Impacts of Post-Thinning Biomass Removal and Soil Amendments on Forest Productivity in Northern Idaho

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Lauren A. Sherman

Major Professor: Mark Coleman, Ph.D.
Committee Members: Deborah Page-Dumroese, Ph.D.; Andrew Nelson, Ph.D.
Department Administrator: Randall Brooks, Ph.D.

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Authorization to Submit Thesis

This thesis of Lauren A. Sherman, submitted for the degree of Master of Science with a Major in Natural Resources and titled "Impacts of Post-Thinning Biomass Removal and Soil Amendments on Forest Productivity in Northern Idaho," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________________ Date: ____________

Mark Coleman, Ph.D.

Committee Members: ______________________________ Date: ____________

Deborah Page-Dumroese, Ph.D.

______________________________ Date: ____________

Andrew Nelson, Ph.D.

Department Administrator: ______________________________ Date: ____________

Randall Brooks, Ph.D.

Abstract

A lack of forest management has led to millions acres of overstocked forests in the northwest United States. Thinning forests increases stand resistance to wildfire, pests, and disease. Traditional forest management leaves thinned trees on site as slash. Forest slash provides stable conditions and supplies nutrients to the soil. Biomass removal from thinning can be used for cellulosic biofuel production. Biomass removal can provide environmental, financial, and ecosystem benefits, though biomass removal may decrease forest productivity and disrupt soil biological properties. Soil amendments can be used to mitigate effects of biomass removal by altering soil properties to increase forest productivity. Biochar is an amendment that adds carbon to the soil and increases water-holding capacity, while fertilizer can improve forest production and replace nutrients removed in biomass. This thesis examines the effect of post-thinning biomass retention levels on forest growth, as well as responses to fertilizer and biochar soil amendments.

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Chapter 1. Literature Review

There is a growing interest in the utilization of biomass for energy production as the global demand to reduce reliance of fossil fuels increases. The Energy Independence and Security Act (2007) requires the United States to replace 36 billion gallons a year of fossil fuels with biofuels. An expanded Renewable Fuel Standard mandates that 16 billion gallons per year come from cellulosic feedstocks by 2022. (Schnepf and Yacobucci, 2015). To meet this demand, forest practices in the United States must adapt.

There is a concern that intensive biomass harvesting will decrease soil quality due to the removal of aboveground nutrients. Many studies have compared the harvest techniques of whole-tree harvesting and bole-only harvesting methods during commercial harvests (Johnson and Todd, 1998; Egnell and Valinger, 2003; Saarsalmi et al., 2010; Kaarakka et al., 2014; Jacobson et al., 2017). Whole-tree harvesting removes the entire felled tree, while bole-only harvesting removes the merchantable stem, leaving branches, crown, leaves, and needles on site. Studies typically find that whole-tree harvesting decreases soil nutrient availability more than stem-only harvest practices (Johnson and Todd, 1998; Saarsalmi et al., 2010) which can decrease subsequent crop productivity (Egnell and Valinger, 2003; Jacobson et al., 2017; Kaarakka et al., 2014). Whole-tree harvesting can lead to warmer and less stable soil temperatures in the summer months than forest soils where bole-only harvesting occurred (Devine and Harrington, 2007). Warmer soils can be advantageous to seedling development. Plants growing in warmer soils in temperate regions have greater root depth potential (Kasper and Bland, 1992). However, warmer soil temperatures may reduce soil moisture (Devine and Harrington, 2007).

The North American Long-Term Soil Productivity Study, an international program started by the USDA Forest Service, examines the long-term consequences of harvesting, soil organic matter removal, and compaction on soil productivity throughout North America. After 10 years, complete removal of surface organic matter lead to significant declines in soil carbon, reduced availability of nitrogen, and a loss of soil carbon and nitrogen, though there were no effects on standing forest biomass (Ponder et al., 2012). In addition, a regional report from this study showed available calcium and potassium were lower in whole-tree harvests than bole-only harvests in the Great Lakes Region (Voldseth et al., 2011). A twenty-year review of this region showed some differences in soil organic matter and soil chemical properties, but responses were site-specific and dependent on soil types (Slesak et al., 2017). While whole-tree harvesting at the commercial level has been shown to impact soil properties and site productivity, the impacts of small-diameter woody biomass between commercial harvests have not been studied as intensively.

The removal of small-diameter woody biomass for biofuel purposes has the potential to provide environmental, financial, and ecosystem benefits. Producing a renewable liquid fuel source can decrease the extraction and use of fossil fuels. Using biomass as a biofuel source provides foresters a secondary crop in between crop rotations, which can help offset management costs. Biomass removal can help protect the commercial timber crop as removing slash may reduce the risk of crop damage from wildfire and disease. Wildfires are common in the Inland Northwest. Biomass removal successfully reduces risk of wildfire, and decreases carbon combustion and emissions when fires do occur (Evans and Finkral, 2009). Biomass removal may also decrease the risk of insect damage. Excessive slash provides ample breeding ground and habitat for insects as it decays, which can increase pest populations and crop damage risk (Schroeder, 2008). However, if too much biomass is removed from the forest floor, insects may breed in and attack the standing trees at a higher rate (Schroeder, 2008).

Forest management often involves pre-commercial thinning as it reduces tree competition for resources such as light, water, and soil nutrients. Thinning forest stands result in increased resource availability for remaining trees, and improves crop tree growth (Brockley, 2005). Thinning has been shown to increase tree macronutrients such as nitrogen and phosphorous accumulations in forest floor (Vesterdal et al., 1995). Thinning overstocked stands in the Inland Northwest was shown to increase available nitrogen in soil, but decrease foliar nitrogen (Chase et al., 2016). Increased light availability in thinned forests can raise soil temperatures, which can increase soil microbial biomass and activity (Thibodeau et al., 2000). Thinning efforts have been shown to increase soil moisture in spring and summer months (Chase et al., 2016). The increased water-availability may improve growth during dry years compared to unthinned stands.

Because forest management plans may include at least one pre-commercial thinning, these small-diameter trees are a potential resource as a biofuel source. Traditional forest practices leave felled trees on the forest floor as slash. The ideal amount of slash required for optimal site quality is unknown, and is likely regionally specific. As slash decomposes it adds organic matter to the soil and nutrients that were in aboveground biomass remain in ecosystem nutrient pools as microbes mineralize nutrients to become plant available (Hazlett et al., 2007). The majority of nutrients in a forest ecosystem are stored in belowground soil nutrient pools (Johnson and Todd, 1998), so woody biomass removal should result in only a small percentage of nutrient loss from the forest ecosystem. The impacts of nutrients removal from whole-tree harvesting are site specific and depend on factors including forest type, harvest technique, soil type, and parent material (Slesak et al., 2017). These factors vary widely between locations, so it is difficult to make generalizations that can be applied in every forest type, however biomass removal may have a greater impact on sites where nutrient capital is lower as compared to sites with abundant nutrients.

Nitrogen is considered to be the limiting nutrient in western forest soils (Edmonds et al., 1989; Coleman et al., 2014) so maintaining adequate nitrogen levels is important when removing biomass from Inland Northwest forests. While some studies found whole-tree commercial harvests reduced nutrient availability, (Johnson and Todd, 1998; Saarsalmi et al., 2010), many studies showed little or no impact on nitrogen levels or site productivity (Voldseth et al., 2011; Slesak et al., 2017). It is reasonable to assume that a less intensive nutrient harvest from biomass removal thinning operations will have a smaller or negligible effect on soil properties and forest productivity. There is concern that biomass removal from pre-commercial thinnings in forests where whole-tree harvesting is practiced will have cumulative impacts of nutrient removal over successive crop rotations (Gollany et al., 2015). Fertilizer has potential to lessen hypothetical negative effects of removing biomass and nutrients from forests. The addition of fertilizer is a common forestry practice and can provide the necessary nutrients for forest growth to increase stand production. A Scandinavian study found that whole tree harvesting with nitrogen fertilizer amendments had equal tree volume production to traditional stem only harvesting without fertilization after 10 years (Helmisaari et al., 2011). Further, a study conducted in the Pacific Northwest suggests that nitrogen fertilization of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) plantations can increase site productivity for 15-22 years in low quality sites (Footen et al., 2009), however these benefits may not be visible initially. A 10-year study looking at whole-tree harvesting effects on Sitka spruce (*Picea sitchensis*) stands with fertilizer applications in upland Britain found that fertilizer increased tree growth in whole-tree harvested stands after 5-6 years (Mason et al., 2012). Nitrogen fertilization impacts soil processes. It has been found to decrease forest soil respiration (Haynes and Gower, 1995) and decrease exoenzyme activity (Schimel and Weintraub, 2003).

Biochar is another soil amendment that may also mitigate the effects of biomass removal with the additional benefit of reducing greenhouse gas emissions. Biochar is a fine-grained, highly porous charcoal produced in the absence of oxygen.

The carbon in biochar is resistant to decomposition and is stable for over 1000 years when added as a soil amendment (Amonette et al., 2009), so the benefits are long-term. It has been proposed that the addition of biochar to 10% of crops worldwide could sequester 29 billon tons of CO_2 (Lehmann, 2007). Since biochar is a byproduct of cellulous biofuel production, it can be returned to the feedstock's harvest site, minimizing carbon and nutrient loss. New technologies of portable pyrolosis units will increase the efficiency of converting biomass to liquid fuel as the biochar and biofuel can be produced on-site (McElligott et al., 2011).

In addition to adding carbon to the soil, the addition of the highly porous structure of biochar can increases water-holding capacity, adsorption, and nutrient cycling (Laird et al., 2010), though biochar studies show variable effects. It has been shown to decrease CO_2 production in soils (Sohi et al., 2010) though one study found some biochars to increased CO_2 production in forest nursery soils (Spokas and Reicosky, 2009), and another study in the Inland Northwest found biochar to have a non-effect on soil respiration (Sarauer, 2017). Biochar has highly oxidized carbon functional groups that can contribute to increased nutrient cycling and higher cation exchange capacity (Liang et al., 2006). In one three-year study in China, cation exchange capacity was increased by 24.5 % compared to the control soil (Chen et al., 2011). Biochar also affects microbial diversity, abundance, and activity rates. It has been shown to increase microbial biomass (Jin, 2010), and stabilize or increase exoenzyme activity for certain enzymes, and to have no effect on others (Elzobair et al., 2016; Lehmann et al., 2011). These effects may be due to biochar's effect on soil nutrient content, water retention, and pH, which influence microbial communities. The potential of increased nutrient availability to the soil may mitigate nutrient loss from biomass removal.

Conclusion

There is great potential for cellulosic biofuel systems in the forested western United States. Most biomass removal studies examine the impacts of biomass removal by comparing whole-tree harvesting methods to bole-only commercial harvests and show varying results of the impacts of nutrient removal on soil and forest productivity. Site responses to biomass removal tend to be site specific. Thinning is already a common forestry practice, and increases tree growth. Small diameter biomass removal from thinning operations is less intensive than commercial harvesting operations, and is a potential solution to increasing biofuel feedstocks. The impacts of biomass removal will be dependent on site-characteristics, so regional studies need to be completed to aide future forest management practices. Soil amendments such as fertilizer and biochar may mitigate potential reduction of site productivity from biomass removal.

Literature Cited

Amonette, J., Amonette, J., Joseph, S., 2009. Biochar for Environmental Management: Science and Technology. Earthscan, London, UK.

Barg, A.K., Edmonds, R.L., 1999. Influence of partial cutting on site microclimate, soil nitrogen dynamics, and microbial biomass in Douglas-fir stands in western Washington. Can. J. For. Res. 29, 705–713.

Brockley, R.P., 2005. Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. Can. J. For. Res. 35, 1952–1964.

Chase, C.W., Kimsey, M.J., Shaw, T.M., Coleman, M.D., 2016. The response of light, water, and nutrient availability to pre-commercial thinning in dry inland Douglas-fir forests. For. Ecol. Manage. 363, 98–109.

Chen, H.-X., Du, Z.-L., Guo, W., Zhang, Q.-Z., 2011. Effects of biochar amendment on cropland soil bulk density, cation exchange capacity, and particulate organic matter content in the North China Plain. Ying yong sheng tai xue bao = J. Appl. Ecol. 22, 2930–4.

Coleman, M. D., Shaw, T. M., Kimsey, M. J., & Moore, J. A. (2014). Nutrition of Douglas-fir in the Inland Northwest. *Soil Science Society of America Journal*, *78*(S1), S11-S22.

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.

Edmonds, R. L.; Binkley, D.; Feller, M. C.; Sollins, P.; Abee, A.; Myrold, D. D. (1989). Nutrient cycling: effects on productivity of northwest forests. In: Perry, D. A.; [and others], eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 17-35.

Egnell, G., Valinger, E., 2003. Survival, growth, and growth allocation of planted Scots pine trees after different levels of biomass removal in clear-felling. For. Ecol. Manage. 177, 65–74.

Elzobair, K.A., Stromberger, M.E., Ippolito, J.A., 2016. Stabilizing effect of biochar on soil extracellular enzymes after a denaturing stress. Chemosphere 142, 114–119.

Evans, A.M., Finkral, A.J., 2009. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. GCB Bioenergy 1, 211–219.

Footen, P.W., Harrison, R.B., Strahm, B.D., 2009. Long-term effects of nitrogen fertilization on the productivity of subsequent stands of Douglas-fir in the Pacific Northwest. For. Ecol. Manage. 258, 2194–2198.

Gollany, H. T., Titus, B. D., Scott, D. A., Asbjornsen, H., Resh, S. C., Chimner, R. A., ... & Hilbert, J. (2015). Biogeochemical research priorities for sustainable biofuel and bioenergy feedstock production in the Americas. *Environmental management*, *56*(6), 1330-1355.

Haynes, B.E., Gower, S.T., 1995. Belowground carbon allocation in unfertilized and fertilized red pine plantations in northern Wisconsin. Tree Physiol. 15, 317–25.

Hazlett, P.W., Gordon, A.M., Voroney, R.P., Sibley, P.K., 2007. Impact of harvesting and logging slash on nitrogen and carbon dynamics in soils from upland spruce forests in northeastern Ontario. Soil Biol. Biochem. 39, 43–57.

Helmisaari, H.-S., Hanssen, K.H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., Tveite, B., 2011. Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. For. Ecol. Manage. 261, 1919–1927.

Jacobson, S., Högbom, L., Ring, E., Nohrstedt, H.-Ö., 2017. The distribution of logging residues and its impact on seedling establishment and early plant growth in two Norway spruce stands. Scand. J. For. Res. 32, 134–141.

Jin, H., 2010. Characterization of microbial life colonizing biochar and biochar-amended soils. Cornell University.

Johnson, D.W., Todd, D.E., 1998. Harvesting Effects on Long-Term Changes in Nutrient Pools of Mixed Oak Forest. Soil Sci. Soc. Am. J. 62, 1725.

Kaarakka, L., Tamminen, P., Saarsalmi, A., Kukkola, M., Helmisaari, H.-S., Burton, A.J., 2014. Effects of repeated whole-tree harvesting on soil properties and tree growth in a Norway spruce (Picea abies (L.) Karst.) stand. For. Ecol. Manage. 313, 180–187.

Kaspar, T. C., & Bland, W. L. (1992). Soil temperature and root growth. *Soil Science*, *154*(4), 290-299.

Laird, D., Fleming, P., Wang, B., Horton, R., Karlen, D., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158, 436–442.

Lehmann, J., 2007. Bio-energy in the black. Front. Ecol. Environ. 5, 381–387.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – A review. Soil Biol. Biochem. 43, 1812–1836.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizão, F.J., Petersen, J., Neves, E.G., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70, 1719–1730.

Mason, W.L., McKay, H.M., Weatherall, A., Connolly, T., Harrison, A.J., 2012. The effects of whole-tree harvesting on three sites in upland Britain on the growth of Sitka spruce over ten years. Forestry 85, 111–123.

McElligott, K., Page-Dumroese, D., Coleman, M., 2011. Bioenergy production systems and biochar application in forests: potential for renewable energy, soil enhancement, and carbon sequestration. Res. Note RMRS-RN-46. Fort Collins, CO Res. Note, 14.

Ponder, F., Fleming, R.L., Berch, S., Busse, M.D., Elioff, J.D., Hazlett, P.W., Kabzems, R.D., Kranabetter, J.M., 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., Ludovici, K.H., Mckenney, D.W., Mossa, D.S., Sanborn, 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.

Saarsalmi, A., Tamminen, P., Kukkola, M., Hautajärvi, R., 2010. Whole-tree harvesting at clear-felling: Impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. Scand. J. For. Res. 25, 148–156.

Sarauer, Jessica. University of Idaho. Personal communication. April 2017.

Schimel, J.P., Weintraub, M.N., 2003. The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: A theoretical model. Soil Biol. Biochem. 35, 549–563.

Schnepf, R., Yacobucci, B.D., 2015. Renewable Fuel Standard (Rfs): Overview and Issues - Scholar's Choice Edition. Scholar's Choice.

Schroeder, L.M., 2008. Insect pests and forest biomass for energy. Springer Netherlands, pp. 109–128.

Slesak, R.A., Palik, B.J., D 'amato, A.W., Kurth, V.J., 2017. Changes in soil physical and chemical properties following organic matter removal and compaction: 20-year response of the aspen Lake-States Long Term Soil Productivity installations. For. Ecol. Manage. 392, 68–77.

Sohi, S.P., Krull, E., Lopez-Capel, } E, Bol, R., 2010. A Review of Biochar and Its Use and Function in Soil. Adv. Agron. 105, 47–82.

Spokas, K.A., Reicosky, D.C., 2009. Impacts of sixteen different biochars on soil greenhouse gas production. Ann. Environ. Sci. 3, 179–193.

Thibodeau, L., Raymond, P., Camiré, C., Munson, A.D., 2000. Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. Can. J. For. Res. 30(2), 229–238.

Vesterdal, L., Dalsgaard, M., Felby, C., Raulund-Rasmussen, K., Jørgensen, B.B., 1995. Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorus in the forest floor of Norway spruce stands. For. Ecol. Manage. 77, 1–10.

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.

Chapter 2: Impacts of Post-Thinning Biomass Removal on Forest Growth

Abstract

The utilization of woody biomass for biofuel can help meet the growing need to increase renewable energy production in this country. However, there is a concern that removing biomass from forests for biofuel production may deplete nutrients from the forest system. Commercial harvest operations that remove whole-trees from forests have been shown to deplete soil nutrients pools more than bole-only harvest techniques that leave residual biomass onsite. Pre-commercial thinning in the Inland Northwest is a common forestry practice as these forests are often overstocked. Removing small diameter biomass from pre-commercial thinning operations can provide a feedstock for biofuel energy systems. This study examined the impacts of four biomass treatments (full biomass removal, full biomass retention, double biomass retention, and unthinned control) and four soil amendment treatments on basal area and total stem volume growth. The objectives of this study aimed to develop short-term indicators to assess the impact of small-diameter woody biomass removal on forest productivity growth, to establish ideal biomass retention levels for the region, and to evaluate the ability of soil amendments to compensate for potential adverse effects from biomass removal. Biomass removal had no affect on plot or crop tree growth compared to normal biomass retention ($P<0.10$). Normal biomass retention was found to increase growth compared to larger amounts of biomass retention ($P<0.10$). Biomass removal and soil amendments did not impact soil moisture or temperature levels. Fertilizer increased basal area growth and total volume growth while biochar had no affect on growth. Initial findings suggest removing small-diameter biomass for biofuel feedstocks is feasible in the Inland Northwest.

Introduction

There has been a global demand to reduce our reliance on fossil fuels and a growing interest in the utilization of biomass for energy production. The Energy Independence and Security Act (2007) requires the United States to replace 36 billion gallons a year of fossil fuels with biofuels and 16 billion gallons per year will need to come from cellulosic feedstocks (Schnepf and Yacobucci, 2015). Small-diameter woody mass from forest residues and slash from thinning efforts can be a secondary product of forest operations, and can be used for bioenergy. There are many benefits to using forest biomass for biofuel, however little is known of the impacts removal operations will have on soil properties and long-term forest productivity.

Most studies that evaluate the impacts of biomass removal examine commercial harvest methods, comparing whole-tree harvesting to conventional bole-only harvests. Fewer studies have been conducted to examine the removal of small-diameter woody biomass from thinning operations. While some studies found whole-tree commercial harvests reduced nutrient availability, (Johnson and Todd, 1998; Saarsalmi et al., 2010), many studies showed little or no impact on nitrogen levels or site productivity (Voldseth et al., 2011; Slesak et al., 2017). It is possible that small-diameter biomass removal will have less impact on site conditions than whole-tree harvests as smaller quantities of biomass will be removed. Pre-commercial thinning is a common forest management practice that reduces tree competition for resources such as light, water, and soil nutrients, which results in higher resource availability (Brockley, 2005).

While conventional forest management leaves forest residue from thinning operations on the forest floor, the alternative of removing this biomass for biofuel purposes shows promising environmental, financial, and ecosystem benefits. Increasing the practice of utilizing woody biomass for bioenergy would increase bioenergy feedstocks and decrease the use of fossil fuels (Perlack et al., 2011). Removing biomass from forests and using it as a biofuel source provides foresters a secondary crop and can reduce the risk of residual tree damage from wildfire and disease, as slash can fuel fires (Evans and Finkral, 2009) and decaying biomass can provide habitat for insects and fungi that could damage the crop trees (Schroeder, 2008).

The impacts of small-diameter biomass removal from a forest site are unknown. The impacts of nutrients removal from whole-tree harvesting are site specific and depend on factors including site nutrient capital, soil type, parent material, climate and moisture regime, forestry type, and harvest technique (Slesak et al., 2017). While it is difficult to make generalizations that can be applied in every forest type, biomass harvesting from nutrient limited sites will have a proportionally greater impact than harvesting from nutrient abundant sites (Thiffault et al., 2011).

The addition of fertilizer is already a common forestry practice and can provide the necessary nutrients for forest growth, most notably nitrogen, so the use of fertilizer also has potential to lessen the negative effects of removing biomass from forests. Nitrogen is considered to be the main limiting nutrient in western forest soils (Edmonds et al., 1989; Coleman et al., 2014) and biomass removal can deplete nitrogen in Inland Northwest soils. Fertilizing forest stands has the potential to increase stand production (Footen et al., 2009; Helmisaari et al. 2011). Whole-tree harvesting with nitrogen fertilizer amendments have shown equal tree volume production to traditional stem only harvesting without fertilization after 10 years (Helmisaari et al. 2011). A Pacific Northwest study found nitrogen fertilization of douglas-fir plantations increased site productivity for 15-22 years in low quality sites (Footen et al., 2009). But growth benefits of fertilization may not be initially visible. A 10-year study examining whole-tree harvesting effects on Sitka spruce stands with fertilizer applications in upland Britain found that fertilizer increased tree growth in whole-tree harvested stands after 5-6 years (Mason et al., 2012).

Biochar may also mitigate the effects of biomass removal as it is a fine-grained, highly porous charcoal that has high water-holding capacity, retains nutrients, and adds carbon to the soil (Laird, 2008). It can potentially lessen soil carbon loss and increase the soil nutrient cycling and water availability for crops. Biochar is thought to improve soil quality and decrease greenhouse gas emissions (Laird, 2008). The carbon in biochar is resistant to decomposition when added as a soil amendment (Amonette et al., 2009), so the benefits are long-term. The porous quality of biochar increases water retention capacity and soil cation exchange capacity, returning more nutrients to the soil and has been shown to increase nutrient availability for plants and increase microbe diversity (Lehmann et al., 2011).

In order to understand the impacts of small-diameter biomass removal on site productivity, there is a need for regional, site-specific studies. We conducted a study that will add to the knowledge of the impacts of biomass removal on forests in the Inland Northwest. The goal of the study is to increase biofuel feedstocks without compromising forest production and soil quality. The objectives of this study are to to develop short-term indicators of the impact of small-diameter woody biomass removal on forest productivity growth, to establish ideal biomass retention levels for the region, and to evaluate the ability of soil amendments to compensate for potential adverse effects from biomass removal such as decreased growth. I hypothesized that forest growth would be marginally better in plots that retained biomass compared to full biomass removal. I expected any difference in growth in sites with biomass removal would be mitigated by fertilizer and biochar amendments, as fertilizer would replace nitrogen lost, and biochar would increase water availability during dry summers.

Methods

Site Characteristics

Two northern Idaho study locations were chosen in different forest types (Figure 2.1). Both sites are regenerated mixed-conifer forests and have predominately silt-loam soils that contain volcanic ash. Sites had different parent material, regeneration methods, and species composition.

The “Pitwood” site is a mixed conifer forest of mostly douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco), grand fir (*Abies grandis*), and western red cedar (*Thuja plicata*) on land owned by Potlatch Corporation and adjacent to the St. Joe River region of the Idaho Panhandle National Forest. Its elevation ranges from approximately 990 to 1060 meters above sea level. The site area has a slope of 20-60% with a northern aspect. The soil parent material is metasedimentary bedrock. The soil order of this location is classified as an Andisol. Andisol soils occur on 621,000 ha of forested land in the western United States (McDaniel and Hipple, 2010) and are defined by its significant ash content. It has been managed as a commercial forest. The last harvest activities before this study occurred in the early 1990’s when douglas-fir was planted in the early 1990’s, though natural regeneration occurred as well. Pre-treatment stand characteristic measurements occurred in 2012 (Table 2.1).

The second site “UIEF” is a naturally regenerated mixed confer stand of ponderosa pine (*Pinus ponderosa*), douglas-fir, grand fir, lodgepole pine (*Pinus contorta*), and western larch (*Larix occidentalis*) at the University of Idaho Experimental Forest near Princeton, ID. This forest is relatively flat with a 0 to 15 % slope and south-facing aspect. The site elevation ranges from 830 to 890 meters above sea level. UIEF has a granite bedrock. The most abundant soil series present are the Santa series and the Helmer series, which both contain significant quantities of ash. The forest is used for grazing cattle, recreation, and research, and is managed for commercial forestry. The last major management activity in the study stands occurred in the late 1980s, when the stands were harvested and seed trees of mostly ponderosa pine were retained for forest regeneration. Seed trees were harvested in 2012 using bole-only harvest, leaving the slash in the stands. Pre-treatment stand characteristic measurements occurred after the seed tree harvest in 2012 (Table 2.1).

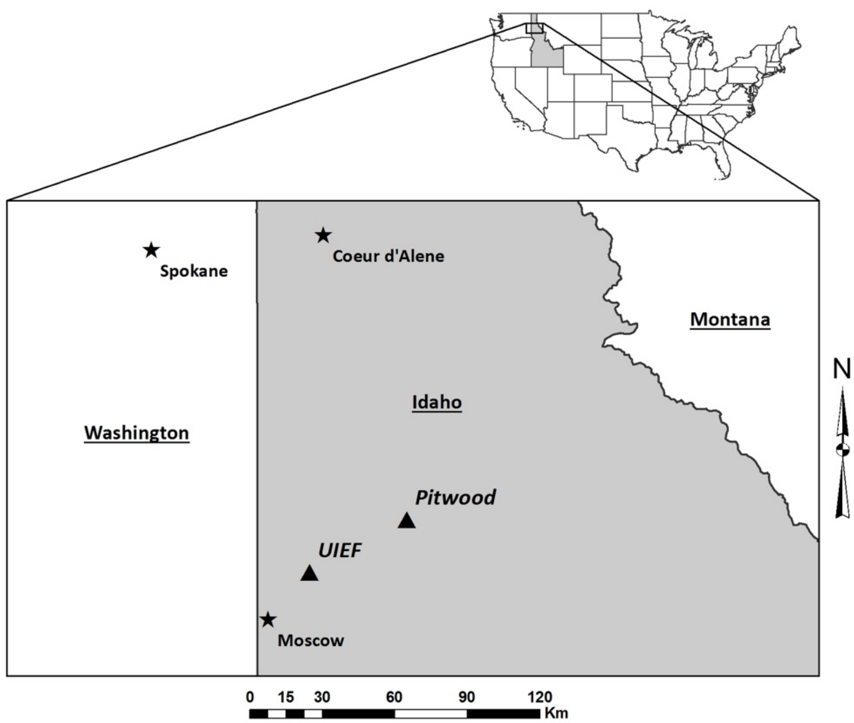

Figure 2.1. *Site locations. Triangles indicate Potlatch Pitwood site and University of Idaho Experimental Forest site (UIEF).*

Table 2.1. *Pretreatment stand characteristics.*

	TPH (trees ha^{-1})	QMD (cm)	BA ($m^2\ h^{-1}$)	SDI (trees ha^{-1})
UIEF	1105	11	11	314
Pitwood	5054	8	24	784

Biomass Treatments

Two replicate stands approximately 6 to 10 ha in size were selected within each location for a total of four project stands. Pitwood stands are referred to as north and south stand, and UIEF stands are referred to as lower and upper stand. Each stand was divided into four biomass treatment whole-plots (Figure 2.2). In each stand, one whole-plot was left unthinned as a control. The remaining three whole-plots were thinned in spring 2013. The stands were thinned from below, removing the smaller trees and trees of less desirable species. Douglas-fir was favored at Pitwood with mostly western red cedar being removed. Ponderosa pine and douglas-fir were the most abundant species left standing at UIEF after the thinning. Thinned treatments were thinned to a relative density of 40%, with approximately 200 trees per hectare. The three thinned whole-plots were distinguished by their three biomass retention levels: 0x, 1x and 2x. In the 0x whole-plot treatment, all thinning residue was removed to mimic a biomass energy harvest. In the 1x whole-plot treatment all thinning residue was retained on site as slash. This treatment represents a conventional thinning treatment. The 2x whole-plot treatment retained full thinning residue, plus the addition of the biomass removed from the 0x treatments within the same stand. These treatments provided the opportunity to compare differences between different biomass retention levels with the goal of determining favorable amounts of biomass retention for the sites.

Full Biomass Removal (0x)		**Full Biomass Retention (1x)**	
Fertilizer (F)	Biochar (B)	Fertilizer (F)	Biochar (B)
Fertilizer + Biochar (FB)	Control (C)	Fertilizer + Biochar (FB)	Control (C)
Double Biomass Retention (2x)		**Unthinned Control**	
Fertilizer (F)	Biochar (B)	Fertilizer (F)	Biochar (B)
Fertilizer + Biochar (FB)	Control (C)	Fertilizer + Biochar (FB)	Control (C)

Figure 2.2. *A representation of the biomass treatment blocks within a stand (colored blocks), and the soil amendment split-plot treatments within each block. The study included two replicates of the block design at each site, for a total of 64 split-plots.*

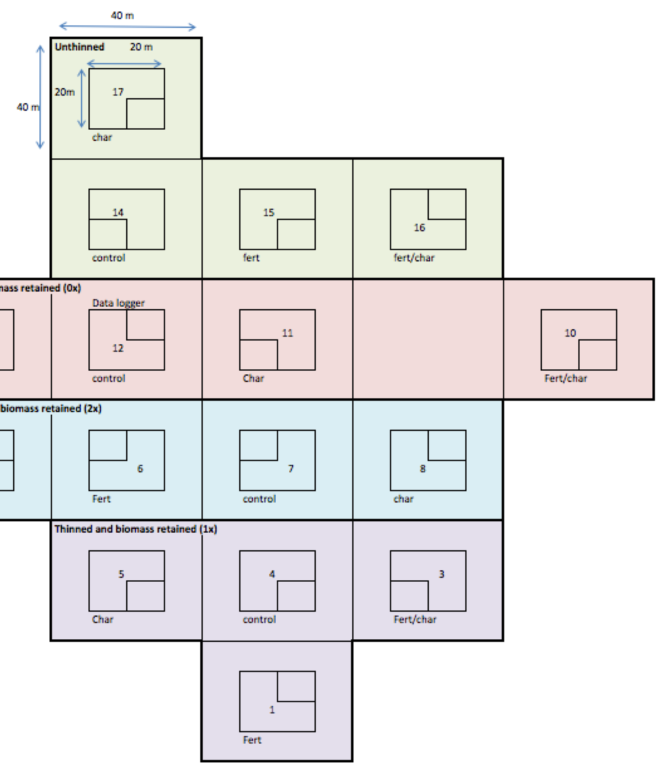

Figure 2.3. *The lower stand at UIEF displaying biomass treatment blocks (colored blocks), and soil amendment split-plot treatments within each block. The squared inside each split-plot represent the 20x20 meter measurement plot, while the corner squares represent the random corner starting location for field measurements. The layout of the other stands is in the appendix.*

Soil Amendments

Within each whole-plot biomass treatment in each stand, four 40x40 meter amendment treatment split-plots were randomly assigned within the treatment block (Figure 2.3) for a project total of 64 split-plots. A 20x20 meter measurement plot was assigned in the middle of each plot, leaving a 10-meter treatment buffer between each plot. The amendment treatments were fertilizer (F), biochar (B), fertilizer and biochar (FB), and a control with no amendments (C). Biochar was added in the amount of 2.5 Mg/ha to each B and FB plots. It was sprayed on UIEF plots in the upper stand in October 2013, and the lower stand in April 2014. It was applied manually at Pitwood in May 2014. Nitrogen fertilizer (urea) was applied to the F and FB plots in November 2013 at UIEF and May 2014 at Pitwood at approximately 630 kg/ha.

There are two treatments that serve as a control in this study, unthinned whole-plot treatment will be referred to as the unthinned controls, and the split-plots without soil amendments will be referred to as unamended control plots.

Biomass Retention Estimates

Three methods were used to estimate the amount of woody debris deposited in each biomass treatment plot. Downed woody debris surveys were completed for the first two methods using a modification of Brown's protocol (Brown, 1978). Post-treatment surveys were completed for each split-plot in the 1x and 2x whole-plots in 2015 (Method 1) and 2016 (Method 2). Method 1 estimated downed downed woody debris using two transects from two random corners of each plot. Method 2 estimated downed woody debris along three transects at random angles from the plot center.

Method 3 estimated biomass retention in the 1x and 2x plots from the pre-treatment standing biomass at each location in tons per hectare, and the post-thinned tons per hectare at each thinned whole-plot. Total aboveground standing biomass was calculated from the tree diameters using an allometric equation specific to each species group (Jenkins et al. 2003) and converted to metric tons per hectare. To calculate the downed biomass treatments, the post-treatment standing biomass was subtracted from the pre-thin treatment aboveground standing biomass in the thinned biomass treatments. This represented the amount cut from each plot in tons per hectare. The amount cut in the 1x plots was assumed to be the amount deposited as downed woody debris. The 0x plots were assumed to have 0 tons per hectare of biomass added, as the amount cut was moved to the 2x plots. The 2x treatment was calculated by adding the plot-average biomass cut in each 0x stand to the amount cut in each 2x plot in the corresponding stand.

Tree growth

A sample of tree heights and diameters were measured at both locations in 2012 prior to thinning. All project trees were measured in the fall of 2013. Diameter at breast height (DBH) for all trees in plots at UIEF and in all thinned plots at Pitwood were measured with a d-tape, identified to species, and tagged with a unique tree ID. In the unthinned plots at Pitwood, trees with a DBH of five inches or larger were measured and identified to species, and tagged an ID. A 5 by 5-meter subplot was randomly selected in each unthinned plot where trees with a diameter of one inch or larger were trees were measured and tagged. The subplot measurements were expanded to estimate the full biomass measurements per hectare. Trees diameters were measured annually each fall from 2013 through fall 2016. Tree heights were measured annually at UIEF with TruPulse (Laser

Technology Inc, Centenial, CO, USA) rangefinder lasers. A sample of tree heights were taken each year at Pitwood. Missing tree heights were estimated using allometric equations specific to tree species (Wykoff et al., 1982).

The six largest live trees in each subplot were defined as crop trees in 2016. Crop trees were used to calculate crop tree growth in each of the previous years. Tree growth was calculated at the plot level and crop tree as basal area growth (m^2/ha) for each of the 64 plots each year from 2013 to 2016. Plot and crop tree total stem volume was calculated from tree diameters and heights using species specific allometric equations (Browne, 1962). Tree growth response to downed woody debris loads was calculated using a quadratic equation $y = x + x^2 + error$, where y is basal area growth and x is downed woody debris in tons per hectare.

Soil Moisture and Temperature

Soil moisture and soil temperature were taken at 10 cm with a soil moisture probe and a soil temperature probe in three random locations in each split-plot every non-winter season from spring 2014 through fall 2016. Additionally, two or more Em5b data loggers (Decagon Devices, Pullman, WA) were installed in biomass treatment blocks in plots with biochar amendments and without. Moisture and temperature readings were recorded throughout each day at 10 cm.

Statistical Analysis

An Analysis of Covariance was performed for both the plot level and crop tree basal area growth and total stem volume growth as the response variables. Each growth year increment and the three-year periodic annual increment (PAI) basal area growth were analyzed separately as response variables. PAI basal area growth and volume growth was defined as the 2013 to 2016 growth divided by three for an average annual growth rate. Initial basal area and volume as measured in 2013 were used as covariates using the "aov" function in the "stats" package in R. Each model included three factors with varying levels including location (n=2), biomass retention/thinning treatment (n=4), and soil amendment (n=4), as well as interactions between factors. If interactions were not significant they were eliminated from the model. A mixed-effects linear model with a random factor of split-plot within whole-plot within stand was completed using the "lme" function in the "nlme" package to evaluate differences within factors and had comparable results of significance to the ANCOVA. Adjusted means were calculated using the "lsmeans" package in R.

A regression analysis was used to calculate growth response to downed woody debris slash loads. This was completed using the "lm" function in the "stats" package. Means were adjusted using the "lsmeans" package.

Tukey's 'Honest Significant Difference' post-hoc test was used to test each pairwise comparisons between biomass retention/thinning treatments and soil amendment treatments using the "TukeyHSD" function in the "stats" package. Differences within factors were assumed to be significant at $\alpha = 0.1$.

Seasonal soil moisture and soil temperature differences between whole-plot biomass treatments and split-plot soil amendment treatments were analyzed using an Analysis of Variance using the "aov" function in the "stats" package with moisture or temperature as the response variable and location (n=2), biomass treatment (n = 4), soil amendment treatment (n=4), and season (n = 3) as factors, as well as interactions. Statistical analysis was computed using R Studio (R Core Team, 2015).

Results

Downed woody debris estimates

The results from the two downed woody debris survey methods differed form each other, more strongly at UIEF (Table 2.2). Both surveys varied strongly from Method 3, which were estimates calculated from allometric equations based on the pretreatment data (Table 2.2). Method 3 was used to calculate the quadratic growth relationship between downed woody debris and basal area growth (Appendix A). The regression results were not significant at $\alpha = 0.1$.

Table 2.2. *Downed woody debris survey averages and estimations of metric tons per hectare per treatment. Method one was calculated from two line transects from plot corners. Method 2 was calculated using three transects from plot center. Method 3 used estimations from estimated the difference in pretreatment standing tons per hectare of stands and the post-treatment standing tons per hectare within treatments.*

	Pitwood		UIEF	
	1x	**2x**	**1x**	**2x**
Method 1				
DWD (t ha^{-1})	57.12	57.66	50.91	44.59
Method 2				
DWD (t ha^{-1})	58.26	45.06	20.20	31.32
Method 3				
DWD (t ha^{-1})	267.32	567.71	32.82	73.89

Growth response

Basal area growth and volume growth responded to locations, biomass treatments and soil amendments at both the plot level (Table 2.3 and Table 2.5) and crop tree level (Table 2.4 and Table 2.6). There were no interactions between soil amendment treatment and biomass treatments. Biomass treatments and soil amendments did not affect soil moisture or temperature. We will first examine growth response to treatments, followed by the soil response to treatments.

Table 2.3. *Plot level ANCOVA F-statistic and p-value for basal area growth in the first three years of growth after thinning in 2013. Variables include site location, biomass treatment, and soil amendment. Initial basal area (basal area in 2013) was used as a covariate. Periodic annual increment (PAI) growth the growth from 2013 – 2016 divided by three years. Asterisk (*) indicates significance within factor at α = 0.05, bold text indicates significance within factor at α = 0.1.*

	1st year growth (m^2 ha^{-1} yr^{-1})		2nd year growth (m^2 ha^{-1} yr^{-1})		3rd year growth (m^2 ha^{-1} yr^{-1})		PAI growth (m^2 ha^{-1} yr^{-1})	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Location (L)	50.46	**0.00***	40.37	**0.00***	40.72	**0.00***	81.73	**0.00***
Biomass (B)	0.92	0.44	3.17	**0.03***	2.95	**0.04***	4.04	**0.01***
Amendment (A)	1.32	0.28	1.93	0.13	2.45	**0.07**	3.19	**0.03***
Initial BA (I)	77.38	**0.00***	39.19	**0.00***	0.82	0.37	32.67	**0.00***
I x L	7.10	**0.01***			5.18	**0.03***	5.07	**0.03***

Table 2.4. *Crop tree ANCOVA F-statistic and p-value for basal area growth in the first three years of growth after thinning in 2013. Variables include site location, biomass treatment, and soil amendment. Initial basal area (basal area in 2013) was used as a covariate. Periodic annual increment (PAI) growth the growth from 2013 – 2016 divided by three years. Asterisk (*) indicates significance within factor at α = 0.05, bold text indicates significance within factor at α = 0.1.*

	1st year growth (m^2 ha^{-1} yr^{-1})		2nd year growth (m^2 ha^{-1} yr^{-1})		3rd year growth (m^2 ha^{-1} yr^{-1})		PAI growth (m^2 ha^{-1} yr^{-1})	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Location (L)	50.51	**0.00***	41.57	**0.00***	13.88	**0.00***	42.37	**0.00***
Biomass (B)	3.15	**0.03***	5.79	**0.00***	5.03	**0.00***	6.11	**0.00***
Amendment (A)	1.20	0.32	3.53	**0.02***	4.37	**0.01***	3.58	**0.02***
Initial BA (I)	10.92	**0.00***	21.89	**0.00***	4.01	**0.05**	14.11	**0.00***

Table 2.5. *Plot level ANCOVA F-statistic and p-value for total stem volume growth in the first three years of growth after thinning in 2013. Variables include site location, biomass treatment, and soil amendment. Initial volume (volume in 2013) was used as a covariate. Periodic annual increment (PAI) growth is the growth from 2013 – 2016 divided by three years. Asterisk (*) indicates significance within factor at α = 0.05, bold text indicates significance within factor at α = 0.1.*

	1st year growth (m^3 ha^{-1} yr^{-1})		2nd year growth (m^3 ha^{-1} yr^{-1})		3rd year growth (m^3 ha^{-1} yr^{-1})		PAI growth (m^3 ha^{-1} yr^{-1})	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Location (L)	62.2277	**0.00***	39.55	**0.00***	52.64	**0.00***	69.67	**0.00***
Biomass (B)	1.5808	0.20	4.51	**0.00***	4.78	**0.01***	4.80	**0.00***
Amendment (A)	1.3945	0.25	3.05	**0.04***	3.89	**0.01**	3.70	**0.02***
Initial volume (I)	73.4029	**0.00***	39.19	**0.00***	0.05	0.83	25.04	**0.00***
I x L	5.1328	**0.03***	3.69	**0.06**	11.85	**0.00***	10.16	**0.00***

Table 2.6. *Crop tree ANCOVA F-statistic and p-value for total stem volume growth in the first three years of growth after thinning in 2013. Variables include site location, biomass treatment, and soil amendment. Initial volume (volume in 2013) was used as a covariate. Periodic annual increment (PAI) growth is the growth from 2013 – 2016 divided by three years. Asterisk (*) indicates significance within factor at α = 0.05, bold text indicates significance within factor at α = 0.1.*

	1st year growth (m^3 ha^{-1} yr^{-1})		2nd year growth (m^3 ha^{-1} yr^{-1})		3rd year growth (m^3 ha^{-1} yr^{-1})		PAI growth (m^3 ha^{-1} yr^{-1})	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Location (L)	52.84	**0.00***	47.50	**0.00***	26.03	**0.00***	48.45	**0.00***
Biomass (B)	5.63	**0.00**	9.49	**0.00***	6.12	**0.00***	8.32	**0.00***
Amendment (A)	1.27	0.29	3.18	**0.03***	3.34	**0.03***	2.77	**0.05**
Initial volume (I)	21.51	**0.00***	25.27	**0.00***	3.14	**0.08**	15.96	**0.00***

Basal area growth response to location

Pitwood basal area growth was greater than UIEF at the plot level and at the crop-tree level for all growth increments (Table 2.7). The plot level periodic annual increment (PAI) basal area growth at Pitwood was 107% greater than UIEF. Pitwood crop tree PAI basal area growth was 44% greater than UIEF. No interactions occurred between locations and main treatment effects. Interactions between initial basal area and location occurred due to a steeper response to initial basal area at Pitwood than UIEF (Figure 2.4).

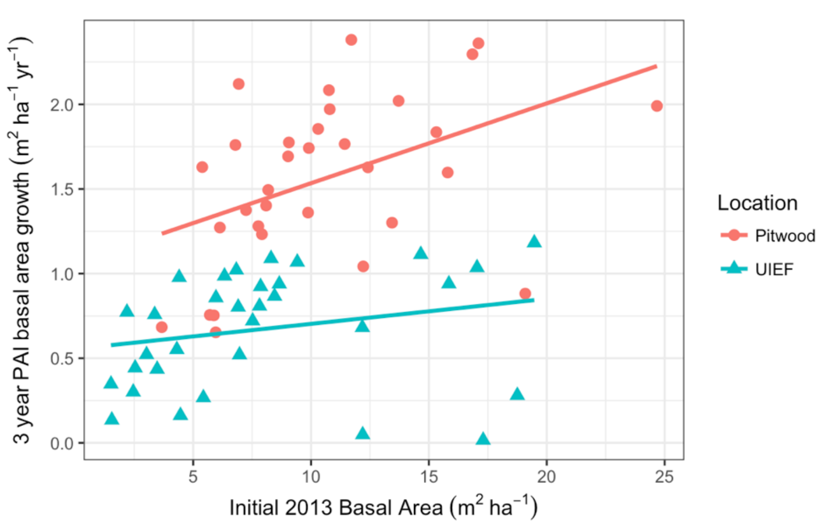

Figure 2.4. *The average plot-level basal area growth over the three years post-thinning by initial basal area and location. Location and initial basal area interaction is significant (p = 0.03)*

Table 2.7. *Average basal area growth by location in each year. Basal area and standard error are in (m^2 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	2013-2014		2014-2015		2015-2016		PAI	
Plot								
Pitwood	1.27 (0.13)	a	1.61 (0.16)	a	1.53 (0.29)	a	1.47 (0.14)	a
UIEF	0.67 (0.13)	b	1.03 (0.16)	b	0.42 (0.3)	b	0.71 (0.14)	b
Crop tree								
Pitwood	0.55 (0.05)	a	0.73 (0.05)	a	0.67(0.06)	a	0.65(0.04)	a
UIEF	0.32 (0.05)	b	0.51 (0.05)	b	0.51(0.06)	b	0.45(0.04)	b

Volume growth response to location

Pitwood volume growth was greater than UIEF at the plot level and at the crop-tree level for all growth increments (Table 2.8). The plot level PAI volume growth at Pitwood was 119% greater than UIEF and Pitwood crop tree PAI volume growth was 68% greater than UIEF (Table 2.8). No interactions occurred between locations and main treatment effects. Interactions between initial volume and location occurred at the plot level due to a steeper response to initial basal area at Pitwood than UIEF (Table 2.5).

Table 2.8. *Periodic annual increment volume growth from 2013 to 2016 by location. Volume and standard error are in (m^3 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	Plot PAI Volume growth		Crop tree PAI Volume growth	
Plot				
Pitwood	12.66 (1.30)	a	6.79 (0.55)	a
UIEF	5.78 (1.30)	b	4.04 (0.55)	b

Basal area response to biomass treatment

Plot level growth represents the growth of live trees in the plot each year. Significant mortality did not occur in the thinned plots, but mortality occurred in the unthinned plots, especially during the 2015-2016 growing season, where the unthinned basal area decreased

(Figure 2.5). The crop tree growth represents the net growth of the six largest trees that survived the entire study period (Figure 2.6).

A regression analysis for tree growth by downed woody debris slash loads as a continuous variable did not find any significant correlations (Appendix A). Growth was also compared between slash treatments, as a categorical factor. Plot growth was affected by biomass treatment starting at the second year of growth (Table 2.3). The PAI basal area growth in the 1x treatments was 30 % greater than the 2x treatment growth, and 44% greater than the unthinned plots (Figure 2.7). The growth in the 1x plots was not significantly greater than the 0x plots in any year increment (Table 2.9), or for the PAI growth (Figure 2.6).

Biomass treatments were significant factors in crop tree growth for all growth year increments (Table 2.4), and were usually due to a thinning response (Table 2.10). The PAI basal area growth in the 1x treatments was 50 % greater than the unthinned treatment growth, while the 0x growth was 44% greater than the unthinned plots (Figure 2.8). There were no differences in PAI growth between the thinned treatments (Figure 2.8). Though, in the third year, the 1x growth was 25% greater than the 2x plots (Table 2.10).

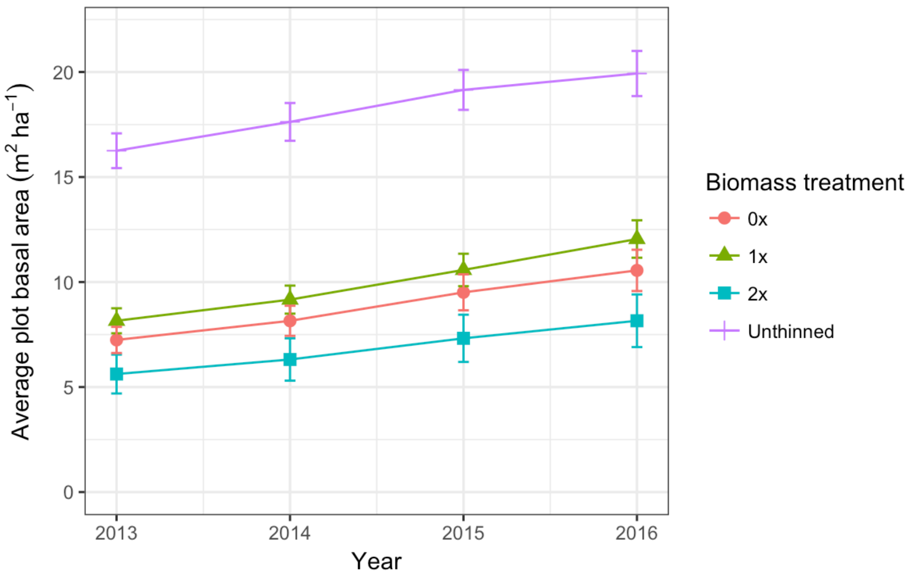

Figure 2.5. *Average plot basal area of both locations each study year by biomass treatment.*

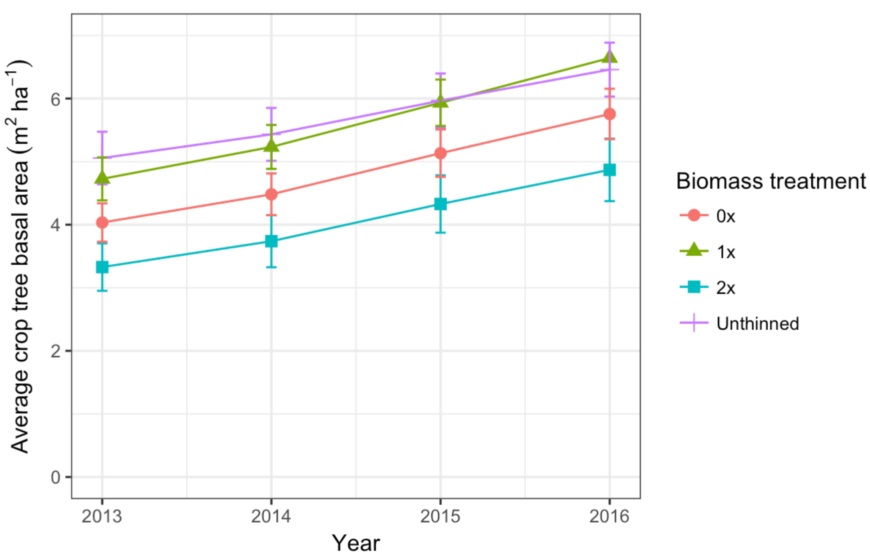

Figure 2.6. *Average crop tree basal area of both locations each study year by*

Table 2.9. *Average plot level basal area growth by treatment in each year. Basal area and standard error are in (m^2 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	1st year growth 2013 - 2014		**2nd year growth 2014 - 2015**		**3rd year growth 2015 - 2016**	
Biomass treatment	BA growth		BA growth		BA growth	
0x	0.98 (0.12)	*a*	1.51 (0.15)	*a*	1.02 (0.27)	*ab*
1x	1.04 (0.12)	*a*	1.50 (0.14)	*a*	1.45 (0.27)	*a*
2x	0.83 (0.13)	*a*	1.28 (0.16)	*a*	0.82 (0.29	*b*
Unthinned	1.02 (0.16)	*a*	1.01 (0.19)	*a*	0.62 (0.35	*b*

Table 2.10. *Average crop tree basal area growth by treatment in each year. Basal area and standard error are in (m^2 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	1st year growth 2013 - 2014		**2nd year growth 2014 - 2015**		**3rd year growth 2015 - 2016**	
Biomass treatment	BA growth		BA growth		BA growth	
0x	0.45 (0.05)	*ab*	0.66 (0.05)	*a*	0.63 (0.06)	*ab*
1x	0.50 (0.05)	*a*	0.68 (0.05)	*a*	0.70 (0.06)	*a*
2x	0.43 (0.05)	*ab*	0.64 (0.05)	*a*	0.56 (0.06)	*b*
Unthinned	0.36 (0.05)	*b*	0.50 (0.05)	*b*	0.48 (0.06)	*b*

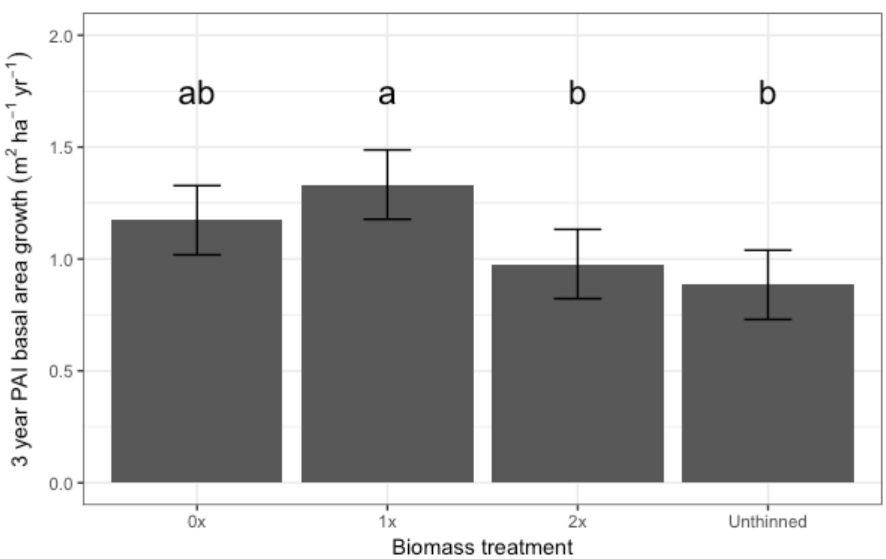

Figure 2.7. *Average annual plot basal area growth 2013 to 2016 by biomass treatment. Same letters over bars indicate no differences between treatment levels at α =0.1.*

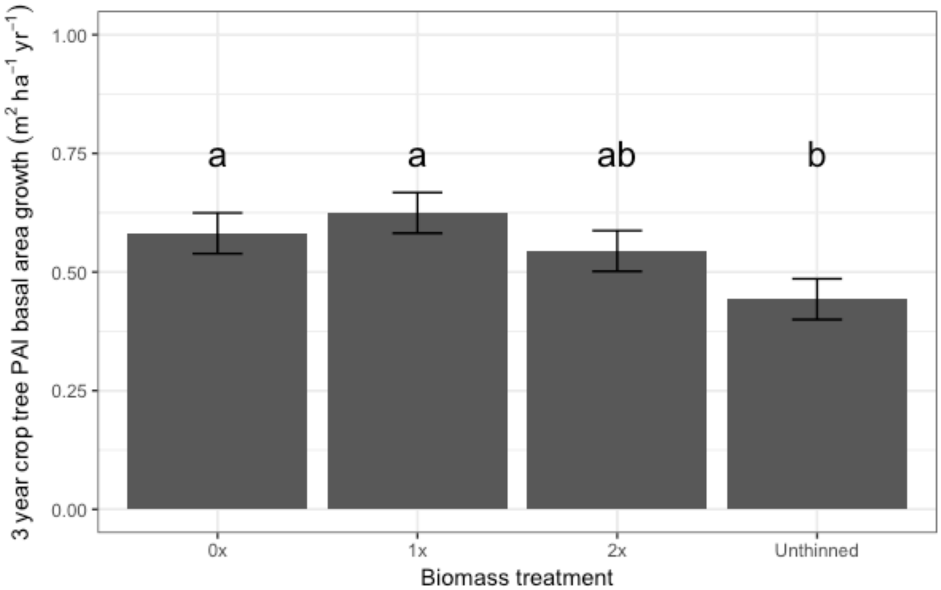

Figure 2.8. *Average annual crop tree basal area growth from 2013 to 2016 by biomass treatment. Same letters over bars indicate no differences between treatment levels at α =0.1.*

Volume growth response to biomass treatment

Plot volume growth was affected by biomass treatment starting at the second year of growth (Table 2.5). The PAI volume growth in the 1x treatments was 45 % greater than the 2x treatment growth, and 52% greater than the unthinned plots (Table 2.11). Volume growth in the 1x plots was not significantly greater than the 0x treatment plots (Table 2.11). Crop tree volume growth was affected by biomass treatment starting at the first year of growth (Table 2.6). The PAI crop tree volume growth in the 1x treatments was 29 % greater than the 2x treatment growth, and 47% greater than the unthinned plots (Table 2.11). The crop tree volume growth in the 1x plots was not significantly greater than the growth in the 0x treatment plots (Table 2.11).

Table 2.11. *Periodic annual increment volume growth by biomass treatment from 2013 to 2016. C = control, B = biochar, F = fertilizer, and FB = fertilizer + biochar. Volume growth and standard error are in (m^3 ha^{-1} y^{-1}). Same letters with each level indicate no differences between treatment levels at α =0.1.*

	Plot level PAI		**Crop tree PAI**	
Biomass treatment	Volume growth		Volume growth	
0x	9.92 (1.27)	*ab*	5.73 (0.55)	*ab*
1x	11.47 (1.26)	*a*	6.48 (0.55)	*a*
2x	7.92 (1.31)	*b*	5.03 (0.56)	*bc*
Unthinned	7.55 (1.38)	*b*	4.42 (0.56)	*c*

Basal area response to soil amendments

Basal area growth typically responded to fertilizer. Soil amendments did not affect plot basal area growth during the first two growing seasons post-thin (Table 2.3). Fertilizer only plots 39% higher PAI basal area growth compared to the unamended control plots (Figure 2.9). Fertilizer only amended plots also had greater plot growth in the third year of the study (Table 2.12). Biochar did not diminish or improve plot growth in any year (Table 2.12).

Soil amendments did not affect crop tree basal area growth during the first growing season post-thin (Table 2.4). Fertilizer only plots 23% higher crop tree PAI basal area growth compared to the unamended control plots, while fertilizer plus biochar (FB) plots had 27% increased basal area growth compared to the control (Figure 2.10). In the third year of the study, fertilizer-only plots had 30% greater growth than biochar-only amended plots (Table 2.13). Biochar did not diminish or improve crop tree growth in any year compared to the unamended control plots (Table 2.13).

Table 2.12. *Average plot level basal area growth by soil amendment by year. For soil amendment, C = Control, B = Biochar, F = fertilizer, and FB = fertilizer + biochar. Basal area and standard error are in (m^2 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	1st year growth 2013 - 2014		**2nd year growth 2014 - 2015**		**3rd year growth 2015 - 2016**	
Soil amendment	BA growth		BA growth		BA growth	
C	0.93 (0.13)	*a*	1.16 (0.16)	*a*	0.63 (0.30)	*a*
B	0.88 (0.13)	*a*	1.26 (0.16)	*a*	0.83 (0.30)	*ab*
F	0.95 (0.13)	*a*	1.50 (0.16)	*a*	1.32 (0.30)	*b*
FB	1.12 (0.13)	*a*	1.38 (0.16)	*a*	1.14 (0.30)	*ab*

Table 2.13. *Average crop tree basal area growth by soil amendment by year. For soil amendment, C = Control, B = Biochar, F = fertilizer, and FB = fertilizer + biochar. Basal area and standard error are in (m^2 ha^{-1} y^{-1}). Same letters with each growth year and measurement indicate no differences between treatment levels at α =0.1.*

	1st year growth 2013 - 2014		**2nd year growth 2014 - 2015**		**3rd year growth 2015 - 2016**	
Soil amendment	BA growth		BA growth		BA growth	
C	0.40 (0.05)	*a*	0.54 (0.05)	*a*	0.50 (0.06)	*a*
B	0.42 (0.05)	*a*	0.61 (0.05)	*ab*	0.53 (0.06)	*ac*
F	0.44 (0.05)	*a*	0.64 (0.05)	*ab*	0.69 (0.06)	*b*
FB	0.48 (0.05)	*a*	0.69 (0.05)	*b*	0.65 (0.06)	*bc*

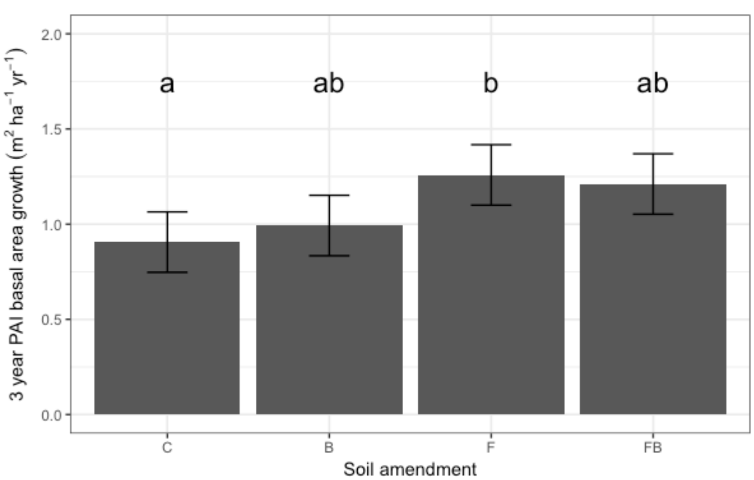

Figure 2.9. *Average annual plot basal area growth 2013 to 2016 by soil amendment. C = unamended control, B = biochar, F = fertilizer, FB = fertilizer + biochar. Same letters over bars indicate no differences between treatment levels at α =0.1.*

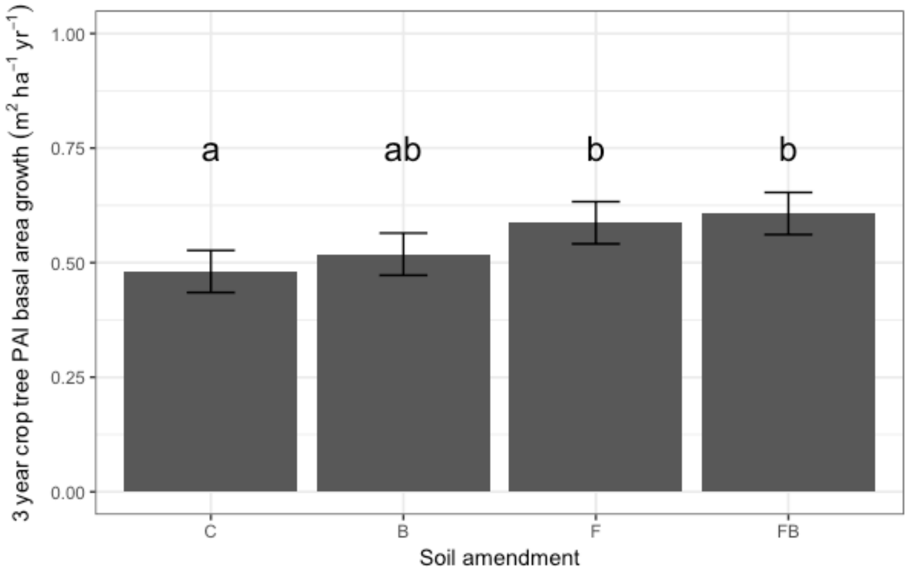

Figure 2.10. *Average annual crop tree basal area growth 2013 to 2016 by soil amendment. C = unamended control, B = biochar, F = fertilizer, FB = fertilizer + biochar. Same letters over bars indicate no differences between treatment levels at* α *=0.1.*

Volume growth response to soil amendments

Volume growth typically responded to fertilizer at the plot level. Soil amendments did not affect plot growth during the first growing season post-thin (Table 2.5). Fertilizer (F) plots and fertilizer plus biochar (FB) plots had 19% and 25% and higher PAI volume growth compared to the unamended control plots (Table 2.14). Biochar did not diminish or improve plot or crop tree basal area growth. There were no differences between amendment treatments on crop tree PAI volume growth.

Table 2.14. *Periodic annual increment volume growth by soil amendment from 2013 to 2016. C = control, B = biochar, F = fertilizer, and FB = fertilizer + biochar. Volume growth and standard error are in (*$m^3\ ha^{-1}\ y^{-1}$*). Same letters with each level indicate no differences between treatment levels at* α *=0.1.*

	Plot level PAI		**Crop tree PAI**	
Biomass treatment	Volume growth		Volume growth	
C	4.84 (0.55)	*a*	7.21 (1.30)	*a*
B	5.00 (0.55)	*ab*	8.71 (1.30)	*a*
F	5.78 (0.55)	*b*	10.52 (1.30)	*a*
FB	6.04 (0.55)	*b*	10.42 (1.30)	*a*

Soil moisture and temperature

There were highly significant seasonal and locational effects on soil moisture and soil temperature. Soil temperatures were highest in the summer and lowest in the fall. Soil moisture was lowest in the summer and highest in the spring. No seasonal differences in soil moisture were found between biomass treatments or soil amendment treatments (Appendix A). Soil temperatures were not also unaffected by biomass treatment of soil amendment treatment (Appendix A).

Discussion

Response to biomass retention level and thinning

During the three years following thinning, full biomass removal did not significantly affect basal area growth or total volume growth compared to the slash retention plots at both the plot level and the crop trees level. This indicates that forests growth in the Inland Northwest with similar soil and forest conditions may be resilient to biomass removal during pre-commercial thinning, and can support harvesting small diameter biomass for biofuel feedstocks. However, some long-term studies have shown negative effects of biomass removal that were not apparent during the first five years (Voldseth et al., 2011), so it is possible that long term impacts in our study may not be seen at this time. Many other long term studies found little or no impacts of commercial harvest biomass removal (Slesak et al., 2017), so it is likely that smaller diameter biomass removal will not impact forest growth on this site. Concurrent soil studies may provide early indicators of biomass removal impacts.

Previous bole-only harvests occurred at both locations in the late 1980's and early 1990's. It is not documented whether the residual biomass from these harvests was retained in all plots, however remnants of decaying logs were visible at both locations, including in the 0x treatments. The decaying biomass from these operations undoubtedly contributed nutrients to soil. The lack of impact of biomass removal on growth might not be replicated on a site that had been whole-tree harvested prior to planting or natural regeneration.

Plots with 2x biomass retention had significantly lower basal area growth and total volume growth compared to other thinned plots with less biomass retention in some years, which was unexpected. Some studies show increased slash retention can increase the risk of crop pests and disease (Schroeder, 2008), which possibly occurred, though significant mortality did not occur in thinned plots. We completed an analysis of soil temperature and moisture differences between biomass treatments as some studies have found well slashed plots to increase soil moisture and decrease soil temperature (Devine and Harrington, 2007), which could affect growth. Soil moisture and temperature were not found to be different between whole-plot treatments (Appendix A). Decreased growth due to excess slash has not been widely shown, and the concept of double slash performed in this study was not found in other studies. While many studies do not report the weight of slash per area, similar studies that did had maximum slash loads of 21.5 tons per hectare (Luiro et al., 2010) and 67.0 tons per hectare (Wall, 2008), though these studies examined nutrient response, and not growth. After reviewing literature, the amount of slash left at Pitwood was unprecedentedly high compared to other reported studies, due to the overstocked pre-treatment conditions and the unique 2x slash treatment. There was not an interaction between location and biomass treatment in the growth response, which makes the underperforming 2x growth more interesting as UIEF had slash levels more in-line with other studies (Wall, 2008).

The results of this study suggest large amounts of slash can decrease growth. Retaining full biomass residue from thinning operations on site did not show any benefits over removing all biomass material on forest growth in the first three years after thinning. Assessing an ideal biomass retention level for this region was an objective of this study. A regression analysis was completed using the downed woody debris estimate. While there was a peak slash level growth response at both locations, the regression results were not significant. This may be due to wide variation in slash levels, the limited sample size, and the accuracy of our method of estimating downed woody debris. It is possible that an ideal biomass retention level is a range between zero biomass retention and more than full biomass retention. Due to this knowledge, management prescriptions of Inland Northwest forests with similar soil conditions may include full biomass removal or retention as convenient during thinning operations if soil impacts are minimized.

Response to soil amendments

Nitrogen is the limiting nutrient for plant growth in this region soils (Edmonds et al., 1989; Coleman et al., 2014), so fertilization was expected to increase forest productivity compared to the control. Fertilized plots showed increased plot level growth and increased crop tree growth compared to unfertilized control plots during the three years of the study. While biomass removal did not result in decreased growth in the first three years of the study, it is reasonable to assume fertilizer would be beneficial in Inland Northwest forests for forest productivity if longer-term research finds biomass removal impacts forest growth later in the rotation cycle.

Biochar did not affect plot-level basal area or volume growth in any year. Crop tree basal area growth in biochar amended plots did not differ from unamended control plots, though crop trees in fertilizer-only amended plots had greater growth than in biochar-only amended plot in one year. Biochar never negatively impacted growth compared to the control plots, so it can still be used as a method of carbon sequestration in forests without impacting growth.

Biochar is a highly variable substance and studies find growth responses ranging from increased growth (Carter et al., 2013; Graber et al., 2010; Hossain et al., 2010), diminished growth (Asai et al., 2009; Hammond et al., 2013) and no response (Schulz et al., 2014). The lack of biochar affect may be due to the existing volcanic ash content in the soils. Andisol soils which are present at Pitwood, tend to have high forest productivity compared to soil orders without ash (Meurisse et al., 1991). The UIEF soil types also include volcanic ash and pumice. The porous quality of volcanic ash in soil increases water-holding capacity in soils, which can increase forest productivity (Meurisse et al., 1991). The increased water holding capacity in Andisol soils is an important factor for forest productivity in the Inland Northwest as the region experiences warm and dry summers (McDaniel et al., 2005). Biochar amended plots may not have increased growth because plots without biochar possibly had a large enough volcanic ash cap to maintain adequate soil moisture during dry seasons. This was also represented by the lack of differences in soil moisture and soil temperature between soil amendment treatments. We expected to see higher seasonal soil moisture content in biochar amended plots than plots without biochar, but this was no found to be true. This may be due to the the amount of biochar that was applied. This study applied 2.5 Mg/ha of biochar to plots, while other biochar field studies with significant findings applied 7.8 Mg ha^{-1} (Ma et al., 2016), 10 Mg ha^{-1} (Brantley et al., 2015), and 47 to 105 Mg ha^{-1} (Ippolito et al., 2015). It is possible that increasing the rate of biochar would have resulted in increased impacts.

Downed Woody Debris Surveys

The initial downed woody debris surveys were found to misrepresent the site. They were repeated using longer transects in 2016, and they again misrepresented the site. The downed woody debris calculations conflicted with whole-plot treatments and visual site knowledge. We determined this was due to lack of homogeneity in the spread of woody biomass, and relatively short distance of transects within our 20 x 20 meter split-plots. A non-random method of calculating debris, such as debris pile volume calculations, would possibly result in more accurate calculations. It was determined that we could get the best estimate of downed woody debris by using the known pre-treatment basal area and the post-treatment basal area of each plot, and factoring in the treatments. These calculations represented the plot treatments more accurately than the downed woody debris surveys.

Limitations

The limitations of this study included a lack of confidence in the biomass amounts applied due to DWD survey variability and a lack of full pre-treatment measurements to be fully confident in our 2012 standing tons per hectare estimates. Our confidence in the volume growth calculations is limited due to missing height data, which was filled in using allometric equations. The biochar rate in this study was low compared to other studies. Further, the biochar was sprayed on some sites, and hand applied on others, which may have resulted in a difference in homogeneity of the treatment.

Conclusions and research implications

This study found full biomass removal from thinning operations did not impact forest productivity in the first three years after thinning. This indicates forests in the inland northwest could support cellulose biofuel systems without impacting site productivity. A follow up study is recommended to look at long term impacts of small diameter biomass removal.

Very few studies look at the effects of slash levels greater than the amount harvested at thinning. This study showed excessive slash negatively impacted forest growth compared to normal biomass retention levels. This is an unprecedented result. This study had slash levels up to 567.71 tons per hectare, and no study found reported slash amounts near this amount. In this study the crop tree growth of thinned plots with double biomass retention was not different than crop tree growth in unthinned plots, which indicates the negative effects of too much slash negate the expected benefits of pre-commercial thins. It is possible to use a quadratic curve to find the ideal amount of slash for the region using the growth response to the DWD amounts that were applied.

This study supports previous studies that found fertilizing forest soil will increase forest productivity, especially in nitrogen limiting environments. The study provides evidence that amending ashy soils with biochar will not result in increased growth but can still be used for carbon sequestration. These findings will help inform forest management of the region.

The findings of this study should be evaluated alongside concurrent studies on soil biological properties and invertebrate diversity at these study sites. This will lead to a broader understanding of the impacts of biomass treatments and soil amendments at an ecosystem level. It is recommended that trees in this study are measured again prior to their commercial harvest to evaluate the long term impacts of biomass removal and slash retention.

Literature Cited

Amonette, J., Amonette, J., Joseph, S., 2009. Biochar for Environmental Management: Science and Technology. Earthscan, London, UK.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield, Field Crops Research.

Barg, A.K., Edmonds, R.L., 1999. Influence of partial cutting on site microclimate, soil nitrogen dynamics, and microbial biomass in Douglas-fir stands in western Washington. Can. J. For. Res. 29, 705–713.

Brantley, K. E., Savin, M. C., Brye, K. R., & Longer, D. E. (2015). Pine Woodchip Biochar Impact on Soil Nutrient Concentrations and Corn Yield in a Silt Loam in the Mid-Southern US. *Agriculture*, *5*(1), 30-47.

Brockley, R.P., 2005. Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. Can. J. For. Res. 35, 1952–1964.

Brown, J.K., 1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Browne, J. E. (1962). Standard cubic-foot volume tables for the commercial tree species of British Columbia, British Columbia Forest Service, Victoria, BC, Canada.

Carter, S., Shackley, S., Sohi, S., Suy, T., Haefele, S., 2013. The Impact of Biochar Application on Soil Properties and Plant Growth of Pot Grown Lettuce (Lactuca sativa) and Cabbage (Brassica chinensis). Agronomy 3, 404–418.

Coleman, M. D., Shaw, T. M., Kimsey, M. J., & Moore, J. A. (2014). Nutrition of Douglas-fir in the Inland Northwest. *Soil Science Society of America Journal*, *78*(S1), S11-S22.

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.

Edmonds, R. L.; Binkley, D.; Feller, M. C.; Sollins, P.; Abee, A.; Myrold, D. D. (1989). Nutrient cycling: effects on productivity of northwest forests. In: Perry, D. A.; [and others], eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 17-35.

Evans, A.M., Finkral, A.J., 2009. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. GCB Bioenergy 1, 211–219.

Footen, P.W., Harrison, R.B., Strahm, B.D., 2009. Long-term effects of nitrogen fertilization on the productivity of subsequent stands of Douglas-fir in the Pacific Northwest. For. Ecol. Manage. 258, 2194–2198.

Graber, E.R., Meller Harel, Y., Kolton, M., Cytryn, E., Silber, A., Rav David, D., Tsechansky, L., Borenshtein, M., Elad, Y., 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. Plant Soil 337, 481–496.

Hammond, J., Shackley, S., Prendergast-Miller, M., Cook, J., Buckingham, S., Pappa, V.A., 2013. Biochar field testing in the UK: outcomes and implications for use. Carbon Manag. 4, 159–170.

Helmisaari, H.-S., Hanssen, K.H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., Tveite, B., 2011. Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. For. Ecol. Manage. 261, 1919–1927.

Hossain, M.K., Strezov, V., Yin Chan, K., Nelson, P.F., 2010. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (Lycopersicon esculentum), Chemosphere.

Ippolito, J. A., Grob, J., & Donnelly, A. (2015). Anatomy of a field trial: Wood-based biochar and compost influences a Pacific Northwest soil. *Biochar Journal*, 1-34.

Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, *49*(1), 12-35.

Laird, D.A., 2008. The Charcoal Vision: A Win–Win–Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality. Agron. J. 100, 178.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – A review. Soil Biol. Biochem. 43, 1812–1836.

Luiro, J., Kukkola, M., Saarsalmi, A., Tamminen, P., Helmisaari, H.-S., 2010. Logging residue removal after thinning in boreal forests: long-term impact on the nutrient status of Norway spruce and Scots pine needles. Tree Physiol. 30, 78–88.

Ma, N., Zhang, L., Zhang, Y., Yang, L., Yu, C., Yin, G., ... & Ma, X. (2016). Biochar Improves Soil Aggregate Stability and Water Availability in a Mollisol after Three Years of Field Application. *PloS one*, *11*(5), e0154091.

Mason, W.L., McKay, H.M., Weatherall, A., Connolly, T., Harrison, A.J., 2012. The effects of whole-tree harvesting on three sites in upland Britain on the growth of Sitka spruce over ten years. Forestry 85, 111–123.

McDaniel, P.A., Hipple, K.W., 2010. Mineralogy of loess and volcanic ash eolian mantles in Pacific Northwest (USA) landscapes. Geoderma 154, 438–446.

McDaniel, P.A., Wilson, M.A., Burt, R., Lammers, D., Thorson, T.D., McGrath, C.L., Peterson, N., 2005. Andic soils of the inland pacific northwest, usa: properties and ecological significance. Soil Sci. 170, 300–311.

Meurisse, R.T., Niehoff, J., Ford, G., 1991. Dominant soil formation processes and properties in western-montane forest types and landscapes: some implications for productivity and management, General technical report INT. Portland, OR.

Perlack, R. D., Eaton, L. M., Turhollow Jr, A. F., Langholtz, M. H., Brandt, C. C., Downing, M. E., ... & Nelson, R. G. (2011). US billion-ton update: biomass supply for a bioenergy and bioproducts industry.

Saarsalmi, A., Tamminen, P., Kukkola, M., Hautajärvi, R., 2010. Whole-tree harvesting at clear-felling: Impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. Scand. J. For. Res. 25, 148–156.

Schnepf, R., Yacobucci, B.D., 2015. Renewable Fuel Standard (Rfs): Overview and Issues - Scholar's Choice Edition. Scholar's Choice.

Schroeder, L.M., 2008. Insect pests and forest biomass for energy. Springer Netherlands, pp. 109–128.

Schulz, H., Dunst, G., Glaser, B., 2014. No Effect Level of Co-Composted Biochar on Plant Growth and Soil Properties in a Greenhouse Experiment. Agronomy 4, 34–51. doi:10.3390/agronomy4010034

Slesak, R.A., Palik, B.J., D 'amato, A.W., Kurth, V.J., 2017. Changes in soil physical and chemical properties following organic matter removal and compaction: 20-year response of the aspen Lake-States Long Term Soil Productivity installations. For. Ecol. Manage. 392, 68–77.

Thiffault, E., Hannam, K. D., Paré, D., Titus, B. D., Hazlett, P. W., Maynard, D. G., & Brais, S. (2011). Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—a review. *Environmental Reviews*, *19*(NA), 278-309.

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. Res. Pap. NRS-17. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 20 p.

Wall, A., 2008. Effect of removal of logging residue on nutrient leaching and nutrient pools in the soil after clearcutting in a Norway spruce stand. For. Ecol. Manage. 256, 1372–1383.

Wykoff, W. R., Crookston, N. L., & Stage, A. R. (1982). *User's guide to the stand prognosis model* (pp. 720-2600). Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Appendix

Pitwood stand layout

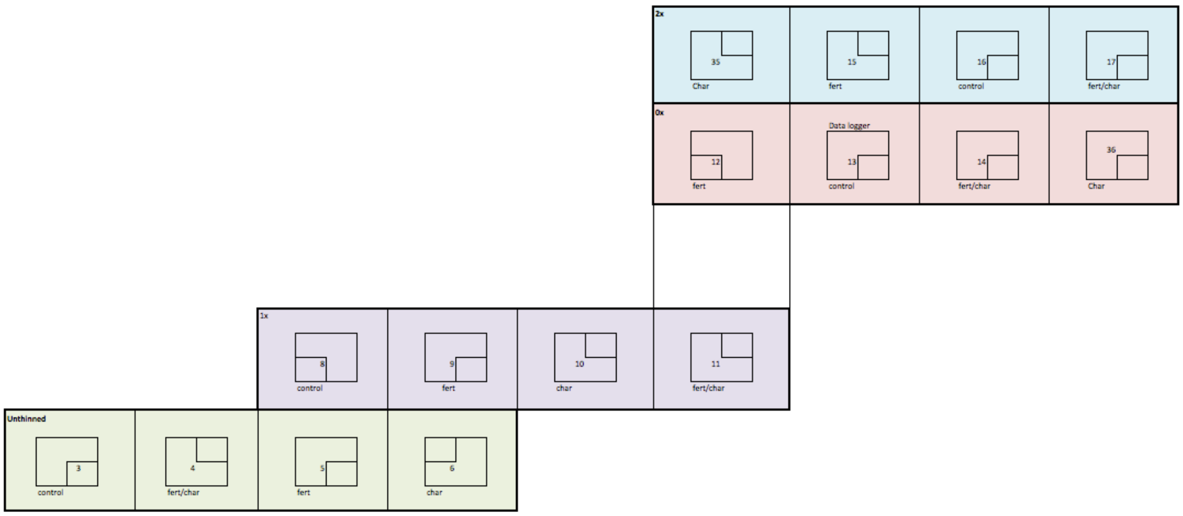

Figure A.1. *Pitwood North stand*

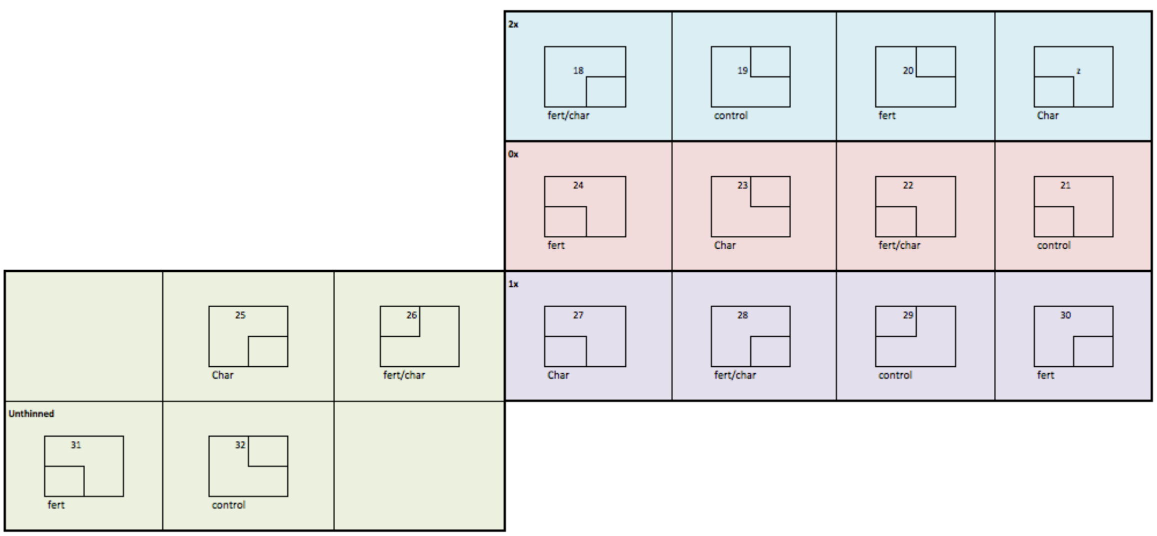

Figure A.2. *Pitwood South stand*

UIEF stand layout

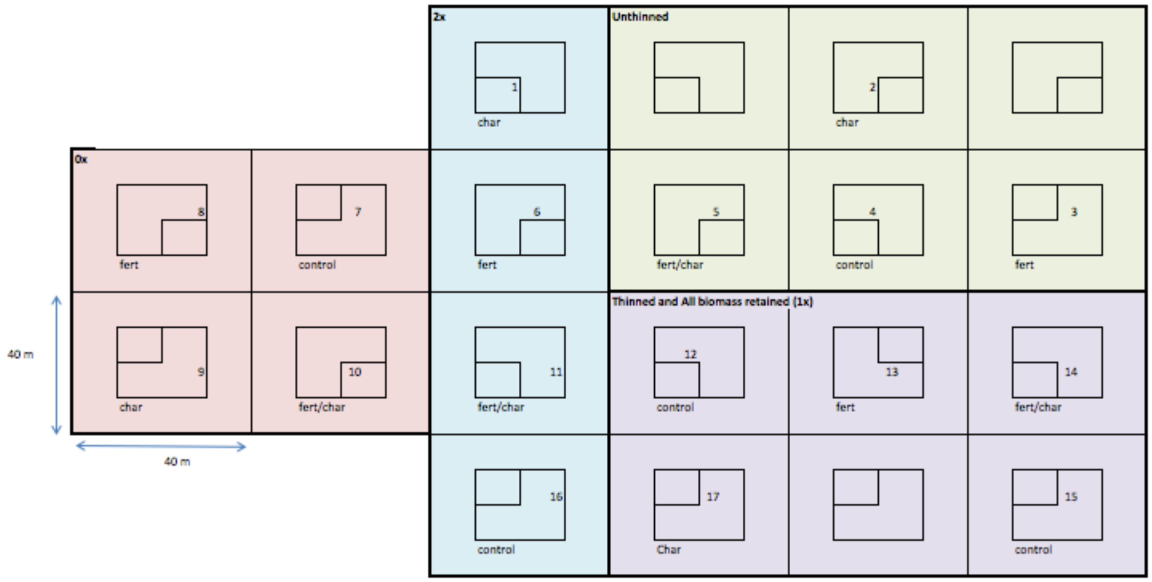

Figure A.3. *UIEF Upper stand*

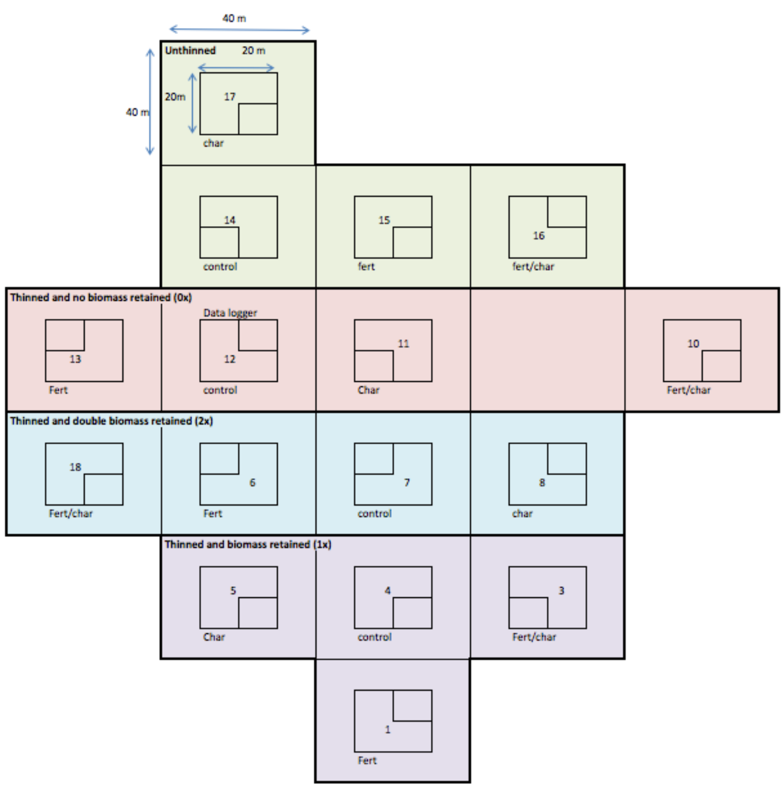

Figure A.4. *UIEF Lower stand*

Soil temperature and moisture

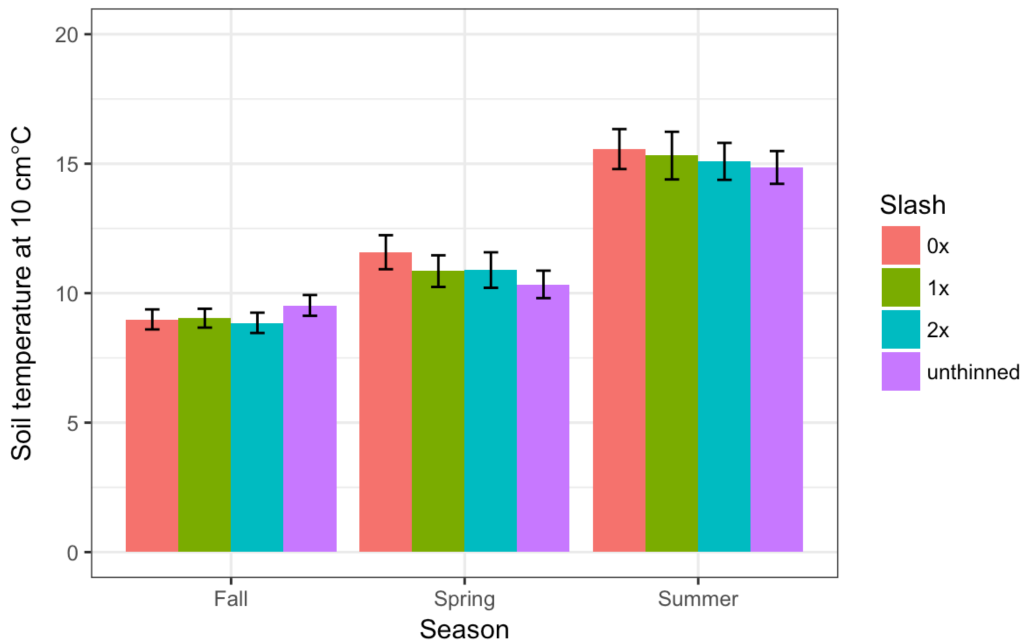

Figure A.5. *Seasonal temperature differences by biomass treatment. No differences between treatment levels within seasons occurred at* α *=0.1.*

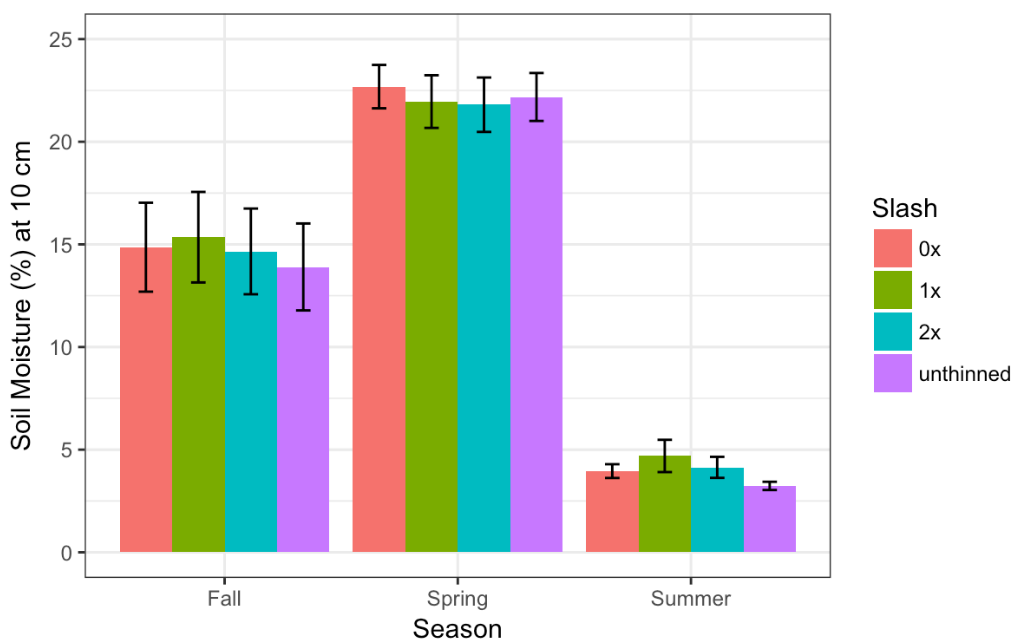

Figure A.6. *Seasonal moisture differences by biomass treatment. No differences between treatment levels within seasons occurred at* α *=0.1.*

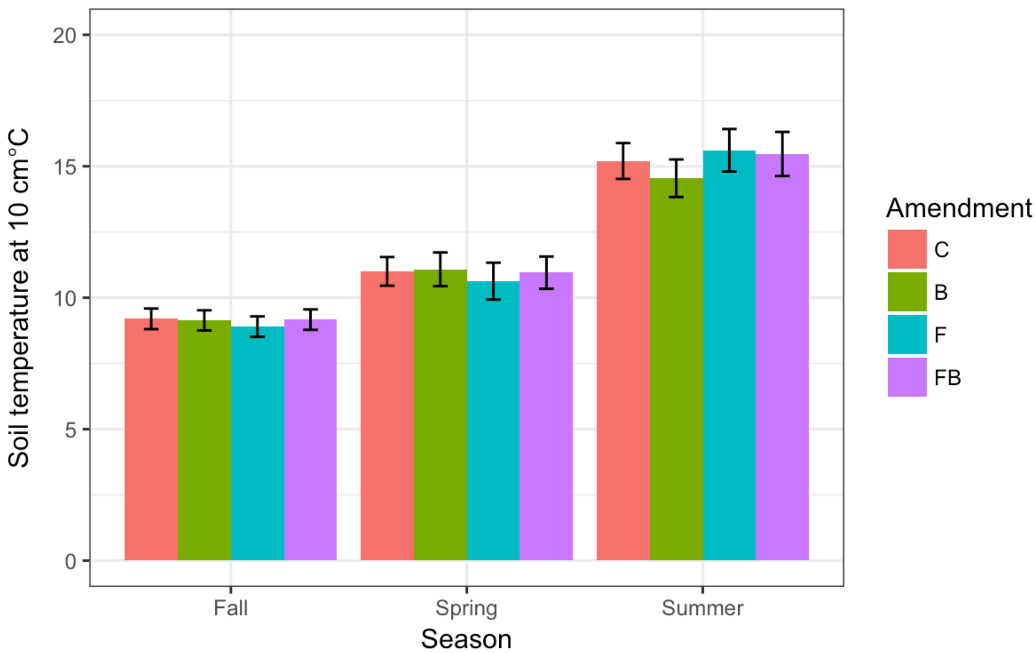

Figure A.7. *Seasonal temperature differences by soil amendment. No differences between treatment levels within seasons occurred at* $\alpha = 0.1$.

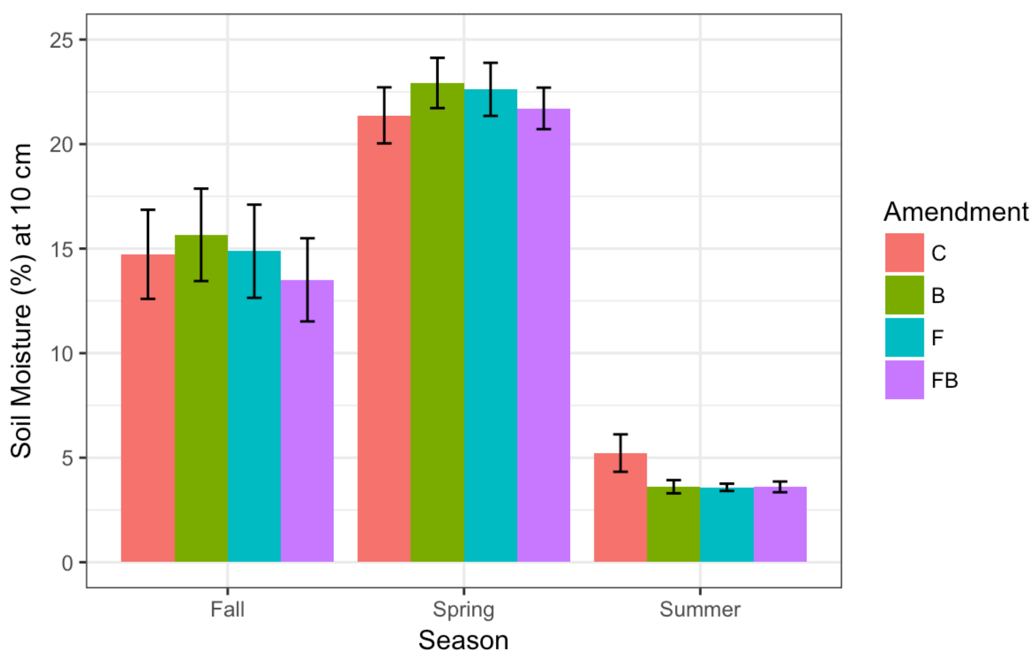

Figure A.8. *Seasonal moisture differences by soil amendment. No differences between treatment levels within seasons occurred at* $\alpha = 0.1$.

Downed woody debris regression

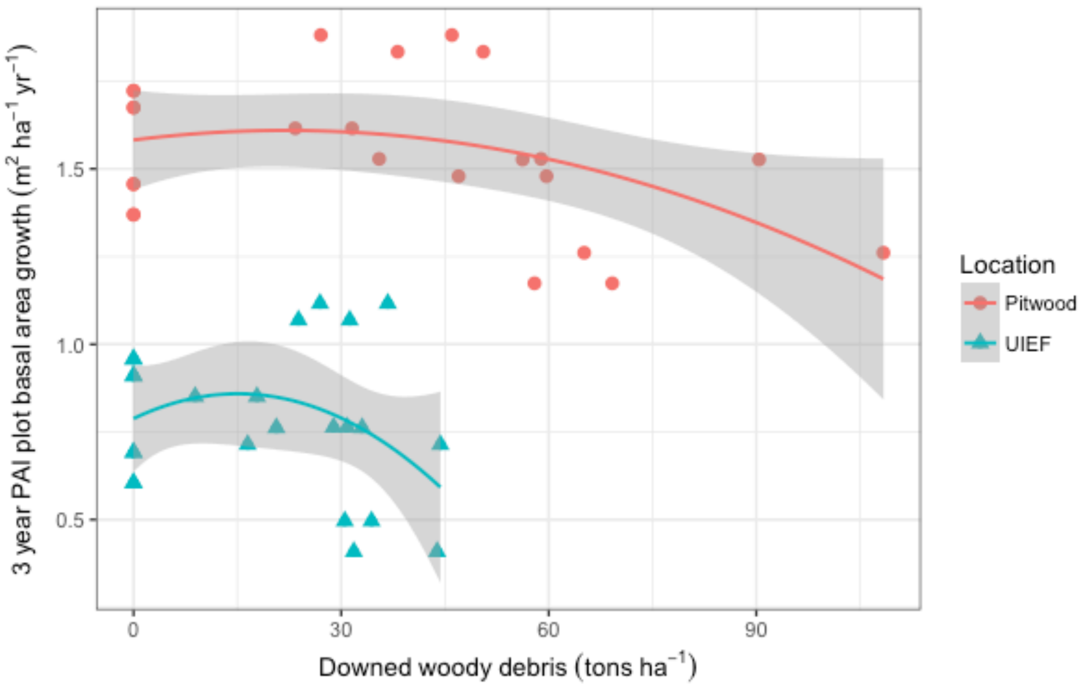

Figure A.9. *PAI basal area growth response to downed woody debris by location with fitted quadratic curve.*

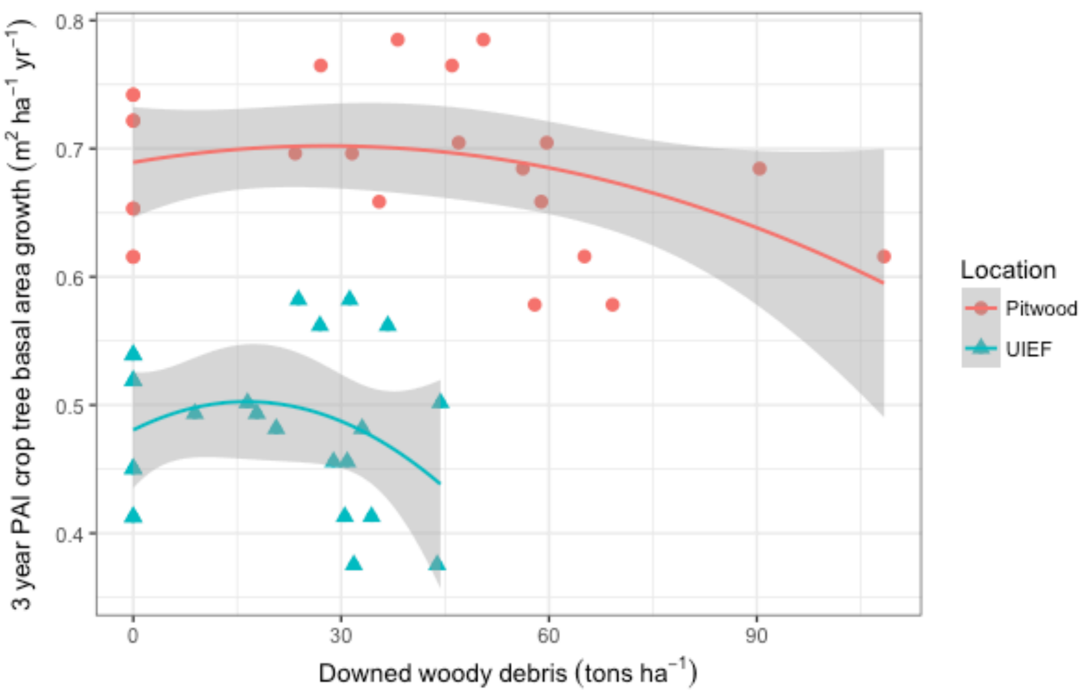

Figure A.10. *PAI crop tree basal area growth response to downed woody debris by location with fitted quadratic curve.*