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PONDEROSA PINE RESPONSES TO BIOCHAR, FERTILIZATION, OR MASTICATION ON THE
BITTERROOT NATIONAL FOREST, USA

By

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Thesis

Presented in partial fulfilment of the requirements
for the degree of

Master of Science
Forestry

The University of Montana
Missoula, MT

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ABSTRACT

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Major
Forestry

Effects of Biochar, Fertilizer, and Masticated Woody Biomass on Ponderosa Pine Tree Growth and Soil Properties

Chairperson: Christopher R. Keyes

Management and restoration practices in even-age ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) stands in the Intermountain West can be improved by developing a more thorough understanding of the effects of soil amendment treatments on tree growth and soil properties. Biochar is a charcoal- soil amendment that is created by burning woody biomass in an environment with limited oxygen through a process known as pyrolysis. Biochar has been recommended as a soil amendment for a number of reasons; including increased water and nutrient retention, and building soil aggregates. However, the effects of biochar on temperate forest soils and ponderosa pine growth, both alone and in conjunction with applying fertilizer and retaining masticated woody biomass, are not well studied. The purpose of this study is to explore tree growth and soil physio-chemical effects of biochar, fertilizer, and masticated wood as soil amendments surface applied to mature ponderosa pine trees in western Montana, USA, and discuss the implications of these amendments as practical methods in the western United States. We found that masticated wood had significant effects on 2-year change in DBH and basal area. High-rate biochar amendments improved carbon pools and at 10-20 cm compared to the control. The high-rate biochar and high-rate biochar with fertilizer treatment increased forest floor pH compared to the masticated wood treatment, and the high-rate biochar treatment increased Ca at the 10-20 cm soil depth compared to the fertilizer treatment. The masticated wood treatment increased organic matter compared to fertilizer at the 10-20 cm soil depth. The low-rate biochar treatment increased Mg at the 0-10 cm soil depth compared to the fertilizer treatment. High-rate biochar improved soil moisture by 57%.

Resilience to drought is a topic of increasing concern and research, which necessitates the need for techniques that can evaluate fine-scale growth periods in water limiting environments and shed light on how these periods are altered by restoration treatments. Considering the variety of dendrometer tools, finding the correct one can be a challenge. Automated (electronic) and mechanical (non-electronic) varieties exist, but mechanical dendrometers are expensive and often times more complex and/or precise than the nature of the study necessitates. The Hook and Screw point dendrometer developed by Reineke (1932) and circumferential dendrometers such as Vernier bands and logger tapes are low-cost and practical mechanical alternatives to automated dendrometers. However, limited information exists on the methodological and practical differences among these types. We compared these three dendrometers by measuring intra-seasonal growth of 40 ponderosa pines by collecting diameter measurements on 14 occasions between May 13, and August 3, 2016. We found the Vernier band and the Hook and Screw dendrometer to be comparable in accuracy, closely followed by the Logger tape. The Logger tape is the least expensive option of the three, and Vernier bands are the most expensive. The Hook and Screw is the most time-consuming method. The nature of the project will greatly influence the selection of dendrometer type. Therefore, pros and cons of each option should be weighed against one another to determine the most appropriate choice of tool.

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Chapter 1:

**EFFECT OF BIOCHAR, FERTILIZER, OR MASTICATED WOODY BIOMASS ON
PONDEROSA PINE TREE GROWTH AND SOIL PROPERTIES**

1.1 INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests in the Intermountain West, of the United States are typically water limited, as the species propagates naturally on dry sites (Arno & Fiedler 2015). Climate change is exacerbating water availability and thereby reducing resilience to drought, decreasing regeneration, and increasing susceptibility to disease and insect related mortality (Feddemma et al. 2013, Ganey & Vojta 2011, Negron et al. 2009). By improving soil water holding capacity in water-stressed ecosystems throughout the Intermountain West, these tree stressors may be mitigated. Water stress and tree vigor might be improved with soil amendments like biochar, fertilizer, and biomass retention. Biochar in particular has gained interest in recent years for its potential to increase tree growth through nutrient availability and/or other physio-chemical properties of the soil (Ladygina & Rineau 2013, Lehmann & Joseph 2009). Biochar is also a carbon sequesterer, and has been discussed at length as a possible way to mitigate the effects of climate change (Woolf et al. 2009). This is because it stores more soil carbon than burning or application of woody biomass alone (Lehmann et al. 2006). However, little is known regarding the effect of biochar on dry pine forests, rendering the need for focused studies on tree growth and soil properties resulting from its application.

Biochar is a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment (Lehmann and Joseph 2015). It is similar to charcoal created during wildfires (DeLuca and Aplet 2008) and can be a byproduct of bioenergy production (Atland & Locke 2012). The documented use of charcoal as a soil amendment in agriculture dates back hundreds of years (Lehmann & Joseph 2009) though it has been gaining momentum in the last decade for its use in forestry (Page-Dumroese 2017). In addition to its role in carbon sequestration, biochar facilitates restoration forests by providing a number of ecological benefits to soil physio-chemical properties and aboveground plant growth (Matovic 2011, Biederman & Harpole, 2013).

Biochar is produced in a number of ways. A low-cost option includes placing biomass material in pits, covering it, and burning the material. A more controlled production method uses pyrolysis, which involves the heating of biomass quickly to high temperatures in an environment of little to no oxygen. The primary product is a bio-oil that forms from the condensation of vapors, but biochar (also referred to as black carbon) is a byproduct of this process (Antal & Gronli 2003). There are marked differences in the effect biochar has on soil as a result of the biomass feedstock materials and the conditions under which it is produced, although biochar is generally hydrophobic and aromatic regardless of the pyrolysis method and type of biomass used. Biochar is produced using a variety of organic materials and under variable temperatures. Materials include forestry feedstocks such as forest or mill residues, and agricultural products including but not limited to switchgrass, poultry stover, and manure. A study conducted to analyze the effect of low-temperature pyrolysis on biochar properties found that biochar produced at lower pyrolysis temperatures has a higher cation exchange capacity than biochar produced at lower temperatures (Gaskin et al., 2008). A study characterizing fast pyrolysis products made from a variety of western USA woody species found evidence that biochars produced from different woody biomass feedstocks have similar pH values, but differ in electrical conductivity and chemical elements (Jarvis et al. 2014).

Biochar has been used as a soil amendment to improve water-holding capacity and infiltration rates. Water holding capacity of sandy soils following biochar addition showed an increased field capacity (Basso et al. 2013). Biochar applications in sandy soils indicate plant-available water increases by increasing soil water-holding capacity, thereby increasing aboveground productivity (Basso et al. 2013, Biederman & Harpole, 2013). Myriad evidence supports biochar's ability to alter soil physio-chemical properties. A meta-analysis on the effect of biochar on plant productivity and nutrient cycling shows that biochar amendments increase soil carbon (C), soil nitrogen (N), soil potassium (K), and soil phosphorus (P), and rhizobia nodulation (Biederman & Harpole, 2013). Biochar application is also associated with reduced nitrification in soils, according to a study comparing biochar to organic and

inorganic fertilizers in a greenhouse setting (Schultz & Glasser, 2012). A study of the molecular characterization of biochar and its influence on soil microbiological properties found that biochar negatively affects the soil microbial activity, in addition to reducing the B-glucosidase and protease enzymes (Chintala et al., 2014).

Biochar application has been shown to promote tree growth in boreal and sub-boreal conifer forests (Saarsalmi et al. 2006, 2012), as well as in temperate forests (Solla-Gullon et al. 2006, 2008, McDonald et al. 1993, Thomas and Gale 2015). However, no information currently exists on the effect of biochar on mature ponderosa pine in dry forests of the Intermountain West. In this study, we evaluate the tree growth and soil property responses to experimental biochar soil amendment at two levels, and compare them to masticated woody biomass (a method of slash reduction used in many western forests), and fertilizer. Our hypotheses were (a) none of the soil amendments would affect tree growth; (b) biochar would not alter soil pH, exchangeable cations (calcium (Ca), magnesium (Mg), or potassium (K)) as compared to mastication or fertilization; (c) biochar would not alter fine or total soil bulk rate at the either soil depth (0-10 cm and 10-20 cm); and (d) biochar would not alter drought stress of individual trees, as indicated by the carbon isotope ratio.

1.2 METHODS

1.2.1 Study Area

The experiment was conducted at a ponderosa pine plantation located in the Swift Creek drainage of the Bitterroot National Forest (Sula Ranger District) south of Darby, Montana, USA. The site is located at 45.53.26 N 113.46.08 W and ranges 1216 to 2350 m ASL. Mean annual precipitation ranges 40.6 to 94 cm. Mean annual air temperature ranges between 4 and 7.2° C. The soil series is Totelake (a sandy-skeletal, mixed, frigid Typic Haplustept)(Soil Survey Staff, 2009). The site index (SI₁₀₀) for the stand is

roughly 58 (Milner et al. 1992). This site is characterized as the *Pinus ponderosa/Festuca idahoensis* (PIPO/FEID) habitat type) (Pfister et al. 1977)). Understory vegetation of the PIPO/FEID habitat type consists primarily of Idaho fescue (*Festuca Idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* Á. Löve), rosy pussytoes (*Antennaria rosea* Greene), onespoke oatgrass (*Danthonia unispicata* Monroe ex Macoun), and rough fescue (*Festuca campestris* Rydberg).

1.2.2 Site Treatment History

The site was clearcut in 1965, and afterward was mechanically prepared for planting with light terracing to improve seedling survival via increased soil water-holding capacity. The site was planted in 1966 with ponderosa pine. Pre-commercial thinning was conducted in 2009 just prior to this experiment.

1.2.3 Experimental Design

A subset of trees within the plantation were selected as experimental units on the basis of relative uniformity in height, diameter (Figures 1.1 and 1.2), and apparent health. Once selected, trees were randomly assigned one seven soil surface treatments, yielding six replicates of each treatment (n=42; Table 1.1). The soil surface treatments consisted of: 1) control, 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg/ha N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate biochar (2.8 Mg ha⁻¹) plus fertilizer (224.1 kg/ha N) and 7) heavy-rate biochar (22.4 Mg ha⁻¹) plus fertilizer (224.1 kg/ha N). Treatments were applied within a 15-foot radius of tree boles in August 2010. Two trees subsequently died (one each from masticated wood chip and low-rate biochar treatments), reducing the sample to 40 trees. One tree in the low-rate biochar treatment also suffered damage to its leader, and was excluded from height and volume analyses.

1.2.4 Biochar

Biochar for the study was sourced from Biochar Solutions, Inc. (Carbondale, Colorado, USA). The biochar had been produced via a two-stage reactor using a small-scale mobile pyrolysis system (Kim

et al. 2015), using agricultural residues and wood waste consisting of green mixed conifer mill residues (90% ponderosa pine), as well as beetle-killed lodgepole pine mill residues (*Pinus contorta* Douglas ex Loud.). The feedstock was ground to achieve a particle size of no greater than 7.62 cm in the longest dimension. Table 1.2 illustrates feedstock characteristics of mill and forest residues used to produce the biochar.

1.2.5 Data Collection

Tree properties

Tree diameter at breast height (DBH) and heights were measured using Spencer logger tapes and lasers during the month of July on four occasions: 2010, 2012, 2015, and 2016. We used these measurements to calculate absolute and percent change in height, DBH, basal area, and volume over a 6-year period. Tree volume was calculated in using a modification of Faurot's (1977) tree-scale derivation equation:

$$V = KBH * 0.0283$$

Where V is stand volume, K is the form factor for ponderosa pine in Montana, and BH is basal area multiplied by height. In this case, we used the individual tree heights and basal areas to calculate per-tree volume.

In order to quantitatively determine fine-scale diameter growth treatment effect within a single growing season, UMS Dendrometer D1 Vernier bands were installed on August 26, 2015 (Figure 1). Bands were used to record DBH on 14 occasions during the period encompassed by May 16 and August 3. The frictionless plastic bands were wrapped around each live tree in the study (n = 40) at breast height (1.37 m above the soil surface).

We used the C₁₂: C₁₃ carbon isotope ratio as an indicator of drought stress, comparing the pre- and post- treatment carbon isotope ratios in trees. Two cores were collected at perpendicular angles at breast

height from each tree after apparent cessation of growth (July 2015). We cut samples from 2006, 2007, 2008 (pre-treatment) and 2013, 2014 and 2015 (post-treatment) latewood rings. Pre-treatment samples from the same tree were composited, as were the three post-treatment latewood samples, yielding n=40 samples of each. Samples were stored in labeled plastic vials and transported to the USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho (USA) where we homogenized them in a ball grinder. Once homogenized, the samples were processed at the Stable Isotope Laboratory at Washington State University in Pullman, Washington (USA). There, carbon and nitrogen isotopic contents were converted to N₂ and O₂ using an elemental analyzer (ECS 4010, Costech Analytical, Valencia, CA). Using a 3m GC column, the N₂ and O₂ gases were separated and then analyzed with a continuous flow isotopic ratio mass spectrometer (Delta Plus XP, Thermofinigan, Bremen (Brenna et al., 1997; Qi et al., 2003). Samples were interspersed with reference material of known isotopic composition for calibration. The ¹⁷O value is corrected for by using the Santrock correction within the IRMS software (Santrock et al. 1985). Carbon isotope results were reported in per mill relative to Vienna Peedee belemnite (VPDB) using NBS 19 and L-SVEC for calibration (Coplen et al. 2006). We compared the post-treatment carbon isotope ratios to *In Situ* soil moisture content taken from two soil depths (0-10 cm and 10-20 cm). Tree drought stress was related to soil moisture content . The ratio of ¹³C/¹²C is expressed in parts per thousand using delta notation, which references a known carbon isotope ratio for a standard material. The equation is as follows:

$$\delta^{13} = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$$

where R_{sample} refers to the ¹²C: ¹³C isotope ratio for the sample and R_{standard} refers to the ¹²C to ¹³C isotope ratio for the standard sample as described by McCarroll and Loader (2004). By comparing these results across treatments, we generated a quantitative comparison of water stress conditions.

Soil properties

We recorded forest floor depth and collected forest floor samples (inclusive of Oa, Oi, and Oe) within 30 cm of each treatment tree using a 30 cm hoop. On treatments with masticated wood, the chips were included in collection. Samples were placed in plastic bags and transported to the lab, where they were dried at 60° C to a constant weight, and were ground to pass a 2 mm sieve. Forest floor pH was determined on a 2:1 water: soil paste. Carbon (C) and nitrogen (N) were determined using a Leco CN analyzer (Leco Corp, St. Joseph, MI).

We collected mineral soil at two depths (0-10 cm and 10-20 cm) using a soil core attached to an impact hammer (4.8 x 10 cm samplers, volume = 57.6 cm³). Soil cores were contained in plastic zip-type bags, kept cool, and transported to the lab, where they were dried at 105° C, weighed, and sieved through a 2 mm sieve. We segregated rock fragments, roots, and other organic material and weighed each component separately. Soil pH was analyzed using a 2:1 water: soil paste. Soil C and N was analyzed using a Leco TruSpec analyzer (Leco Corp, St. Joseph, MI). Cations were extracted (Ca, Mg, K) using pH neutral ammonium acetate and analysis by atomic absorption (Ca and Mg) or flame emission (K) using a Perkin Elmer (Model PinAAcle 500, Perkin Elmer, Shelton, CT, USA).

We calculated total bulk density by dividing oven-dried mass by sample volume. We calculated fine-fraction bulk density (Pbt) using volumetric and gravimetric rock-fragment contents, and using 2.65 Mg m⁻¹ as the average rate of rocks on the site (Andraski et al 1991, Page-Dumroese et al. 1999). Soil C and N pools were converted to a per-hectare basis using the fine fraction bulk rate (Homann et al. 1995, Federer et al. 1993). Organic matter (OM) of the forest floor and mineral soil were analyzed by loss-on-ignition at 400°C for 8 hours (Ball, 1964).

1.2.6 Data Analysis

We analyzed individual tree growth curves from the deondrometer dataset to determine when trees reached 99.99% of their total growth over the course of the growing season, in order to identify the

terminal date at which growth ended. We fit a linear regression between those two measurement intervals to allow for interpolation of the precise day at which this threshold of growth occurred.

Normality of response data was evaluated using the Skewness and Kurtosis (Omnibus) test ($\alpha = 0.10$), and variance homoscedasticity was evaluated using the Brown-Forsythe and Levene tests ($\alpha = 0.10$). If normality and equal variance assumptions were satisfied, we conducted one-way analysis of variance (ANOVA) tests ($\alpha = 0.10$), with Bonferroni pairwise comparison tests conducted if warranted ($\alpha = 0.10$). If the assumptions of normality and equal variance were not satisfied, we conducted Kruskal-Wallis non-parametric tests ($\alpha = 0.10$), with Kruskal-Wallis multiple comparisons test ($\alpha = 0.10$) conducted to determine pairwise differences between treatment groups if warranted. Tables 1.6 - 1.8 lists the tests conducted for each parameter based on those results.

1.3 RESULTS

1.3.1 Tree properties

At start of the experiment in 2010, trees ranged 23.1 cm to 30.0 cm in diameter, with a median of 26.8 cm. Six years following treatment (2016), diameters ranged 24.6 cm to 33.0 cm, with a median of 29.6 cm. Median diameter of 2.8 cm over 6 years, or 0.47 cm per year. Before treatment, tree heights ranged 10.7 m to 15.0 m with a median of 12.7 m. Six years later, heights ranged from 12.5 m to 16.7 m, with a median of 14.9 m. Median height increased 2.2 m over 6 years, or 0.37 m per year.

Masticated wood significantly boosted absolute and percent change in DBH after 2 years by 95.3% (p-value = 0.05924, Figure 1.3) and 96.8%, (p-value = 0.09474, Figure 1.4) respectively. The masticated woody biomass treatment also significantly increased absolute change in tree basal area (cm²) by 104.46% after 2 years (p-value = 0.04834, Figure 1.5), however, no differences exist between treatments for 2-, 5-, and 6-year percent change in basal area (Figure 1.6). There was no significant

difference in 2-, 5-, and 6-year absolute or percent change in volume between treatments (Figures 1.7 and 1.8). Height growth (absolute or percent) was unaffected by treatment over the study period (Figures 1.9 and 1.10). No treatment increased absolute or percent change in DBH (cm), basal area (cm²), or volume (m³) after 6 years. Refer to Table 1.6 (absolute change) and Table 1.7 (percent change) for non-significant p-values related to all tree growth parameters (DBH (cm), Basal Area (cm²), volume (m³), and height (m)).

Drought stress was unaffected by treatment, as indicated by the carbon isotope ratio (p-value=0.67586, Figure 1.11). However, soil moisture is closely tied to drought stress in trees and may be an early indication of moisture stress before it is detectable in trees. The high-rate biochar treatment (median = 24.5%) increased soil moisture by 57% (p-value = 0.01767, Figure 1.12) versus the control (median = 15.6%) suggesting that biochar applied at high-rates improves soil water holding capacity. No treatment effect on growing season duration was observed (p-value = 0.68199, Figure 1.13).

1.3.2 Soil properties

Soil amendments produced few effects on forest floor and mineral soil physical or chemical properties. The C content in the biochar was 83.7%; therefore, we estimate that the high-rate biochar treatment sequestered 18.7 Mg ha⁻¹ of C, and the low-rate biochar treatment sequestered 2.3 Mg ha⁻¹. The high-rate biochar treatment significantly increased C pools at the 10-20 cm soil depth by 67.7% (p-value = 0.0289, Figure 1.14), suggesting that biochar has migrated deeper into the soil from its surface application in 2010. The masticated wood treatment (median = 22.49 Mg ha⁻¹) had significantly higher OM than the fertilizer treatment (median = 9.54 Mg ha⁻¹) at the 10-20 cm soil depth (p-value = 0.07136, Figure 1.15). The forest floor pH for the high-rate biochar treatment (median = 5.97) and high-rate biochar with fertilizer treatment (median = 5.85) is significantly higher than the masticated wood treatment (median = 5.27) (by 13.3% and 11.0%, respectively (p = 0.02636, Figure 1.16). The mineral soil Ca for the high-rate biochar treatment (median = 16131.72 Mg ha⁻¹) is significantly higher than the

fertilizer treatment (median = 10695.49 Mg ha⁻¹) at the 10-20 cm depth (50.8%, p-value = 0.0430, Figure 1.17). The mineral soil Mg for the low-rate biochar treatment (median = 1677.01 Mg ha⁻¹) is significantly higher than the fertilizer treatment (median = 1165.92 Mg ha⁻¹) at the 0-10 cm soil depth (43.8%, p-value = 0.0149, Figure 1.18). Soil amendments had no significant effects on soil mineral bulk density, N, pH, and K at either sample depth (0-10 cm and 10-20 cm) (Figures 1.19-1.22). In addition, there were no significant effects on forest floor C, N, OM, Ca, Mg, or K (Figures 1.23-1.28). Refer to Table 1.8 for non-significant p-values related to all mineral soil properties, and Table 1.9 for all non-significant p-values related to forest floor properties.

1.4 DISCUSSION

1.4.1 Treatment Effects on Growth

Biochar did not significantly improve growth in mature ponderosa pine, though it did provide a temporary boost in short-term growth (2-5 years) that was no longer detectable 6 years following application. Other studies have shown a strong positive growth response to biochar in a variety of ecosystems and soils where up to a 41% increase in biomass was reported (Thomas and Gale 2015). However, many studies reported in a meta-analysis (Thomas and Gale 2015) investigated tree species and ages different than our experiment; additionally some of those studies involved pot trails and were not field experiments.

No treatment affected volume (absolute or percent) throughout the study period. That result deviates from several other studies that detected short-term (2-5 years) positive effects of charcoal-based soil amendments on immature conifer growth. However, the stands in previous studies were immature, ranging from 0-9 years in age (Solla-Gullon et al. 2006, Solla-Gullon et al. 2008, McDonald et al. 1993). The ponderosa pine trees in this study may be too old (50 years) to benefit from soil amendments, any

effects were undetectably modest. The overall non-significant effects of biochar on tree growth are comparable to several studies on mature conifers in Finland where long-term changes in growth following biochar applications were measured (Saarsalmi et al. 2004, Saarsalmi et al. 2005, Saarsalmi et al. 2006). Significant increases in tree growth have only been measured when N fertilizers were also applied (Saarsalmi et al. 2010, Saarsalmi et al. 2012). We detected no significant tree growth effects after 6-years in any of the treatments, indicating that any effects dissipated after five growing seasons. Within the Intermountain West, several field trials on tree growth responses to biochar are currently ongoing, though short-term (1-2 year) responses to biochar applications on two sites depend greatly on soil type, specifically between fine-textured, highly productive Andisols and relatively infertile coarse-textured Inceptisol (McElligott, 2011). We note that our site had a coarse-textured soil; a greater biochar response might be more likely at a more fertile site with fine-textured soils.

We observed the greatest increase in basal area and DBH over a two-year period (2010-2012) in the masticated woody biomass treatment group. This is consistent with another study that assessed the effect of mulch treatments on tree growth (Haywood, 1999), and indicates that mastication may be a suitable option to increase tree growth over a short-term period. However, trees in the masticated treatment showed no significant diameter or volume increases after 6 years relative to any other treatment. Although masticating wood was not more effective than biochar and fertilizer at altering tree growth, it is a less expensive option and on other sites could be considered more cost-effective for reducing forest residues to mitigate wildfire hazard (Restaino and Peterson 2013). However, some research suggests that if burned, masticated forest residues can result in lethal soil temperatures (Busse et al. 2005). Additionally, if C sequestration is the goal of a forest restoration treatment, then masticated wood may not increase belowground C, but instead eventually decompose and release CO₂ (Boddy and Watkinson 1995).

Though many of the treatment effects on tree growth metrics (DBH, basal area, height, volume) were statistically non-significant, differences in medians existed between treatments that otherwise may have been significant if it were not for high variability and the study's small number of replicates. This was the case with 5-year and 6-year absolute change in DBH (cm) basal area (cm²), and volume (m³), in which all treatments had greater median values than the control. Of those treatments, masticated woody biomass had the greatest median values. The masticated woody biomass treatment medians for 5-year and 6-year changes in DBH (cm) (3.05 cm and 3.81 cm, respectively) were 80.5% and 75.6% greater than the control group medians (1.69 cm and 2.17, respectively). The masticated woody biomass treatment medians for 5-year and 6-year changes in basal area (132.55 cm² and 167.97 cm², respectively) were 81.6% and 93.8% greater than the control medians (73.00 cm² and 86.68 cm², respectively). The masticated woody biomass treatment medians for 5-year and 6-year change in volume (0.122 m³ and 0.138 m³, respectively) were 58.4 % and 68.3% greater than the control medians (0.077 m³ and 0.082 m³, respectively).

1.4.2 Treatment Effects on Soil Moisture and Related Water Use

Wood contains two stable, non-radioactive carbon isotopes that are nearly physically and chemically identical with the exception of the number of protons (McCarroll & Loader, 2004). The discrimination against the ¹³C isotope as indicated by the isotopic ratio of ¹³C/¹²C is a signal of water stress and availability in seasonally dry climates (Warren et al. 2001). Declines in δ¹³C represent the depletion of ¹³C material in the ¹³C/¹²C ratio. In other words, as plants experience water stress, there is less discrimination of the heavier ¹³C isotope, resulting in higher ¹³C values, and higher ¹³C/¹²C ratios. This outcome was not observed in our study. Soil moisture and drought stress are linked; therefore, a lack of differences in drought stress among the fertilizer, mastication, low-rate biochar, and low-rate biochar and high-rate biochar plus fertilizer treatment groups are explained by the lack of detectable differences in *In Situ* moisture for those same treatments. However, the lack of significant effect on drought stress in the

high-rate biochar group, despite the increase in soil moisture, indicates that this site may not be moisture limited at all. In other words, the trees in all treatment groups were receiving sufficient moisture. If the trees were not receiving sufficient moisture, however, the soil moisture increase associated with the high-rate biochar addition could reasonably reduce drought stress in trees as indicated by the stable carbon isotope ratio.

In this study, no treatment effect on growing season duration was evident. Our results contradict a study on the impact of drought on the temporal dynamics of wood formation in Scots pine (*Pinus sylvestris* L., Gruber et al. 2010). Wood formation in Scots pine at a xeric site stopped four weeks earlier than a lesser moisture-limited dry-mesic site, indicating that drought stress has a strong influence on cell differentiation and, therefore, growing season duration. This discrepancy may be because the trees were not greatly moisture limited prior to biochar application, such that a 57% increase in soil moisture did little to affect tree growth at a detectable level. It may also be because the difference in soil moisture between the high-rate biochar treatment and the control may not be enough to cause a detectable difference in growing season duration.

1.4.3 Treatment Effect on Soil Physiochemical Properties

High-rate biochar increased forest floor pH, probably directly attributable to the high pH of the applied biochar (pH = 8.7). Soil C was also higher in the high-rate biochar treatments at 10-20 cm soil depth. Our soil was relatively coarse-textured and had considerable amounts of rocks (median gravimetric rock content = 36.7%) which is likely one reason biochar translocated from the upper depth to the lower depth within the 6 years. Whether the biochar will stay at this depth or continue to move to bedrock is unforeseeable at this time. An additional effect of the biochar was increased Mg and Ca in the mineral soil, suggesting its potential to restore mineral cations that were removed during thinning. There is no evidence from this study to support the release of K bound to the exchange sites on the biochar into the soil, though this is inconsistent with other research (Biederman and Harpole 2012).

High-rate biochar application improved soil moisture by 57% from 2010-2015, but no improvements were observed in the other biochar treatments, and each had considerable variability. Though it is generally accepted that biochar increases water-holding capacity due to its porous nature (Major et al. 2009), no information exists on the effect of biochar in dry pine forests in the Intermountain West. Tree stress caused by low moisture and high temperatures can lead to insect outbreaks and therefore, increased soil moisture may help prevent large-scale insect outbreaks (Raffa et al. 2008). Several studies document the increase of water holding capacity or increasing available water as a result of biochar application. For example, biochar amendments at the 10-tons/acre rate resulted in greater soil water retention (up to 15%) on an Iowa agricultural soil (Laird et al. 2010) and Karhu et al. (2011) reported a water holding-capacity increase of 11%. However, agricultural soils are usually much different from forest soils. Our site had considerable variability in soil OM, which may account for the variability we see in *In Situ* moisture. The forest floor material also acts a mulch to help keep water from evaporating. All treatments had no significant effect on mineral soil OM at the 0-10 cm soil depth, or on forest floor OM. These results are consistent with a study that reported no evidence supporting the increased degradation of or decreased stability of OM following biochar application (Bruun and EL-Zehery 2012). However, in our study, the masticated woody biomass treatment resulted in significantly higher OM compared to the fertilizer treatment.

None of the soil amendments affected soil bulk density. Very little information exists on the effect of biochar and other charcoal-based soil amendments on total bulk density of forest soil. However, studies on other types of soils found reduced agricultural and crop soil bulk densities associated with biochar application (Oguntunde et al 2008, Chen et al. 2011, Laird et al. 2010). Biochar has shown to be an effective tool for reducing bulk density of decommissioned forest roads (Verheijen et al. 2009), but in a field study conducted on decommissioned roads in central Montana, biochar did not significantly reduce bulk density compared to ripping (Page-Dumroese et al. 2017). In our study, biochar was not incorporated

into the soil as it is for road or other restoration treatments, so changes in bulk density should perhaps not have been expected.

High application rates of biochar resulted in significantly higher forest floor pH than the masticated wood treatment. Masticated wood was incorporated into the forest floor samples when analyzed, and therefore may have caused the pH to be lower than the other treatments. This result is consistent with several other studies on the effect of charcoal-based soil amendments on the organic layer (Bramryd and Fransman 1995, Saarsalmi et al. 2001, Saarsalmi et al. 2004, Saarsalmi et al. 2005, Helmisaari 2009). Rising pH following treatment is the result of the basic cation-rich biochar, which effectively raises the pH of the soil over time. Neither low-rate biochar nor fertilization affected forest floor pH. Although the pH of the forest floor increased, there was no detectable change in the mineral soil pH after 5 years. One explanation is that an insufficient amount of biochar was added to affect mineral soil pH. Additionally, the biochar may have been slightly buffered during its movement through the forest floor and into the mineral soil. Multiple studies on the effect of wood-ash amendments on soil properties detected increases in soil pH (Solla-Gullon et al. 2008, Saarsalmi et al. 2004), with the greatest differences occurring close to the surface (Saarsalmi et al. 2004). Increases in pH levels occur naturally over time, resulting from the continual leaching of base cations (Saarsalmi et al. 2004). Changes in pH in the organic layer alone are not unheard of (Helmisaari et al. 2009). Because the biochar was applied to the surface rather than incorporated into the soil, it has a lower solubilization than if it had been incorporated (Solla-Gullon et al. 2006).

Since carbon increases were only detected at the 10-20 cm depth, residence time in this coarse-textured soil may not have been long enough to enable detection above the 10 cm depth. Other studies report an increase in C associated with biochar application (Laird et al 2010, Prommer et al. 2014), but did not specify whether C increased deeper in the soil. The latter study also reported decreased extractable organic carbon pools associated with the increased C as a result of biochar application, which may be a

negative long-term effect associated with biochar application. In this study none of the surface soil amendments had an effect on N at either soil depth. Nitrogen levels were highly variable by sample. Biochar has been reported to increase N in agricultural soils (Laird et al. 2010), though evidence suggests that biochar results in a decoupling of N cycles, increasing N, and reducing inorganic N output (Prommer et al. 2014). Increased soil N has been associated with masticated wood amendments, but not until the third growing season following application (Miller and Seastedt, 2009). In this study, masticated wood did not increase mineral soil N. In fact, masticated wood produced the second lowest N level, possibly a result of the wood's C: N ratio. The mineral soil C levels varied greatly within treatments and depths, but were generally comparable to those of other ponderosa pine sites within the Inland Northwest (Gundale et al. 2005, Page-Dumroese and Jurgensen 2006). Nitrogen levels also varied greatly within treatments, but were much lower than other conifer-dominated sites in the Inland Northwest (Page-Dumroese and Jurgensen 2006), indicating that this site is N-limited – perhaps so much so that the rates at which we applied N were ineffective. Variability in C and N pools between sites may be attributed to several factors including species (both understory and overstory), soil type, harvesting methods, and time since harvesting.

Magnesium content at the 0-10 cm depth and Ca at the 10-20 cm depth were increased by high-rate biochar. Potassium rates were unaffected by any surface treatment. Several studies report increases in not only Ca and Mg, but also K following wood ash applications, indicating that wood ash replenishes soil mineral nutrients (Saarsalmi et al. 2005, 2006, 2010, 2012, Solla-Gullon et al. 2006, 2008). It has also been shown to increase the Mg and Ca in the soil humus layer (Saarsalmi et al. 2004). Another study by Page-Dumroese et al. (2017) found initial increases in K followed by later boosts in Mg and Ca. Since we collected the soil samples after the fifth growing season, K levels may have increased and dissipated prior to collection, whereas the Mg and Ca increases were still detectable (Page-Dumroese et al. 2017).

1.5 CONCLUSIONS AND FURTHER CONSIDERATIONS

Biochar had minimal effect on tree volume growth. However, at the high application rate biochar improved soil water holding capacity, and increased Mg at the surface 0-10 cm in the mineral soil, forest floor pH, and SOC at the deeper soil layer (10-20 cm). Land managers should weigh the cost of amendment application against the benefits of the desired tree changes. Understory vegetation at the study site may be competing with trees for resources offered by the amendments and thereby obscuring the potential effect of these amendments on tree growth and soil properties. In retrospect, pre-treatment understory preparation with herbicides would have helped direct the amendments to trees rather than understory vegetation. Further, measurements were collected two, five, and six growing seasons following application. A more precise understanding of treatment effects can be developed by collecting measurements every growing season.

1.6 SUMMARY

- Biochar did not significantly improve short-term (2-6 years) tree growth, reduce moisture stress (as measured by $^{13}\text{C}:$ ^{12}C ratio), or increase growing season duration in mature ponderosa pine, though it did increase forest floor pH and soil organic C at deeper soil depths at the high rate.
- At the application rate of 22.4 Mg ha^{-1} and a C content in the biochar of 83.66%, we sequestered 18.7 Mg ha^{-1} of C
- Biochar enhanced soil mineral nutrients (Mg and Ca) that can be lost from harvesting
- Masticated woody biomass applied at a rate of 38.1 Mg ha^{-1} was the most effective soil amendment for boosting short-term growth
- The high-rate biochar treatment significantly increased soil moisture by 57%

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1.7 FIGURES AND TABLES

Table 1.1. Treatments applied in 2010 and densities of application.

Treatment	Application Rate
Control	N/A
Masticated Woody Biomass	38.1 Mg ha ⁻¹
Fertilizer	224.1 kg ha ⁻¹ N
Low-Rate Biochar	2.8 Mg ha ⁻¹
High-Rate Biochar	22.4 Mg ha ⁻¹
Low-Rate biochar + Fertilizer	2.8 Mg ha ⁻¹ + 224.1 kg/ha ⁻¹ N
High-Rate biochar + Fertilizer	22.4 Mg ha ⁻¹ + 224.1 kg ha ⁻¹ N

Table 1.2. Mill residues of biochar and feedstock used for 2010 application

	Moisture (%)	Ash (%)	Fixed C (%)	Organic Cations (%)	
				C	N
Biochar	2.31	9.38	71.66	83.66	0.43
Feedstock	7.89	1.23	11.29	45.57	0.1

Table 1.3. Synthesis of field studies on effects of charcoal-based soil amendments on soil properties.

Location	Feedstock	Application Rate	Duration of Study	Effect on Mineral Soil Properties	Citation
Finland	Loose wood ash	3 tons/ha ⁻¹	10 years	Increase in soil pH at all soil depths and Ca and Mg in humus layer	Saarsalmi et al. 2004
Finland	Loose wood ash	1, 2.5, 5 tons/ha ⁻¹	10 years	Increased soil pH, Ca, Mg, and K	Saarsalmi et al. 2005
N. Finland	Wood ash	1, 2.5, 5 tons/ha ⁻¹	23 years	5 tons/ha ⁻¹ rate increased soil pH, Ca, P, Mg, and K in all soil layers, especially humus	Saarsalmi et al. 2006
Finland	Wood ash	3 tons/ha ⁻¹	15 years	3 tons/ha ⁻¹ increased soil pH, Ca, Mg, and P, and in some cases K	Saarsalmi et al. 2010
Finland	Wood ash	1, 2.5, 5 tons/ha ⁻¹	30 years	Increased soil pH, Ca, Mg, and K	Saarsalmi et al. 2012
N. Spain	Mixed wood-bark ash	5 tons/ha ⁻¹	5 years	Increased soil pH, P, Ca, Mg, and K	Solla-Gullon et al. 2008
N. Spain	Wood-bark ash	10 and 20 tons/ha ⁻¹	5 years	Increased soil pH, Ca, Mg, and K	Solla-Gullon et al. 2006

Table 1.4. Synthesis of field studies conducted on the effect of charcoal-based soil amendments on coniferous tree growth.

Location	Forest Type	Species	Application Rate	Feedstock	Stand Age at Assessment	Duration of Study	Wood Ash Effect on Tree Growth	Citation
Finland	Boreal	Mixed (Scots Pine & Norway Spruce)	3 tons/ha ⁻¹	Loose wood ash	Middle aged & older	10 years	No significant effect on volume growth	Saarsalmi et al. 2004
Finland	Boreal	Scots pine	1, 2.5, 5 tons/ha ⁻¹	Loose wood ash	100 years	10 years	No significant effect on volume growth	Saarsalmi et al. 2005
N. Finland	Boreal	Scots pine	1, 2.5, 5 tons/ha ⁻¹	Wood ash	60 years	23 years	Positive effect on growth, but not significant	Saarsalmi et al. 2006
Finland	Boreal	Scots pine & Norway spruce (2 separate stands)	3 tons/ha ⁻¹	Wood ash	46 years – Scots pine 60 years – Norway spruce	15 years	Slight positive growth in spruce after third 5-year period	Saarsalmi et al. 2010
N. Finland	Boreal	Scots pine	1, 2.5, 5 tons/ha ⁻¹	Wood ash	60 years	30 years	Positive effect on basal area mean increment when applied with N	Saarsalmi et al. 2012
N. Spain	Temperate	Douglas-fir	10 and 20 tons/ha ⁻¹	Wood-bark ash	5 years	5 years	Increases in all biomass measurements	Solla-Gullon et al. 2006
N. Spain	Temperate	Monterey pine	5 tons/ha ⁻¹	Mixed wood-bark ash	Seedlings	5 years	Height and diameter growth significant after 5 years	Solla-Gullon et al. 2008

Vancouver Island, BC, Canada	Temperate	Western redcedar	5 tons/ha ⁻¹	Wood ash	9 years	2 years	No effect on tree growth	McDonald et al. 1993
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Table 1.5. P-values for Diameter at breast height (DBH) (cm), basal area (cm²), and height (m) for 2010, 2012, 2015, and 2016, at $\alpha = 0.10$ based on the Kruskal-Wallis non-parametric test. There are no significant differences between treatment groups for any combination of growth parameter and year.

	2010	2012	2015	2016
DBH (cm)	0.74664	0.82418	0.68651	0.73894
Basal Area (cm²)	0.80609	0.79263	0.66999	0.72126
HT (m)	0.40882	0.50174	0.28194	0.32066
Volume (cm³)	0.37540	0.46133	0.40623	0.40102

Table 1.6. Satisfaction of normality and equal variance assumptions, analysis of variance test used with associated p-value, and follow-up test used if significance was found for absolute changes in growth parameters. The follow up test for ANOVA and Kruskal-Wallis tests are the Bonferroni test and Dunn's test, respectively. For both ANOVA and Kruskal-Wallis tests, $\alpha = 0.10$. Significant p-values are highlighted in yellow.

Variable		Normality Satisfied?	Equal Variance Satisfied?	Test	P-value	Multiple Comparison test
Absolute Change in Height (m)	2-year	No	No	Kruskal-Wallis	0.59005	N/A
	5-year	No	Yes	Kruskal-Wallis	0.48989	N/A
	6-year	Yes	No	Kruskal-Wallis	0.88001	N/A
Absolute Change in DBH (cm)	2-year	Yes	Yes	ANOVA	0.05924	Bonferroni test
	5-year	Yes	Yes	ANOVA	0.20589	N/A
	6-year	No	Yes	Kruskal-Wallis	0.43340	N/A
Absolute Change in Basal Area (cm ²)	2-year	Yes	Yes	ANOVA	0.04834	Bonferroni test
	5-year	Yes	Yes	ANOVA	0.20828	N/A
	6-year	No	Yes	Kruskal-Wallis	0.42440	N/A
Absolute Change in Volume (cm ³)	2-year	No	No	ANOVA	0.63735	N/A
	5-year	Yes	Yes	ANOVA	0.16449	N/A
	6-year	Yes	Yes	ANOVA	0.45206	N/A

Table 1.7. Satisfaction of normality and equal variance assumptions, analysis of variance test used with associated p-value, and follow-up test used if significance was found for percent changes in growth parameters. The follow up test for ANOVA and Kruskal-Wallis tests are the Bonferroni test and Dunn’s test, respectively. For both ANOVA and Kruskal-Wallis tests, $\alpha = 0.10$. Significant p-values are highlighted in yellow.

Variable		Normality	Equal Variance	Test	P-value	Multiple Comparison test
Percent Change in Height	2-year	No	Yes	Kruskal-Wallis	0.60214	N/A
	5-year	No	Yes	Kruskal-Wallis	0.52329	N/A
	6-year	No	No	Kruskal-Wallis	0.90803	N/A
Percent Change in DBH	2-year	Yes	Yes	ANOVA	0.09474	Bonferroni test
	5-year	Yes	Yes	ANOVA	0.26190	N/A
	6-year	Yes	Yes	ANOVA	0.59949	N/A
Percent Change in Basal Area	2-year	Yes	Yes	ANOVA	0.11291	N/A
	5-year	Yes	Yes	ANOVA	0.26996	N/A
	6-year	Yes	Yes	ANOVA	0.74125	N/A
Percent Change in Volume	2-year	No	No	Kruskal-Wallis	0.34526	N/A
	5-year	No	Yes	Kruskal-Wallis	0.20864	N/A
	6-year	Yes	Yes	ANOVA	0.77707	N/A

Table 1.8. Satisfaction of normality and equal variance assumptions, analysis of variance test used with associated p-value, and follow-up test used if significance was found for growing season duration, *In Situ* moisture, and soil parameters at two sample depths for mineral soil. The follow up test for ANOVA and Kruskal-Wallis tests are the Bonferroni test ($\alpha = 0.10$) and Dunn's test ($\alpha = 0.10$), respectively. For both ANOVA and Kruskal-Wallis tests, $\alpha = 0.10$. Significant p-values are highlighted in yellow.

Variable	Soil Depth	Normality Satisfied?	Equal Variance Satisfied?	Test	P-value	Follow-up
Growing season duration (days)	N/A	Yes	Yes	ANOVA	0.68199	N/A
Moisture Stress ($^{13}\text{C}:^{12}\text{C}$)	N/A	No	Yes	Kruskal-Wallis	0.67586	N/A
Soil moisture (%)	N/A	No	Yes	Kruskal-Wallis	0.01767	Dunn's Test
Total bulk rate (Mg/m^3)	0-10 cm	Yes	Yes	ANOVA	0.38181	N/A
	10-20cm	Yes	Yes	ANOVA	0.84183	N/A
Mineral Soil pH	0-10 cm	Yes	Yes	ANOVA	0.13214	N/A
	10-20cm	Yes	Yes	ANOVA	0.44486	N/A
Mineral soil C (Mg ha^{-1})	0-10 cm	Yes	No	Kruskal-Wallis	0.64793	N/A
	10-20 cm	Yes	Yes	ANOVA	0.02890	Bonferroni Test
Mineral soil N (kg/ha^{-1})	0-10 cm	No	No	Kruskal-Wallis	0.82682	N/A
	10-20 cm	No	Yes	Kruskal-Wallis	0.52776	N/A
Mineral soil OM (Mg ha^{-1})	0-10 cm	Yes	No	Kruskal-Wallis	0.69675	N/A
	10-20 cm	No	Yes	Kruskal-Wallis	0.07136	Dunn's Test
Mineral soil Ca (Mg ha^{-1})	0-10 cm	Yes	Yes	ANOVA	0.69019	N/A
	10-20 cm	Yes	Yes	ANOVA	0.04304	Bonferroni Test
Mineral soil Mg (Mg ha^{-1})	0-10 cm	No	Yes	Kruskal-Wallis	0.01488	Dunn's Test
	10-20 cm	No	Yes	Kruskal-Wallis	0.16487	N/A
Mineral soil K (Mg ha^{-1})	0-10 cm	Yes	Yes	ANOVA	0.25495	N/A
	10-20 cm	No	Yes	Kruskal-Wallis	0.37836	N/A

Table 1.9. Satisfaction of normality and equal variance assumptions, analysis of variance test used with associated p-value, and follow-up test used if significance was found for forest floor (FF). The follow up test for ANOVA and Kruskal-Wallis tests are the Bonferroni test ($\alpha = 0.10$) and Dunn's test ($\alpha = 0.10$), respectively. For both ANOVA and Kruskal-Wallis tests, $\alpha = 0.10$. Significant p-values are highlighted yellow.

Variable	Normality Satisfied?	Equal Variance Satisfied?	Test	P-value	Follow-up
FF pH	No	No	Kruskal-Wallis	0.02636	Dunn's Test
FF C (Mg/ha³)	No	No	Kruskal-Wallis	0.40774	N/A
FF N (kg/ha³)	No	Yes	Kruskal-Wallis	0.40243	N/A
FF OM (Mg/ha³)	No	Yes	Kruskal-Wallis	0.47220	N/A
FF Ca (Mg/ha³)	No	Yes	Kruskal-Wallis	0.41432	N/A
FF Mg (Mg/ha³)	No	Yes	Kruskal-Wallis	0.49528	N/A
FF K (Mg/ha³)	No	Yes	Kruskal-Wallis	0.13762	N/A

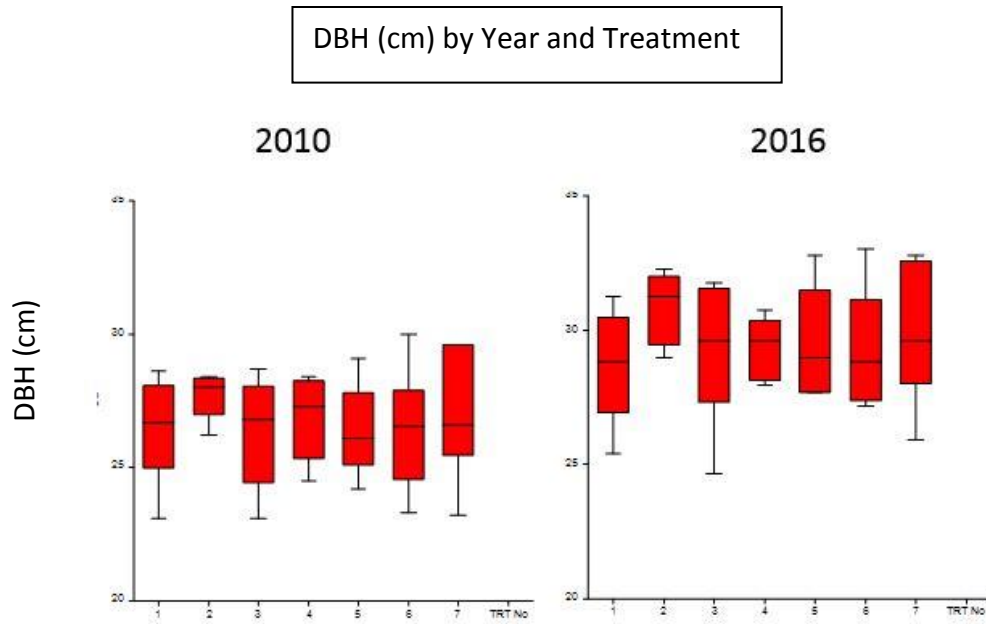


Figure 1.1. DBH (cm) by year and treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

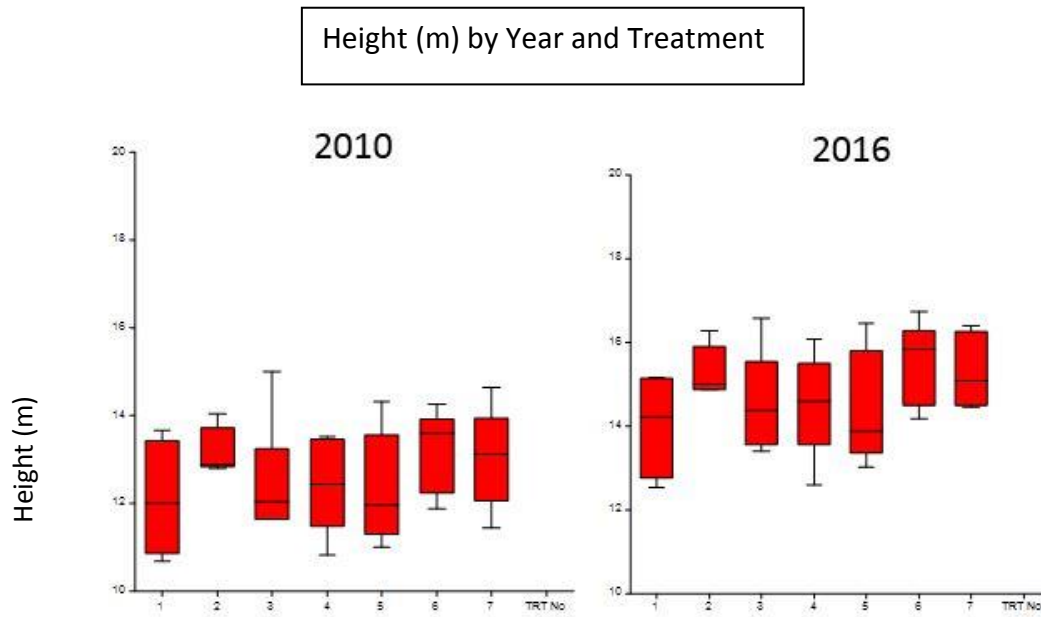


Figure 1.2. Height (m) by treatment in 2010 and 2016. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

Change in DBH (cm) by Treatment and Year

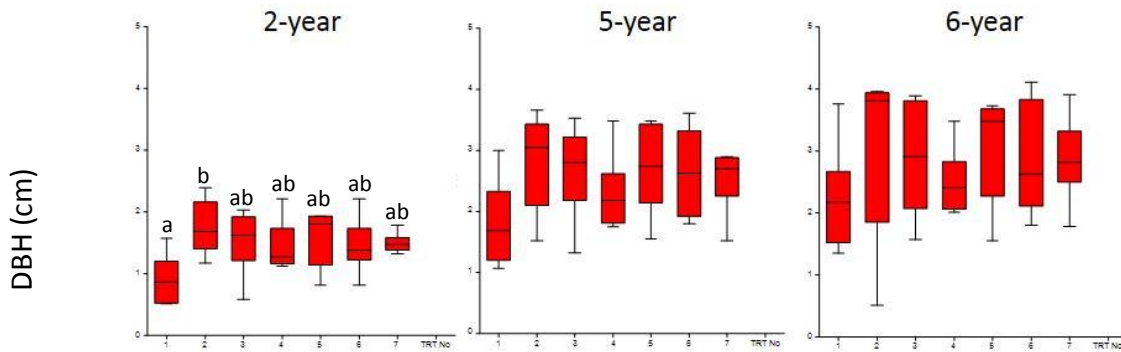


Figure 1.3. 2-, 5-, and 6- year changes in DBH by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

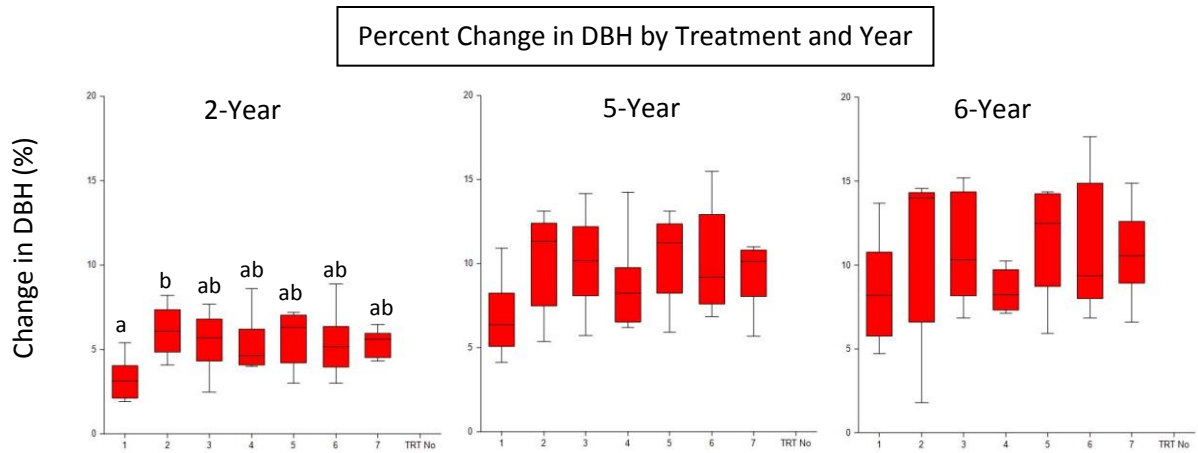


Figure 1.4. 2-, 5-, and 6-year percent change in DBH by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

Change in Basal Area (cm²) by Treatment and Year

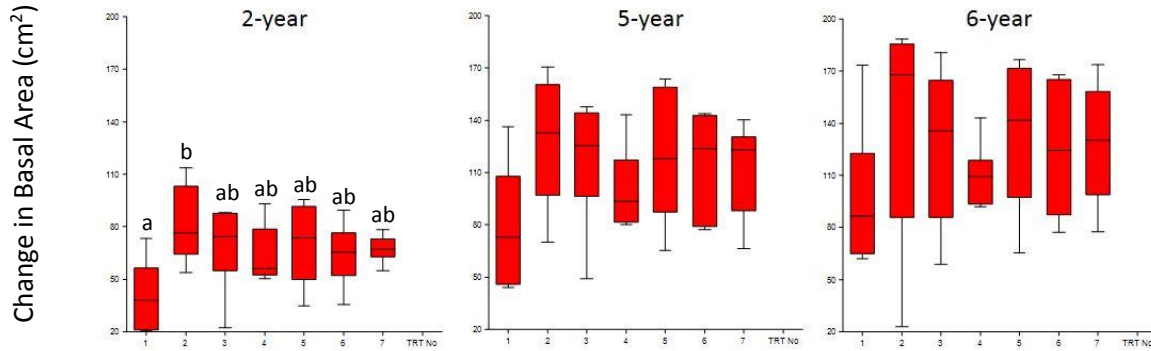


Figure 1.5. 2-, 5-, and 6-year change in basal area (cm²) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

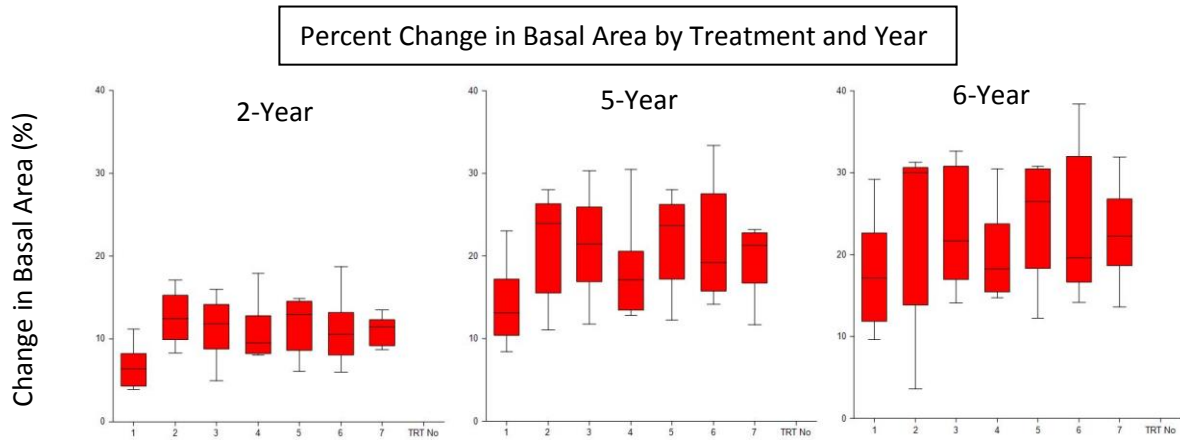


Figure 1.6. 2-, 5-, and 6-year percent change in basal area by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

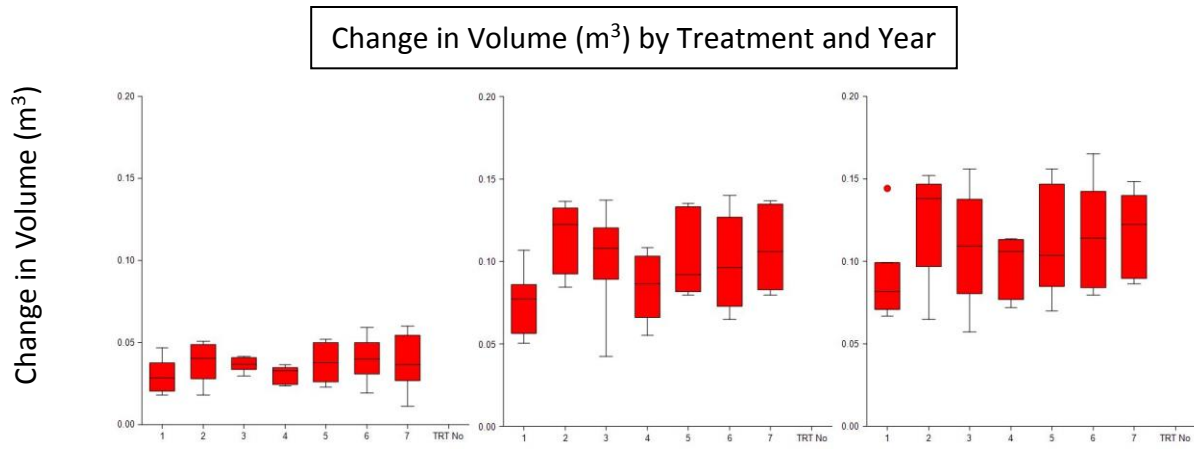


Figure 1.7. 2-, 5-, and 6-year change in volume (m³) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N).

Percent Change in Volume by Treatment and Year

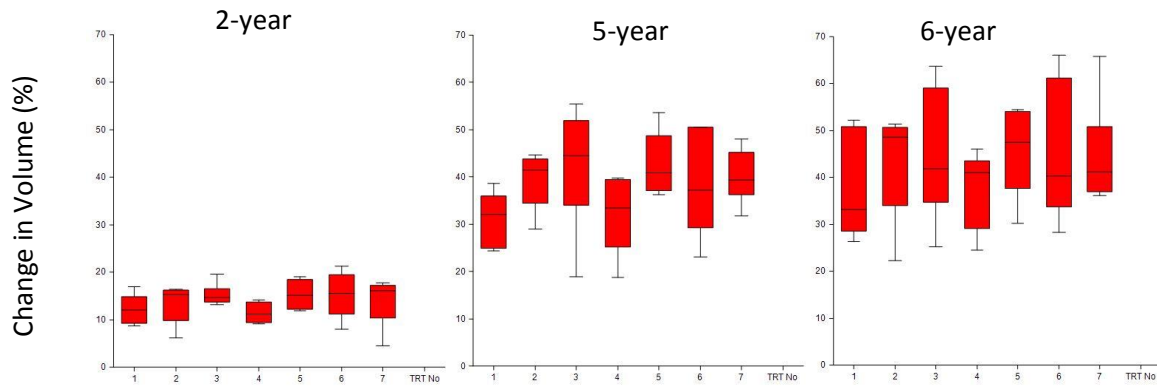


Figure 1.8. Percent changes in volume for each treatment 2, 5, and 6 years following application. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$)

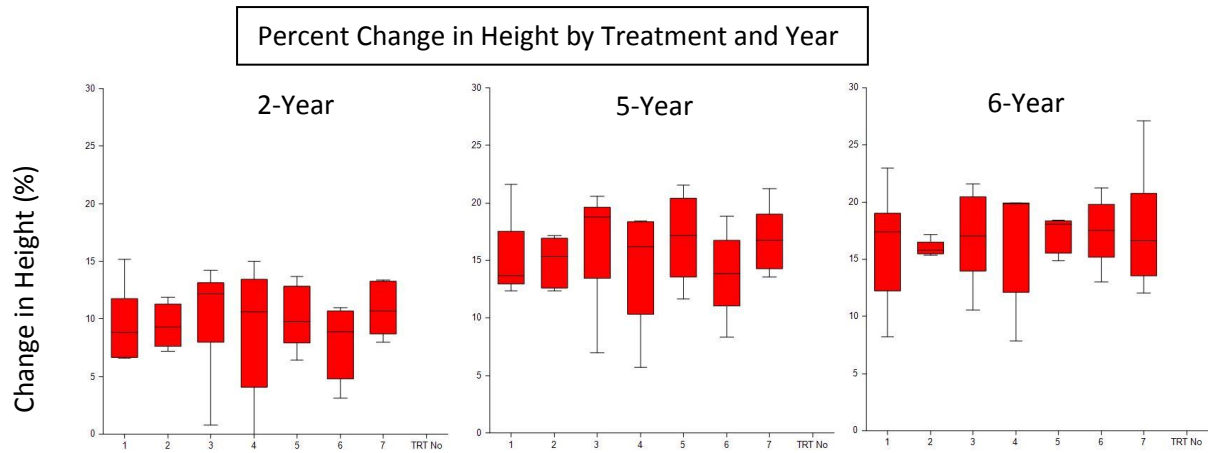


Figure 1.9. 2-, 5-, and 6-year percent change in height by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

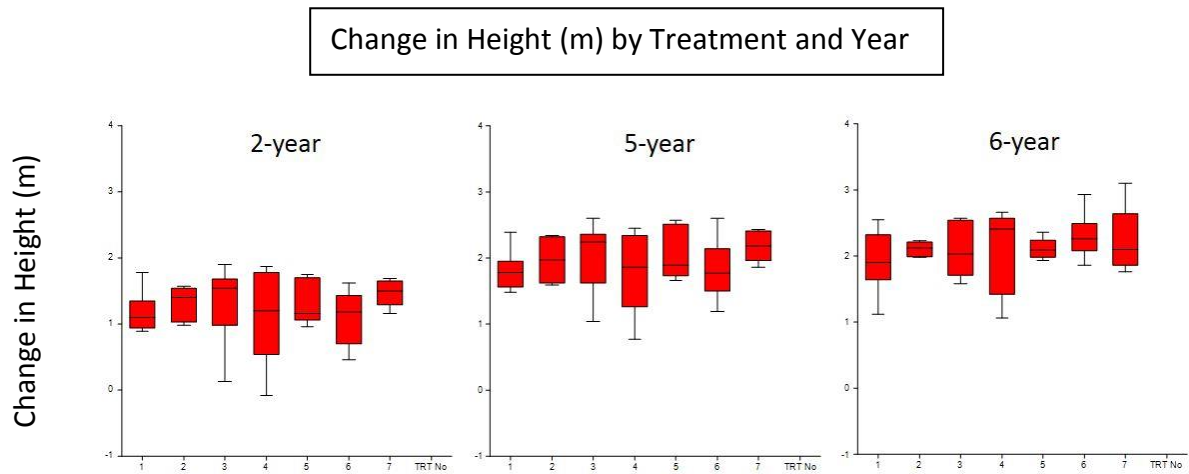


Figure 1.10. 2-, 5-, and 6-year change in height (m) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

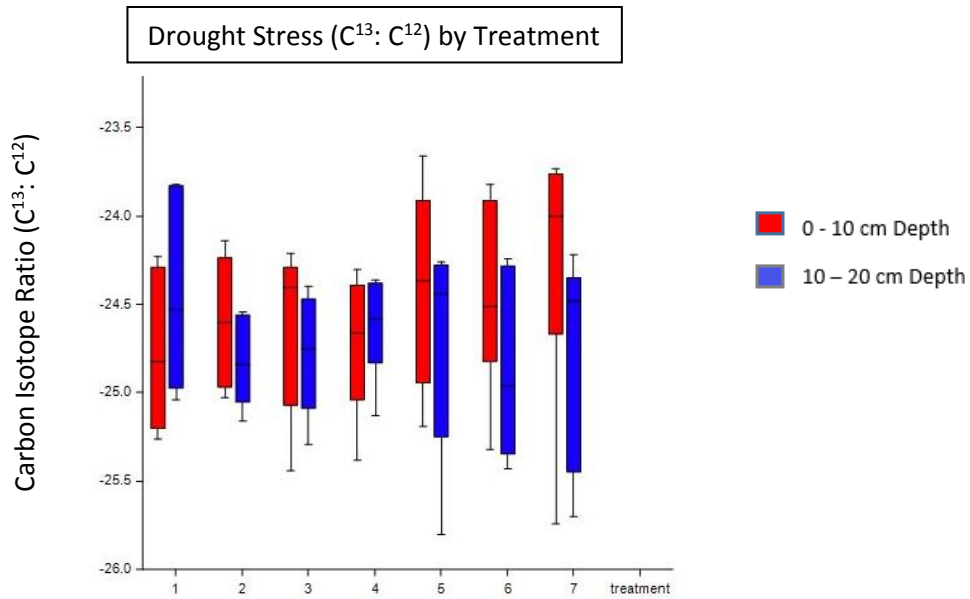


Figure 1.11. Drought stress as indicated by stable carbon isotope ratio of tree cores pre- and post-treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N).

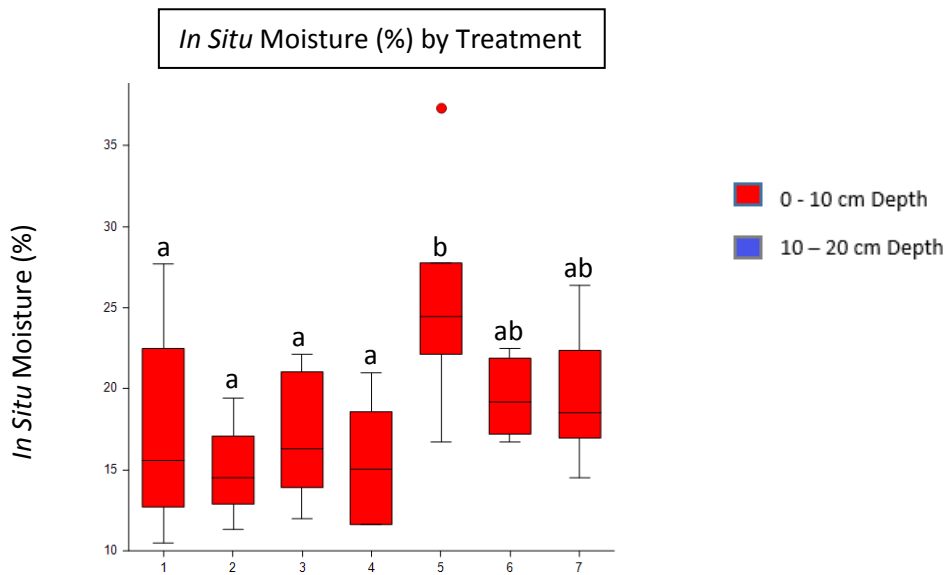


Figure 1.12. *In Situ* moisture (%) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

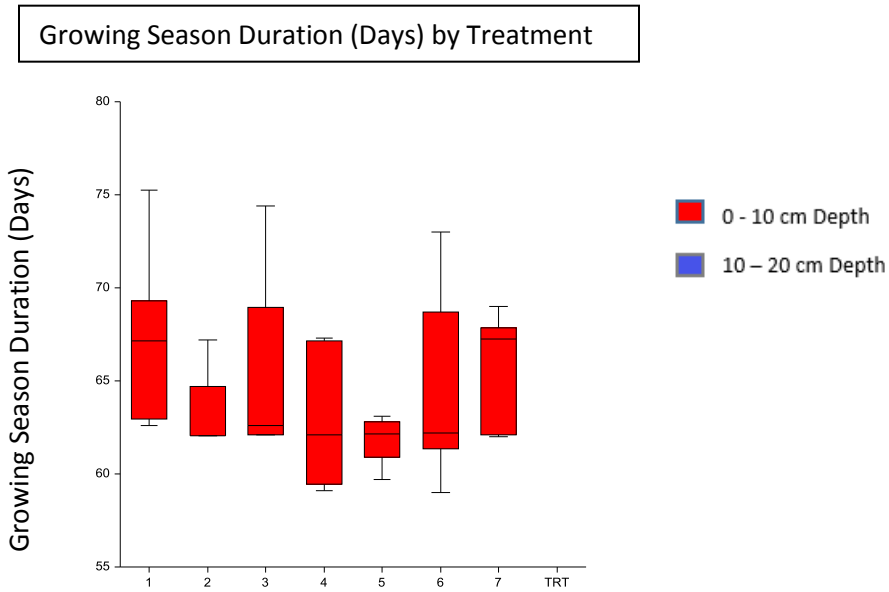


Figure 1.13. Growing season duration by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

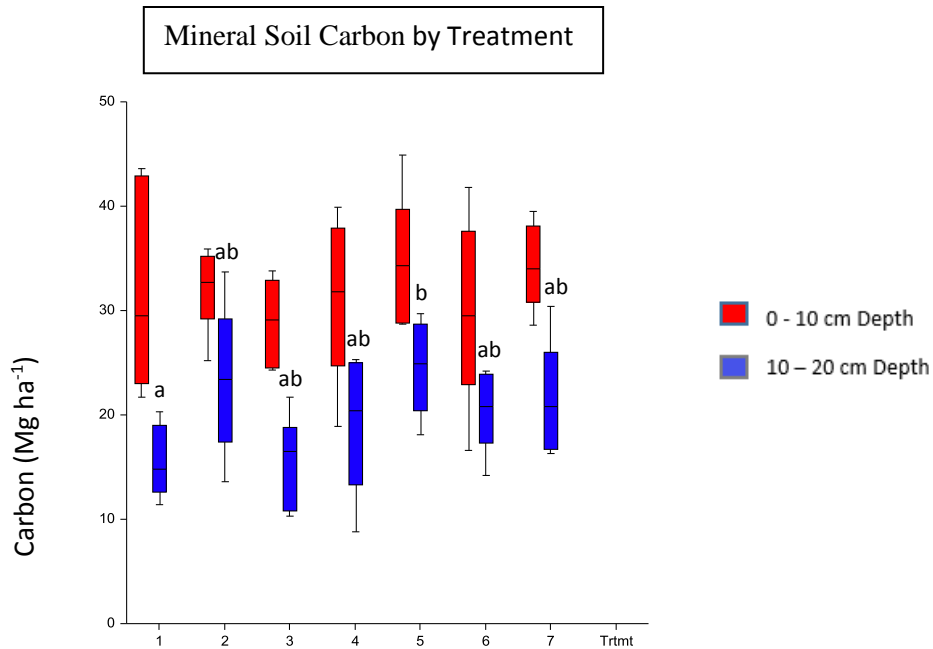


Figure 1.14. Mineral soil carbon (Mg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2). Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups at the 10-20 cm depth ($\alpha = 0.1$).

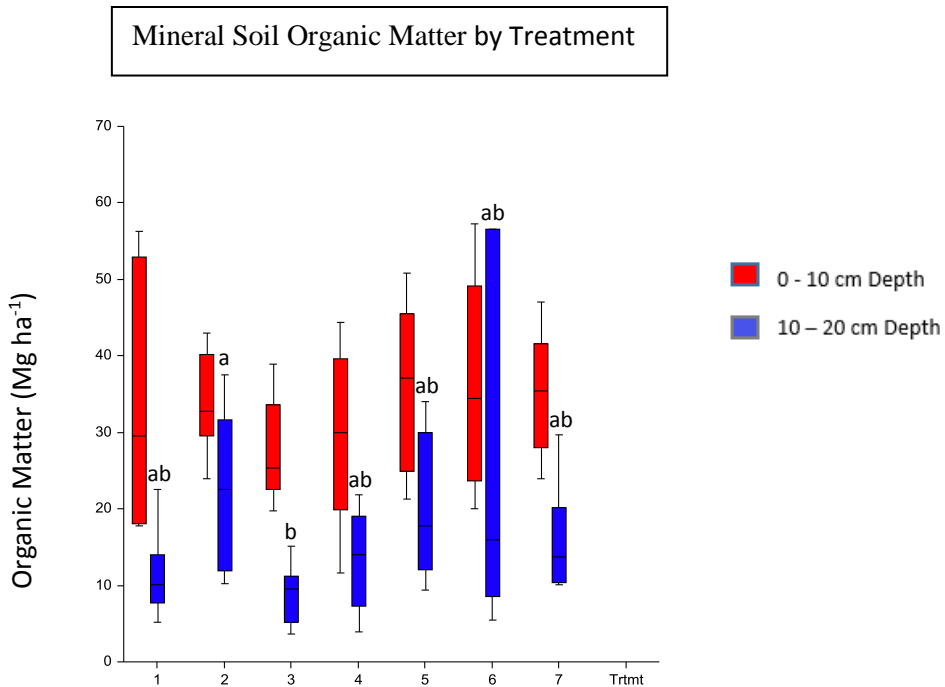


Figure 1.15. Mineral soil organic matter (Mg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups at the 10-20 cm depth ($\alpha = 0.1$).

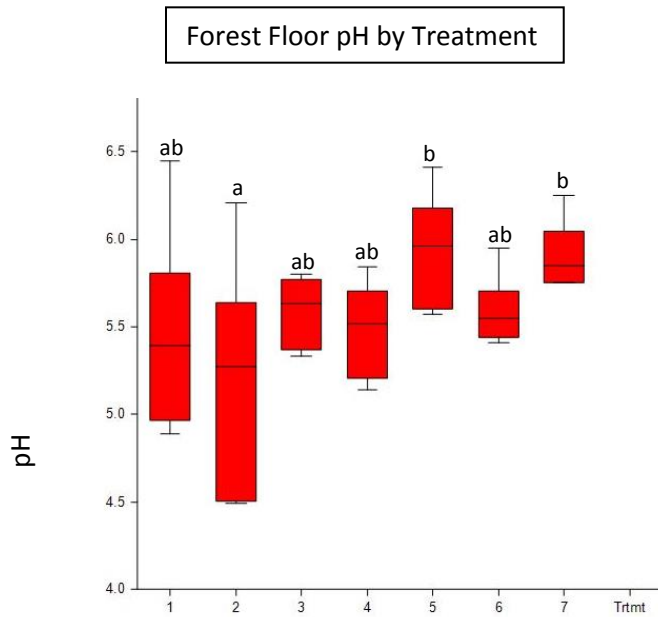


Figure 1.16. Forest floor pH by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups ($\alpha = 0.1$).

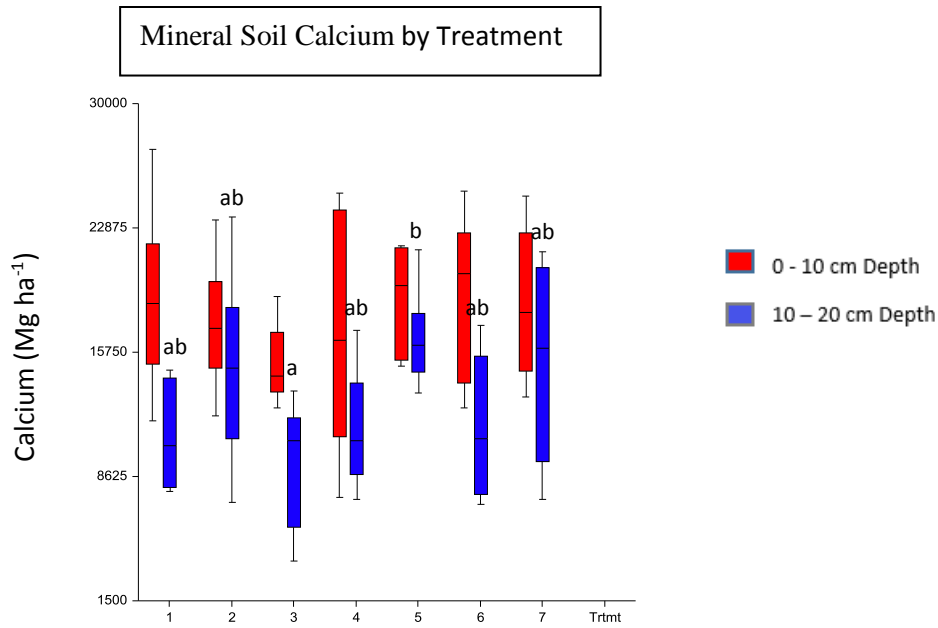


Figure 1.17. Extractable calcium (Mg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups at the 10-20 cm depths ($\alpha = 0.1$).

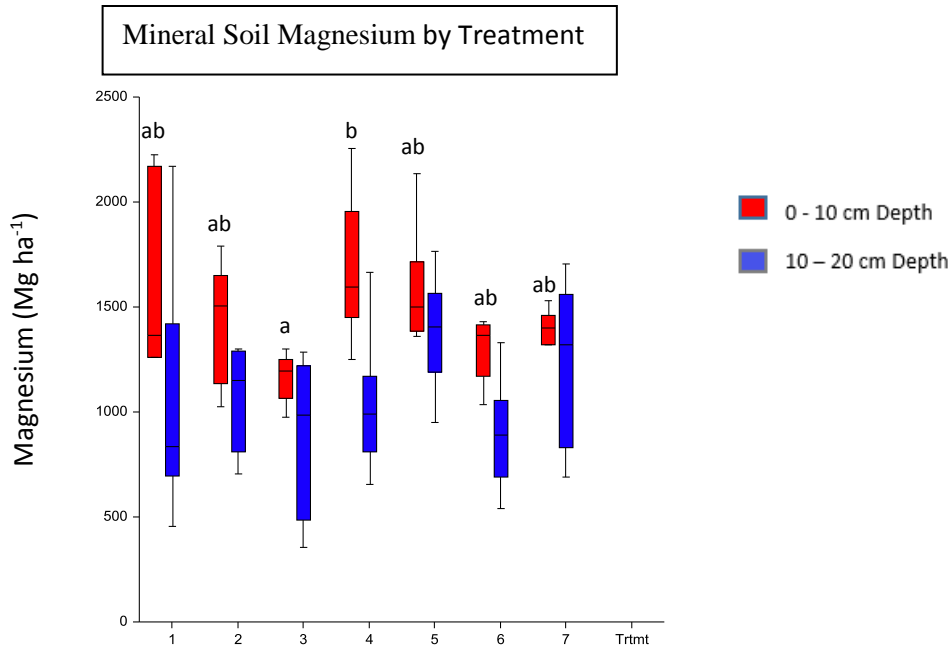


Figure 1.18. Extractable magnesium (Mg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$). Different letters indicate statistically significant differences between treatment groups at the 0 – 10 cm soil depth ($\alpha = 0.1$).

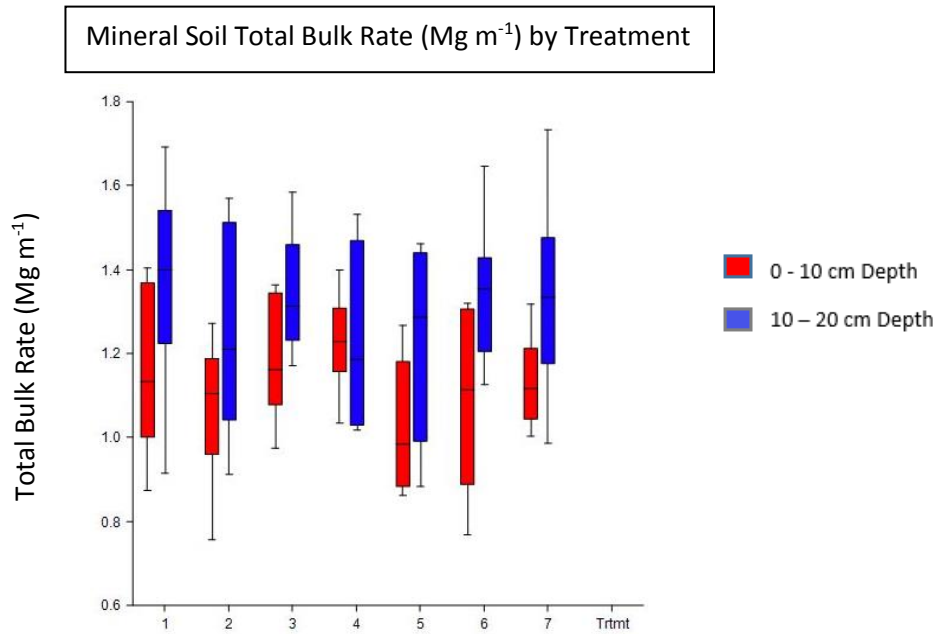


Figure 1.19. Total bulk rate (Mg m^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2). Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

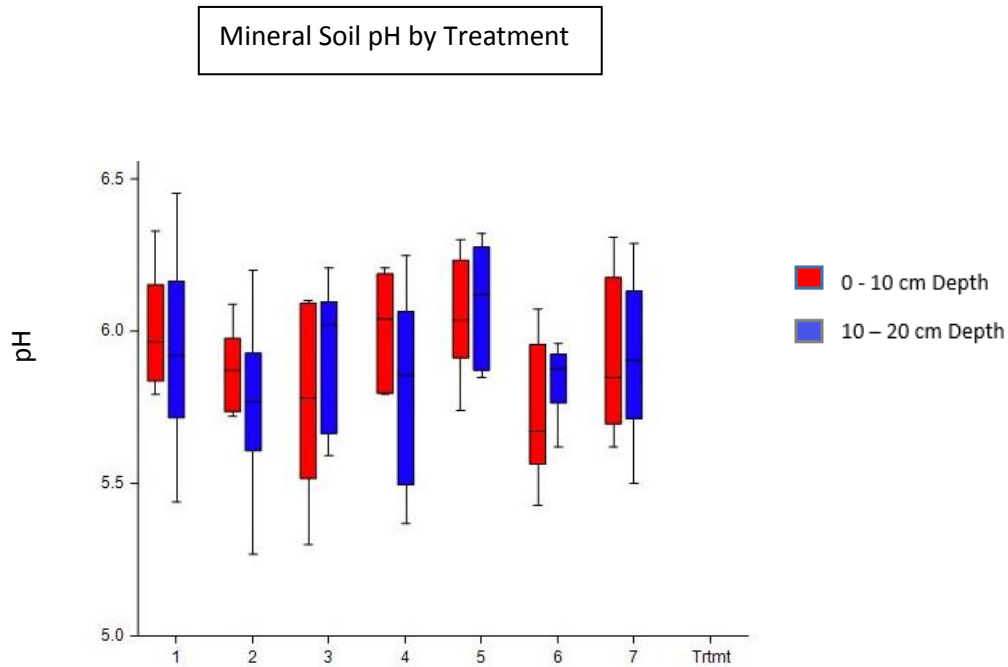


Figure 1.20. Mineral soil pH by treatment for 0-10 cm depths (1) and 10-20 cm depths (2). Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

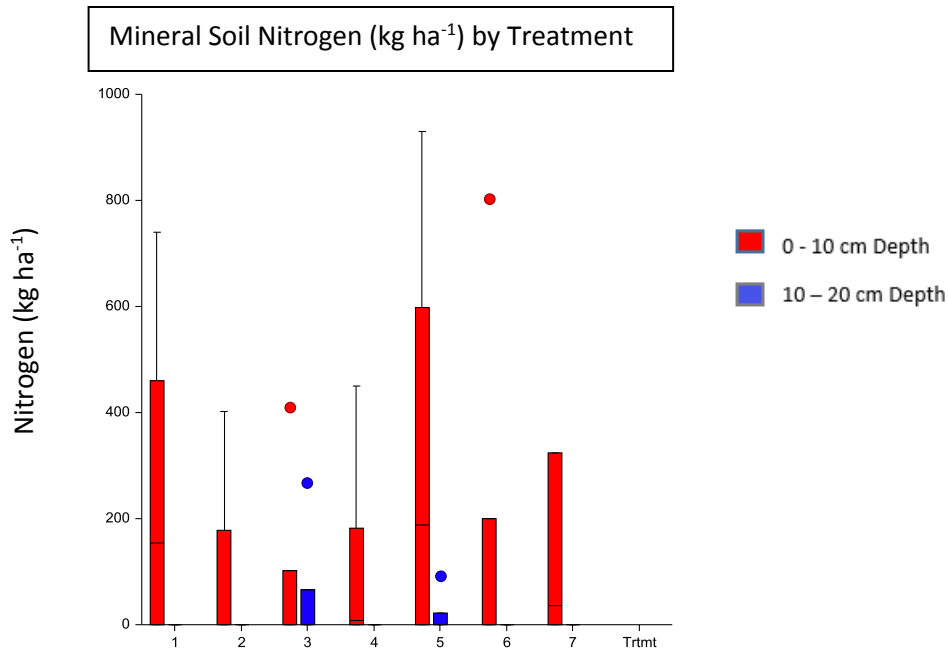


Figure 1.21. Mineral soil nitrogen (kg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2). Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

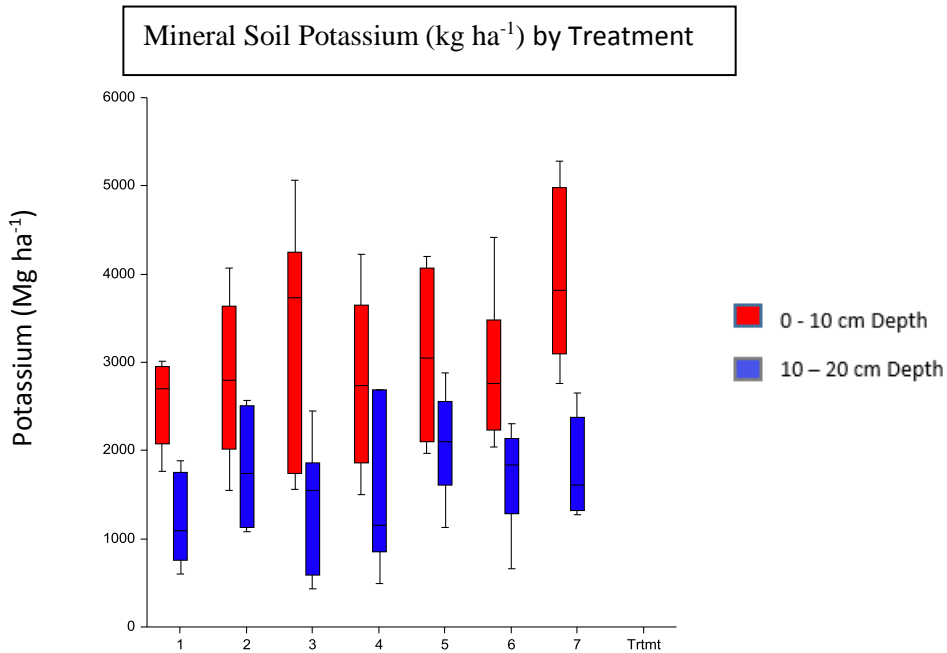


Figure 1.22. Extractable potassium (Mg ha^{-1}) for 0-10 cm depths (1) and 10-20 cm depths (2) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

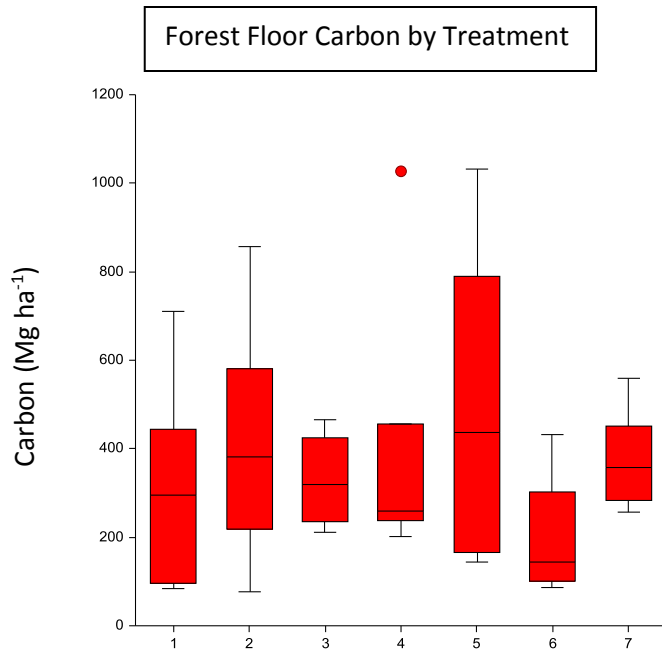


Figure 1.23. Forest Floor Carbon (Mg ha^{-1}) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

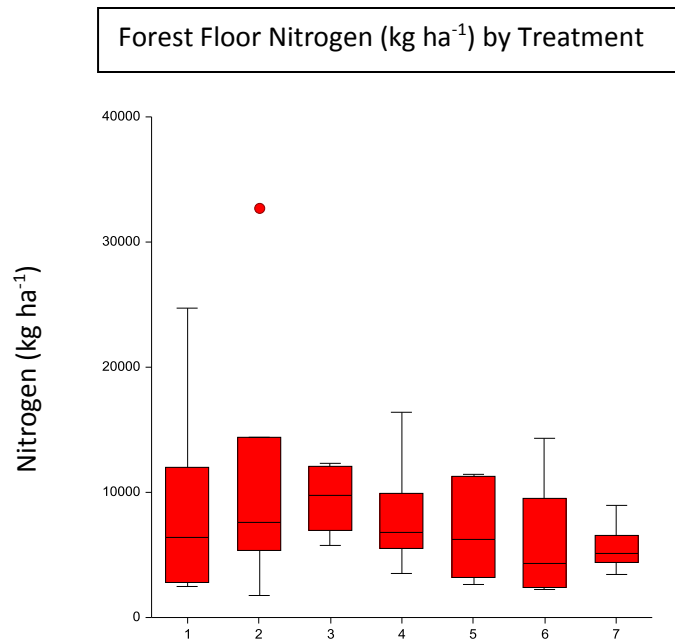


Figure 1.24. Forest Floor Nitrogen (kg ha⁻¹) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N).

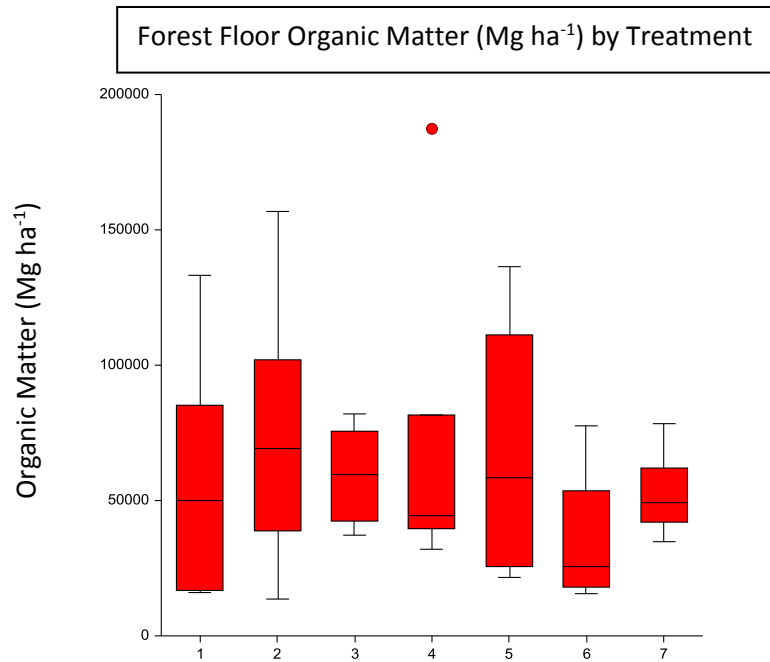


Figure 1.25. Forest Floor Organic Matter (Mg ha⁻¹) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N).

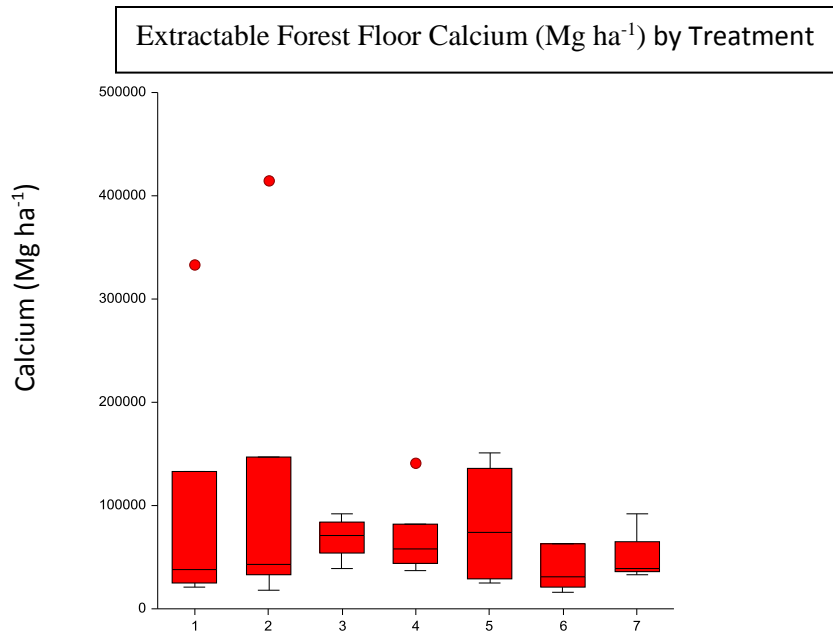


Figure 1.26. Extractable forest floor calcium (Mg ha^{-1}) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

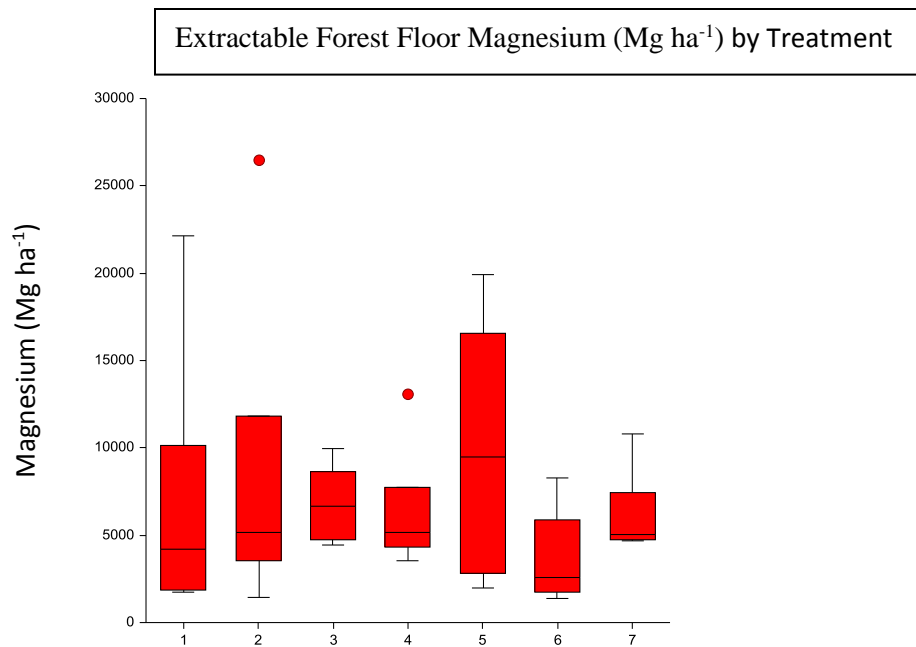


Figure 1.27. Extractable forest floor magnesium (Mg ha^{-1}) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha^{-1}), 3) fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$), 4) low application rate of biochar (2.8 Mg ha^{-1}), 5) heavy application rate of biochar (22.4 Mg ha^{-1}), 6) low-rate of biochar (2.8 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$) and 7) heavy rate of biochar (22.4 Mg ha^{-1}) with fertilizer ($224.1 \text{ kg ha}^{-1} \text{ N}$).

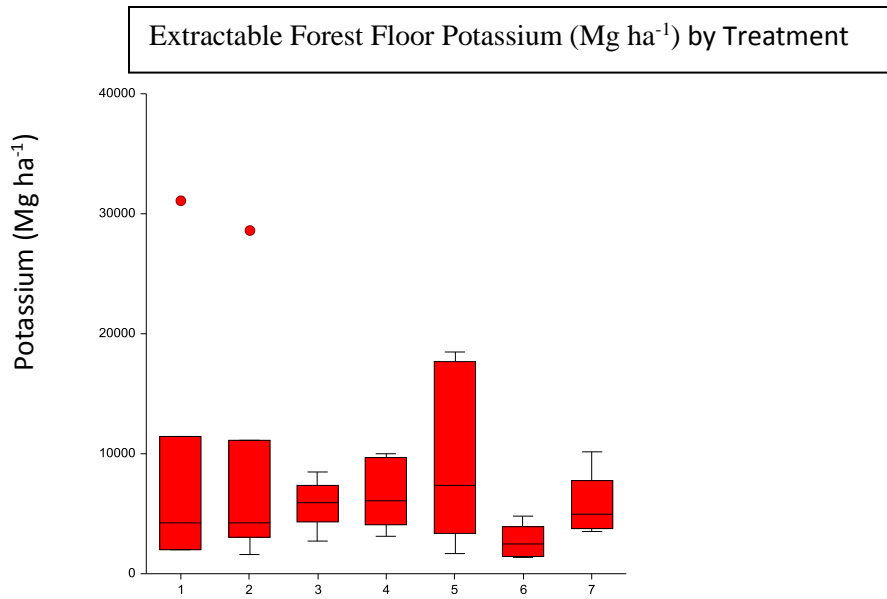


Figure 1.28. Extractable forest floor potassium (Mg ha⁻¹) by treatment. Treatments are 1) control (biomass left), 2) masticated wood chips (38.1 Mg ha⁻¹), 3) fertilizer (224.1 kg ha⁻¹ N), 4) low application rate of biochar (2.8 Mg ha⁻¹), 5) heavy application rate of biochar (22.4 Mg ha⁻¹), 6) low-rate of biochar (2.8 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N) and 7) heavy rate of biochar (22.4 Mg ha⁻¹) with fertilizer (224.1 kg ha⁻¹ N).

Figure 1.29. The Swift Creek plantation study site is made up of even-aged ponderosa pine selected for uniformity of heights, diameters, and health.



Figure 1.30. Treatments applied within a 4.57-meter radius around selected trees.

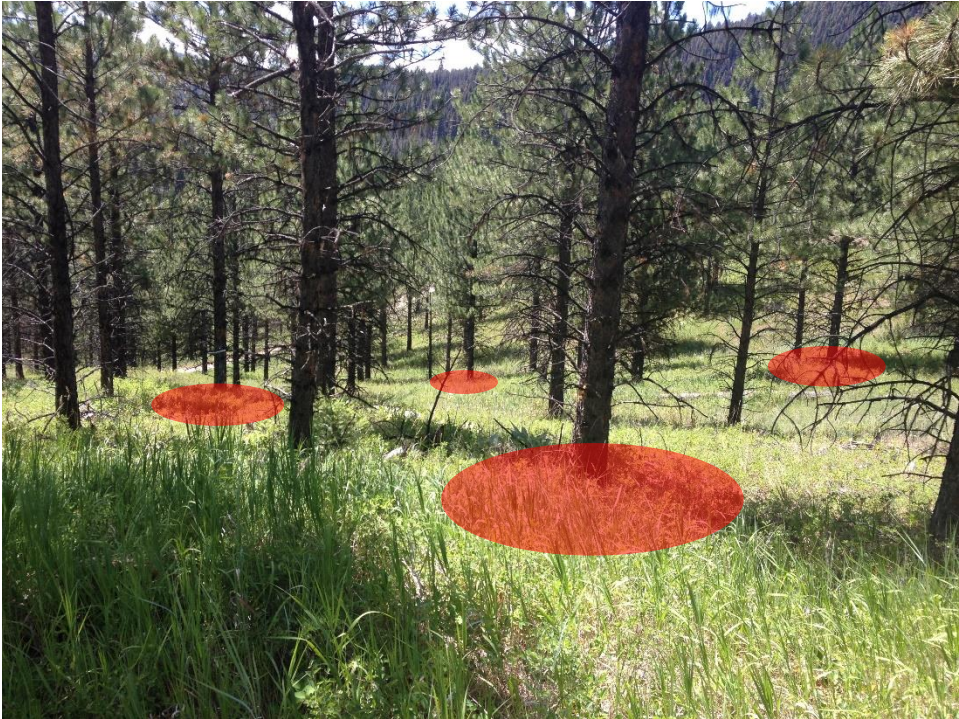


Figure 1.31. Biochar applied to the ground.



Figure 1.32. Spreader used to distribute biochar in experimental trial in the Lolo National Forest.



Appendix 1.B: Biochar Characteristics

The biochar was dried in a kiln to achieve 10% moisture content. The feedstock was placed in 55-gallon drums and shipped to Biochar Solutions Incorporated (BSI) in Carbondale, CO, where it was then converted to biochar. BSI uses a modular pyrolysis system designed to produce biochar from biomass. BSI pyrolysis system is made up of a two-stage reactor. The primary reactor carbonizes the feedstock in a closed environment with limited oxygen at a temperature between 700 and 750 ° C for less than 60 seconds. The material is then moved to the second reactor, where it receives a sweep gas treatment for ten to fifteen minutes at a temperature between 400 and 500 ° C. The gas produced in the first stage of the pyrolysis as a byproduct is used as the sweep gas in the second stage of this process, and is largely comprised of carbon monoxide, nitrogen, methane, hydrogen, and a small amount of oxygen. The material contents are then removed from the pyrolysis system using a liquid-cooled auger with an air lock.

Chapter 2:

**COMPARATIVE ANALYSIS OF VERNIER BAND AND HOOK-AND-SCREW
DENDROMETERS FOR MONITORING INTRA-SEASONAL TREE GROWTH**

2.1 INTRODUCTION

Climate change is exacerbating declining water availability and thereby reducing resilience to drought, decreasing seedling survival rates, and increasing susceptibility to disease and insect related mortality (Feddema et al. 2013, Ganey & Vojta 2011, Negron et al. 2009). These climate-induced threats to forest health necessitate the need for researchers and landowners to understand these changes so that land management practices may be adapted. Resilience to drought is a topic of increasing concern and research that renders the need for forestry techniques that can evaluate fine-scale growth periods in water limiting environments and shed light on how these periods are altered by restoration treatments. The use of dendrometers (diameter measuring instruments) is extensive in forest research (Clark et al. 2000). They are especially relevant in the midst of current climatic changes. Dendrometers are commonly used to track changes in diameter at breast height (DBH) in both agriculture (Link et al. 1998) and forestry research (Brown et al. 1947, Kuroda and Kiyono 1997) applications, providing reliable measurements to inform management decisions. Dendrometers are also used to detect small changes in tree diameter at regular intervals to better understand diurnal hydrological processes (Vose and Swank 1994), treatment effects over time (Stromgren and Linder 2002), growing season duration (Fowells 1941) and intra-seasonal growth (Deslauriers et al. 2007).

Several dendrometer types exist with varying complexity, accuracy, and cost. Tradeoffs exist between these factors and are especially relevant when considering the specific nature of the monitoring project. For a project involving a large sample size of trees or trees spread across a large area, efficiency in collecting measurements may be a greater priority than accuracy. Conversely, someone conducting a monitoring project prioritizing low cost may be willing to concede temporal efficiency to remain within the constraints of their budget.

Low-cost dendrometer options have practical, real-world applications in many situations. For example, landowners and small-scale tree farmers may be interested in monitoring the growth of trees on their property to better tailor their management practices. In addition, community-based forest monitoring, also referred to as “citizen science” has gained momentum across North America in recent decades. This type of citizen-driven research is a cost effective way to accomplish large-scale surveys of forest stands by recruiting community volunteers to collect forest measurements. The budgets for these surveying efforts are often limited. The cost of equipment can further limit the scope of these monitoring efforts, rendering the need for cost-effective tools.

We recently conducted a study wherein 40 plantation ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) trees were measured fourteen different times throughout one growing season to determine the experimental treatment effects of biochar alone and in conjunction with nitrogen (N)-based fertilizer, compared to masticated wood and N-based fertilizer alone (Anderson 2017). Precise measurements were necessary to detect the minute changes in diameter over the course of the growing season. Although cost-effective and easy to use, it was unclear whether a traditional diameter tape would suffice, as it is less precise than most dendrometer options. We chose to simultaneously install two low-cost dendrometers to evaluate how those alternatives and the diameter tape perform for tracking intra-seasonal growth.

Dendrometers can be classified into two broad categories, those that make direct contact with the stem and those that do not (Clark et al. 2000). Breitsprecher and Hughes (1975) distinguish between radial and circumferential dendrometers within the stem contact category. Radial dendrometers contact the stem at a single point, thus serving as point estimates of radial change upon which changes in stem diameter are estimated. Circumferential dendrometers encircle the stem using a band, effectively integrating changes in stem volume at all points around the tree. Dendrometers can be further classified as

either automated or mechanical. Automated dendrometers can be programmed to collect measurements at any regular interval. Mechanical dendrometers necessitate data collection in person.

The advantages of automated dendrometers include remote recording, low maintenance, small size and versatility of application. However, this technology is much more expensive than the mechanical types. Estimates for automated dendrometer systems range from several hundred to several thousand dollars inclusive of wires, wire covers, modems to transmit data, and data logging stations, and power supplies. Those costs can be prohibitive depending on study design, sample size, and quality of equipment. Automated dendrometers have also been criticized for unreliable functioning, as a calibration period is necessary to ensure the logged information is accurate (Pesonen et al. 2004). Automated dendrometers are not within the constraints of many monitoring budgets. We chose to evaluate mechanical dendrometer options in order to inform the selection of low cost alternatives.

Mechanical dendrometers are less expensive than automated dendrometers, but pose several disadvantages in the data collection process. In order to achieve accurate data, mechanical dendrometers require readings be taken at specified times of the day (Fritts, 1976). If the monitoring focus is to track diurnal changes, data must be collected pre-dawn, when the stem is at maximum size due to water retention. Furthermore, these types include the need for labor-intensive, on-site recording, and a greater potential for measurement error (Fritts, 1976). Yet, they represent a more cost-effective option for monitoring projects over large temporal and/or spatial scales than automated dendrometers. Mechanical dendrometers include Reineke hook-and-screw point dendrometers (Reineke 1932) and Vernier bands (Ralph 1944) (Drew and Downes, 2009).

Reineke hook-and-screw point dendrometers are classified as radial dendrometers. This type of dendrometer is installed by placing a screw in the bark layer of the tree at breast height (4.5 ft.), and placing a screw hook into the cambium layer roughly one inch from the screw so that the tip of the screw hook is on the same tangential plane as the screw. As the tree stem expands, the screw will expand with

the tree, but the screw hook will remain embedded in the tree and immobile. Therefore, the distance between the screw head and the end of the screw hook can be measured to track changes in the girth of the stem. Radial dendrometer types allow for multiple radial measurements to be taken on a single stem (Young 1952), but because a radial dendrometer contacts the stem at only one point, it may result in misrepresentation of the tree's true diameter (Biging and Wensel, 1988; Matern, 1990). Therefore, it is recommended to install dendrometers at multiple locations at breast height around the stem to minimize bias to estimated radius.

Band dendrometers include any type of dendrometer that encircles the tree; these include Vernier bands and diameter tapes. A Vernier band consists of a low-friction plastic band that is wrapped around a tree at breast height and held in place with a spring. As the tree stem expands and contracts, the spring allows the band to expand and contract with the tree. The Vernier scale is a precise measuring tool secured to the band from which diameters are read, typically to 0.01 cm. An initial adjustment period of several months to a year after installation is required for Vernier band dendrometers to settle on the stem as it expands and contracts. This ensures the measurements are accurate. Band dendrometers have a tendency to overestimate actual diameter (Pesonen et al. 2004), as a band inevitably leaves space between the band and the tree in some points around a tree. Other sources of error in band dendrometers include insect, wildlife and human interference of the band. A diameter tape is a device commonly used to collect multiple tree girth measurements quickly and easily by wrapping the tape around the stem at breast height (4.5 ft.). It is not mounted on the tree so it introduces the potential for more measurement error than the Vernier band. It also measures with lower precision than the Vernier band, typically either at 0.1 in or 0.1 cm.

Reineke hook-and-screw point dendrometers, diameter tapes and Vernier bands are common tools in collecting tree measurements in forest monitoring. Each method has advantages and disadvantages that render it more or less appropriate for specific uses. Comparisons of dendrometer bands in forestry research have been conducted (Keeland and Sharitz, 1993, Parker and Matney, 1999, Clark et

al. 2000), though comparisons of low-tech and inexpensive dendrometers are scarce, and none to date compare the Reineke hook-and-screw and Vernier band dendrometers to one another and to the diameter tape (Table 2.1). Therefore, we conducted a comparative analysis of low-cost dendrometers as part of a larger study conducted in a ponderosa pine plantation (Anderson 2017). We compare two low-cost dendrometers based on logistics and use, accuracy, and cost, and discuss the advantages and tradeoffs of each to one another and to the conventional diameter tape as a baseline comparison. This will help us determine the best cost-effective dendrometer option that is easy to use yet sufficiently accurate for community-based intra-seasonal growth monitoring purposes and private landowner use.

2.2 METHODS

2.2.1 Study Area

The study is located at a ponderosa pine plantation on the Sula Ranger District of the Bitterroot National Forest south of Darby, Montana (USA). The site is located at 45.53.26N 113.46.08 W and ranges from 1216 to 2350 meters in elevation. The mean annual precipitation ranges between 40.6 to 94 cm. The mean annual air temperature ranges 4 to 7.2 degrees C. The site index (SI₅₀) is roughly 18 meters. (Milner et al. 1992). This site is characterized as the *Pinus ponderosa/Festuca idahoensis* habitat type (PIPO/FEID, Pfister et al. 1977). The understory vegetation of this habitat type consists primarily of Idaho fescue (*Festuca Idahoensis*), bluebunch wheatgrass (*Agropyron spicatum*), rosy pussytoes (*Antennaria rosea*), onespoke oatgrass (*Danthonia unispicata*), and rough fescue (*Festuca scabrella*).

We conducted this study on 40 ponderosa pine trees in a plantation that was part of a biochar soil amendment experiment (Anderson 2017). The site had been established following a clearcut in 1965. Site

preparation included terracing in an effort to improve seedling survival and increase site waterholding capacity. The site was planted in 1966 with ponderosa pine. In 2009 a precommercial thinning was conducted. A series of surface amendment treatments were applied after that thinning as part of a biochar experiment (for details, see Anderson 2017).

2.2.2 Sampling Procedures

The UMS Dendrometer D1 Vernier bands were installed on August 26, 2015, or 265 days prior to first measurement (as an adjustment period to allow the band to settle). This was accomplished by wrapping the frictionless plastic band around each live tree in the study (n=40) at breast height (Figure 2.1). A metal spring kept the band in place and flush with the bark of the tree. The spring allows the band to expand with the tree as it grows. Stem diameter was recorded to the nearest 0.01 cm.

The materials for the hook-and-screw dendrometers included 6.6 cm zinc screw hooks and 8 x 3/4 flat head Phillips wood screws. We installed four hook-and-screw point dendrometers on the same trees as the Vernier bands on May 13, 2016. We used a chisel to remove excess bark and allow for a relatively smooth surface with in which to install the hardware. We screwed screw hooks into the tree at breast height into the phloem, with the end of the hook pointing left. We then placed the screw 2.5 cm to the left of the base of the hook just into the bark layer, to ensure that the screw would move as the tree grew. We installed the hook-and-screw point dendrometers at 90-degree angles, beginning with the macro-topographical downslope position. We aligned screw heads and the hook ends on the tangential plane. The initial distances between the screw heads and hook ends varied between 1.27 cm and 2.79 cm.

2.2.3 Data Collection

We collected dendrometer measurements on 14 occasions during the 2016 growing season. We took the first measurements on May 16, 2016, and the last measurements on August 3, 2016. On each date, we measured the distance between the hooks and screws using a digital micrometer (Traceable digital carbon-fiber caliper, Control Company; Webster TX) to 0.0025 cm (Table 2.2). We recorded Vernier band measurements to 0.01 cm. On each date, we also recorded diameter to 0.1 cm using a Spencer steel logger tape. We consistently collected measurements from 8 am to 2 pm to reduce variability due to diurnal changes in water retention of the trees.

2.2.4 Statistical analysis

We used the initial Vernier band dendrometer measurements as the baseline for initial DBH per tree. We then averaged the distance between the four hook ends and screws on each tree. We repeated this for each measurement. These averaged differences represent the change in radius across the four hook-and-screw point dendrometers. They were then doubled to represent the average change in stem diameter. The hook-and-screw measurements were converted to incremental diameter growth by adding them to the initial Vernier band measurement for each tree.

We averaged the diameter measurements across all trees for each measurement date and each dendrometer option. We plotted these diameter measurements to illustrate growth as measured by each tool over the course of the 2016 growing season. We also plotted the diameter measurements taken by each dendrometer for the 40 trees on four occasions throughout the 2016 growing season using box plots to illustrate the variability in measurements between the three tools. In order to assess the reliability of the periodic growth increment values for each dendrometer and the diameter tape, we counted the total number of negative growth increments for all 40 trees for three measurement periods, totaling 120 measurements for each tool. These measurement periods were selected from the 14 days we collected

measurements based on comparable duration and range from 25-28 days in length (Increment 1: days 0-28, Increment 2: days 28-53 Increment 3: days 53 and 79). We accomplished these analyses by using Microsoft Excel software (2016) and NCSS 11 statistical software (2016).

2.3 RESULTS AND DISCUSSION

2.3.1 Logistics and Use

The Vernier Band required a careful initial installation involving placement of the band exactly 1.37 meters from the uphill side of the tree, flush with the bark, and perfectly level. It also requires a settling period of several months prior to recording values. These bands are applicable for trees 10 cm to 66 cm in diameter, at which point a second band must be attached to the first to be used. Vernier bands require no additional tools to gather measurements. The bands are precise to the nearest hundredth of a centimeter, making them extremely precise. Further, the fact that the band remains on the tree ensures that the measurement is taken in the exact same place each time, thereby minimizing measurement error.

Following its introduction in the literature (Ralph 1944), documented studies on tree growth using the Vernier band date back to 1957, where their accuracy was compared to dendrometer tapes (Liming 1957). Liming (1957) concluded that Vernier bands are appropriate for short-term measurements, so long as they have a settling period of one year. A later study compared Vernier bands to dial gauge dendrometers (Bormann and Kozlowski 1962), and found that Vernier bands and dial gauge dendrometers produce similar seasonal growth curves. However, in some instances the dial gauge produced more erratic measurements than the Vernier band. Since these earlier studies, the Vernier band has been employed in countless studies to reliably collect tree growth measurements (e.g., McGuire et al. 2010, Grogan and Schulze 2011, Allen et al. 2016).

The hook-and-screw dendrometer requires careful placement of each hook and screw exactly 1.37 m from the ground on the uphill side of the slope, perpendicular to the bole, at a 45-degree angle to one another. Additionally, each screw must be installed one inch to the left or right of each hook and secured into the bark but not into the cambium. The materials for this type of dendrometer are easily acquired at any local hardware store. However, there are several unavoidable drawbacks associated with its use. If using the hook-and-screw dendrometer to track diameter growth of the tree, the initial diameter of the tree must be measured using a different dendrometer, as the hook-and-screw only allows for the calculation of incremental change. In addition, the angle at which the digital micrometer is held greatly affects the distance measured between the hook and the screw. The slightest change in angle can alter the measurement several hundredths of a cm. Further, securing the screw into the bark such that it is perfectly perpendicular to the face of the tree and exactly parallel to the screw hook is impossible. The installation of this method is the most physically demanding of the three options, as each screw hook must be screwed into the phloem by hand. Finally, securing the screw far enough into the bark layer without imbedding it into the phloem is very difficult, and undoubtedly results in some screws coming loose. This may cause inaccurate measurements. Once the hook and screw hardware are installed, taking measurements is straightforward, though both installation and subsequent measurements require more time than the Vernier band.

Reineke (1932) originally developed the hook-and-screw dendrometer method. It was a popular option for tracking intra-seasonal diameter growth in the 1940's, 50's and 60's. Fowells (1941) was perhaps the first person besides Reineke to employ the use of the hook-and-screw method to measure radial tree growth. He chose this dendrometer due to its "cheapness, simplicity, and apparent accuracy." He confirmed the accuracy of this dendrometer by statistically comparing the hook-and-screw measurements to increment cores with t-tests, and concluded that the hook-and-screw is as accurate as increment cores for measuring growth, though it slightly overestimates measurements. Another study used hook-and-screw dendrometers to monitor seasonal diameter growth of several different,

predominantly coniferous species in Jackson State Forest in California (Bawcom et al. 1961). That study noted the major drawback associated with this dendrometer was that changes of less than one hundredth of an inch between the hook and the screw within a two week period could not be detected, therefore making slow-growth rates undetectable. They speculated that this resulted in a possibly inaccurate observation that trees with the most diameter growth also had the longest growing season (Bawcom et al. 1961). Another study installed hook-and-screw dendrometers to monitor radial growth of trees in the Georgia Piedmont Experimental Forest (Jackson 1952). Jackson (1952) chose to use this dendrometer as it was more “sensitive and reliable” than diameter tapes in measuring radial changes within a growing season.

2.3.2 Accuracy

The study’s 40 trees grew an average of just 0.25 cm in diameter during the 79 days between the study’s start and end. On May 13, 2016, DBH of the 40 trees ranged 24.75 cm to 32.79 cm (average = 29.27 cm). At the study’s end on August 3, 2016, DBH ranged 24.78 cm to 33.07 cm (average = 29.52 cm). It took the trees an average of 42 days from the initial measurement to accomplish half of their total recorded growth. Recorded growth should not be mistaken for absolute total growth, as it is possible that growth for these trees began before the initial measurements were collected, as ponderosa pine commonly begin growing between April and May (Fowells 1941).

The average initial diameter tape measurement (29.4 cm) was 0.13 cm and 0.153 cm greater than the initial Vernier band (29.27 cm) and hook-and-screw dendrometer measurements, respectively (29.247 cm, Figure 2.2). The average initial hook-and-screw and Vernier band measurements differ only by less than 0.05 cm over the course of the entire growing season. Both dendrometers had similar ending values compared to the diameter tape (diameter tape = 29.5 cm, Vernier band = 29.52 cm, hook-and-screw = 29.50 cm).

Measured trees should not have experienced negative growth over the intervals assessed, and therefore we can reasonably assume that negative growth increments were due to inaccurate measurements. In an assessment of the periodic increment values for the diameter tape and each dendrometer between days 0 and 28 (Increment 1), days 28-53 (Increment 2), and days 53 and 79 (Increment 3) (Figure 2.3), we found that the diameter tape measurements resulted in negative growth increments 24 times out of a total of 120 observations (20%, average = -0.3 cm). The Vernier band measurements resulted in just one negative growth increment of -0.1 cm out of 120 total observations (0.8%). The hook-and-screw measurements resulted in 27 negative growth increments out of 120 total observations (22.5%, average = -0.079 cm). Although the hook-and-screw had a greater frequency of negative growth intervals, these negative increments had a lower absolute value than those of the diameter tape. Six representative trees were selected to illustrate the differences in incremental diameter growth on an individual basis over these three growth intervals for the Vernier band, hook-and-screw, and the diameter tape (Figure 2.2 a – f).

Variances in diameter measurements are likely due to recorder error. Measurements from both the diameter tape and the hook-and-screw exhibited spikes and dips over the growing season, though they were less exaggerated than the diameter tape (Figure 2.3). For the hook-and-screw, sources of error were most likely due to the angle at which the micrometer was positioned. Differences between the spikes and dips in the diameter tape and Vernier band measurements did not exceed 0.15 cm, whereas, for the hook-and-screw, these spikes and dips did not exceed .08 cm.

The range of average growth increment values for a given time interval differ greatly between each of the dendrometer options and the logger tape. The range of growth increment for the diameter tape during the first measurement interval (-0.3 cm – 0.5 cm) was 371% greater than that of the Vernier band (0 cm – 0.17 cm) and 267% greater than the hook-and-screw (0.058 cm - 0.276 cm) (Figure 2.4). The range of growth intervals for the diameter tape during the second measurement period (-0.5 cm – 0.8 cm)

was 900% greater than the Vernier band (0.02 cm - 0.15 cm) and 329% greater than the hook-and-screw (-0.173 cm – 0.13 cm). The range of growth intervals for the diameter tape during the third measurement period (-0.5 cm – 0.3 cm) was 700% greater than the Vernier band (0.0 cm – 0.1 cm) and 340% greater than the hook-and-screw (0.009 cm – 0.191 cm). Because the Vernier band had the smallest range in average growth increment values compared to the diameter tape and the hook-and-screw, we conclude it is the most consistent (and least variable).

2.3.3 Equipment Costs

The total cost of the hook-and-screw for this study of 40 trees was \$155.81, or \$3.90 per tree, which includes 4 screw hooks, and 4 screws. This cost does not include the electronic caliper needed to measure the distance between the hook and the screw, or the Philips head screwdriver and the chisel needed for installation. The hooks and screws are durable and would likely remain in the tree for years before requiring replacement. Frequency of adjustments of the hook depends on the tree's growth rate and the distance between the hook and screw at time of installation. Once the hooks and screws are no longer needed, the hardware can be easily removed.

The total cost of the Vernier Band was \$841.60, or \$21.04 per tree. This band is durable and can remain in place until the tree becomes too large for the band to measure. Vernier bands can also be reused. However, the spring may need replacing if it loses its ability to secure the band around the bole (\$5.00 inclusive of shipping, Decagon Devices, Pullman, WA). The band may also need replacing (\$6.00/meter inclusive of shipping, Decagon Devices, Pullman, WA) if the numbers become illegible due to wear, or if the band is damaged.

The English Steel Diameter Tape (Model 343D, Forestry Suppliers Inc., Jackson, MS) costing \$39.95, can be used to measure an indefinite number of trees. They are durable and can be used for decades if properly cleaned and cared for. Tapes (\$27.95 plus shipping) may need to be replaced and are

readily available. Other replacement components such as the center hub and screws are covered by warranty and can be replaced free of charge.

Note that the costs discussed here do not include the cost of labor or time for any of the three tools. Labor costs are factor that we did not measure in this study, but installation and measurement times are likely to differ for each dendrometer. We estimated the per-tree measurement time as 10 seconds for the Vernier band and for the diameter tape, and 60 seconds for four hook-and-screw dendrometers per tree, or 15 seconds per hook-and-screw pair.

2.4 CONCLUSIONS

The diameter tape is the most cost effective, user friendly, and time efficient method of measuring diameter, but the high level of variability and high incidence of negative growth increments make it an inappropriate option for measuring intra-seasonal diameter growth altogether. The Vernier band is very accurate and easy to use, but the setup and subsequent settling time for the band, as well as the high cost per band makes it an unappealing option. The Hook and Screw dendrometer is a less expensive alternative to the Vernier band with slightly lower accuracy but with much higher incidence of negative growth measurement increments. The Hook and Screw is also a more time-consuming dendrometer compared to the Vernier band in both setup and collecting measurements. The Hook and Screw results in many negative growth increments for the data to be considered accurate for small changes in diameter. In conclusion, a citizen-science program or average landowner focused on monitoring the intra-seasonal growth of trees on his or her land should use the Vernier band, as it provides sufficiently accurate data for tracking changes in inter-seasonal growth. Therefore, the relatively high cost of the band compared to the Hook and Screw is a necessary inconvenience of collecting accurate data.

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2.5 TABLES AND FIGURES

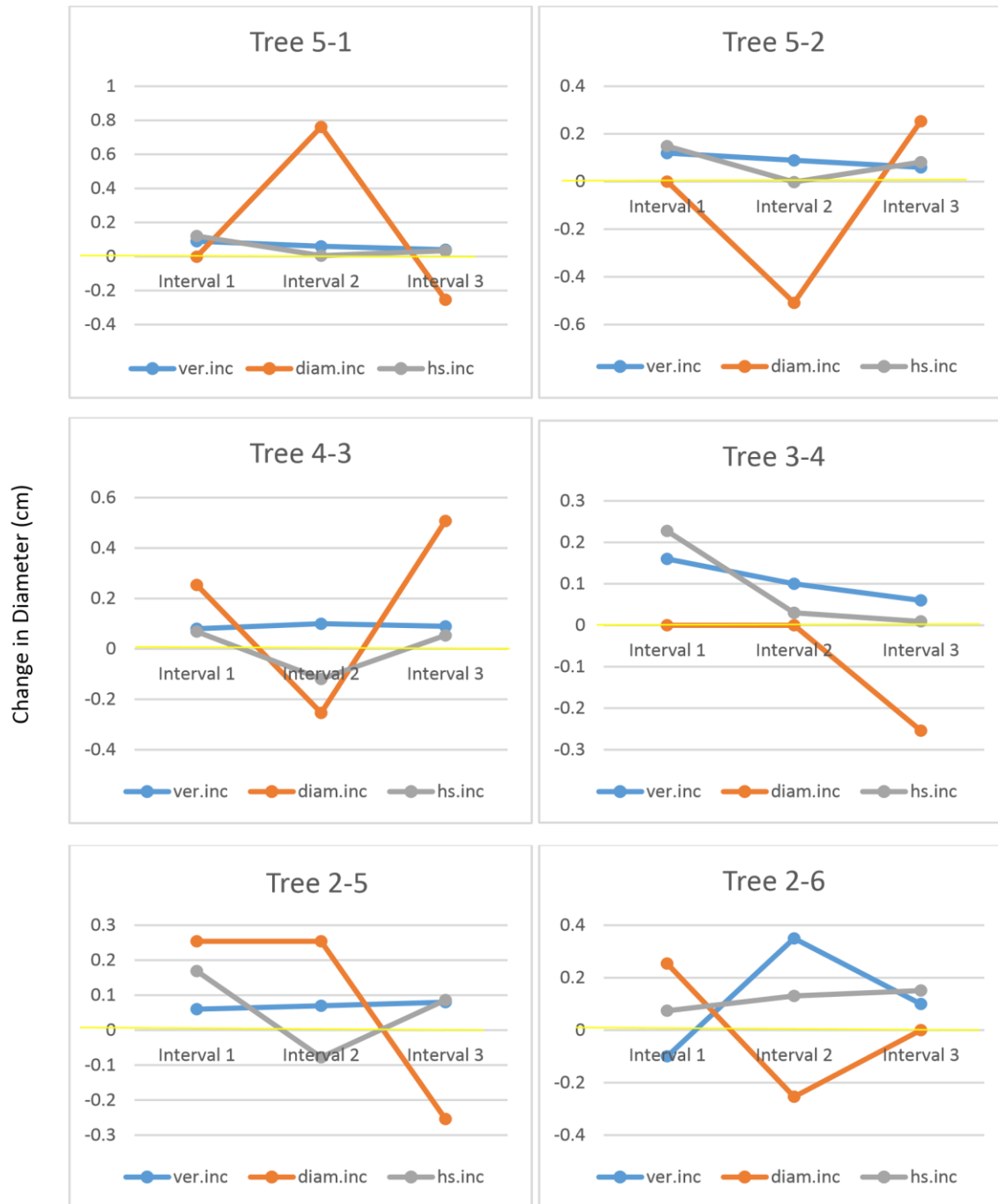
Table 2.1. Comparison of several quantitative factors (total cost, cost per tree and precision) for each of the three methods for collecting diameter.

	Diameter Tape	Vernier Band	Hook and Screw
Total Cost	\$39.95	\$841.60	\$155.81
Cost per tree	\$1.00	\$21.04	\$3.90
Precision	0.1 in /0.1 cm	0.01 cm	0.001 cm



Figure 2.1 (Left) UMS Dendrometer D1 Vernier band dendrometer (Right) Reineke hook-and-screw point dendrometer

Periodic Diameter Change of Individual Trees by Dendrometer Type



Figures 2.2 (a - f). Periodic changes in diameter for individual trees for three types of dendrometers (Vernier band, hook-and-screw, and diameter tape) over three intervals across the growing season (Increment 1: days 0 -28, Increment 2: days 28-53, and increment 3: days 53 – 79).

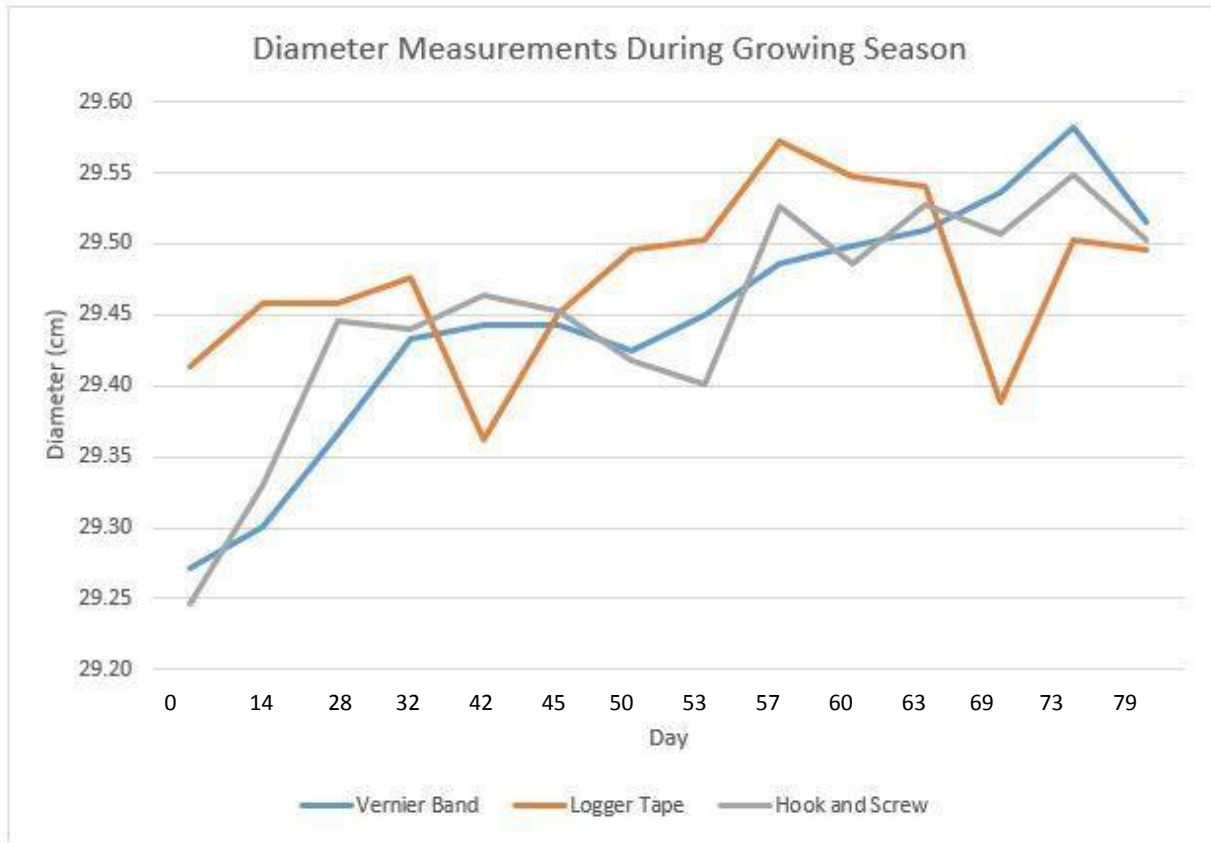


Figure 2.3. Line graph of the average diameter measurements (cm) taken using Vernier bands, Diameter tapes, and hook-and-screw dendrometers 14 times throughout the 2016 growing season starting on May 13, 2016 and ending on August 3, 2016.

Periodic Diameter Change of Ponderosa Pine Using Three Types of Dendrometers

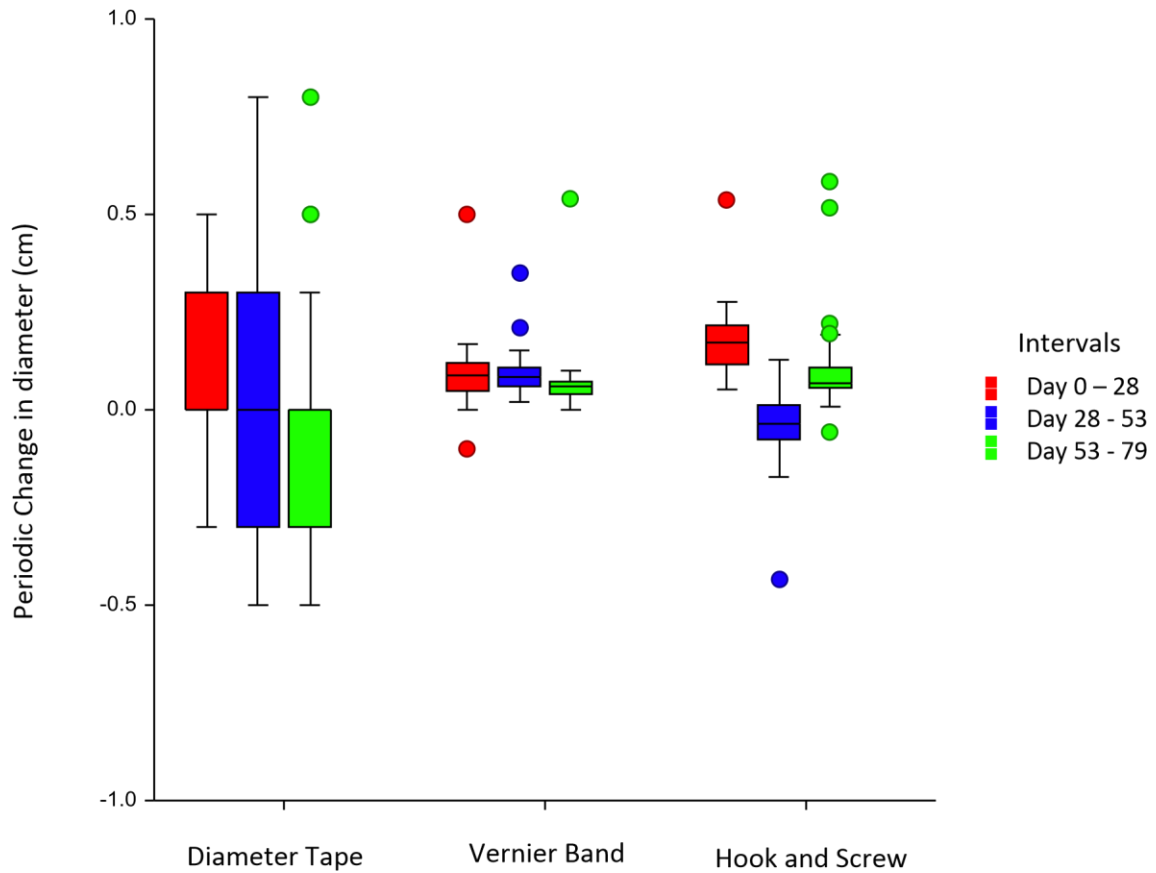


Figure 2.4. Boxplot of periodic changes in diameter of Ponderosa Pine using three types of dendrometers (Vernier band, hook-and-screw, and diameter tape) over three intervals during the growing season (Interval 1: days 0-28; Interval 2: days 28-53; and Interval 3: days 53-79).