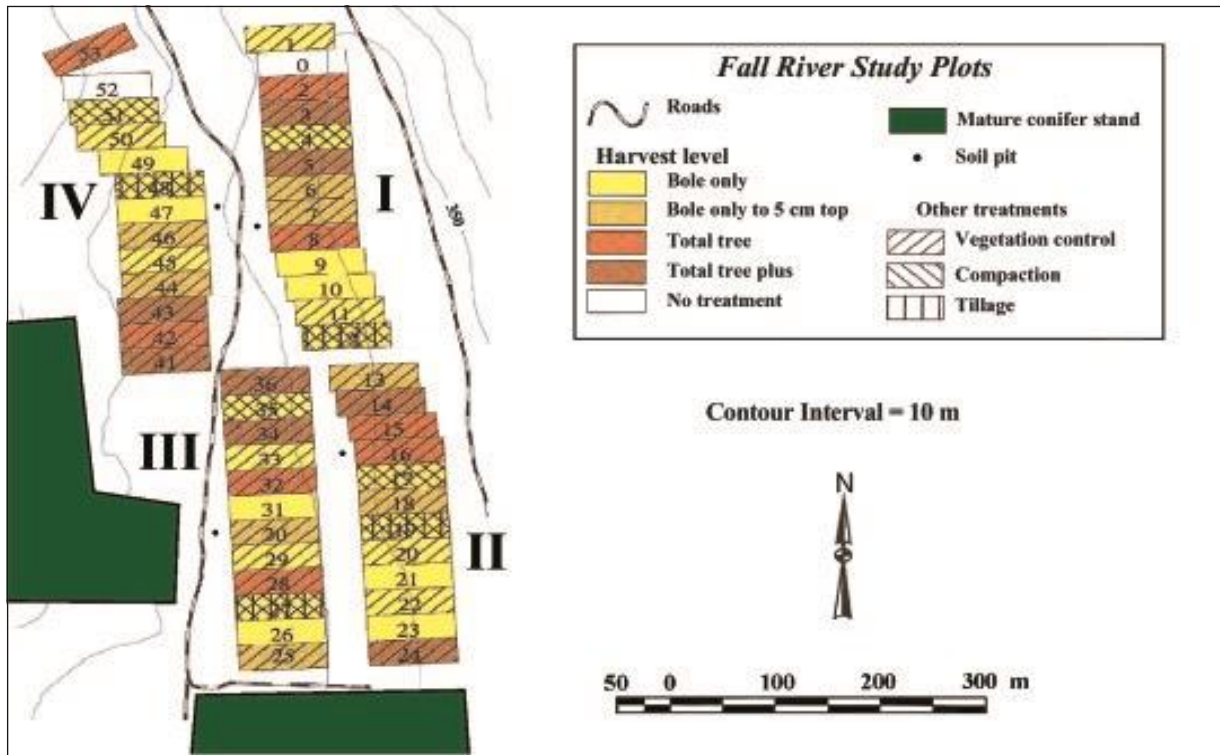
- Meehan, N.A. 2006. Response of needle-litter decomposition and soil nitrogen mineralization to logging-debris manipulation and competing vegetation control in western Oregon and Washington. M.S. thesis, Oregon State University, Corvallis, OR. 137 p.
- Niinemets, U., Kull, O., 1995. Effects of light availability and tree size on the architecture of assimilative surface in the canopy of *Picea abies*:
- Parker, B., Miller, G., Burrill, L.C., 1994. Scotch broom, *Cytisus scoparius* (L.) Link. Pacific Northwest Weeds Bulletin No. 103, revised July 1994. Corvallis, OR, USA; Oregon State University Cooperative Extension Service, 4 pp.
- Ponder, F., Fleming, R.L., Berch, S., Busse, M.D., Elioff, J.D., Hazlett, P.W., Kabzems, R.D., Marty Kranabetter, J., Morris, D.M., Page-Dumroese, D., Palik, B.J., Powers, R.F., Sanchez, F.G, Scott, D.A., Stagg, R.H., Stone, D.M., Young, D.H., Zhang, J.W., Ludovici, K.H., McKenney, D.W., Mossa, D.S., Sandborn, P.T., Voldseth, R.A., 2012. Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons. *For. Ecol. Manage.* 278: 35–54.
- Powers, Robert F., Alban, D.H., Miller, R.E., Tiarks, A.E., Wells, C.G., Avers, P.E., Cline, R.G., Fitzgerald, R.O., Loftus, N.S., 1990. "Sustaining site productivity in North American forests: problems and prospects." In: Gessel, S.P. et al. (Eds.), Sustained productivity of forest soils. Forest Publications, University of British Columbia, Vancouver, B.C. pp 49-80.
- Radwan, M.A., Brix, H., 1986. Nutrition of Douglas-fir. In: Oliver, Chadwick Dearing; Hanley, Donald P. ; Johnson, Jay eds . Douglas -fir: stand management for the future: Proceedings of a symposium; 1985 June 18-20; Seattle, WA. Contribution no. 55. Seattle: College of Forest Resources, University of Washington
- Read, D.J., Leake, J.R., Perez-Moreno J., 2004. Mycorrhizal fungi as drivers of ecosystem processes in heathland and boreal forest biomes. *Can J Bot Revue Can De Bot.* 82:1243–1263
- Rifai, S.W., Markewitz, D., and Borders, B., 2010. Twenty years of intensive fertilization and competing vegetation suppression in loblolly pine plantations: impacts on soil C, N, and microbial biomass. *Soil Biology and Biochemistry* 42.5: 713-723.
- Roberts, S.D., Harrington, C.A., Terry, T.A., 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir growth. *For. Ecol. Manage.* 205:333–350.
- Rustad, L., Campbell, J., Marion, G., Norby, R., Mitchell, M., Hartley, A., Cornelissen, J., Gurevitch, J., 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia.* 126:543-562.
- Sanchez, F.G, Tiarks, A.E., Kranabetter, J.M., Page-Dumroese, D.S., Powers, R.F., Sanborn, P.T., Chapman, W.K., 2006. Effects of organic matter removal and soil compaction on fifth year mineral soil carbon and nitrogen contents for sites across the United States and Canada. *Canadian Journal of Forest Resources.* 36:564–575
- Scott, D.A., Novosad, J., Goldsmith, G., 2004. Ten-year results from the North American long-term soil productivity in the Western Gulf Coastal Plain. Advancing the fundamental sciences: proceedings of the Forest Service national earth sciences conference, PNWGTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

- Singh, B., Narang, M.P., 1991. Potential extent of digestion in some grass and legume forages. *Ind. J. Anim. Nutr.* 8:285–287.
- Sherrod, D.R., Smith, J.G., 2000. Geologic map of the upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon. United States Geologic Service. Geologic Investigations Series Map I-2569.
- Slesak, R.A., Harrington, T.B., Peter, D.H., DeBruler, D.G., Schoenholtz, S.H., Strahm, B.D., 2016. Effects of intensive management practices on 10-year Douglas-fir growth, soil nutrient pools, and vegetation communities in the Pacific Northwest, USA. *Forest Ecology and Management.* 365: 22-33
- Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A., 2004. Forest Resources of the United States, 2002. General Technical Report NC-241. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Research Station.
- Snowdon, P. and Waring, H.D., 1984. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In: Grey, D.C., Shonau, A.P.G., Shutz, C.J. (Eds.), *Site and Productivity of Fast Growing Plantations. Proceedings of International Union of Forestry Research Organizations.*
- Switzer, G.L., L.E. Nelson, L.E. Hinesley, 1981. Effects of utilization on nutrient regimes and site productivity. In: Gessel, S.P. et al. (Eds.), *Proc. Forest Fertilization Conf., Union, WA. 25-27 Sept, 1979. Inst. Forest Resources Contrib. No. 40, College of Forest Resources, University of Washington, Seattle.*
- Terry, T.A., Harrison, R.B., Harrington, C.A., 2001. Fall River long-term site productivity study: objectives and design. *Forestry Research Tech. Note 01-1. Centralia, WA: Weyerhaeuser Company, Western Timberlands Research and Development.* 10 p.
- Teste, F.P., Simard, S.W., Durall, D.M., Guy, R.D., Jones, M.D., Schoonmaker, A.L., 2009. Access to mycorrhizal networks and roots of trees: importance for seedling survival and resource transfer. *Ecology.* 90: 2808–2822.
- Voldseth, R., Palik, B., Elioff, J., 2011. Ten-year results from the Long-term Soil Productivity Study in aspen ecosystems of the northern Great Lakes region. *USDA For. Serv. Northern Research Station, Res. Paper. NRS-17, pp. 20.*
- Van den Driessche, R., and Webber, J. E., 1975. Total and soluble nitrogen in Douglas-fir in relation to plant nitrogen status. *Canadian Journal Forest Resources.* 5:580-585.
- Wagner, R.G., Newton, M., Cole, E.C., Miller, J.H., Shiver, B.D., 2004. The role of herbicides for enhancing forest productivity and conserving land for biodiversity in North America. *Wildlife Soc. Bull.* 32: 1028–1041
- Walker, T.W. and Adams, A.F.R., 1958. Studies on soil matter: Influence of phosphorus content of parent materials on accumulations of carbon, nitrogen, sulfur, and organic phosphorus in grassland soils. *Soil Science.* 85: 307-318.
- Watt, M.S., Clinton, P.W., Whitehead, D., Richardson, B., Mason, E.G., Leckie, A.C., 2003. Aboveground biomass accumulation and nitrogen fixation of broom (*Cytisus scoparius* L.) growing with juvenile *Pinus radiata* on a dryland site. *Forest Ecology and Management.* 2003: 93-104.
- Wang, G.G., and Klinka, K., 1997. White Spruce foliar nutrient concentrations in relation to tree growth and soil nutrient amounts. *Forest Ecology and Management.* 98: 89-99.
- Wink, M., Hartmann, T., Witte, L., Rheinheimer, J., 1982. Interrelationship between quinolizidine alkaloid producing legumes and infesting insects—exploitation of the

alkaloid-containing phloem sap of *Cytisus scoparius* by the broom aphid *Aphis cytisorum*. Zeitschrift Fur Naturforschung C J Biosci 37: 1081–1086

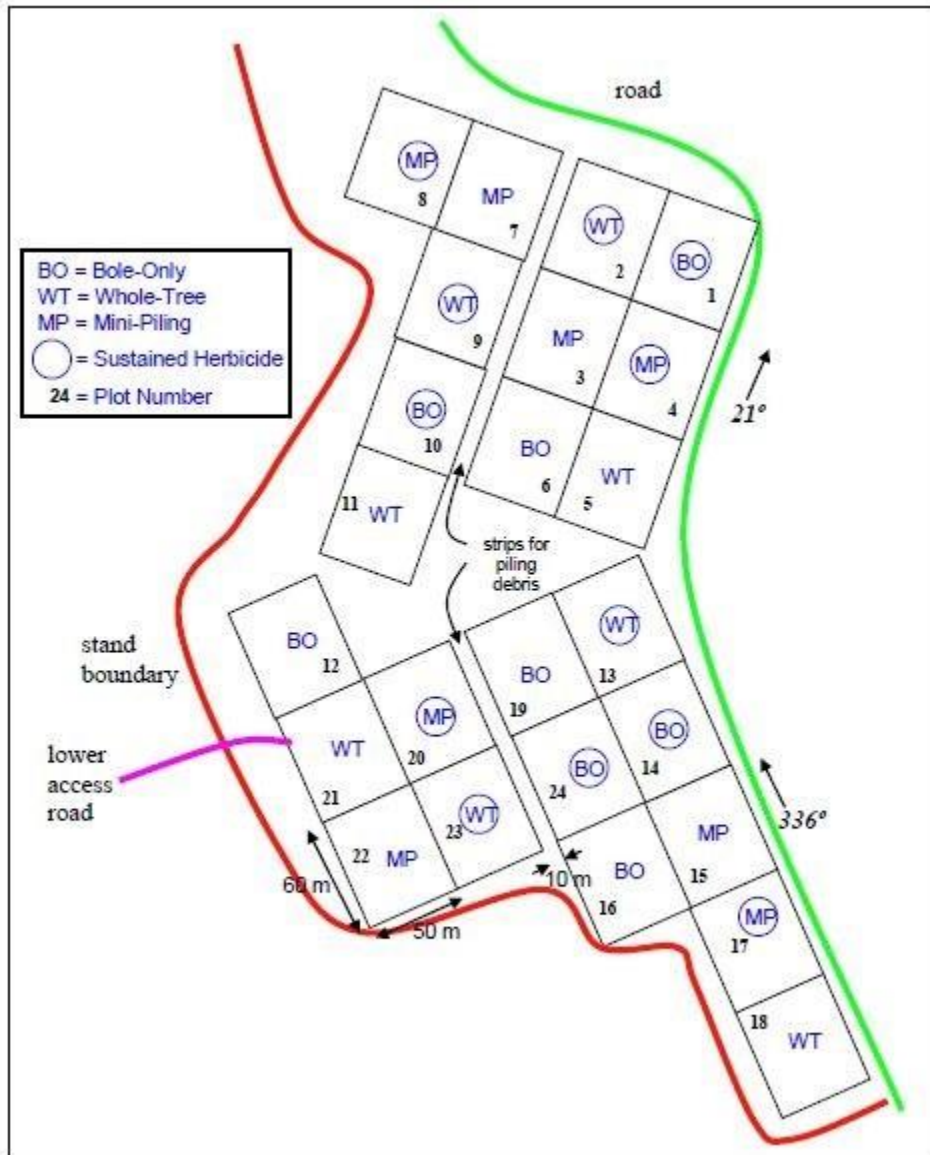
Wink, M., Witte, L., Hartmann, T., Theuring, C., Volz, V., 1983. Accumulation of quinolizidine alkaloids in plants and cell-suspension cultures—genera *Lupinus*, *Cytisus*, *Baptisia*, *Genista*, *Laburnum*, and *Sophora*. Planta Med 48(8): 253–257

Appendix A:



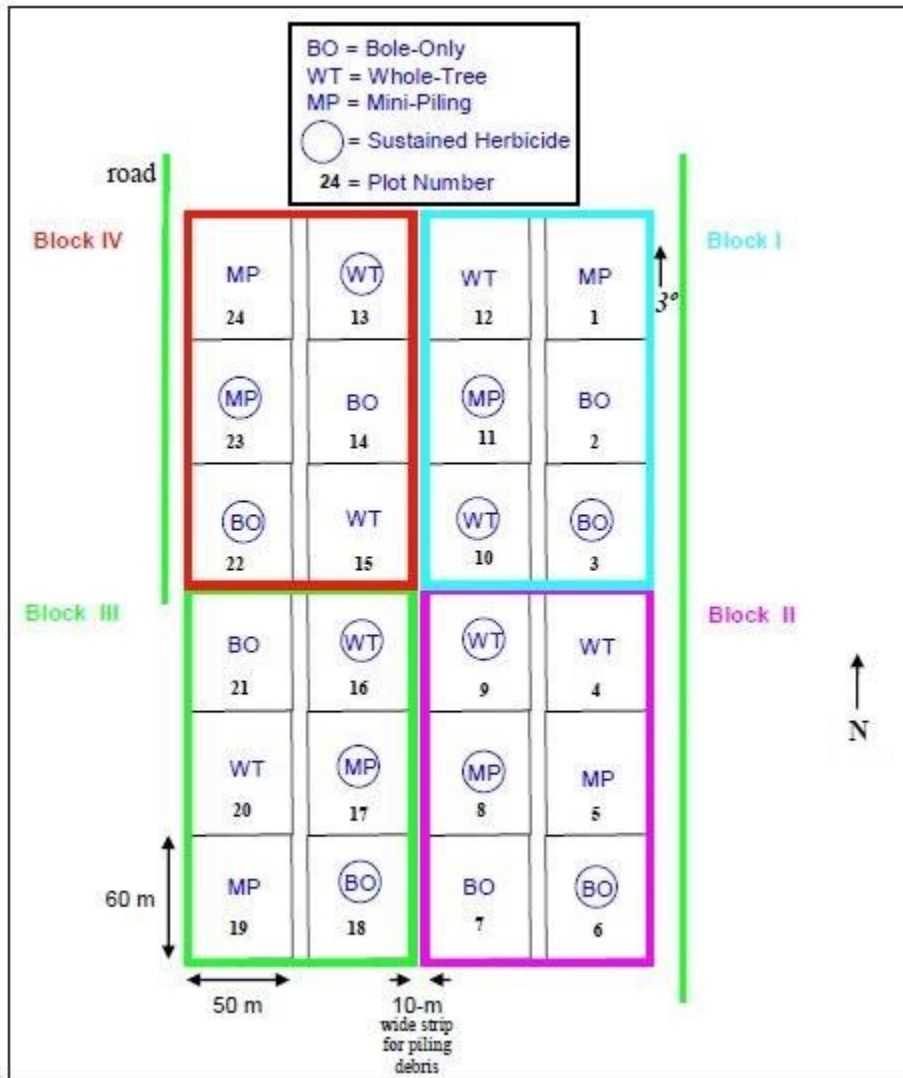
Fall River, WA site layout. Four biomass removal treatments were applied (bole-only (BO), bole-only to 5cm, total tree (WT), and total tree plus) and two weed control treatments (initial (NWC) and annual control (WC)) to 50x60m plots. The tillage, bole-only to 5cm, and total tree plus plots were not used in this study. From Ares et al. (2007).

**Appendix B:**



Molalla, OR site layout. A two by two factorial design was applied, two biomass removal treatments (bole-only (BO), whole tree (WT)) and two weed control treatments (initial (NWC) and annual control (WC)) to 50x60m plots. The minipiling plots were not used in this study. From Meehan (2006).

Appendix C:



Matlock, WA site layout. A two by two factorial design was applied, two biomass removal treatments (bole-only (BO), whole tree (WT)) and two weed control treatments (initial (NWC) and annual control (WC)) to 50x60m plots. The minipiling plots were not used in this study. From Meehan (2006).