THE EFFECTS OF BIOCHAR AS A SOIL AMENDMENT ON SOIL QUALITY AND PLANT GROWTH: A STUDY FOR THE NORTH CAROLINA HIGH COUNTRY

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by
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Abstract

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The use of biochar as a soil amendment is gaining traction, as a natural way to increase soil quality and also to mitigate climate change. The effects of biochar vary widely based on soil characteristics, plant species and feedstock characteristics. This study investigated the effects of biochar derived from High Country biomass on high country agricultural soil, and plants growing therein.

Biochar from four feedstocks sourced from the North Carolina High Country, cane sorghum bagasse, Fraser fir, wood chips, and hog bone was used. The biochar was mixed with agricultural soil from a High Country farm and one of two nutrient solutions.

The addition of biochar increased root mass and total mass in two biochar treatments and increased shoot mass and total mass in another. Three biochars increased soil P and K, and all increased soil water holding capacity. The independence of the biochar and nutrient effects was tested, and the effects were found to be dependent.

Characterizing and testing biochar made from different feedstocks is important in understanding the beneficial soil amending properties and allowing for optimization of biochars. Because of the differences between biochars and how they interact with soils and nutrients, different biochars could be used for different purposes, or even different crops. The more complete of a characterization we have of different biochars may enable the design of biochars, picking specific properties to meet specific needs. With a complete characterization, biochar application could be as precise as nutrient application, picking what properties are desired from a wide range of specifically designed products. This would allow for agriculture to optimize its nutrient and irrigation needs and improve agricultural yields.

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Commonly Used abbreviations

CO_2	Carbon dioxide
CEC	Cation Exchange Capacity
RSR	Root to Shoot Ratio
GHG	Greenhouse gas
CC	Control
SC	Sorghum Control
WC	Wood chip Control
FC	Fraser fir Control
BC	Bone Control
CH	Control hydroponics nutrient
CL	Control compost leachate
°C	Degrees Celsius
$°C\ s^{-1}$	Degrees Celsius per second
$cmol_c/kg$	Centi-mol per kilogram
g	grams
ml	milliliter
mm	millimeter
cm	Centimeter
$Mg\ yr^{-1}$	Mega grams per year
$m^2\ g^{-1}$	Square meters per gram
g/kg	Gram per kilogram
(m/m)	a ratio of mass to mass

Terms

Humic Matter: A measure of humic and fulvic acids in soil as a percent. This is a representation of the chemically active fraction of the soil.

Bulk Density (W/V): The bulk density of a soil is a measure of mass or weight per volume. It is a measure of the overall density of soil, including all air spaces.

Cation Exchange Capacity: Cation exchange capacity is a measure of the nutrient holding capacity of a soil.

Base Saturation: This is a percentage of the CEC that is already occupied by base cations, specifically calcium, magnesium, and potassium.

Combined Effect: The effect observed by the comparison of all treatments with a certain condition as compared to the control version of that condition. E.g. the combined effects of sorghum biochar are a comparison of the mean of all treatments with sorghum biochar versus all treatments with control soil.

Isolated Effect: The effect observed by the comparison of the mean of a single treatment that has either control soil or control nutrients to the mean of the treatment with both control soil and control nutrients. E.g. hydroponics isolated effects are found by comparing the means from control soil and hydroponics nutrients to control soil with control nutrients.

Introduction

What is Biochar?

Biochar is a stable form of carbon created by heating biomass in a low or no oxygen environment. When used as a soil amendment, biochar has an extremely porous carbon structure which allows for effective water and nutrient storage, as well as providing a habitat for high quantities of soil microbes. Biochar forms a dynamic substrate, so it provides numerous benefits, including increasing nutrient availability, increasing soil water retention, improving crop yield, and sequestering carbon for hundreds to thousands of years. Biochar applications have been proposed to increase the productivity and quality of some soils.

However, biochar research has been concluded by many studies that biochar's effectiveness depends largely on the biomass feedstock and the soil to which it is applied. This study proposes to expand current knowledge in comparison of various biochar feedstocks, as well nutrient treatments.

Statement of Problem

The benefits of biochar as a soil amendment are widely accepted in the academic literature (Alburquerque, et al., 2014; Usman et al., 2016; Vaugn et al., 2014). Experiments consistently indicate that biochar improves soil quality against a control of no biochar. There are, however, significant gaps in the current knowledge base of the community. Individual biochars made from different feedstocks perform differently against each other, and the magnitudes of their effects can be dependent on many factors within the soil. Testing different feedstocks against each other under different soil conditions is needed in order to gain a full picture of the potential of biochar.

Purpose of study

The purpose of this study is to compare the effects of several types of biochar created from individual feedstocks on soil quality and plant growth in soils found in the North Carolina High Country region. This study will look at using cane sorghum bagasse, hardwood chips, Fraser fir, and hog bone as feedstocks, with mineral and organic aqueous nutrients to determine their effects on plant growth and soil quality.

By focusing on the North Carolina High Country region, a region where little biochar research has occurred, this research has the potential to help farmers and the greater High Country community. Expanding what is known about how biochar works in the High Country can assist local farmers when making a decision about soil amendments and other treatments for their crops.

Research Hypotheses

H1:

The application of biochars will improve soil quality versus a control of no biochar.

H2:

There will be a symbiotic effect between biochar and nutrients, the impact of combined treatments will be greater than if the effects were independent.

Research Questions

Q1:

What are the differences in physical between the biochars and biochar-soil treatments based on biochar feedstocks?

Q2:

Which feedstock will create the largest impact on adolescent plant growth in High Country loam soil?

Q3:

Is there an observable effect between the agronomic properties of the biochar-soil treatments and plant yield?

Limitations of the Study

This study is limited in multiple facets, mostly by time and scope. This experiment was completed over the course of 35 days, just under 1/3 of the time to maturity of the selected plants. Thus this experiment only covers the early stages of the plants' development. The scope of this experiment is limited largely due to the specific conditions selected for it. In practice the conditions under which plant growth occur span an extremely wide range over a number of variables. This experiment only looked at one cultivar of plant, one soil, one lighting condition, one watering regiment, two nutrient additions and four biochar feedstocks produced under identical conditions. Any change in one of these variables could produce a change in any number of results of plant growth.

The narrow scope of this experiment in necessary to be able to pinpoint the effects of the selected changing variables, in this case the soil additives. It would be possible to expand the scope, but not without significant complications and unwieldy experiments. The role of this experiment within the larger literature is simply expanding the knowledgebase in one particular area.

Review of Literature

Non-Yield Benefits of Biochar

Climate change and carbon sequestration.

Carbon dioxide (CO_2) is a greenhouse gas which prevents the earth from becoming too cold for life. Since at least the beginning of the industrial revolution, the burning of fossil fuels has released CO_2 in excess of what natural systems are capable of cycling, leaving the atmosphere saturated with CO_2 and causing unprecedented global temperature increases. During photosynthesis, plants take in CO_2; some of the carbon taken in during the process is stored in the plant's stem and leaves. If these plants decompose, some of that carbon is temporarily sequestered in the soil, if they are burned, that carbon is released into the atmosphere as CO_2 and CO. In biochar, the carbon in the plant biomass remains intact and becomes recalcitrant carbon, thus sequestering the carbon for an extended period of time (Lehmann & Joseph, 2009).

Global climate change.

The Global Risks Report 2016 (World Economic Forum [WEF], 2016) lists failure of climate change mitigation and adaptation as the number one most impactful global risk Climate change is also the global risk of second highest concern over the next decade, preceded only be water crises, which is integrally related. For the previous three years, failure of climate change mitigation and adaptation has been in the top five most impactful risks, but has moved to the top spot in 2016 (WEF, 2016).

WEF (2016) also identifies a cluster of global risks surrounding failure of climate change mitigation and adaptation, including water crises, mass involuntary migration, and food security risks. Nearly 70% of the world’s fresh water is used for agriculture, with 40% of world agricultural production requiring irrigation on only 20% of cultivated areas worldwide. (UNESCO, 2016).

Under current agricultural and irrigation practices, competition for water will only increase given the effects of global warming. If every country meets their target Intended Nationally Determined Contributions plans that they agreed to at the Paris Climate Conference in December 2015, warming is projected to reach well above the 2°C level that scientists have warned implies a high risk of catastrophic climate change (WEF 2016).

Carbon sequestration.

CO_2 is cycled naturally through the atmosphere on both a diurnal and seasonal fluctuation (Keeling et al. 1976; Sabine et al. 2004). As plants go through their own seasonal cycle, they absorb CO_2 during the spring and summer months, and as their leaves fall and begin to decay through autumn and winter, the global CO_2 levels increase again. Earth's soil is itself an extremely large carbon sink, containing nearly four times as much carbon as Earth's atmosphere (Sabine et al., 2004; Lehmann & Joseph, 2009). The seasonal CO_2 uptake by plants is eight times the anthropogenic emissions of CO_2 and the entirety of the atmospheric CO_2 is cycled through the biosphere every 14 years (Sabine et al., 2004; Lehmann & Joseph, 2009). Vast amounts of CO_2 are cycling annually between plants and the atmosphere. If CO_2 in plants was removed in the form of recalcitrant carbon that would remain in the soil for a longer period than it normally would, carbon would be sequestered. Diverting 1 percent of the annual plant uptake into biochar would mitigate nearly 10 percent of anthropogenic C emissions (Lehmann & Joseph, 2009). This process only works if two conditions are met. First, the rate at which plants are grown has to be equal to or greater than the rate at which they are charred, and second the biochar needs to hold the C in a more stable form than the biomass from which it is made (Lehmann & Joseph, 2009).

Soil erosion.

Soil erosion is both a major agricultural and environmental issue worldwide. Brown (1984) estimated that soil loss due to erosion worldwide was 26 Billion Mg yr^{-1}. Eleven years later, Pimentel et al. (1995) reported that soil loss due to wind and water erosion was nearly three times higher, at 75 Billion Mg yr^{-1}. Nearly 90% of the world's agricultural land suffers from some sort of erosion, with almost 80% of agricultural land worldwide suffering from moderate to severe erosion. This erosion can reduce the water availability and soil fertility, some corn yields reaching 65% reduction on severely eroded soils in Georgia (Pimentel et al., 1995).

Around two thirds of global erosion is caused by water, with wind making up another third (Bini & Zilioli, 2011). Water erosion has been responsible for the degradation of 1094 million hectares since the middle of the twentieth century (Zuazo, Tejero, Martinez, & Fernandez, 2011). Biochar has been shown to be able to reduce soil loss from water erosion. A laboratory experiment by Lee, Shah, Awad, Kumar, and Ok (2015) determined that using oak biochar could reduce soil loss by 19.9% against a control, when subjected to 100mm h^{-1} simulated rainfall. Doan, Henry-des-Tureaux, Rumpel, Janeau, and Jouquet (2015) also found that biochar reduced soil detachment in a significant way. If biochar can reduce water erosion on agricultural lands, the rate of land degradation can be decreased, vastly increasing the total possible agricultural yield.

North Carolina High Country Region

The North Carolina High Country is a region of western North Carolina in the Appalachian Mountains which is climatically and geophysically different from the rest of the state. The climate of the North Carolina High Country is colder than the majority of the state, with United States Department of Agriculture (USDA) plant hardiness zones 6b and 6a dominating the area, versus 7b and 7a for the majority of the state (USDA ARS, 2012). East of the Appalachian Mountains, zone 6 runs through southern Pennsylvania, Rhode Island, and eastern Massachusetts. Zone 6b is the same zone as nearly all of Ohio and coastal Michigan (USDA ARS, 2012). Zone 6a has an average annual minimum temperature between -23.3°C and -20.6°C, zone 6b extends up to -17.8°C. Zone 7 extends to -12.2°C, with the line between 7a and 7b being drawn at -15.0°C (USDA ARS, 2012).

The North Carolina High Country is dominated by soils from the Inceptisol order, whereas the rest of the state is dominated by Ultisol soils (USDANRCS, 2006). These differences make the North Carolina High Country a unique agricultural region. This means that if the results were to have any relevance to the High Country, then feedstocks and soil had to be sourced locally, and the plant grown had to also be grown locally.

Biochar Properties

Surface area.

Surface area is a critical factor in the fertility of soils, as it affects microbial activity, nutrient, air, and water cycling (Downie, Crosky, & Munroe, 2009). According to Troeh and Thompson (2005), sands have a surface area ranging from 0.01m^2 g^{-1} to 0.1m^2 g^{-1}, and clays have a surface area ranging from 5m^2 g^{-1} to 750m^2 g^{-1}. Soils with high clay contents tend to have high water holding capacity, but often lack proper aeration; high sand soils have the opposite problem, with high aeration and low water holding capacity. Both of which may be overcome with the addition of organic matter (Troeh & Thompson, 2005). Biochar can help both sandy and clay soils.

Ścisłowska, Włodarczyk, Kobyłecki, and Bis (2015) reported surface areas of their biochars between 0.52m^2 g^{-1} from willow and 2.49m^2 g^{-1} from pine. Usman et al. (2016) found that their biochar made from *conocarpus* wood had a surface area of 109.8 m^2 g^{-1}, and Han, Ren and Zhang (2016) found that biochar made from Chinese pine and locust had a surface area of 247m^2 g^{-1}.

The biochar database maintained by the University of California at Davis (UC Davis, 2017) has 525 entries of biochar with included surface area measurements. The surface area ranges from 0.02m^2 g^{-1} to 907.4m^2 g^{-1} with an average of 110.53m^2 g^{-1} and a standard deviation of 151.21m^2 g^{-1}. Nearly two thirds (66.3%) of the biochars are under 100m^2 g^{-1} and 90.8% are less than 350m^2 g^{-1} (UC Davis, 2017). The surface area of biochar has a wide range, but with great potential on the high end to compete with clay, without the aeration issues.

Porosity.

The majority of the surface area of biochar comes from pores of less than 2nm diameter, known as micropores (Downie et al., 2009). Micropores are important because of their adsorptive capacities for small molecules such as gases or solvents (Downie et al., 2009; Rouquerol, Rouquerol, Sing, Maurin, & Llewellyn, 2014). There is also a strong correlation between the highest treatment temperature (HTT) the biochar reached during pyrolysis, as well as the time it spent at that temperature also known as residence time. There is an HTT at which deformation occurs and the walls in between micropores are destroyed reducing the surface area and increasing total pore volume (Downie et al., 2009).

Macropores are pores greater than 50nm in diameter and are useful in improving soil aeration and hydrology (Downie et al., 2009; Troeh & Thompson, 2005). Macropores constitute a complex network with up to 23,562 networks/m^3 of sandy loam soil (Perret, Prasher, Kantzas, & Langford, 1999). Generally, 70% of water flowing through soil moves through pores which take up only 1% of total soil volume (Giminez, 2006). Bacteria, fungal hyphae, root hairs, and nematodes are all under 5nm in diameter, so macropores found in biochar may be of suitable dimensions for clusters of micro-organisms to inhabit (Cameron & Buchan, 2006; Downie et al., 2009).

Zhang and You (2013) found that the water holding capacity of soils fit a trend with the total pore space of biochar. Total pore space was positively correlated with water holding capacity, with a Pearson correlation coefficient of 0.986. Total pore space played a more important role in this determination than the surface area of the biochar (Zhang & You, 2013).

Cation exchange capacity.

Cation Exchange Capacity (CEC) is an important measure of the productivity and quality of soils, as it measures exchangeable cations, such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ (Mukome & Parikh, 2016). CEC is also important in the prevention of nutrient leaching and water retention (Dong, Wu, & Zhong, 2016; Cai & Chang, 2016). Plants generally uptake nutrients as simple ions in solution, however in cases where that solution is depleted, exchange desorption allows adsorbed cations to be exchanged, providing a reserve to replenish the solution (Bache, 2006). The CEC of biochar increases with age, due to abiotic oxidization effects in the soil; Cheng, Lehmann, Thies, Burton, and Engelhard (2006) found that when incubated at $70^{O}C$ for 4 months biochar and biochar-soil mix increased in CEC by 538% and 285% respectively, and samples of just soil did not increase their CEC.

The UC Davis Biochar database (UC Davis, 2017) has 213 biochar samples that include a CEC measure, ranging from 0.1cmol$_c$/kg to 516cmol$_c$/kg with an average of 50.2cmol$_c$/kg and a standard deviation of 69.3cmol$_c$/kg. According to the Cornell University Cooperative Extension (2007), coarse sandy soils with low organic matter have CEC levels of less than 3cmol$_c$/kg, whereas Clay soils with high organic matter content can exceed 20cmol$_c$/kg. Of the 213 samples in the UC Davis Biochar database (UC Davis, 2017), ten (4.7%) have a CEC less than 3cmol$_c$/kg, and sixty-nine (32.4%) have CEC above 20cmol$_c$/kg. Like surface area, CEC is similarly varied across a wide range.

Types of pyrolysis used to produce biochar.

The pyrolysis process is separated into several distinct pyrolysis systems based on several factors. Chief among them are the HTT, the residence time, and the heating rate of the biochar, which is partially also based on the particle size of the feedstock as shown in Table 1 (Thangarajan et al., 2016). Lua, Yang and Guo (2004) found that HHT and heating rate were the two factors with the most significant effect on biochar surface area and porosity. Higher temperatures tend to yield less char, and a lower heating rate tends to increase microporosity.

Table 1: Types of Pyrolysis. From Thangarajan et al., 2016.

Pyrolysis system	Main Products	By-Products	Temperature (°C)	Heating Rate (°C s^{-1})
Slow Pyrolysis	Biochar, biogas	Bio-oil	300-550	.01-2
Fast pyrolysis	Gas	Liquid, very low biochar	>600	>10^5
Flash Pyrolysis	Liquid	Liquid, very low biochar	400-600	10-1000
Gasification	Gas	Liquid, char	>800	—

The degradation of lignocellulose occurs at temperatures above 120°C. Below 300°C, the dominant pyrolysis pathway is the biochar and gas formation pathway, but between 300°C and 600°C the liquid and tar forming pathway becomes dominant; over this range, biochar yield decreases greatly (Amonette & Joseph, 2009). The end products of pyrolysis tend to depend greatly on the mode of pyrolysis as well as the feedstock used (Bridgwater, 2010; Downie et al., 2009). Fast pyrolysis tends to produce significantly more liquid by mass (75%) than it does gas or char (23%, 12% respectively). Slow pyrolysis tends to create equal amounts of liquid and char by mass (35% each) with the remainder being gas (Bridgwater, 2010)

If the hold time of the biochar is too long it can decrease the surface area of the biochar (Lua et al. 2004). This effect is possibly due to a sintering and shrinking effect on the biochar as suggested by Guo & Lua (1998) or that the pores are not destroyed, simply covered over at high temperatures (Lewis, 2000).

Higher heating rates can, like high HHT, cause plastic transformations and melting cell structures that decrease surface complexity (Downie et al. 2009). Cetin, Moghtaderi, Gupta and Wall (2004) tested heating rates of 500°C s^{-1} and 20°C s^{-1} on pyrolysis of pine sawdust. Though the HHT was the same, and the retention time was only 20 seconds, they found that at the higher heating rate "The cell structure practically does not exist after devolatilisation" (Cetin et al, 2004, p. 2143). The driving factor in this was believed to be the quickness of the release of volatiles from cells in the fast heating rate causing melting and plastic deformations (Cetin et al, 2004).

Plant Root:Shoot Ratio

The size of a plants roots is an important measure of a plant's ability to obtain resources from the soil, but only insofar as it is used in relation to the size of the rest of the plant (Comas, Becker, Cruz, Byrne, & Dierig, 2013). The measure usually used for this is the root:shoot ratio (RSR) of dry biomass, or less often the root mass fraction; that is, the fraction of total mass represented by the root mass. Functional equilibrium theory and optimal partitioning theory both suggest that plants may be adapted to a specific RSR, but that external factors may cause the plants to shift resource allocation with some degree of plasticity (Comas et al., 2013).

A higher RSR may be an indicator of nutrient deficiencies in the soil, specifically a lack of nitrogen, or moisture stress (Harris, 1992; Australian Society of Plant Scientists, 2016). Phosphorus has been shown to increase the shoot growth in plants, drastically reducing RSR. Regardless of cause, an otherwise identical plant with larger roots has a better ability to uptake nutrients and moisture (Australian Society of Plant Scientists, 2016).

Effects of Biochar on Soil Quality

An experiment done by Agegnehu, Bass, Nelson, and Bird (2016) looked at the effects of biochar, compost and a combination thereof on maize yield and GHG emissions. The biochar was made from willow wood, and the compost was made of green waste, bagasse, chicken manure and compost. Soil available phosphorus (P), CEC and exchangeable calcium were all shown to increase with a biochar amendment (Agegnehu et al., 2016).

Han, Ren and Zhang (2016) examined the effects of different rates of biochar application on multiple abandoned farms. The farms were abandoned at different times and so had different starting compositions. The experiment was over a three-year time period, examining the soil qualities before and after the three years of biochar application. They found that biochar amendments resulted in significant improvements in soil organic carbon, nitrate nitrogen and total soil nitrogen. The biochar did not have significant effect on soil ammonium nitrogen, and reduced soil P, indicating the need for P fertilizer (Han et al. 2016).

Alburquerque et al. (2014) tested biochar made from five feedstocks at five different application rates each. They grew sunflowers in a greenhouse for two months, and tested both soil and plant yield. Biochar was found to reduce the bulk density and increase field capacity of the soils. The biochars were not treated prior to mixing with soil, and biochar application was found to reduce available N in the soil.

Vaughn et al. (2015) replicated golf course root zones to USGA standards and tested the effects of three types of biochar on creeping bentgrass in the USGA root zones. They used a commercially available fast pyrolysis biochar, and biochars made in a gasifier from Paulownia and Frost grape. The root zones were mimicked in long PVC tubes, with different biochar application amounts mixed into the sand part of the root zone. They found that biochar enhanced the nutrient and water holding capacities of the substrates, generally more than treatments which used peat in place of biochar. In all cases, biochar increased nutrient retention, PH, and pore space, in most cases more than peat.

Effects of Biochar on Plant Yield

Agegnehu et al. (2016) found that in a field study growing maize the total biomass and grain yield for both a willow biochar treatment and a compost treatment were greater than the control's, biochar producing a 29% increase and compost 10%.

Alburquerque et al. (2014) found that the sunflower germination was significantly affected by both the biochar feedstock and the rate of application. The biochar also impacted the allocation of biomass within the plants, with biochar samples showing higher leaf allocation and decreased stem allocation. Root allocation was also lower than the control, but not statistically significant.

Ścisłowska et al. (2015) examined three biochars from three feedstocks, pine, willow and miscanthus. Based on proximate, ultimate and porosimetric analysis of the three biochars, the authors decided to use miscanthus biochar for a field test based on its high carbon content and porosity. In their brief article, they did not conduct a statistical analysis, but did conclude that the physiochemical and porosimetrical properties are highly dependent on feedstock, and that biochar amendments positively affect plant growth and can increase plant mass.

Trying to ascertain the benefits of biochar in sandy soil using sea water as is done in some Middle Eastern countries, Usman et al. (2016) tested biochar application rates in soil irrigated with saline and non-saline water. They found that biochar significantly increased the water use efficiency, a measure of unit yield per unit water, versus a control for both water types, 13% for non-saline and 36% for saline water irrigation. Biochar also improved yield with both non-saline and saline irrigation, and under saline irrigation conditions biochar increased yield by 14.0%-43.3%, which was higher than a treatment of just organic matter. There was also evidence that biochar could alleviate stress cause by saline soils and thus increase yield in these situations.

After the five-week period Vaughn et al. (2015) found that grass grown in biochar treatments had greater height and root length, whereas less than half had increased dry weight compared to a control. Their conclusion was that some biochars appear to be very useful in sand-based root zones.

Research Methods

Equipment and Facilities

Nexus bioshelter greenhouse.

One of the research efforts underway at the Nexus Bioshelter Greenhouse (NEXUS) at Appalachian State University is looking at season extension for High Country farmers using renewable energy inputs. The project is centered on a hoop house style greenhouse with a thermal battery hot water tank. The tank is heated by a solar thermal array and a heat exchanger in the biochar batch kiln. The thermal battery is a 1,500 gallon insulated water tank with active controls for zoned heat, primarily for an aquaponics pond, but also for heated grow beds. The NEXUS greenhouse is located at 36.217°, -81.630°. The greenhouse is 20'x 35' with two layers of greenhouse plastic, raisable sides, and an optional shade layer to control heat.

Biochar Batch Kiln.

The biochar batch kiln is a simple but effective apparatus for producing biochar in approximately 4.5kg batch loads. The kiln is 160cm deep, 152.5cm tall, and 120cm wide, with an internal firebox measuring 122cm x 105cm x 96cm (see Figure 1). All external walls were constructed from insulating ceramic fire brick, and the one internal wall was constructed from hard fire brick. The kiln structure was based off of rolling style ceramic kilns. The kiln is designed to be a wood-fired, but could be heated using a gas fuel and a venturi burner. The kiln uses a 30-gallon barrel as a pyrolysis chamber. The barrel pyrolysis chamber is based off of the design described by Teel (2012) using steel pipe to deliver syngas from the pyrolysis reaction to a zone beneath the pyrolysis chamber. Thus, the pipe acts as a burner similar to one that may be found in a propane or natural gas grill, returning energy from the pyrolysis reaction into the driving combustion reaction in the form of syngas.

Figure 1: Side view of biochar kiln.

Pyrolysis

Preparation of biochar feedstocks for pyrolysis.

Each biochar feedstock is shown in Figure 2.

Hardwood Chips.

Hardwood chips were obtained in a pre-chipped form. The chips were dried in open air for several weeks until they were dry.

Frasier fir.

The Frasier fir trees were collected from local Christmas tree farms. Limbs from the trees were chipped using a commercial wood chipper. The Frasier fir chips were dried in an oven for 48 hours.

Figure 2: Biochar feedstocks. from left to right, sorghum, Fraser fir, wood chip, and bone.

Sorghum.

Sorghum bagasse was obtained from a local farm, where they had already pressed the stalks to create sorghum syrup to be turned into molasses. The bagasse was put through a commercial chipper shredder, and then dried in a drying oven for 48 hours.

Bone.

Bone was taken from a local Watauga county farm. The bone came from hogs on the farm, and the bones had been kept in compost until the composting process had cleaned the bone of all flesh materials.

Pyrolization of feedstocks.

Samples of each biochar feedstock were put into two individual one-gallon sealed steel containers each with several gas-release holes, which were all placed into the pyrolysis chamber, which was then sealed. The biochar batch kiln was loaded up with 59.5 lbs. of wood and 1.0 lb. of corrugated cardboard to assist in the ignition of the fire. This wood provided the fuel for the driving combustion reaction.

The wood was ignited and the kiln was closed. The temperatures inside the kiln were measured at four points using a 4-channel thermocouple data logger and four k-type thermocouples. Data was logged at one second intervals. The kiln was kept closed and the pyrolysis chamber remained inside the kiln until after the internal kiln temperature matched the ambient temperature outside of the kiln. Biochar (see Figure 3) was removed from the kiln and ground to pass through a #8 (2.6mm) sieve.

Figure 3: Pryolized feedstocks, biochar before grinding. Clockwise from top left: Fraser fir, sorghum, bone, and wood chip.

Preparation of nutrient solutions.

Two nutrient solutions and a control were used. Leachate from a commercial composting facility (CL), biologically inert hydroponics nutrients (HN), and a control of distilled water (C). The compost leachate was collected in 19 liter containers, and sealed until it was used. The hydroponics nutrients were mixed in a container when needed.

Preparation of hydroponic nutrient solution.

11.35 liters of distilled water were poured into a clean 19-liter container. 59.2 ml of General Hydroponics FloraMicro was added, and the mixture stirred thoroughly. 88.7 ml of General Hydroponics FloraGro, and 29.6 ml of General Hydroponics FloraBloom were then added, and the mixture was mixed thoroughly.

Preparation of compost leachate.

Compost leachate was obtained from Appalachian State University's compost facility. The compost leachate is stored underground and sprayed on composting materials before draining back to its underground tank. The compost leachate was stored until it was used.

Control nutrient.

The control nutrient solution was created by pouring 11.35 liters of distilled water into a 19-liter container.

Preparation of biochar for soil treatments.

Sixty samples of 100g of control soil were measured out, and twelve 1g samples of each biochar were put in a permeable bag. Each sample of biochar had a mass of 10g/kg of the mean weight from the control soil samples. A 1% (m/m) biochar mix is a low percentage mix that is still common (Alburquerque et al., 2014; Vaughn et al. 2015). Alburquerque et al. (2014) estimate a 1% addition of biochar at 30 Mg ha^{-1}. This is a more reasonable expenditure for High Country farmers than some higher percentage mixes seen in the literature.

All bags from each nutrient solution were put into a weighted bag and submerged in the nutrient solution for 48 hours. Five samples of each biochar were put into each nutrient solution, so that each nutrient container now had twenty biochar samples; five from each of the four biochar feedstocks.

Preparation of soils

Control soil.

The control soil was obtained from the top 60cm of topsoil at a local farm. As defined by the USDA Natural Resources Conservation Service Soil Survey, the soil obtained was Saunook Loam (USDANRCS, 2016). Saunook Loam has a dark brown loam surface layer, and a brown loam subsoil down to the depth of collection (NCDANRCS, 2005). The soil comes from colluvial parent materials of felsic to mafic, igneous or high grade metamorphic rock. The USDANRCS lists Saunook loam as well suited for cropland up to an 8% slope, and well suited for pasture, orchards and ornamental crops up to a 15% slope (NCDANRCS, 2005).

This soil, while it comes from an area of the farm that was not in production, is the same base soil as the rest of the farm. It is well suited for agricultural purposes, which is to say it is not marginal land. A full analysis of High Country soils would be needed to place or rank Saunook loam soils against other High Country soils, but a preliminary examination of Watauga county soils specifically indicates it is quite high.

Of the 67 soils classified by the NCDANRCS (2005) in Watauga county, only 3 soils rated as well suited for vegetable production. Saunook loam 2% to 8% slope was one of them, indicating that Saunook loam soils have the potential to be amongst the best in Watauga county.

The soil was sieved though 12.7mm mesh into a storage container. The soil was mixed to ensure homogeneity.

Treatment soils.

At the end of the 48-hour period of soaking for the biochar, all 48 bags were opened and the biochars were weighed again, and the difference in wet and dry weight recorded. An average for each nutrient solution was recorded. Each biochar sample was mixed with one of the sixty 100g soil samples. Five samples of each nutrient solution were measured out, to a mass equal to the difference in dry and wet mass of the corresponding biochar. These samples were then added to the remaining 100g soil samples. Each sample was individually mixed until homogenous, then added to a 140mm long Cone-tainer. The Cone-tainers have a 40mm top opening, and are tapered slightly (Approximately .06mm/mm) to 30mm above the base, where the taper increases (To approximately .67mm/mm) to a 13mm bottom hole. The bottom taper also contains 4 oblong side holes. The fifteen treatments are shown in Table 2.

Table 2: Matrix of all treatments and abbreviations.

Treatment	Control	Sorghum	Wood chips	Fraser fir	Bone
Control	Control (CC)	Sorghum Control (SC)	Wood Chip Control (WC)	Fraser Fir Control (FC)	Bone Control (BC)
Hydroponic Nutrients	Control Hydroponic (CH)	Sorghum Hydroponic (SH)	Wood Chip Hydroponic (WH)	Fraser Fir Hydroponic (FH)	Bone Hydroponic (BH)
Compost leachate	Control Leachate (CL)	Sorghum Leachate (SL)	Wood Chip Leachate (WL)	Fraser Fir Leachate (FL)	Bone Leachate (BL)

Preparation of samples

Grow Table.

A grow table was built using dimensional lumber as shown in Figure 4. The table had a footprint of 2’x4’. The table was enclosed using Reflectix reflective insulation. Six 225 LED lights were hung 511mm above the top of the plant containers.

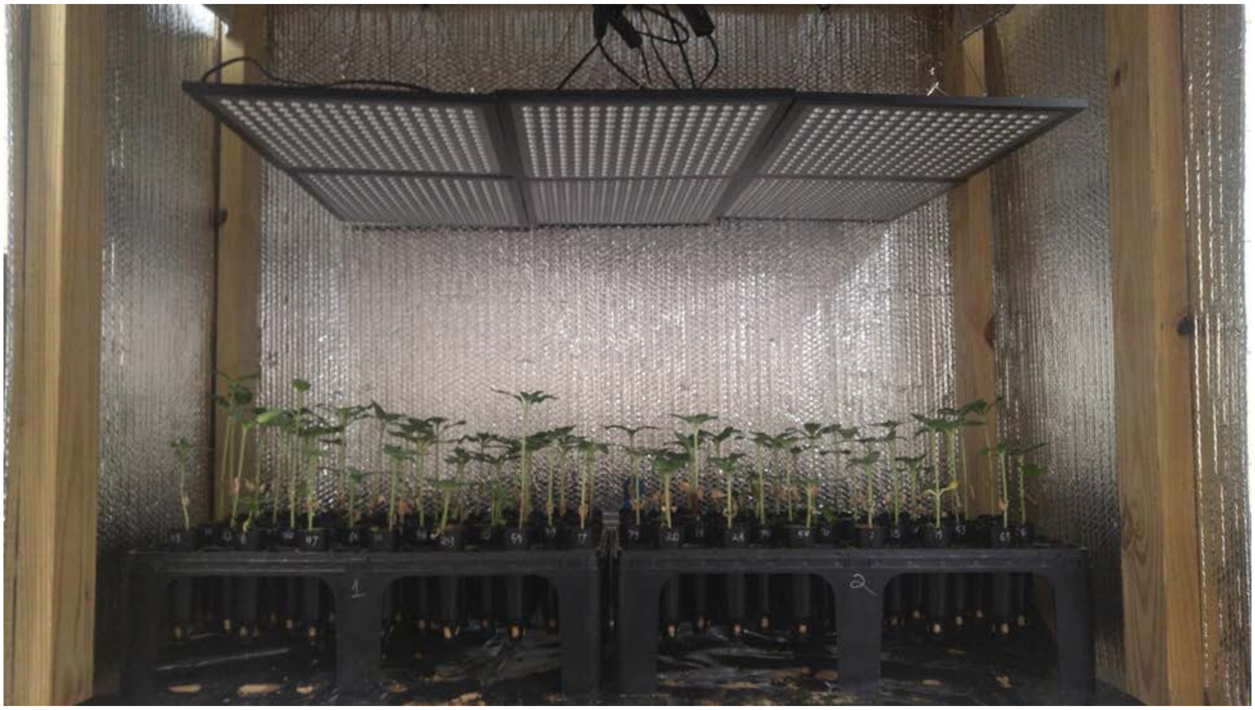

Figure 4: Internal view of growing table prior to plant harvesting.

Planting seeds.

The mass of one seed was collected for each container. The seed was pressed into the soil until it was between 10cm and 20cm below the soil surface. The containers were placed randomly in two 7x14 container stands. The lights were not turned on for 2 days.

Watering.

Plants were watered six days a week unless soil saturation was too high. Between 5ml and 30ml of tap water was added to each plant manually. When the soil was oversaturated such that additional water was likely to pass through the container without being absorbed, the plants were not watered.

Ambient data logging.

Ambient temperature and relative humidity were logged using a data logger. Logging did not begin until after the experiment began, but the results are very cyclical, so extrapolation backwards does not seem unreasonable.

Plant Harvesting and Testing

At the end of the 35-day period, plants were harvested by pulling the plant up by the roots and replacing as much soil as possible from the roots. Each plant had its height recorded, as well as dry mass for both roots and shoots, and wet weight for both roots and shoots. Dry mass was measured after drying in a drying oven for 48 hours at 75 degrees. Seeds that failed to germinate were recorded. Plant tissue analysis was completed by the North Carolina Department of Agriculture and Consumer Services.

Six plants either did not germinate or grew in such a way as to be unrecognizable as being alike to the other plant samples.

Testing of Biochars

Biochar PH and electrical conductivity were measured after diluting the biochar in a 1:20 solid/solution ratio after being shaken on a mechanical shaker for 90 minutes in distilled deionized water.

NCDA&CS soil testing.

Five soil samples were sent to the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for research soil testing. The soils were prepared by first measuring out 99g of control soil in 5 containers. Four of the containers had 1g of biochar added to them and were mixed until homogenous. Thus, the five samples were one 100% control soil, and 1% biochar for each of the four biochars. Each sample was tested three times.

Water Holding Capacity.

As mentioned above, there is a strong positive correlation between water holding capacity and total (Zhang & You, 2013). The water holding capacity of the control soil and mixtures of control soil with the four biochar types were tested. The soil and biochar mixes were all tested at 1%, 5%, 10%, 50% and 100% biochar concentrations, all soils were mixed until homogenous prior to testing. The testing apparatus used was created by removing the bottom of a 470ml container and replacing the bottom with a coffee filter. The container was nested inside of a slightly smaller container so that there was 26.67mm of space between the coffee filter and the bottom of the smaller container.

Each soil mixture was placed into one of these apparatuses, which was then filled with water to a height enough to fully submerge the soil. Each soil mixture was then gently stirred to ensure all soil particles had equal contact with the water. One hour later, additional water was added to return the water level to its original depth. The samples were left for 24 hours after water was added.

After the soils were able to saturate for 24 hours, the bottom container was removed and all water in it was removed. The larger container was nested back in the smaller container where water was allowed to pass through the coffee filter, but soil remained in the larger container. After two hours had elapsed, the process was repeated to ensure that water had not filled up the bottom container preventing soil drainage.

After being allowed to drain for 24 hours, three samples were taken from each of the soil mixtures and weighed. The samples were then put into a drying oven at 115^{O}C for 24 hours before being weighed again. The change in mass was recorded in both grams and percent change.

Data Analysis

The plant samples all had 6 measurements recorded. The length, fresh mass, and dry mass of both the roots and shoots was recoded. Five additional metrics were calculated and used to determine the effects that the treatments had on plant growth; they are summarized below in table 3. The values were examined by biochar type, by nutrient treatment, and by both biochar and nutrient type.

Table 3: List and description of calculated metrics.

Total Length (mm)	Sum of shoot length and root length.
Total Fresh Mass (g)	Sum of shoot fresh mass and root fresh mass.
Total Dry Mass (g)	Sum of shoot dry mass and root dry mass.
Dry Root:Shoot Ratio (RSR)	Dry root mass divided by dry shoot mass
"mg/mm" Dry (mg/mm)	Dry shoot mass in mg divided by shoot length in mm.

Statistical significance.

Significance testing was performed in the r programming environment, using r version 3.3.3. All two sample t-tests were Welch's two sample T-tests, performed using the t.test command. Welch's t-tests do not assume equal variances, and when used to test populations that have equal variances, Welch's t-test does not suffer substantial disadvantages, having slightly less power compared to a student-t test (Ruxton, 2006).

By biochar type.

To analyze the effects of each of the biochar types on plant growth, data collected for all treatments was separated by biochar type. The 75 samples were split into five groups based off of their biochar type, sorghum, Fraser fir, wood chip, bone, or control. This gave each of the groups 15 samples. The mean and standard deviation for each of the eleven metrics for each of the groups was collected. The means of each group was compared to the mean of the control group to find a percent change from control.

Biochar isolated effects were also examined, which looked at the comparison of just the biochar-control treatment against control-control. This eliminates all nutrient effects, but only looks at the effects of four treatments, SC, FC, WC, and BC compared to CC.

By nutrient treatment.

The nutrient treatments were analyzed similarly to the biochar treatments. The samples were separated into three groups, hydroponic nutrients, compost leachate, and control, each with 25 samples per group. Each group had its mean and standard deviation recorded for the eleven metrics above. Means were compared to the mean of the control to find a percent change from control.

Again, the isolated effects of nutrient solution were also examined. This was a comparison between control-nutrient and control-control. This eliminates any effects cause by biochar, but only looks at two treatments, CH and CL compared to CC.

By soil and nutrient treatment.

The soil and nutrient treatment analysis was slightly more complex that the two above analyses. The samples were separated into the fifteen treatments listed in the Treatment Soils section. The average and standard deviation of each of the 5 samples in each treatment was recorded, and the means were used for comparative purposes.

The means of the 15 treatments were compared in three ways. First, every treatment was compared against the treatment that had control soil and control nutrients. Secondly, each treatment was compared against the control soil sample with the same nutrient treatment. i.e. SC was compared to CC, and SH was compared to CH, etc. The third comparison compared each treatment against the treatment with the same soil type but with control nutrients. So FH and FL were compared to FC, and WH and WL were compared to WC, and so on. The three variants were to see if the cross effects of both treatment variables, the soil treatment impacts of the cross effects, and the nutrient impact on cross effects respectively.

Model of independence.

To test the independence of the effects, a model of expected means was made. This model took the isolated effects of the biochar for a treatment, and the isolated nutrient effect for the treatment and summed them, creating a total expected change from the control-control mean. This change was added to 1 and multiplied by the control-control mean for each metric. An example of this process applied to the SH treatment is found in table 4. Other treatments can be generalized from the example.

Table 4: Example of what the predictive sum model looks like for sorghum.

	Sorghum Isolated effects	Hydroponics Isolated effects	Sum of effects	control-control means	Expected SH Means
(mm)	4%	(-25%)	(-21%)	130.75	103.29
Root Length	(-9%)	2%	(-7%)	162.50	151.13
(mm)	(-4%)	(-10%)	(-14%)	293.25	252.20
(g)	0%	3%	3%	1.34	1.38
Root fresh Mass	25%	(-6%)	19%	0.70	0.83
Mass (g)	8%	0%	8%	2.03	2.20
(g)	13%	(-10%)	3%	0.23	0.23
Shoot Dry mass	(-1%)	(-7%)	(-8%)	0.23	0.21
(g)	6%	(-8%)	(-2%)	0.46	0.45
Mass	12%	4%	16%	1.01	1.17
"mg/mm" dry	(-2%)	23%	21%	1.79	2.16

The isolated effect for sorghum was found, as well as the isolated effect of hydroponics. These were summed to find the expected effect that sorghum biochar and hydroponics would have under the hypothesis that the effects are independent. To create the expected means for SH, one plus the sum of the effects was multiplied by the mean of CC, creating an expected mean for SH in each metric.

Results

A note about the language used in this section is required here. In everyday speech saying a something decreased by –x% would be a double negative and indicate an x% increase. Within the discussion of this paper a decrease of –x% is equivalent to a –x% deviation from the mean, that is to say, whenever the text says a deviation is a decrease, the deviation is negative, regardless of the sign of the numeral.

Soil and Biochar testing

Soil analysis.

The soil test reports eighteen values per test, and five samples were tested in triplicate to create 15 tests total. Table 5 contains selected results discussed here, a full table of results can be found in Appendix B.

Table 5: Means and standard deviations of results from NCDA&CS soil testing. Full table of results is available in Appendix B.

ID	Unit		Control	Bone	Sorghum	Fraser fir	Woodchip
HM	g/100cc	Mean	0.22	0.22	0.22	0.22	0.22
		Std. dev	0.00	0.00	0.00	0.00	0.00
W/V	g/cc	Mean	0.96	0.97	0.94	0.94	0.92
		Std. dev	0.02	0.02	0.02	0.01	0.02
CEC	meq/100cc	Mean	11.40	14.53	11.13	11.23	10.77
		Std. dev	0.10	0.15	0.31	0.29	0.29
BS	%	Mean	84.67	88.67	85.33	85.33	84.67
		Std. dev	0.58	0.58	0.58	0.58	1.15
pH		Mean	5.80	5.97	5.73	5.83	5.83
		Std. dev	0.00	0.06	0.06	0.06	0.06
P	mg/dm3	Mean	17.00	213.00	23.67	19.00	17.00
		Std. dev	1.73	9.54	2.31	1.73	0.00
K	mg/dm3	Mean	301.00	381.33	390.67	313.00	275.00
		Std. dev	8.54	14.74	24.58	15.52	5.29
Ca	mg/dm3	Mean	1248.00	1791.67	1176.67	1227.00	1161.67
		Std. dev	28.51	34.53	30.07	35.37	63.36
Mg	mg/dm3	Mean	322.67	362.33	315.33	320.00	312.33
		Std. dev	6.11	5.03	15.82	16.37	4.51

Cation Exchange Capacity

Sorghum, Fraser fir, and wood chip soils showed a decrease in CEC, -2%, -1% and -5% respectively. Bone soil was the only soil that showed increased cation exchange capacity, 27% higher than the mean. This number may not be an accurate measure of actual CEC, as the method used by the NCDA&CS is a summation of cations, which adds the concentration of exchangeable Ca, Mg, K, Na, and AI Cations in the soil. According to Sumner and Miller (1996), methods such as this may produce inflated values for soils that include salts of carbonates. As bone contains calcium carbonate, it is entirely possible that the result of this test is due to the carbonate content of the bone, rather than the actual ability of the soil to exchange cations.

Base Saturation

Bone, sorghum, and Fraser fir all had higher base saturations, a potential indicator of fertility, than the control (5%, 1%, and 1%, respectively). Base saturation the percent of the CEC that is already filled by a base cation, Ca^{2+}, Mg^{2+}, or K^{+}. As such a higher base saturation indicates a better buffer against acidification, as well as more available nutrients in the form of Ca, Mg, and K.

Nutrients

Bone, sorghum and Fraser fir chars have phosphorus (P) and potassium (K) levels higher than the control, bone has over 11 times as much phosphorus as each of the control soil, Fraser fir, and wood chip as well as over 9 times as much as sorghum.

Bone biochar sample soils were the only soils which had higher levels of calcium and magnesium that the control soil. Bone biochar provided the highest increase for most nutrients tested, the only nutrient in which this was the case was potassium, in which sorghum biochar provided 30% more than the control soil, and 2% more than bone biochar.

Wood chip biochar showed no change from the control in P, and a decrease of 9% in K. Wood chip biochar also had the largest magnitude decrease from the control soil in Ca and Mg. This was the only biochar treatment that showed any increase in manganese or copper, with a 3% increase for each.

Bulk density, pH, and Humic Matter

The bulk density of the soils with sorghum, Fraser fir, and wood chip biochars were all lower than the bulk density of the control soil, while the soil with bone biochar had a higher bulk density.

Only sorghum biochar was found to decrease the pH of the soil, while bone, Fraser fir, wood chip biochars Increased the pH, which can buffer the soil against acidification. Humic matter is a measurement of the humic and fulvic acid portions of soil organic matter (Hardy, Tucker, & Stokes, 2013). This is not a direct measure of soil organic matter, but the decomposed, active organic fraction (Hardy, Tucker, & Stokes, 2013). The addition of biochar had no effect on the humic matter percent across any of the samples, indicating that the biochar is not chemically active.

Water holding capacity.

In all instances, the introduction of biochar into the control soil increased water holding capacity, and there is a strong positive correlation between the concentration of biochar and the water holding capacity as shown in Figure 5. The water holding capacity is measured as the ratio between of the difference in wet and dry mass to the dry mass of the soil samples. The unit presented is a percentage of the dry soil mass that is held in water, numbers over 100% indicate that a soil can hold more than its dry mass in water mass.

The Coefficient of variation (CV) for each biochar type at each concentration was calculated by the following formula.

$$\frac{Sample\ standard\ deviation}{Mean} X100 = Coefficient\ of\ variation$$ (Everitt, 2002)

The CV is an indicator of dispersion in statistical signals. The CV is a relative measure that is also dimensionless, which allows for comparison between values with unlike means (Bąkowski, Radziszewski, & Žmindak, 2017).

Of the 21 CV determined, only two were above 5%. The 100% woodchip biochar sample had a CV of 5.19% with water holding capacities measured at 424%, 468%, and 483% over the three samples. The 50% sorghum biochar sample had a CV of 16.97% with water holding capacities measured at 494%, 428%, and 290% over three samples.

Most of the samples had some degree of moisture stratification, with the top being significantly drier than the bottom. This effect seemed most prevalent in the 100% biochar samples. This is the most likely cause of the high CV in the 100% woodchip sample. In the case of the 50% sorghum sample the issue was likely one of homogeneity. Because the bulk densities of the sorghum and the control soil have a ratio of 1:7.8 creating a mix that is 1:1 (m/m) effectively creates a mix that is 1:7.8 (v/v). Because of this and the difference in soil buoyancy, when water was introduced to saturate the soil, despite being mixed for homogeneity the control soil settled to the bottom, and the sorghum to the top. As mentioned in the methodology, an attempt was made to get a vertical cross section in each sample, but in this sample the above factors made that more difficult than other samples. If the singular sample with the 290% water holding capacity was removed, the mean would become 461%, but the CV would remain above the 5% level.

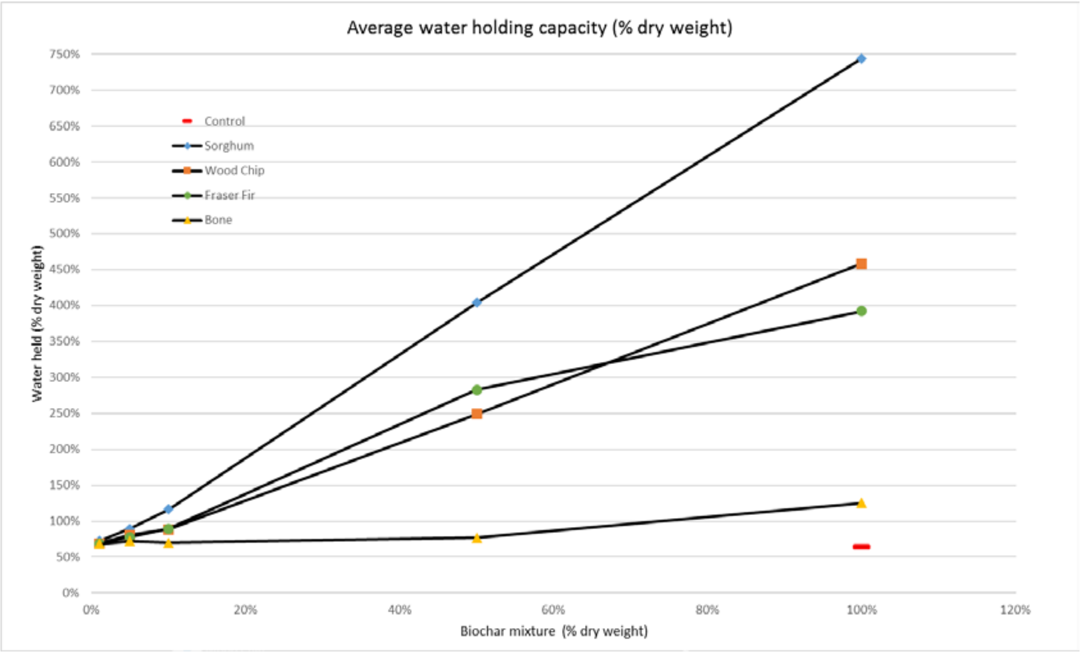

Figure 5: Water holding capacity of soil biochar mixtures as a percent of mixture dry mass.

Differences of Means

This section deals specifically with the means of each treatment or treatment group, the full raw data set can be found in appendix A, and boxplots of combined biochar effects, combined nutrient effects, and biochar-nutrient treatments can be found in Appendix E.

By biochar type.

The difference in means for the combined effects was not conclusive across the board, as seen in table 7. Only one metric had a consistent direction of change from the control over all four biochar types. All shoot lengths increased with the biochar applications. Seven of the other metrics were consistent across three of the biochar types. None of the metrics had a CV of under 10% for any biochar.

Table 6: Difference of means by biochar combined effects.

	Sorghum	Fraser Fir	Woodchip	Bone
Shoot length (mm)	2%	2%	10%	11%
Root Length (mm)	-4%	1%	-1%	4%
Total length (mm)	-1%	1%	4%	7% *
Fresh shoot mass (g)	-2%	-6%	-2%	10%
Fresh root mass (g)	22%	5%	25%	-16%
Fresh total mass (g)	6%	-2%	8%	0%
Dry root mass (g)	5%	-2%	10%	0%
Dry shoot mass (g)	5%	-3%	-3%	12%
Dry total mass (g)	5%	-3%	3%	7%
mg/mm	-1%	-1%	13%	-7%
RSR	5%	-2%	-8%	6%

Table 8 shows that the isolated effects were slightly clearer across the board. Bone biochar was clearly an outlier against the other three, as it was the only one that showed increased length and decreased RSR.

Table 7: Difference of means by biochar isolated effects.

	Sorgum	Fraser Fir	WoodChip	Bone
Shoot length (mm)	4%	-6%	-19%	8%
Root Length (mm)	-9%	-8%	-3%	3%
Total length (mm)	-4%	-7%	-10%	5%
Fresh shoot mass (g)	0%	1%	-5%	10%
Fresh root mass (g)	25%	36%	58%	10%
Fresh total mass (g)	8%	13%	16%	10%
Dry root mass (g)	13%	0%	9%	-22%
Dry shoot mass (g)	-1%	-3%	4%	12%
Dry total mass (g)	6%	-2%	7%	-5%
mg/mm	-2%	5%	29%	4%
RSR	12%	7%	9%	-8%

Sorghum.

As seen in table 7, sorghum treatments had shorter roots, and a shorter total length. The shoot fresh mass was 2% less than the control, but because the root fresh mass was 22% higher, the total fresh mass was 6% above the control. This total carried over similarly to the total fresh mass where the sorghum was 5% above the control, while both root and shoot dry masses were 5% greater than the control. The sorghum samples also showed a decrease from the mean in RSR.

For the isolated effects, table 8, total length decreased, and the total fresh and dry mass both increased. The shoot length did increase, so the mg/mm metric showed a decrease. Root masses increased significantly more than the shoot masses, which in the case of dry mass, actually decreased. Thus it is very much expected that the RSR increases, which it did, by 12%.

Fraser fir.

Fraser Fir showed slightly longer roots and shoots than the control samples in table 7, 1% and 2% respectively. The fresh shoot mass was 6% less than the control, whereas the root fresh mass was 5% higher, leaving total mass at 2% below the control. Fraser fir dry mass was lower than control in roots and shoots; the only biochar treatment that did not show an increase in total dry mass from the control. RSR and mg/mm were down against the control.

The isolated effects, seen in table 8, of Fraser fir were similar to that of sorghum, other than the total dry mass decreased, and root dry mass showed no change. The decrease in shoot fresh mass created an increase in RSR.

Wood chip.

As seen in table 7, wood chips showed an increase against the control in total length and total mass, both fresh and dry. In the case of both fresh and dry mass, wood chip biochar had less shoot mass (2% less for fresh, 3% less for dry) but compelling increases in root mass, 25% and 10% for fresh and dry respectively. Unsurprisingly then, wood chip biochar had the largest increase in RSR, at 20% above the control.

When the effect of the woodchip biochar was isolated, seen in table 8, all length metrics decreased from the control mean, the total length decrease being driven overwhelmingly by the shoot length. Mass increased in every metric other than fresh shoot mass, and in the dry case the increase in root mass was much higher than the increase in shoot mass. Root fresh mass had the highest deviation of any of the isolated effects at 58%.

Bone.

Bone biochar treatments showed characteristics not found in the other three biochars, as is clearly displayed in table 7. The RSR of bone biochar treatments was 7% below the control, the also the largest magnitude difference in that metric. Shoot, root, and total length of bone treatments were all above the control. Fresh shoot mass was 10% above the control and root mass was 16% below, dry masses were 18% higher and even for shoots and roots respectively. Total masses were 7% above the control for dry mass, and even to the control in fresh mass.

In table 8 the isolated bone effects are also largely an inversion from the other three biochars. The length of the plants increased in root, shoot and total. Fresh masses increased in equal parts across all three fresh mass metrics. Root dry mass greatly decreased, while shoot dry mass increased moderately, netting a small decrease in total dry mass, and a decrease in RSR.

By nutrient type.

The treatments that had each nutrient were analyzed against the control. These treatments hade more consistent results with each other; only total dry mass increased under one treatment and decreased under the other. Fresh and dry root mass showed a decrease under one treatment and no change under the other. All other metrics either increased or decreased with both nutrient treatments, with varying magnitudes. Again, no metrics for either nutrient type had a CV of less than 10% (range 13% to 40%).

Both nutrient solutions showed a decrease in root and shoot length, -2% and -8% for hydroponic nutrients respectively, and -8% and -2% for compost leachate respectively, as seen in table 9. Shoot mass increased 9% with hydroponics nutrients and 7% for compost leachate, across both fresh and dry masses. Both had increased total fresh mass, but a large drop in RSR (-24% and -11% for hydroponics and compost respectively) which were mirrored closely by increases in mg/mm (13% and 10% respectively).

Table 8: Combined nutrient effects.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	Compost Leachate	Hydroponics Nutrients
Shoot length (mm)	-2%	-8%
Root Length (mm)	-8% *	-2%
Total length (mm)	-5%	-5%
Fresh shoot mass (g)	7%	9%
Fresh root mass (g)	0%	-10%
Fresh total mass (g)	4%	2%
Dry root mass (g)	0%	-13% *
Dry shoot mass (g)	7%	9%
Dry total mass (g)	4%	-2%
mg/mm	-11%	-24% **
RSR	10%	23% **

The isolated effects largely mirror the combined effects under compost leachate, see table 10, only varying in direction of deviation from metrics that showed no change; the hydroponics nutrients showed a reversal in four.

Table 9: Isolated nutrient effects.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	Compst Leachate	Hydroponics Nutrients
Shoot length (mm)	-7%	-25% *
Root Length (mm)	-18% **	2%
Total length (mm)	-13% ***	-10% **
Fresh shoot mass (g)	14%	3%
Fresh root mass (g)	42%	-6%
Fresh total mass (g)	24%	0%
Dry root mass (g)	-9%	-10%
Dry shoot mass (g)	20%	-7%
Dry total mass (g)	5%	-8%
mg/mm	29% *	23%
RSR	-26%	4%

Hydroponics nutrients.

Hydroponics nutrients showed a decreased root mass, -10% fresh and -13% dry against the control nutrient, as seen in table 9. The large negative deviation in root dry mass and smaller (2%) positive deviation in dry shoot mass created a -2% deviation in total dry mass. As suggested by the literature the addition of hydroponic nutrients decreased RSR, by 24% in this study.

Table 10 shows that the isolated effects similarly show a decrease in a decrease in total length driven by a decrease in shoot length. The fresh shoot mass increased, but was covered over by a decrease in fresh root mass, netting no change in total fresh mass. All dry mass metrics decreased, with root mass decreasing most. Interestingly in the isolated effects, RSR increases.

Compost leachate.

Compost leachate showed no deviations from the control in root mass, either dry or fresh in table 9. The total dry and total fresh masses increased by 4% under compost leachate treatment. The negligible deviations on root mass from the control combined with increases in shoot mass creates an 11% decrease in RSR. Again, the decrease in RSR was expected based on the literature.

The isolated effects of compost leachate differ from the combined effects in magnitude alone. The magnitude of deviation was increased in all cases for the isolated effects, compared to combined effects, as seen in table 10.

By biochar and nutrient type.

When looking at the treatments with regard to both biochar and nutrient, each treatment only has five samples, and as each are subject to the uncertainties of biological growth. This makes pulling meaningful information from any one observation difficult, and requires looking at general trends more than single observations.

Of the 165 observation metrics taken, 43 (35%) were found to have a CV of 10% or under. This further indicates that the individual observations may not provide a particularly strong image of these effects. The minimum CV was 5% (Root length and total length) and the maximum was 76% (RSR), with two others over 50% (Fresh and dry root masses).

Compared to control soil and control nutrients.

Table C1 shows that in thirteen of the fourteen treatments being compared to control-control total fresh mass was found to be between 4% and 20% above the control, one treatment found no change. Root fresh mass increased in all but two treatments, nine of those increases were 10% above the mean or higher. The two decreases were -4% and -17% for CH and BH respectively, but the means of root fresh mass had the highest increase from the control of all metrics tracked. The measurement for mg/mm increased in eleven treatments, eight of them by over 15%. Three showed decreases, at -2% -2%, and -3%. The dry and fresh shoot masses were higher in 10 treatments, though only 6 treatments had an increase in both fresh and dry shoot mass.

Root length and total length decreased from the control in twelve of fourteen treatments, eleven treatments showed a decrease in both, BC actually increased in both. Root length means were between a 3% increase and a -22% decrease, total length means ranged between a 6% and a -15% deviation from the control mean.

The full table of results, Table C1 shows that the many of the observed results were not statistically significant, but table 11 highlights both sorghum and control soil treatments, which contain several significant observations. Most notable is the dramatic increase in dry shoot mass in the SH treatment. SH and BH were the only treatments to show a significant difference in any of the dry mass treatments, both at the .1 level. SH and BH and CL were the only treatments that showed a significant change in the mg/mm of the plant shoots, with SH and BH both increasing more than 50% and significant at the .05 level.

Table 10: Combined effects of biochar and nutrient treatments versus a control with no nutrients and no biochar for sorghum biochar and no biochar. Full results available in table C1.
****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SH	SL	CC	CH	CL
Shoot length (mm)	4%	-16%	-14%	---	-25% *	-7%
Root Length (mm)	-9%	-14% *	-6%	---	2%	-18% **
Total length (mm)	-4%	-15% ***	-9%	---	-10% **	-13% ***
Fresh shoot mass (g)	0%	15%	-3%	---	3%	14%
Fresh root mass (g)	25%	44% *	48%	---	-6%	42%
Fresh total mass (g)	8%	25% *	14%	---	0%	24%
Dry root mass (g)	13%	-17%	-2%	---	-10%	-9%
Dry shoot mass (g)	-1%	31% *	3%	---	-7%	20%
Dry total mass (g)	6%	7%	1%	---	-8%	5%
mg/mm	-2%	59% **	15%	---	23%	29% *
RSR	12%	-36%	-4%	---	4%	-26%

Compared to control nutrients with soil of same type.

Shoot Dry mass, shoot fresh mass, and mg/mm all increased in 8 of 10 treatments, as can be seen in table C2. Five treatments increased in all three metrics. The mg/mm metric had the highest average of deviation across treatment means at 12%, it also had the highest range of all of the metrics, ranging from a -26% decrease in WL, to a 62% increase in SH.

Shoot length and RSR decreased in eight treatments, six treatments showed a decrease in both. RSR had the second highest magnitude average of deviation across treatment means with a decrease of -11%. The total length only showed an increase in one treatment (WH), no change in another, and a decrease in the remaining seven. Five of the six treatments that had a decrease in both RSR and shoot length also showed a decrease in total length. The remaining treatment showed no change.

Most of the results were not found to be statistically significant, as can be seen in the full table C2. Highlighted here in table 12 is the treatment SH, which had the most significant results. Of specific note are the dry root mass, dry shoot mass and RSR. As described in the literature, the expected effects of additional nutrients on plant growth is an increase in shoot mass, and a decrease in root mass, and thus RSR. What we see in table 12 is that adding nutrients to control soil had no significant impacts on root or shoot mass or RSR. Adding hydroponics nutrients to soil with Sorghum biochar in it had significant impacts on all three of those metrics, and in the direction that would be expected with the addition of nutrients. This points to sorghum biochar increasing the efficacy of nutrient additions.

Table 11: Effects of adding nutrients to a soil with sorghum biochar and to control soil. Full results available in table C2.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SH	SL	CC	CH	CL
Shoot length (mm)	---	-19%	-17%	---	-25% *	-7%
Root Length (mm)	---	-6%	4%	---	2%	-18% **
Total length (mm)	---	-12% *	-6%	---	-10% **	-13% ***
Fresh shoot mass (g)	---	15%	-3%	---	3%	14%
Fresh root mass (g)	---	16%	18%	---	-6%	42%
Fresh total mass (g)	---	15% *	6%	---	0%	24%
Dry root mass (g)	---	-27% *	-14%	---	-10%	-9%
Dry shoot mass (g)	---	32% **	4%	---	-7%	20%
Dry total mass (g)	---	1%	-5%	---	-8%	5%
mg/mm	---	62% **	18%	---	23%	29% *
RSR	---	-42% **	-14%	---	4%	-26%

Compared to control soil with nutrients of same type.

Table C3 shows the full results for this comparison. Root fresh mass, shoot length, total fresh mass, root dry mass, and total length all increased in eight of the twelve treatments. Only one treatment showed an increase in all five metrics, while four more showed an increase in four metrics, and an additional five more showed an increase in three metrics. Root fresh mass had the highest range, from a -27% decrease to an 85% increase. Root fresh mass also had the highest single treatment magnitude of deviation at 58% increase over CC under WC. The WH treatment had a 56% increase in shoot length over CH.

Root length and mg/mm both decreased under seven treatments. The average across treatment means for mg/mm was a 1% increase, and the average across treatment means for root length was zero. This was the lowest amongst all metrics, so no metrics showed a mean decrease across treatment means.

Independence of Effects of Biochar×Nutrient

Comparing the Observed means to the predicted means yielded compelling evidence that the effects of the biochar and the nutrient were not independent. Effects that were different from the expected mean show evidence of dependence. In areas where the observed values are greater than the expected mean these are positive dependencies, an additive effect of the combination of nutrients and biochar. A full table of these results can be found in table A6.

Of the eight treatments that have both biochar and a nutrient solution in them, all but two showed positive effects in total length, with seven showing positive dependencies in shoot length and five had positive dependencies in root length. Five showed positive dependencies in total dry mass, while only did in dry shoot mass; fewer than half in root dry mass. RSR showed a negative dependency in all but two of the treatments.

Of the 88 metrics observed across all eight treatments with both biochar and a nutrient solution, 29 (33%) were significant at the .1 level at least. Of those, 19 (22%) were significant at the .05 level at least. There is only one treatment that has no metrics significant at the .05 level, indicating that the effects of biochar and nutrients are not independent.

Discussion

Soil Analysis

The CEC of sorghum, Fraser fir and wood chip biochars all appear to be less than 11.40, which is the CEC of the soil. When added in a 1% concentration by soil mass, they all lowered the mean CEC over three tests, each with A CV of 3% or less. One thing to note is the previously mentioned study by Cheng et al. (2006) that found that oxidization of biochar increases the biochar CEC. These biochar samples were pyrolized, crushed, and sieved over a period of two days, then stored in an airtight container until they were removed to be mixed with the soil and sent for testing. The opportunity for the biochar to oxidize was quite limited, so it is likely that the CEC of these soils would increase over time, by virtue of biochar oxidization reactions.

Bone biochar was found to increase the soil CEC, though due to the methodology of the testing used, this may not be an accurate result. As mentioned in the previous chapter, soils which contain carbonates may return artificially inflated results. To avoid these effects, a different methodology would need to be used, such as the methodology titled "Cation Exchange Capacity of Soils Containing Salts, Carbonates or Zeolites" from Sumner and Miller (1996, p. 1213).

The increase in pH found in bone, Fraser fir, and woodchip biochars is most likely created by ash in the biochar, but this may be useful to High Country farmers. As seen in the control soil pH, High Country soils can be acidic. The addition of biochar, though likely not an annual amendment, may temporarily eliminate the need for liming the soil.

Water Holding Capacity

The water holding capacity of the biochars were found to be much higher than the control soil. This was not unexpected due to the porosity generally found in biochar. Sorghum biochar was found to be able to hold nearly seven and a half times its dry mass in water, while wood chip was able to hold over four and a half times its dry mass, and Fraser fir four times. Further tests would need to be done to find out if the water being held is available to plants, or if the increase in water holding capacity is matched by an increase in the permanent wilting point, the soil moisture level at which a plant permanently loses turgidity.

Biochar Effects

The most crucial impact we can see from the biochar combined effects are that the total dry mass of the plants increased on average in all but one treatment, and that root dry masses tended to increase more than shoot dry masses, though both tended to increase.

Sorghum.

Sorghum dry mass increased across the board, and in equal amounts for both root and shoot. Root length and RSR decreased, as did the fresh shoot mass. Every other metric showed improvement. This indicates that the sorghum biochar would increase yield and root mass in equal parts. The isolated effects indicate much the same, only showing a larger increase in RSR, greater root mass and total mass.

Fraser Fir.

Fraser fir biochar treatments increased in all length metrics, and also the root fresh mass. Aside from the root fresh mass, all mass metrics showed a decrease, albeit a small one. Isolated Fraser fir biochar effects showed an increase in fresh masses, but also RSR and mm/mg. This together indicates that Fraser fir biochar is likely to create shorter, stockier plants with slightly less mass, and a higher allocation of biomass in the roots.

Wood Chip.

Wood chip combined effects increased total length driven by shoot length and mass driven by root mass, in both the fresh and dry cases. This increased the RSR as would be expected. Isolated results did not increase in length, and also showed a larger increase in both shoot and total dry masses. The effects of wood chip biochar are then quite similar to Sorghum biochar, increasing root mass considerably, while creating shorter plants as well. The main difference is that the increase in RSR for woodchip biochar would be greater, due to the fact that its impact on shoot mass is smaller, and potentially negative.

Bone.

Bone biochar was the outlier of the biochars. From its increased nutrient content in the soil tests, its high bulk density and low water holding capacity, to its effects on plant growth, it was different in all cases. In both the isolated and combined effects, bone increased the total plant length, driven largely by increased shoot height, though root length also increased too. Because of bone biochar's increased nutrients, and the link between RSR and nutrients in the literature, it is not surprising that bone biochar was the only one that showed a sizeable decrease in RSR in both isolated and combined effects. Bone biochar is an interesting one to speculate on, as it is in effect a nutrient and a biochar. Nutrients by nature are short term amendments, and biochar is permanent on a human timescale. What effects of bone biochar are permanent and which are negative is impossible to tell by this experiment, and would require a multiple growing season experiment.

Nutrient Effects

Surprisingly, nutrients, in both combined and isolated effects tended to create plants with less length in both roots and shoots. They also increased the shoot mass in all cases except the hydro isolated effects. Root mass was found to either not change or to decrease in all cases. Interestingly, in both combined and isolated effects, compost leachate increased the total dry mass by a small (~5%) amount, and hydroponics nutrients decreased total dry mass. So it appears that on their own, the compost leachate helped assist plant growth in terms of mass, producing shorter but stockier plants, whereas hydroponics nutrients created shorter plants with less mass.

Combined Effects

The three different ways of looking at the combined effects all provided very different results. Comparing biochar to control with similar nutrients provided results most similar to the biochar effects. Comparing nutrients to control within biochar treatments provided results most similar to the nutrient effect. Comparing treatments to the control-control treatment provided results somewhere in between. The individual biochar and nutrient results cover most of the combined effects, and deviations from that are addressed by synthesis effects, so this section will receive no further discussion.

Dependent Effects

Looking at both the difference in observed and expected means and the significance from the test of independence, it is clear that the effects of biochar and nutrients cannot be considered as independent.

All three length metrics showed significant positive dependencies in at least two treatments, and only root length showed any significant negative dependencies. Dry shoot mass and total dry mass also had significant positive effects in two treatments and no negative effects. Root dry mass only showed a significant negative dependency in one treatment. The mg/mm metric had four treatments with significant negative effects, and none with positive, indicating that the combination of biochar and nutrients makes plant shoots less massive per unit height than if the effects were independent.

Though they were not necessarily significant, hydroponics tended to show positive dependencies on shoot mass, and minor negative dependencies on root mass. Compost leachate showed the opposite, but the magnitude of the negative dependencies was greater than in the case of hydroponics.

Conclusions

Which biochar is best?

Based on the results of the study, Sorghum biochar has provides the most promise for a useful soil amendment. Sorghum was found to have the highest water holding capacity, and thus by proxy, the highest total pore space. In the combined effects, comparing soil with sorghum biochar and hydroponics nutrients to soil with just sorghum biochar yielded several significant changes. These changes were in line with what the literature indicated what would happen with the addition of nutrients. Conversely the addition of nutrients to control soils had a lesser and non-significant impact. Indicating that sorghum biochar may make the nutrients more available to the plants.

The addition of sorghum biochars to control soils with like nutrients did not yield any significant beneficial results, but this was the case for all biochars. The combined effects of hydroponics nutrients and sorghum biochar generated the largest increase in dry shoot mass. Looking at the dependence effects, sorghum biochar also created the greatest dependence-driven gain in shoot mass.

Does this follow from the physical properties?

The third research question asked if we could draw a line from the physical properties of the biochar and biochar soil mixes to the impacts on plant growth. The answer is not clear. Sorghum appeared to be the best performing biochar, and also seemed to have the most pore space. Beyond that though there is not much that differentiates it significantly from the other three vegetative biochars, yet it did remarkably better.

Bone did show much higher levels of nutrients, specifically P in the soil tests. Bone biochar behaved differently than the other biochars, and in fact more like a nutrient might. So the line between physical properties and growth outcomes seems clear there, but much murkier in other regards.

Recommendations for Further Research

There are a lot of areas for further research identified by this experiment. This experiment identifies more new questions to answer than it does answer. Because of the breadth of this experiment, with five soil types and three nutrient types (including controls), the number of samples of each treatment can have is limited by the overall complexity of the experiment. For that reason, the results of this experiment have a strong indication but are far from conclusive.

Each biochar should be tested in more detail. Additional information about factors like surface area and porosity, also ash content should be investigated. More specific information about the biochar nutrient contents could be found, as opposed to information in 1% (m/m) mixture. Once the biochar is tested in further depth, growth experiments could be attempted.

Growth experiments into the biochars should have fewer treatments and more subjects in each treatment, to provide more conclusive ideas of the biochar impacts. Growth test should be both short term and multiple growing cycles long. Local farmers could be willing participants in assisting with these experiments, and are likely very interested to see their direct benefits.

Biochar research beyond this study.

Beyond the results from this study there are several directions biochar research can go locally. The biochar for this experiment was made in a generally uncontrolled apparatus. There was no way to fine tune the temperature, heating rate, or hold time. Anyone wanting to recreate this study would only be able to get close to matching the exact conditions. One step that needs to be taken is the construction of an apparatus that can be finely controlled to create biochar with specific pyrolysis profiles. This allows for test to be recreated, matched, and also more precise in their findings.

The next step following that is to be able to collect the other outputs of the pyrolysis process. Specifically, being able to collect and then evaluate the contents of the syngas. Collecting the syngas and using a gas chromatograph to classify the constituent parts of the syngas and calculate the energy density of syngas from various feedstocks. Finding the energy output of combusting and pyrolizing the feedstocks could provide extremely useful in calculating the carbon balance of a pyrolysis system.

References

Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016) Benefits of Biochar, Compost and Biochar-Compost for Soil Quality, Maize Yield and Greenhouse Gas Emissions in a Tropical Agricultural Soil. *Science of the Total Environment, 543,* 295-306.

Alburquerque, J. A., Calero, J. M., Barrón, V., Torrent, J., del Campillo, M. C., Gallardo, A., & Villar, R. (2014) Effects of Biochar Produced from Different Feedstocks on Soil Properties and Sunflower Growth. *Journal of Plant Nutrition,* 177, 16-25.

Amonette, J. E., & Joseph, S. (2009) Characteristics of Biochar: Microchemical Properties. In J. Lehmann, & S. Joseph (Eds.) *Biochar for Environmental Management* (pp. 33-52)

Australian Plant Science Society (2016) Plants in Action. Retrieved from: http://plantsinaction.science.uq.edu.au/

Bache, B. W. (2006) Ion Exchange. In R. Lal (Ed.) *Encyclopedia of Soil Science* (2nd ed.) (pp. 916-919).

Bąkowski, A., Radziszewski, L., & Žmindak, M. (2017) Analysis of the coefficient of variation for injection pressure in a compression ignition engine. *Procedia Engineering,* 177, 297-302.

Bini, C., & Zilioli, D. (2011) Soil Erosion Between Geomorphological Fragility and Sustainable Land Use in Mountain Areas (Italy). A. J. Fournier (Ed.) *Soil Erosion Causes, Processes and Effects. (pp. 35-67).*

Bridgwater, T. (2010). Biomass Pyrolysis [Presentation slides]. Retrieved from http://www.ieabioenergy.com/wp-content/uploads/2013/10/ExCo66-P2-Biomass-pyrolysis-Tony-Bridgwater1.pdf

Brown, L. R. (1984). The global loss of topsoil. *Journal of Soil and Water Conservation, 39,* 162 – 165.

Cai, Y. & Chang, S. X. (2016) Biochar Effects on Soil Fertility and Nutrient Cycling. In Y.S. Ok, S. M. Uchimiya, S. X. Chang, N. Bolan (Eds.) Biochar Production, Characterization, and Applications. (pp. 246-271).

Cameron, K. C., Buchan, G. D. (2006) Porosity and Pore Size Distribution. In R. Lal (Ed.) *Encyclopedia of Soil Science* (2nd ed.) (pp. 1350-1353).

Cassel, D. K., & Nielsen, D. R. (1986) Field capacity and available water capacity. In G. S. Campell, R. D. Jackson, M. M. Mortland, D. R. Nielsen, & A. Klute (Eds.), *Methods of soil analysis Part 1 – Physical and Mineralogical Methods* (pp. 901- 926). Retrieved from https://dl.sciencesocieties.org/publications/books/tocs/sssabookseries/methodsofsoilan1

Cetin, E., Moghtaderi, B., Gupta, R., & Wall, T.F. (2004) Influence of Pyrolysis Conditions on the Structure and Gasification Reactivity of Biomass chars. *Fuel, 83,* 2139-2150.

Cheng,C., Lehmann, J., Thies,J. E., Burton, S. D., and Engelhard, M. H. (2006) Oxidation of Black Carbon by Biotic and Abiotic Processes. *Organic Geochemistry, 37*, 1477-1488.

Comas, L. H., Becker, S. R., Cruz, V., Byrne, P. F., Dierig, D. A. (2013) Root Traits Contributing to Plant Productivity Under Drought. *Frontiers in Plant Science, 4*.

Cornell University Cooperative Extension (2007) Cation Exchange Capacity (CEC) *Agronomy Fact Sheet Series, 22*. Retrieved from http://nmsp.cals.cornell.edu/publications/factsheets/factsheet22.pdf

Diez, C., Sanchez, M. E., Haxaire, P., Martinez, O., Moran, A. (2005) Pyrolysis of tyres: A comparison of the results from a fixed-bed laboratory reactor and a pilot plant (rotatory reactor). *Journal of Analytical and Applied Pyrolysis, 74*, 254-258.

Doan, T. T., Henry-des-Tureaux, T., Rumpel, C., Janeau, J. L., and Jouquet, P. (2015) Impact of Compost, Vermicompost, and Biochar on soil fertility, Maize Yield and Soil Erosion in Northern Vietnam: A three Year Mesocosm Experiment. *Science of the Total Environment, 514,* 147-154.

Dong, D., Wu, W., Zhong, T. (2016) Effects of Straw-Derived Biochar on Rice Paddy. In Y.S. Ok, S. M. Uchimiya, S. X. Chang, N. Bolan (Eds.) Biochar Production, Characterization, and Applications. (pp. 294-326).

Downie, A., Crosky, A., & Munroe, P. (2009) Physical properties of Biochar. In J. Lehmann, & S. Joseph (Eds.) *Biochar for Environmental Management* (pp. 13- 32).

Everitt, B. S. (2002) *The Cambridge Dictionary of Statistics* (Second edition). Cambridge, UK: Cambridge University Press.

Giminez, D. (2006) Macroporosity. In R. Lal (Ed.) *Encyclopedia of Soil Science* (2nd ed.) (pp. 1042 - 1044).

Gua, J., & Lua, A. C. (1998) Characterization of Chars Pyrolyzed from Oil Palm Stones for the Preparation of Activated Carbons. *Journal of Analytical and Applied Pyrolysis, 46,* 113-125.

Han, F., Ren, L., & Zhang, X. (2016) Effects of Biochar on the Soil Nutrients About Different Grasslands in the Loess Plateau. *Catena, 137,* 554-562.

Harris, R. W. (1992) Root Shoot Ratios. *Journal of Arboriculture 18(1),* 39-42.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl C. A., Guenther, P. R., & Waterman, L. S. (1976) Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus 23(6),* 539- 551.

Lee, S. S., Shah, H. S., Awad, Y. M., Kumar, S., and Ok, Y. S. (2015) Synergy effects of biochar and polyacrylamide on plant growth and soil erosion control. *Environmental Earth Sciences, 74 (3),* 2463-2473.

Lehmann, J., & Joseph, S. (2009) Biochar for Environmental Management: An Introduction. In J. Lehmann, & S. Joseph (Eds.) *Biochar for Environmental Management* (pp. 1- 12).

Lewis, A. C., (1999) Production and Characterization of Structural Active Carbon from Wood Precursors (Unpublished master's thesis) The Johns Hopkins University, Baltimore, MD.

Lua, A. C., Yang, T., & Guo, J. (2004) Effects of Pyrolysis Conditions on the Properties of Activated Carbons Prepared from Pistachio-Nut Shells. *Journal of Analytical and Applied Pyrolysis, 72,* 279-287.

Perret, J., Prasher, S. O., Kantzas, A., & Langford, C. (1999) Three-Dimensional Quantification of Macropore Networks in Undisturbed Soil Cores. *Soil Science Society of America Journal, 63,* 1530- 1543.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K. Kurz, D., McNair, M., … Blair, R. (1995) Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science, 267,* 1117-1123.

Rouquerol, F., Rouquerol, J., Sing, K. S. W., Maurin, G., & Llewellyn, P. (2014) Introduction. In F. Rouquerol, J. Rouquerol, K. S. W. Sing, G. Maurin, & P. Llewellyn (Eds.) *Adsorption by Powders and Porous Solids: Principles, Methodology and Applications.* (pp. 1- 24).

Ruxton, G. (2006) The unequal variance t-test is an underused alternative to Student's t-test and the Mann–Whitney U test. *Behavioral Ecology, 17(4),* 688-690.

Sabine, C. L., Heimann, M., Artaxo, P., Bakker, D. C. E., Chen, C. A.,Field, C. B., … Valentini, R. (2004) Current Status and Past Trends of the Clobal Carbon Cycle. In C. B. Field & M. R. Raupach (Eds.) *The Global Carbon Cycle* (pp. 17 – 44).

Ścisłowska, M., Włodarczyk, R., Kobyłecki, R., & Bis, Z. (2015) Biochar To Improve the Quality and Productivity of Soils. *Journal of Ecological Engineering*, *16*(3), 31-35.

Sumner, M. E., & Miller W. P. (1996) Cation Exchange Capacity and Exchange Coefficients. in J. M. Bigham, J. M. Bartels, D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, & M. E. Sumner (Eds.), *Methods of Soil Analysis Part 3 – Chemical Methods* (pp.1201- 1229). Retrieved from https://dl.sciencesocieties.org/publications/books/tocs/sssabookseries/methodsofsoilan3

Teel, W. S. (2012) Capturing Heat from a Batch Biochar Production System for Use in Greenhouses and Hoop Houses. *Journal of Agricultural Science and Technology, 2,* 1332-1343.

Thangaranjan, R., Bolan, N., Mandal, S., Kunhikrishnan, A., Choppala, G., Karunanithi, R., & Qi, F. (2016) Biochar for Inorganic Contaminant Management in Soil. In Y.S. Ok, S. M. Uchimiya, S. X. Chang, N. Bolan (Eds.) Biochar Production, Characterization, and Applications. (pp. 100- 138)

Troeh, F. R. & Thompson, L.M., (2005) Physical Properties of Soils. In F. R. Troeh & L.M. Thompson (Eds.) Soils and Soil Fertility (6th ed.) (pp37-64). Ames, IA: Blackwell.

UNESCO (United Nations Educational, Scientific and Cultural Organization). 2016. *The United Nations World Water Development Report: Water and Jobs*. Retrieved from http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2016-water-and-jobs/

USDA ARS (United States Department of Agriculture Agricultural Research Service). (2012) [Interactive Map of USDA 2012 Plant Hardiness Zones]. USDA Plant Hardiness Zone Map. Retrieved from http://http://planthardiness.ars.usda.gov/PHZMWeb/InteractiveMap.aspx

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service). (2005) Soil Survey of Watauga County, North Carolina. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/north_carolina/NC189/0/Watauga_NC.pdf

USDA NRCS (2006) [Map of dominant soil orders in the United States of America]. Dominant Soil Orders. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_MEDIA/stelprdb1237749.pdf

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service). (2016) [Interactive Map of SSURGO geospatial data] Web Soil Survey. Retrieved from https://websoilsurvey.nrcs.usda.gov/

Usman, A. R., Al-Wabel, M., OK, Y., Al-Harbi, A., Wahb-Allah, M., El-Naggar, A. H., … Al-Omran, A. (2016) Conocarpus Biochar Induces Changes in Soil Nutrient Availability and Tomato Growth Under Saline Irrigation. *Pedosphere, 26*(1), 27-38.

Vaughn, S. F., Dinelli, F. D., Tisserat, B., Joshee, N., Vaughan, M. M., & Peterson, S. C. (2015) Creeping Bentgrass Growth in Sand-Based Root Zones With or Without Biochar. *Scientia Horticulturae, 197,* 592-596.

Wolf, B. (1982) A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. *Communications in Soil Science and Plant Analysis, 13,* 1035-1059.

World Economic Forum. (2016). *The Global Risks Report 2016*. Retrieved from https://www.weforum.org/reports/the-global-risks-report-2016

Zhang, J., & You, C., (2013) Water Holding Capacity and Absorption Properties of Wood Chars. *Energy and Fuels. 27,* 2643-2648.

Zuazo V. H.D., Tejero, I. G., Martinez, J. R. F., Fernandez, J. L. M. (2011) Soil Erosion: Causes, Processes and Effects. In A. J. Fournier (Ed.) *Soil Erosion Causes, Processes and Effects.* (pp.1-34).

Appendix A: Biochar Growth Data

Table A 1: Raw values for each plant in all metrics.

Container	biochar type	Nutrient solution	Seed Mass (g)	Shoot length (mm)	Root Length (mm)	Total length (mm)	Shoot fresh Mass (g)	Root fresh Mass (g)	Total Mass (g)	Root Dry mass (g)	Shoot Dry mass (g)	Total Dry Mass (g)	Dry root: shoot Mass
1	sorghum	Control	0.13	159	154	313	1.41	0.67	2.08	0.29	0.23	0.52	1.26
2	sorghum	Control	0.1	133	141	274	1.39	1.09	2.48	0.26	0.26	0.52	1.00
3	sorghum	Control	0.11	91	173	264	1.14	0.57	1.71	0.19	0.21	0.4	0.90
4	sorghum	Control	0.08	157	152	309	1.4	0.86	2.26	0.2	0.21	0.41	0.95
5	sorghum	Control	0.15	137	117	254	1.33	1.15	2.48	0.35	0.23	0.58	1.52
6	sorghum	Hydro	0.14	127	145	272	1.67	1.16	2.83	0.17	0.33	0.5	0.52
7	sorghum	Hydro	0.11	123	126	249	1.27	1.24	2.51	0.25	0.26	0.51	0.96
8	sorghum	Hydro	0.13	124	141	265	1.52	1.05	2.57	0.2	0.31	0.51	0.65
9	sorghum	Hydro	0.11	72	142	214	1.32	0.87	2.19	0.18	0.24	0.42	0.75
10	sorghum	Hydro	0.14	102	142	244	1.91	0.7	2.61	0.14	0.37	0.51	0.38
11	sorghum	Compost	0.13	120	117	237	1.68	1.46	3.14	0.32	0.34	0.66	0.94
12	sorghum	Compost	0.11	142	142	284	1.48	1.38	2.86	0.26	0.32	0.58	0.81
13	sorghum	Compost	0.09	65	115	180	0.76	0.37	1.13	0.1	0.1	0.2	1.00
14	sorghum	Compost	0.13	116	212	328	1.14	0.93	2.07	0.24	0.18	0.42	1.33
15	sorghum	Compost	0.09	120	179	299	1.43	0.99	2.42	0.19	0.25	0.44	0.76
16	Fraser Fir	Control	0.11	150	158	308	1.78	1.01	2.79	0.25	0.31	0.56	0.81
17	Fraser Fir	Control	0.08	115	130	245	1.09	0.95	2.04	0.22	0.15	0.37	1.47
19	Fraser Fir	Control	0.13	146	170	316	1.45	0.79	2.24	0.21	0.22	0.43	0.95
20	Fraser Fir	Control	0.09	81	140	221	1.08	1.02	2.1	0.23	0.21	0.44	1.10
21	Fraser Fir	Hydro	0.09	96	155	251	1.27	1.13	2.4	0.26	0.26	0.52	1.00
22	Fraser Fir	Hydro	0.09	154	157	311	1.18	0.68	1.86	0.17	0.17	0.34	1.00
23	Fraser Fir	Hydro	0.13	135	145	280	1.63	0.83	2.46	0.17	0.3	0.47	0.57
24	Fraser Fir	Hydro	0.14	72	131	203	1.01	0.32	1.33	0.08	0.18	0.26	0.44

Container	biochar type	Nutrient solution	Seed Mass (g)	Shoot length (mm)	Root Length (mm)	Total length (mm)	Shoot fresh Mass (g)	Root fresh Mass (g)	Total Mass (g)	Root Dry mass (g)	Shoot Dry mass (g)	Total Dry Mass (g)	Dry root: shoot Mass
25	Fraser Fir	Hydro	0.13	120	190	310	1.39	1.09	2.48	0.17	0.27	0.44	0.63
26	Fraser Fir	Compost	0.08	84	166	250	1.15	0.57	1.72	0.18	0.22	0.4	0.82
27	Fraser Fir	Compost	0.15	161	138	299	1.45	0.6	2.05	0.25	0.23	0.48	1.09
28	Fraser Fir	Compost	0.1	98	141	239	1.36	0.75	2.11	0.26	0.23	0.49	1.13
29	Fraser Fir	Compost	0.13	132	166	298	1.58	1.12	2.7	0.26	0.31	0.57	0.84
31	Wood Chip	Control	0.1	115	195	310	1.23	1.07	2.3	0.3	0.22	0.52	1.36
32	Wood Chip	Control	0.15	83	148	231	1.37	0.9	2.27	0.19	0.3	0.49	0.63
33	Wood Chip	Control	0.13	129	152	281	1.58	1.41	2.99	0.27	0.31	0.58	0.87
34	Wood Chip	Control	0.11	99	142	241	0.92	1.12	2.04	0.27	0.17	0.44	1.59
35	Wood Chip	Control	0.14	105	155	260	1.22	0.98	2.2	0.21	0.2	0.41	1.05
36	Wood Chip	Hydro	0.13	188	180	368	1.33	0.7	2.03	0.16	0.19	0.35	0.84
37	Wood Chip	Hydro	0.13	155	163	318	1.73	0.61	2.34	0.19	0.25	0.44	0.76
38	Wood Chip	Hydro	0.17	165	161	326	1.67	1.03	2.7	0.24	0.26	0.5	0.92
39	Wood Chip	Hydro	0.13	102	132	234	1.5	1.51	3.01	0.31	0.28	0.59	1.11
41	Wood Chip	Compost	0.11	105	140	245	1.28	0.86	2.14	0.24	0.19	0.43	1.26
42	Wood Chip	Compost	0.1	130	152	282	1.4	0.99	2.39	0.21	0.26	0.47	0.81
43	Wood Chip	Compost	0.11	144	146	290	1.59	1.05	2.64	0.26	0.31	0.57	0.84
45	Wood Chip	Compost	0.13	149	94	243	1.28	0.63	1.91	0.19	0.13	0.32	1.46
46	Bone	Control	0.14	150	167	317	1.8	1.14	2.94	0.28	0.34	0.62	0.82
47	Bone	Control	0.08	103	165	268	1.16	0.88	2.04	0.15	0.22	0.37	0.68
48	Bone	Control	0.12	133	188	321	1.71	0.56	2.27	0.14	0.38	0.52	0.37
49	Bone	Control	0.11	125	150	275	0.7	0.46	1.16	0.15	0.07	0.22	2.14
50	Bone	Control	0.14	193	165	358	1.96	0.79	2.75	0.17	0.28	0.45	0.61
51	Bone	Hydro	0.14	105	135	240	1.55	0.69	2.24	0.3	0.32	0.62	0.94
52	Bone	Hydro	0.15	105	180	285	1.66	0.75	2.41	0.23	0.31	0.54	0.74
53	Bone	Hydro	0.11	140	141	281	1.68	0.37	2.05	0.16	0.27	0.43	0.59
54	Bone	Hydro	0.11	68	180	248	1.27	0.38	1.65	0.16	0.24	0.4	0.67
55	Bone	Hydro	0.16	140	133	273	1.82	0.45	2.27	0.19	0.28	0.47	0.68
56	Bone	Compost	0.13	94	153	247	1.36	1.06	2.42	0.49	0.28	0.77	1.75

Container	biochar type	Nutrient solution	Seed Mass (g)	Shoot length (mm)	Root Length (mm)	Total length (mm)	Shoot fresh Mass (g)	Root fresh Mass (g)	Total Mass (g)	Root Dry mass (g)	Shoot Dry mass (g)	Total Dry Mass (g)	Dry root: shoot Mass
57	Bone	Compost	0.17	125	160	285	1.55	0.62	2.17	0.19	0.28	0.47	0.68
58	Bone	Compost	0.13	118	160	278	1.99	0.63	2.62	0.21	0.37	0.58	0.57
59	Bone	Compost	0.11	177	141	318	1.43	0.53	1.96	0.17	0.26	0.43	0.65
60	Bone	Compost	0.19	172	150	322	1.71	0.73	2.44	0.2	0.2	0.4	1.00
62	Control	Control	0.08	108	180	288	1.19	0.79	1.98	0.32	0.21	0.53	1.52
63	Control	Control	0.15	110	170	280	1.27	0.78	2.05	0.24	0.22	0.46	1.09
64	Control	Control	0.11	148	160	308	1.21	0.42	1.63	0.14	0.2	0.34	0.70
65	Control	Control	0.12	157	140	297	1.68	0.79	2.47	0.21	0.29	0.5	0.72
66	Control	Hydro	0.08	87	180	267	1.07	0.44	1.51	0.19	0.18	0.37	1.06
67	Control	Hydro	0.12	117	160	277	1.63	0.54	2.17	0.2	0.33	0.53	0.61
68	Control	Hydro	0.12	105	143	248	1.35	0.74	2.09	0.24	0.15	0.39	1.60
69	Control	Hydro	0.12	82	177	259	1.44	0.9	2.34	0.19	0.2	0.39	0.95
71	Control	Compost	0.09	135	122	257	1.46	0.84	2.3	0.17	0.23	0.4	0.74
72	Control	Compost	0.15	110	144	254	1.56	0.32	1.88	0.11	0.3	0.41	0.37
73	Control	Compost	0.12	110	123	233	1.56	1.39	2.95	0.27	0.3	0.57	0.90
74	Control	Compost	0.12	120	157	277	1.46	1.04	2.5	0.23	0.28	0.51	0.82
75	Control	Compost	0.14	131	121	252	1.6	1.33	2.93	0.25	0.27	0.52	0.93

Table A 2: Means of biochar treatments, across all nutrient treatments.

	Sorghum	Fraser Fir	Woodchip	Bone	Control
Shoot length (mm)	119.20	118.77	128.38	129.87	116.92
Root Length (mm)	146.53	152.85	150.77	157.87	152.08
Total length (mm)	265.73	271.62	279.15	287.73	269.00
Fresh shoot mass (g)	1.39	1.34	1.39	1.56	1.42
Fresh root mass (g)	0.97	0.84	0.99	0.67	0.79
Fresh total mass (g)	2.36	2.18	2.38	2.23	2.22
Dry root mass (g)	0.22	0.21	0.23	0.21	0.21
Dry shoot mass (g)	0.26	0.24	0.24	0.27	0.24
Dry total mass (g)	0.48	0.44	0.47	0.49	0.46
mg/mm	0.92	0.91	1.04	0.86	0.92
RSR	2.21	2.08	1.95	2.25	2.11

Table A 3: Means of all nutrient treatments across all biochar treatments.

	Compost Leachate	Hydroponics Nutrients	Control
Shoot length (mm)	124.26	116.70	127.26
Root Length (mm)	145.17	153.87	157.04
Total length (mm)	269.43	270.57	284.30
Fresh shoot mass (g)	1.45	1.47	1.35
Fresh root mass (g)	0.88	0.79	0.88
Fresh total mass (g)	2.32	2.26	2.23
Dry root mass (g)	0.23	0.20	0.23
Dry shoot mass (g)	0.25	0.26	0.24
Dry total mass (g)	0.48	0.46	0.46
mg/mm	0.93	0.80	1.05
RSR	2.10	2.35	1.92

Table A 4: Means of each biochar-nutrient treatment.

	SC	SH	SL	FC	FH	FL	WC	WH	WL	BC	BH	BL	CC	CH	CL
Shoot length (mm)	135.40	109.60	112.60	123.00	115.40	118.75	106.20	152.50	132.00	140.80	111.60	137.20	130.75	97.75	121.20
Root Length (mm)	147.40	139.20	153.00	149.50	155.60	152.75	158.40	159.00	133.00	167.00	153.80	152.80	162.50	165.00	133.40
Total length (mm)	282.80	248.80	265.60	272.50	271.00	271.50	264.60	311.50	265.00	307.80	265.40	290.00	293.25	262.75	254.60
Fresh shoot mass (g)	1.33	1.54	1.30	1.35	1.30	1.39	1.26	1.56	1.39	1.47	1.60	1.61	1.34	1.37	1.53
Fresh root mass (g)	0.87	1.00	1.03	0.94	0.81	0.76	1.10	0.96	0.88	0.77	0.53	0.71	0.70	0.66	0.98
Fresh total mass (g)	2.20	2.54	2.32	2.29	2.11	2.15	2.36	2.52	2.27	2.23	2.12	2.32	2.03	2.03	2.51
Dry root mass (g)	0.26	0.19	0.22	0.23	0.17	0.24	0.25	0.23	0.23	0.18	0.21	0.25	0.23	0.21	0.21
Dry shoot mass (g)	0.23	0.30	0.24	0.22	0.24	0.25	0.24	0.25	0.22	0.26	0.28	0.28	0.23	0.22	0.28
Dry total mass (g)	0.49	0.49	0.46	0.45	0.41	0.49	0.49	0.47	0.45	0.44	0.49	0.53	0.46	0.42	0.48
mg/mm	1.75	2.83	2.05	1.87	2.16	2.19	2.31	1.74	1.71	1.85	2.69	2.20	1.79	2.19	2.31
RSR	1.13	0.65	0.97	1.08	0.73	0.97	1.10	0.91	1.09	0.92	0.72	0.93	1.01	1.05	0.75

Table A 5: Expected means based on assumption of biochar and nutrient effect independence

	SC	SH	SL	FC	FH	FL	WC	WH	WL	BC	BH	BL	CC	CH	CL
Shoot length (mm)	135.40	102.40	125.85	123.00	90.00	113.45	106.20	73.20	96.65	140.80	107.80	131.25	130.75	97.75	121.20
Root Length (mm)	147.40	149.90	118.30	149.50	152.00	120.40	158.40	160.90	129.30	167.00	169.50	137.90	162.50	165.00	133.40
Total length (mm)	282.80	252.30	244.15	272.50	242.00	233.85	264.60	234.10	225.95	307.80	277.30	269.15	293.25	262.75	254.60
Fresh shoot mass (g)	1.33	1.37	1.53	1.35	1.39	1.54	1.26	1.30	1.46	1.47	1.50	1.66	1.34	1.37	1.53
Fresh root mass (g)	0.87	0.83	1.16	0.94	0.90	1.23	1.10	1.06	1.39	0.77	0.73	1.06	0.70	0.66	0.98
Fresh total mass (g)	2.20	2.20	2.68	2.29	2.29	2.77	2.36	2.36	2.84	2.23	2.23	2.71	2.03	2.03	2.51
Dry root mass (g)	0.26	0.24	0.24	0.23	0.21	0.21	0.25	0.23	0.23	0.18	0.16	0.16	0.23	0.21	0.21
Dry shoot mass (g)	0.23	0.21	0.27	0.22	0.21	0.27	0.24	0.23	0.29	0.26	0.24	0.30	0.23	0.22	0.28
Dry total mass (g)	0.49	0.45	0.51	0.45	0.41	0.48	0.49	0.45	0.51	0.44	0.40	0.46	0.46	0.42	0.48
mg/mm	1.13	1.17	0.87	1.08	1.12	0.82	1.10	1.14	0.84	0.93	0.97	0.67	1.01	1.05	0.75
RSR	1.75	2.15	2.27	1.87	2.27	2.39	2.31	2.71	2.84	1.85	2.26	2.38	1.79	2.19	2.31

Appendix B: Biochar Testing Data

NCDA&CS Soil Testing

Table B 1: Raw data, averages, standard deviations, and coefficient of variation for NCDA & CS Soil testing.

	ID	HM	W/V	CEC	BS	Ac	pH	P	K	Ca	Mg	S	Mn	Zn	Cu	Na	K	Ca	Mg
		g/100cc	g/cc	meq/100cc	%	meq/100cc		mg/dm3								meq/100cc			
Control	1A	0.22	0.95	11.50	85.00	1.80	5.80	16.00	292.00	1276.00	316.00	46.00	29.60	2.00	1.00	0.00	0.75	6.38	2.60
	1B	0.22	0.95	11.30	84.00	1.80	5.80	16.00	302.00	1219.00	324.00	45.00	29.90	1.90	1.00	0.00	0.77	6.10	2.66
	1C	0.22	0.98	11.40	85.00	1.70	5.80	19.00	309.00	1249.00	328.00	47.00	29.30	1.90	1.00	0.00	0.79	6.25	2.70
Bone	2A	0.22	0.96	14.70	89.00	1.60	6.00	224.00	398.00	1827.00	367.00	52.00	26.60	4.00	1.00	0.00	1.02	9.14	3.02
	2B	0.22	0.97	14.50	88.00	1.70	6.00	207.00	370.00	1790.00	357.00	51.00	28.90	4.00	1.00	0.00	0.95	8.95	2.94
	2C	0.22	0.99	14.40	89.00	1.60	5.90	208.00	376.00	1758.00	363.00	54.00	28.60	4.40	1.00	0.00	0.96	8.79	2.99
Sorghum	3A	0.22	0.92	10.80	85.00	1.60	5.80	21.00	363.00	1155.00	298.00	44.00	27.50	2.20	0.90	0.00	0.93	5.78	2.45
	3B	0.22	0.95	11.20	85.00	1.70	5.70	25.00	410.00	1164.00	319.00	49.00	27.90	3.00	1.00	0.00	1.05	5.82	2.62
	3C	0.22	0.94	11.40	86.00	1.60	5.70	25.00	399.00	1211.00	329.00	49.00	28.00	2.60	1.00	0.00	1.02	6.06	2.71
Fraser fir	4A	0.22	0.95	10.90	85.00	1.60	5.90	17.00	297.00	1197.00	302.00	45.00	27.90	1.90	0.90	0.00	0.76	5.99	2.48
	4B	0.22	0.93	11.40	85.00	1.70	5.80	20.00	328.00	1218.00	334.00	48.00	31.00	2.50	1.10	0.00	0.84	6.09	2.75
	4C	0.22	0.94	11.40	86.00	1.60	5.80	20.00	314.00	1266.00	324.00	47.00	29.60	2.30	1.00	0.00	0.80	6.33	2.66
Woodchip	5A	0.22	0.90	11.10	86.00	1.60	5.90	17.00	279.00	1234.00	317.00	46.00	33.10	3.00	1.10	0.00	0.71	6.17	2.61
	5B	0.22	0.93	10.60	84.00	1.70	5.80	17.00	277.00	1116.00	312.00	47.00	29.30	2.70	1.00	0.00	0.71	5.58	2.57
	5C	0.22	0.92	10.60	84.00	1.70	5.80	17.00	269.00	1135.00	308.00	46.00	29.20	2.40	1.00	0.00	0.69	5.68	2.53

	ID	HM	W/V	CEC	BS	Ac	pH	P	K	Ca	Mg	S	Mn	Zn	Cu	Na	K	Ca	Mg
		g/100cc	g/cc	meq/100cc	%	meq/100cc		mg/dm3								meq/100cc			
Average	1	0.22	0.96	11.40	84.67	1.77	5.80	17.00	301.00	1248.00	322.67	46.00	29.60	1.93	1.00	0.00	0.77	6.24	2.65
	2	0.22	0.97	14.53	88.67	1.63	5.97	213.00	381.33	1791.67	362.33	52.33	28.03	4.13	1.00	0.00	0.98	8.96	2.98
	3	0.22	0.94	11.13	85.33	1.63	5.73	23.67	390.67	1176.67	315.33	47.33	27.80	2.60	0.97	0.00	1.00	5.89	2.59
	4	0.22	0.94	11.23	85.33	1.63	5.83	19.00	313.00	1227.00	320.00	46.67	29.50	2.23	1.00	0.00	0.80	6.14	2.63
	5	0.22	0.92	10.77	84.67	1.67	5.83	17.00	275.00	1161.67	312.33	46.33	30.53	2.70	1.03	0.00	0.70	5.81	2.57
Std.Dev	1	0.00	0.02	0.10	0.58	0.06	0.00	1.73	8.54	28.51	6.11	1.00	0.30	0.06	0.00	0.00	0.02	0.14	0.05
	2	0.00	0.02	0.15	0.58	0.06	0.06	9.54	14.74	34.53	5.03	1.53	1.25	0.23	0.00	0.00	0.04	0.18	0.04
	3	0.00	0.02	0.31	0.58	0.06	0.06	2.31	24.58	30.07	15.82	2.89	0.26	0.40	0.06	0.00	0.06	0.15	0.13
	4	0.00	0.01	0.29	0.58	0.06	0.06	1.73	15.52	35.37	16.37	1.53	1.55	0.31	0.10	0.00	0.04	0.17	0.14
	5	0.00	0.02	0.29	1.15	0.06	0.06	0.00	5.29	63.36	4.51	0.58	2.22	0.30	0.06	0.00	0.01	0.32	0.04
CV	1	0.00	0.02	0.01	0.01	0.03	0.00	0.10	0.03	0.02	0.02	0.02	0.01	0.03	0.00	0.00	0.03	0.02	0.02
	2	0.00	0.02	0.01	0.01	0.04	0.01	0.04	0.04	0.02	0.01	0.03	0.04	0.06	0.00	0.00	0.04	0.02	0.01
	3	0.00	0.02	0.03	0.01	0.04	0.01	0.10	0.06	0.03	0.05	0.06	0.01	0.15	0.06	0.00	0.06	0.03	0.05
	4	0.00	0.01	0.03	0.01	0.04	0.01	0.09	0.05	0.03	0.05	0.03	0.05	0.14	0.10	0.00	0.05	0.03	0.05
	5	0.00	0.02	0.03	0.01	0.03	0.01	0.00	0.02	0.05	0.01	0.01	0.07	0.11	0.06	0.00	0.02	0.05	0.02

Water Holding Capacity

Table B 2: Raw data from water holding capacity experiment.

ID	Tin Mass	Wet Mass	Dry Mass	Wet Sorghum Soil Mass	Dry Sorghum oil Mass
Control A	15.32	39.34	29.88	24.02	14.56
Control B	14.94	47.09	34.69	32.15	19.75
Control C	15.54	30.4	24.58	14.86	9.04
Sorghum 1% A	14.55	54.1	37.14	39.55	22.59
Sorghum 1% B	15.27	47.58	33.81	32.31	18.54
Sorghum 1% C	16.01	53.57	38.39	37.56	22.38
Sorghum 5% A	15.33	45.6	30.39	30.27	15.06
Sorghum 5% B	16.41	50.37	34.26	33.96	17.85
Sorghum 5% C	14.55	63.74	42.33	49.19	27.78
Sorghum 10% A	16.12	56.86	35.05	40.74	18.93
Sorghum 10% B	15.99	51.52	32.33	35.53	16.34
Sorghum 10% C	15.7	48.77	30.93	33.07	15.23
Sorghum 50% A	16.67	46.57	21.7	29.9	5.03
Sorghum 50% B	15.35	45.21	21	29.86	5.65
Sorghum 50% C	16.32	39.58	22.29	23.26	5.97
Sorghum 100% A	15.65	44.67	19.04	29.02	3.39
Sorghum 100% B	17.02	39.7	19.75	22.68	2.73
Sorghum 100% C	16.93	47.34	20.53	30.41	3.6
Fraser Fir 1% A	15.09	43.53	31.81	28.44	16.72
Fraser Fir 1% B	15.14	41.15	30.33	26.01	15.19
Fraser Fir 1% C	15.48	52.87	38.13	37.39	22.65
Fraser Fir 5% A	15.54	40.54	28.95	25	13.41
Fraser Fir 5% B	15.7	54.2	37.71	38.5	22.01
Fraser Fir 5% C	15.38	50.03	35.63	34.65	20.25

ID	Tin Mass	Wet Mass	Dry Mass	Wet Sorghum Soil Mass	Dry Sorghum oil Mass
Fraser Fir 10% A	14.97	58.19	38.32	43.22	23.35
Fraser Fir 10% B	15.02	45.01	30.43	29.99	15.41
Fraser Fir 10% C	15.59	44.66	31.02	29.07	15.43
Fraser Fir 50% A	14.8	47.93	23.77	33.13	8.97
Fraser Fir 50% B	15.08	36.48	20.89	21.4	5.81
Fraser Fir 50% C	16.47	43.61	23.09	27.14	6.62
Fraser Fir 100% A	15.48	43.65	21.29	28.17	5.81
Fraser Fir 100% B	15.49	43.35	21.19	27.86	5.7
Fraser Fir 100% C	15.07	39.47	19.92	24.4	4.85
Wood Chip 1% A	14.9	51.86	36.45	36.96	21.55
Wood Chip 1% B	14.86	41.28	30.52	26.42	15.66
Wood Chip 1% C	16.53	40.06	30.63	23.53	14.1
Wood Chip 5% A	15.14	50.61	34.69	35.47	19.55
Wood Chip 5% B	15.63	43.88	30.77	28.25	15.14
Wood Chip 5% C	15.59	42.34	30.97	26.75	15.38
Wood Chip 10% A	15.01	53.27	34.65	38.26	19.64
Wood Chip 10% B	15.61	53.08	35.85	37.47	20.24
Wood Chip 10% C	15.77	47.16	32.75	31.39	16.98
Wood Chip 50% A	16.43	42.9	23.15	26.47	6.72
Wood Chip 50% B	15.29	39.29	22.46	24	7.17
Wood Chip 50% C	15.81	37.82	22.74	22.01	6.93
Wood Chip 100% A	15.18	40.78	20.07	25.6	4.89
Wood Chip 100% B	15.61	35.09	18.95	19.48	3.34
Wood Chip 100% C	15.41	34.79	18.82	19.38	3.41
Bone 1% A	17.66	52.26	37.91	34.6	20.25
Bone 1% B	15.41	52.07	37.51	36.66	22.1
Bone 1% C	16.08	45.97	33.88	29.89	17.8

ID	Tin Mass	Wet Mass	Dry Mass	Wet Sorghum Soil Mass	Dry Sorghum oil Mass
Bone 5% A	15.91	48.34	34.47	32.43	18.56
Bone 5% B	16.63	40.28	30.42	23.65	13.79
Bone 5% C	17.54	46.21	34.32	28.67	16.78
Bone 10% A	15.79	55.15	38.7	39.36	22.91
Bone 10% B	15.71	47.48	34.42	31.77	18.71
Bone 10% C	16.34	46.49	34.25	30.15	17.91
Bone 50% A	17.15	52.23	36.86	35.08	19.71
Bone 50% B	15.44	55.8	38.5	40.36	23.06
Bone 50% C	16.03	48.42	34.29	32.39	18.26
Bone 100% A	15.84	50.29	31.06	34.45	15.22
Bone 100% B	15.22	42.34	27.16	27.12	11.94
Bone 100% C	16.05	44.68	28.96	28.63	12.91

Appendix C: Difference of Means

Table C 1: Difference of means from control soil and control nutrient.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SH	SL	FC	FH	FL	WC	WH	WL	BC	BH	BL	CC	CH	CL
Shoot length (mm)	4%	-16%	-14%	-6%	-12%	-9%	-19%	17%	1%	8%	-15%	5%	---	-25% *	-7%
Root Length (mm)	-9%	-14% *	-6%	-8%	-4%	-6%	-3%	-2%	-18%	3%	-5%	-6%	---	2%	-18% **
Total length (mm)	-4%	-15% ***	-9%	-7%	-8%	-7%	-10%	6%	-10%	5%	-9% **	-1%	---	-10% **	-13% ***
Fresh shoot mass (g)	0%	15%	-3%	1%	-3%	4%	-5%	16%	4%	10%	19%	20%	---	3%	14%
Fresh root mass (g)	25%	44% *	48%	36% *	17%	9%	58% **	38%	27%	10%	-24%	3%	---	-6%	42%
Fresh total mass (g)	8%	25% *	14%	13%	4%	6%	16%	24%	12%	10%	5%	14%	---	0%	24%
Dry root mass (g)	13%	-17%	-2%	0%	-25%	4%	9%	-1%	-1%	-22%	-9%	11%	---	-10%	-9%
Dry shoot mass (g)	-1%	31% *	3%	-3%	3%	8%	4%	7%	-3%	12%	23% *	21%	---	-7%	20%
Dry total mass (g)	6%	7%	1%	-2%	-11%	6%	7%	3%	-2%	-5%	8%	16%	---	-8%	5%
mg/mm	-2%	59% **	15%	5%	21%	22%	29%	-3%	-4%	4%	51% **	23%	---	23%	29% *
RSR	12%	-36%	-4%	7%	-28%	-4%	9%	-10%	8%	-8%	-28%	-8%	---	4%	-26%

Table C 2: Difference of means from treatment with same biochar type and control nutrients.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SH	SL	FC	FH	FL	WC	WH	WL	BC	BH	BL	CC	CH	CL
Shoot length (mm)	---	-19%	-17%	---	-6%	-3%	---	44% *	24% *	---	-21%	-3%	---	-25% *	-7%
Root Length (mm)	---	-6%	4%	---	4%	2%	---	0%	-16%	---	-8%	-9% *	---	2%	-18% **
Total length (mm)	---	-12% *	-6%	---	-1%	0%	---	18%	0%	---	-14% *	-6%	---	-10% **	-13% ***
Fresh shoot mass (g)	---	15%	-3%	---	-4%	3%	---	23% *	10%	---	9%	10%	---	3%	14%
Fresh root mass (g)	---	16%	18%	---	-14%	-19%	---	-12%	-19%	---	-31%	-7%	---	-6%	42%
Fresh total mass (g)	---	15% *	6%	---	-8%	-6%	---	7%	-4%	---	-5%	4%	---	0%	24%
Dry root mass (g)	---	-27% *	-14%	---	-25%	4%	---	-9%	-9%	---	17%	42%	---	-10%	-9%
Dry shoot mass (g)	---	32% **	4%	---	6%	11%	---	2%	-7%	---	10%	8%	---	-7%	20%
Dry total mass (g)	---	1%	-5%	---	-10%	8%	---	-4%	-8%	---	13%	22%	---	-8%	5%
mg/mm	---	62% **	18%	---	15%	17%	---	-25%	-26%	---	45%	19%	---	23%	29% *
RSR	---	-42% **	-14%	---	-33% *	-10%	---	-18%	-1%	---	-22%	1%	---	4%	-26%

Table C 3: Difference of means from treatment with same nutrient type and control soil.

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SH	SL	FC	FH	FL	WC	WH	WL	BC	BH	BL	CC	CH	CL
Shoot length (mm)	4%	12%	-7%	-6%	18%	-2%	-19%	56% **	9%	8%	14%	13%	---	---	---
Root Length (mm)	-9%	-16% **	15%	-8%	-6%	15%	-3%	-4%	0%	3%	-7%	15% *	---	---	---
Total length (mm)	-4%	-5%	4%	-7%	3%	7%	-10%	19%	4%	5%	1%	14% *	---	---	---
Fresh shoot mass (g)	0%	12%	-15%	1%	-6%	-9%	-5%	13%	-9%	10%	16%	5%	---	---	---
Fresh root mass (g)	25%	53% **	4%	36%	24%	-23%	58%	47%	-10%	10%	-19%	-27%	---	---	---
Fresh total mass (g)	8%	25% *	-7%	13%	4%	-15%	16%	24%	-10%	10%	5%	-8%	---	---	---
Dry root mass (g)	13%	-8%	8%	0%	-17%	15%	9%	10%	9%	-22%	1%	22%	---	---	---
Dry shoot mass (g)	-1%	40%	-14%	-3%	10%	-10%	4%	14%	-19%	12%	32%	1%	---	---	---
Dry total mass (g)	6%	17%	-5%	-2%	-3%	1%	7%	12%	-7%	-5%	17%	10%	---	---	---
mg/mm	-2%	29%	-11%	5%	-1%	-5%	29%	-21%	-26%	4%	23%	-5%	---	---	---
RSR	12%	-38%	29%	7%	-31%	29%	9%	-14%	46%	-8%	-31%	24%	---	---	---

Table C 4: Difference of means between observed (table A4) and expected based on assumption of independence (table A5).

****- significant at .01 level, **- significant at .05 level, *- significant at .1 level.*

	SC	SHN	SCL	FFC	FFHN	FFCL	WCC	WCHN	WCCL	BC	BHN	BCL	CC	CHN	CCl
Shoot length (mm)	---	7%	-11%	---	28%	5%	---	108% **	37% **	---	4%	5%	---	---	---
Root Length (mm)	---	-7% **	29%	---	2%	27% **	---	-1%	3%	---	-9%	11% **	---	---	---
Total length (mm)	---	-1%	9%	---	12%	16% *	---	33% *	17% **	---	-4%	8%	---	---	---
Fresh shoot mass (g)	---	12%	-15%	---	-6%	-10%	---	20% *	-5%	---	6%	-3%	---	---	---
Fresh root mass (g)	---	21%	-11%	---	-10%	-38% **	---	-9%	-36% **	---	-27% *	-32% **	---	---	---
Fresh total mass (g)	---	16% **	-13%	---	-8%	-23% *	---	7%	-20% **	---	-5%	-14% **	---	---	---
Dry root mass (g)	---	-20% *	-6%	---	-17%	16%	---	0%	-1%	---	33%	61%	---	---	---
Dry shoot mass (g)	---	42% **	-13%	---	13%	-8%	---	9%	-22%	---	17% **	-9%	---	---	---
Dry total mass (g)	---	9% *	-10%	---	-2%	2%	---	4%	-13%	---	23% *	15%	---	---	---
mg/mm	---	-44% ***	12%	---	-35% **	18%	---	-21% **	30%	---	-25% **	40%	---	---	---
RSR	---	32% *	-10%	---	-5%	-9%	---	-36% *	-40% **	---	19%	-8%	---	---	---

Appendix D: Pyrolysis data

Time above 500 °C	Time above 400 °C	Time above 300 °C	Time above 200 °C	Time above 100 °C
0:30:21	0:56:22	1:27:17	2:8:9	3:46:24

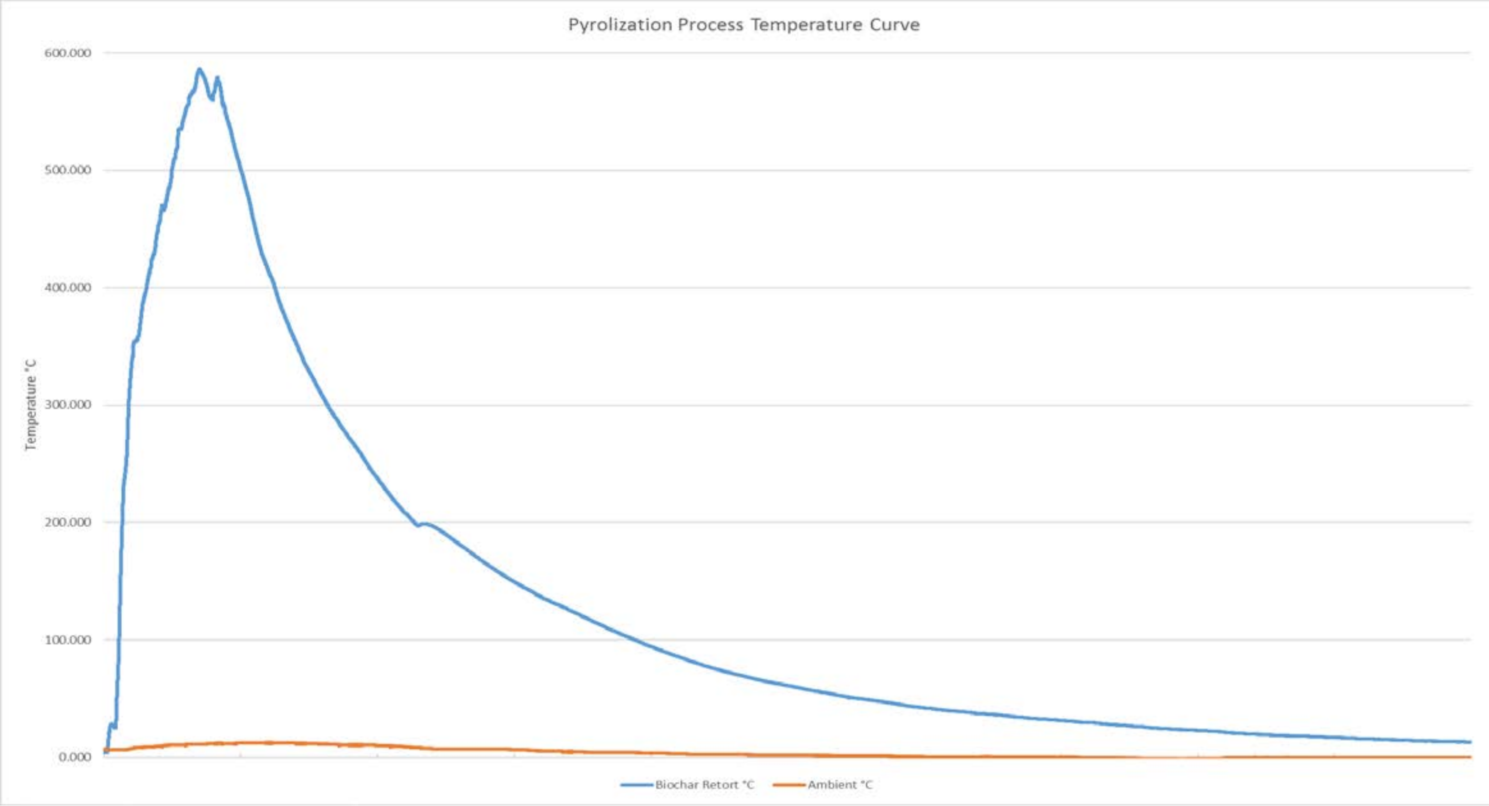

Figure D 1: pyrolysis process for creating biochar used in this experiment. Graph shows 10 hours of data.

Table D 1: Pre and post pyrolysis feedstock masses.

Feedstock Mass (g)				Biochar Mass (g)			
	Container 1	Container 2	sum	Container 1	Container 2	sum	% of feedstock mass
Sorghum	450.73	346.7	797.43	116.71	104.34	221.05	28%
Fir	530.13	506.32	1036.45	162.09	156.98	319.07	31%
Woodchips	419.76	412	831.76	118.2	117.1	235.3	28%
Bone	953.1	1124.86	2077.96	604	717.29	1321.29	64%

Appendix E: Boxplots

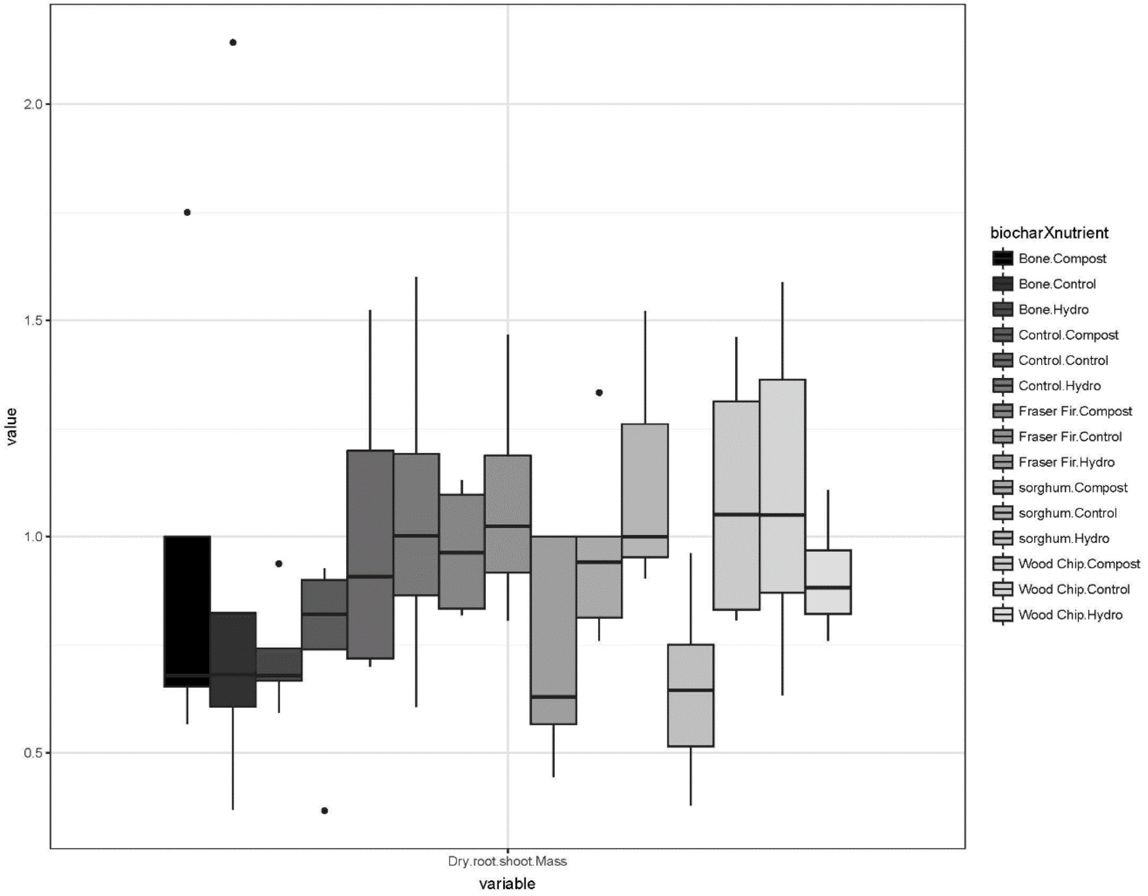

Figure E 1: Boxplot of RSR separated by biochar and nutrient.

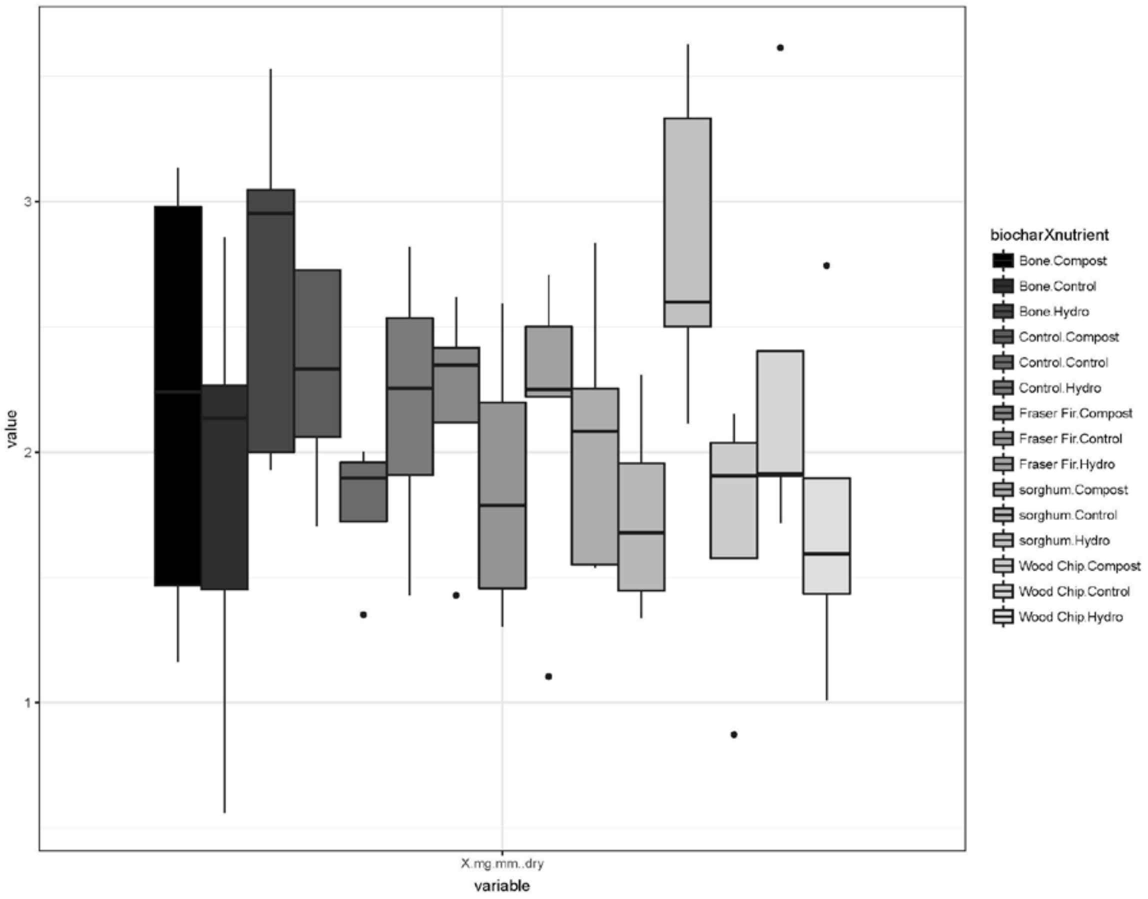

Figure E 2: Boxplot of mg/mm separated by biochar and nutrient.

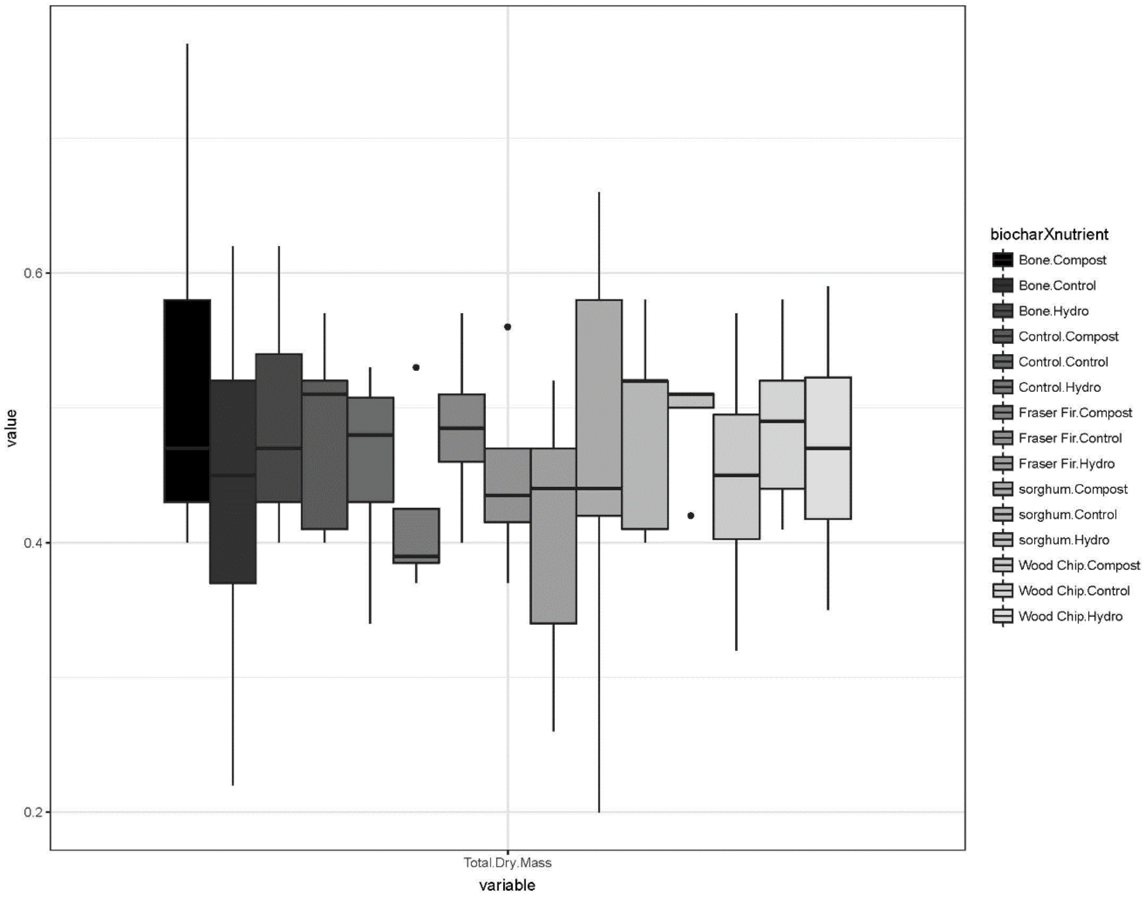

Figure E 3: Boxplot of total dry mass separated by biochar and nutrient.

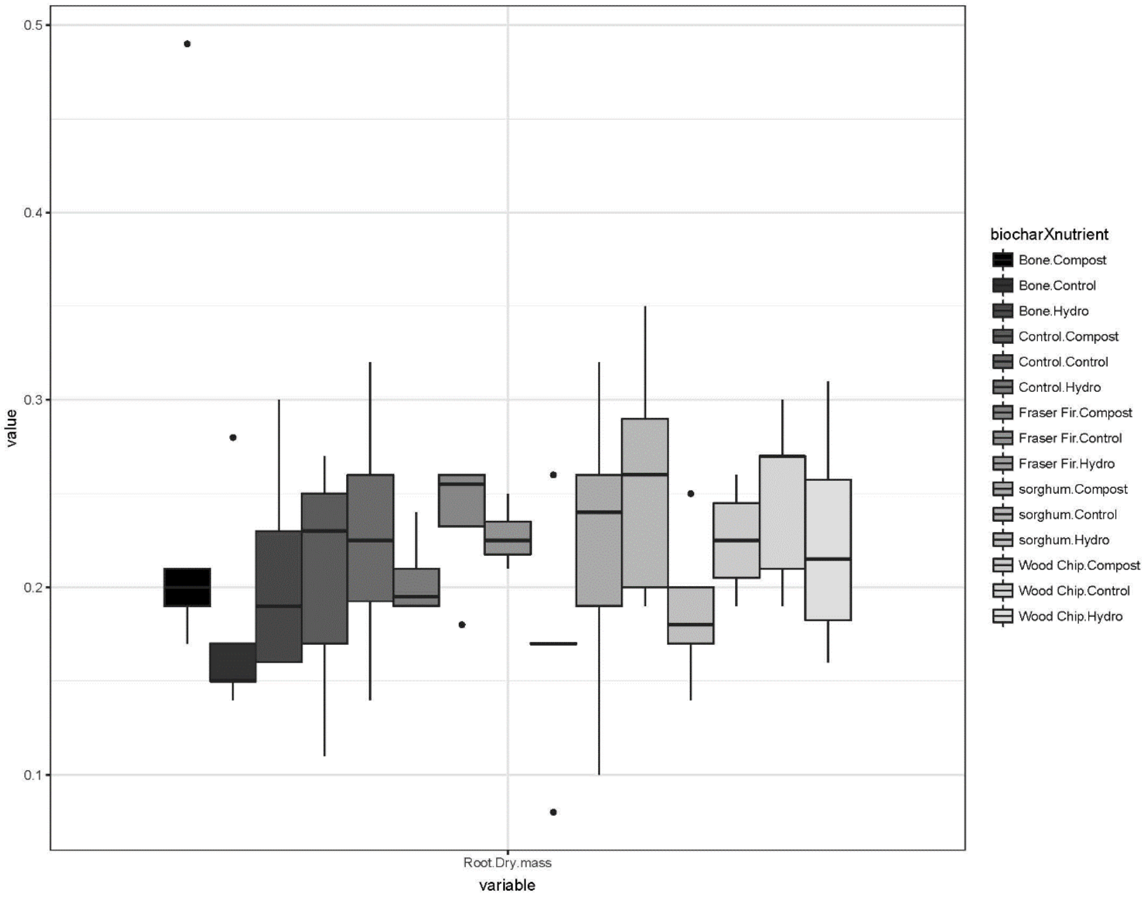

Figure E 4: Boxplot of root dry mass separated by biochar and nutrient.

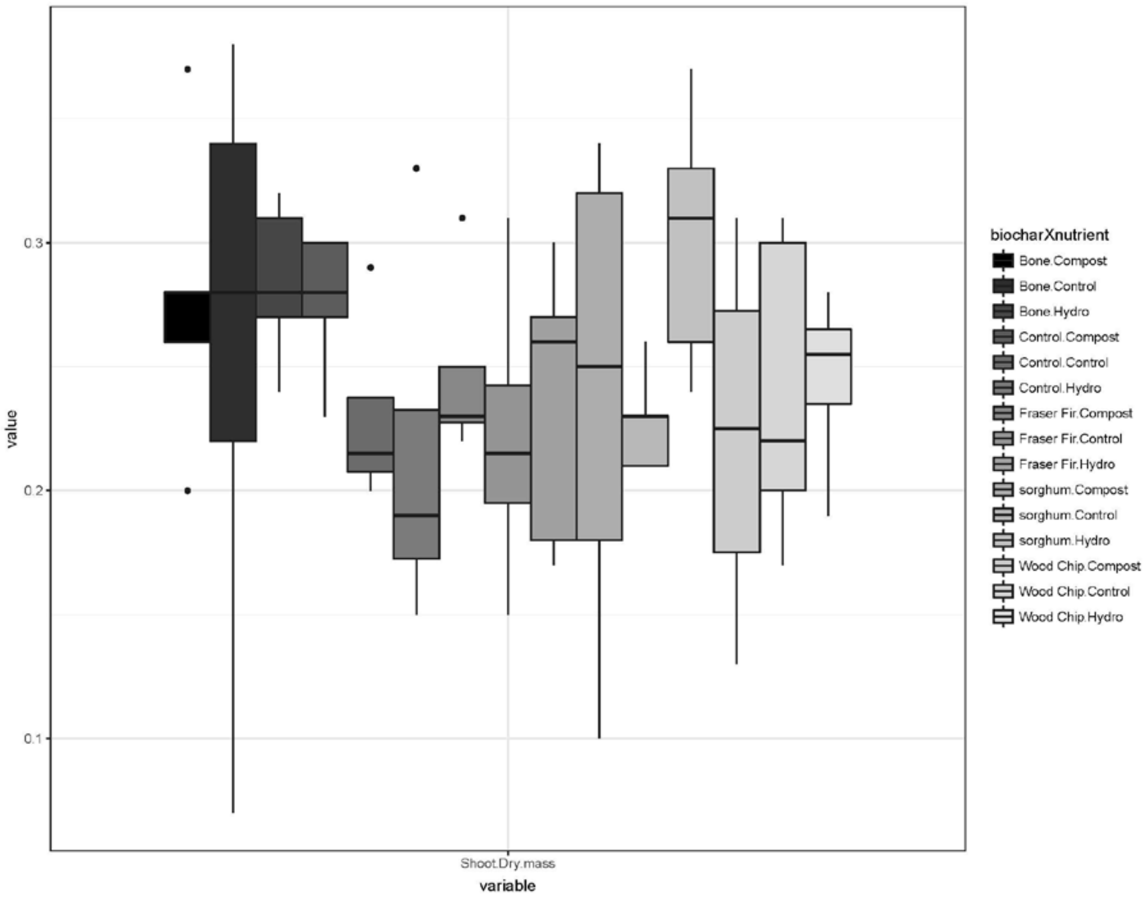

Figure E 5: Boxplot of shoot dry mass separated by biochar and nutrient.

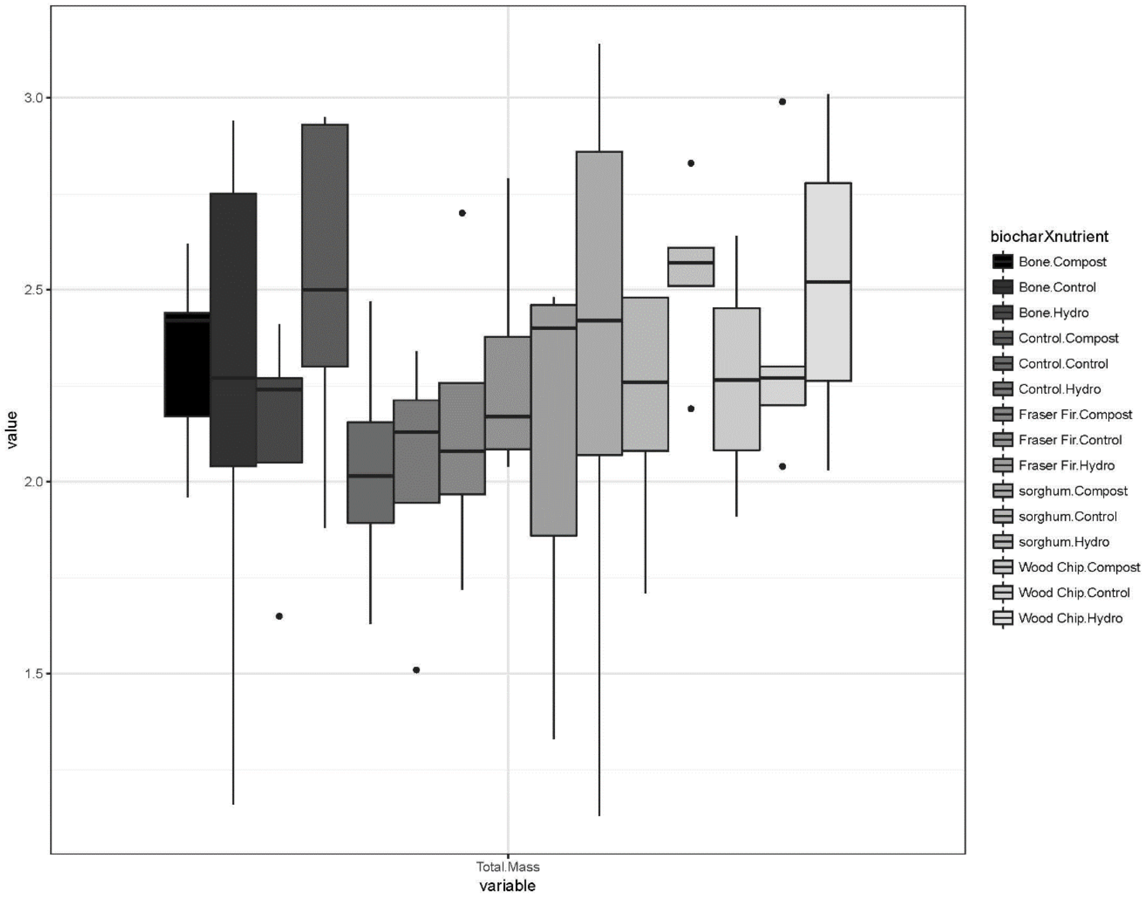

Figure E 6: Boxplot of total fresh mass separated by biochar and nutrient.

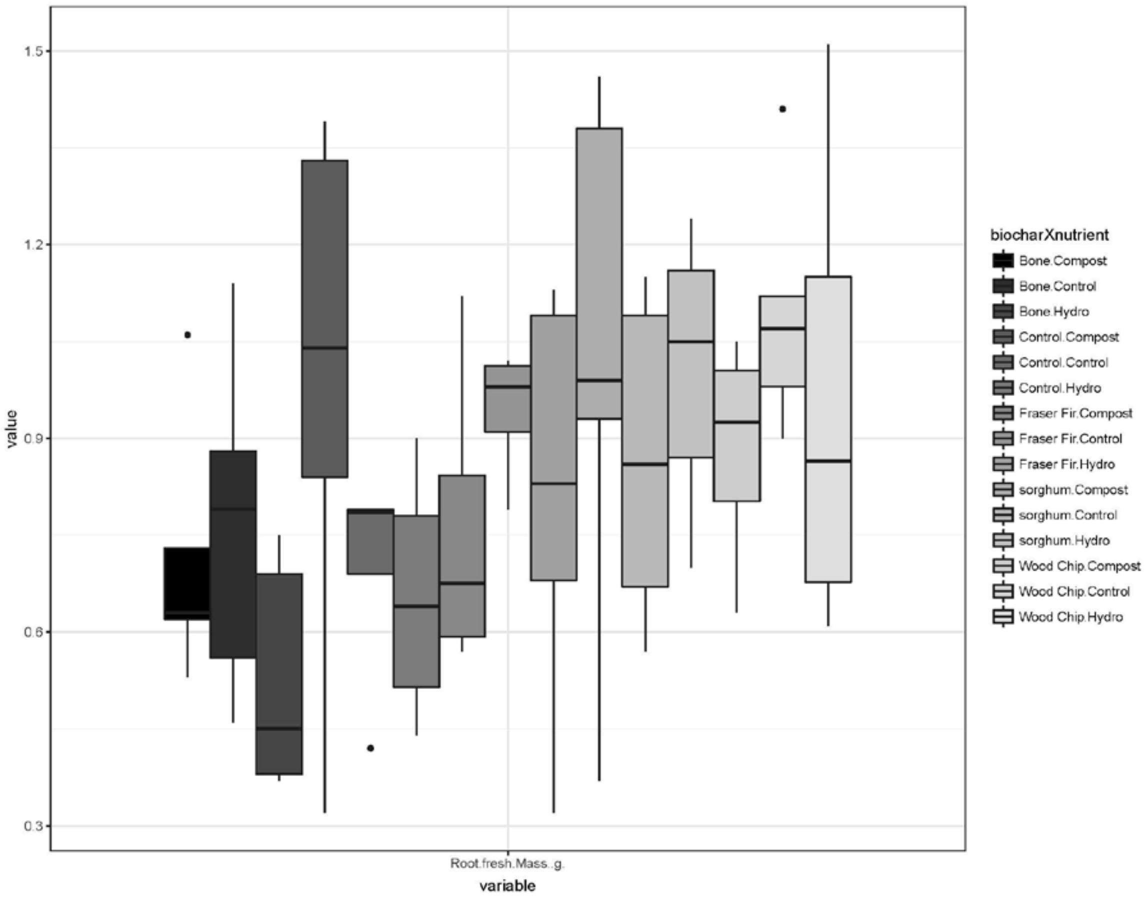

Figure E 7: Boxplot of root fresh mass separated by biochar and nutrient.

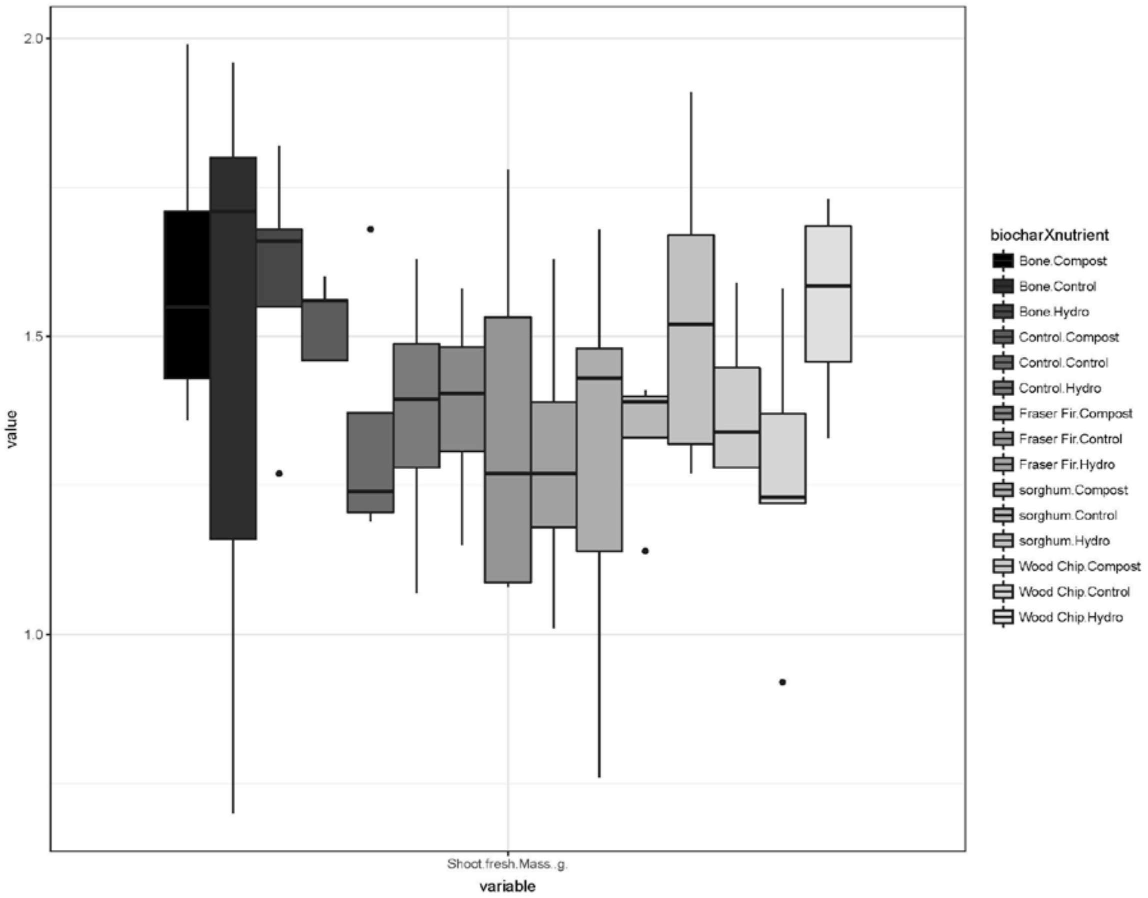

Figure E 8: Boxplot of shoot fresh mass separated by biochar and nutrient.

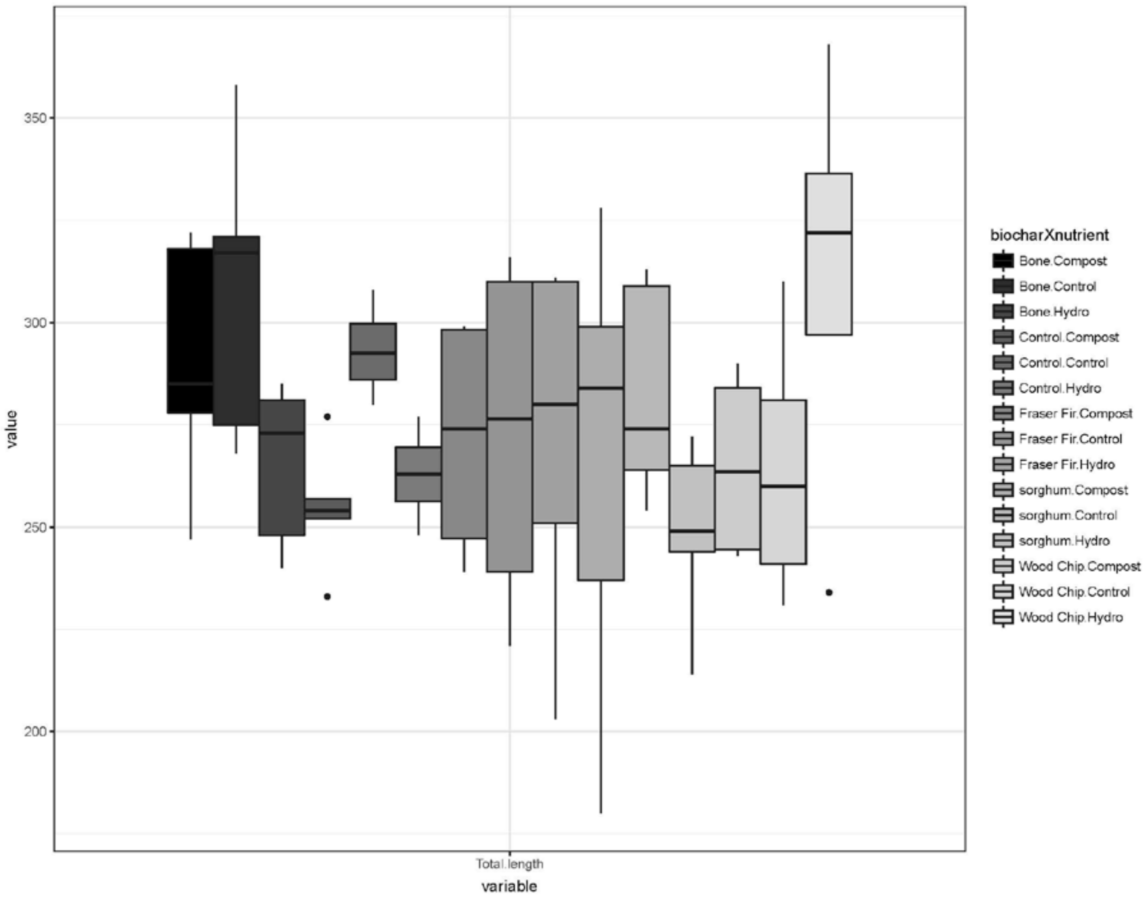

Figure E 9: Boxplot of total length separated by biochar and nutrient.

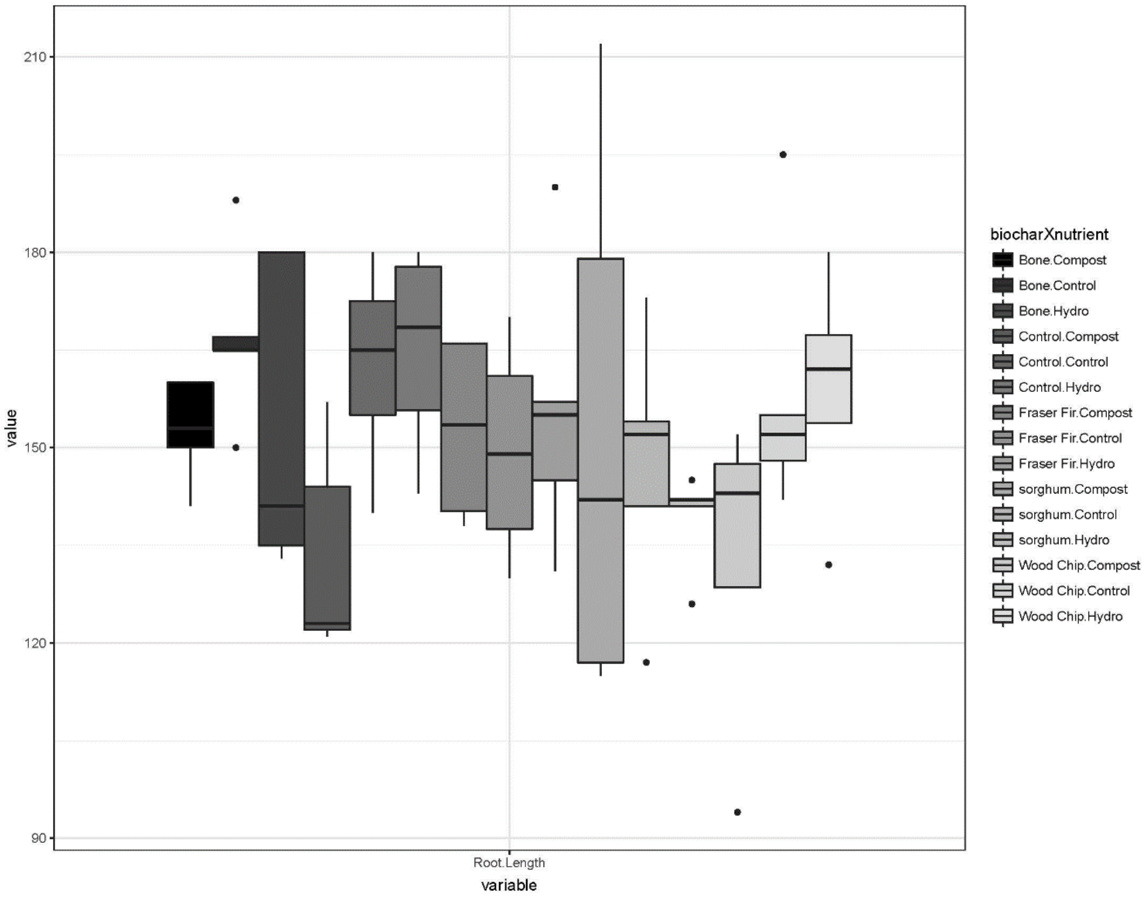

Figure E 10: Boxplot of root length separated by biochar and nutrient.

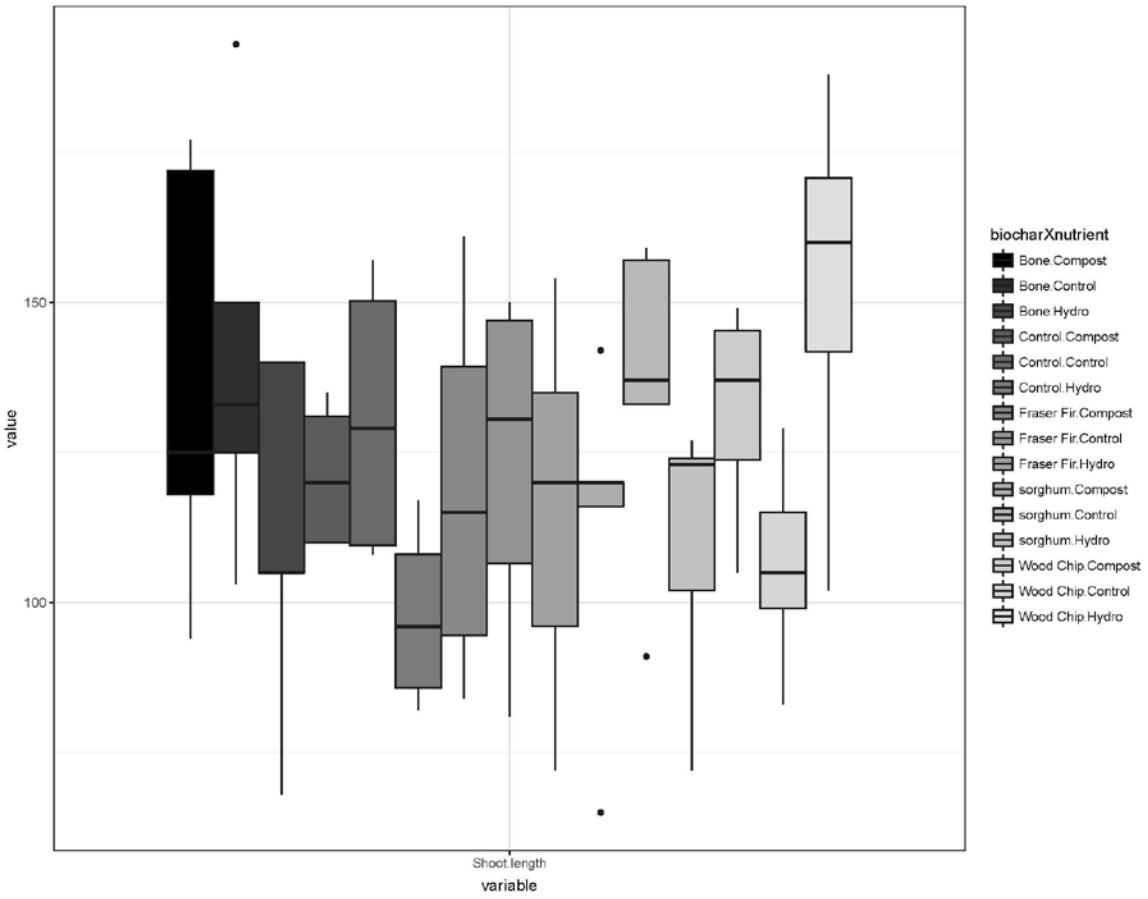

Figure E 11: Boxplot of shoot length separated by biochar and nutrient.

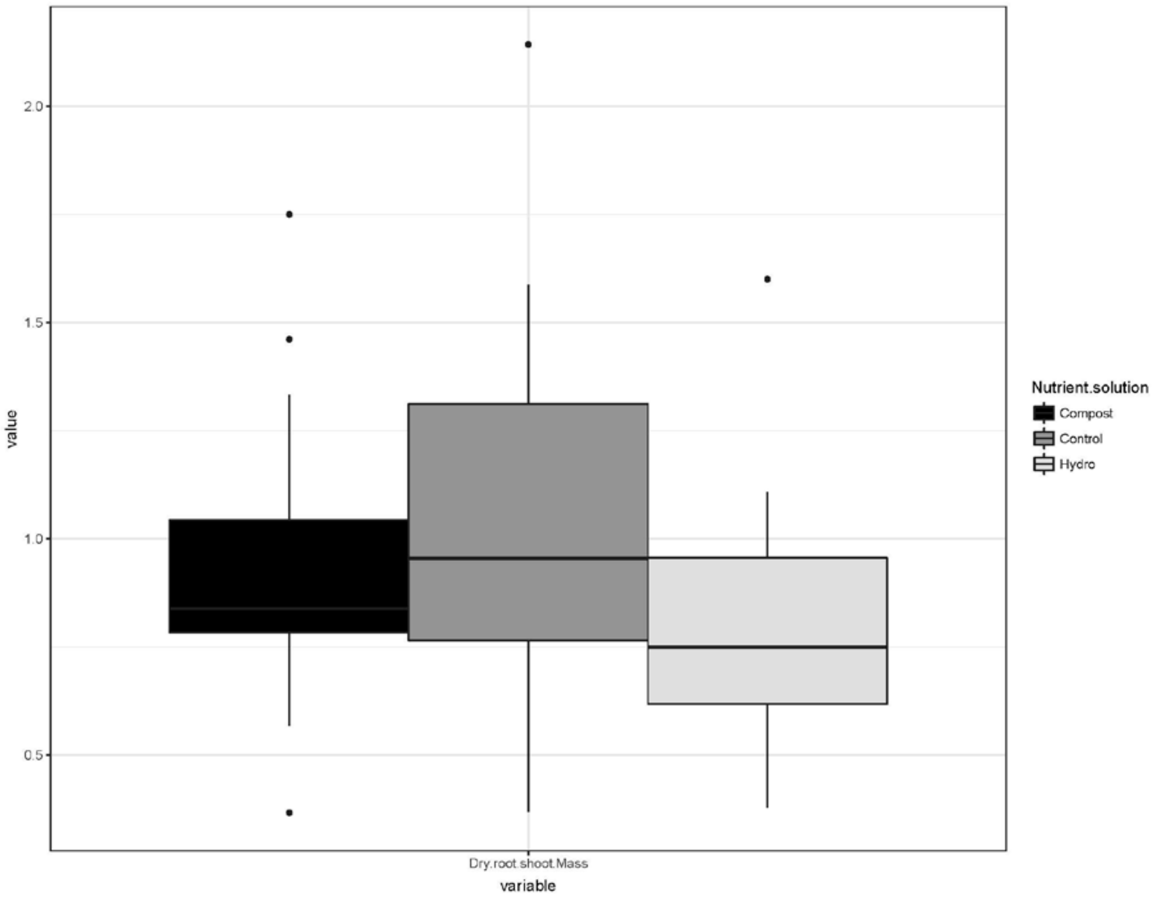

Figure E 12: Boxplot of RSR separated by biochar and nutrient.

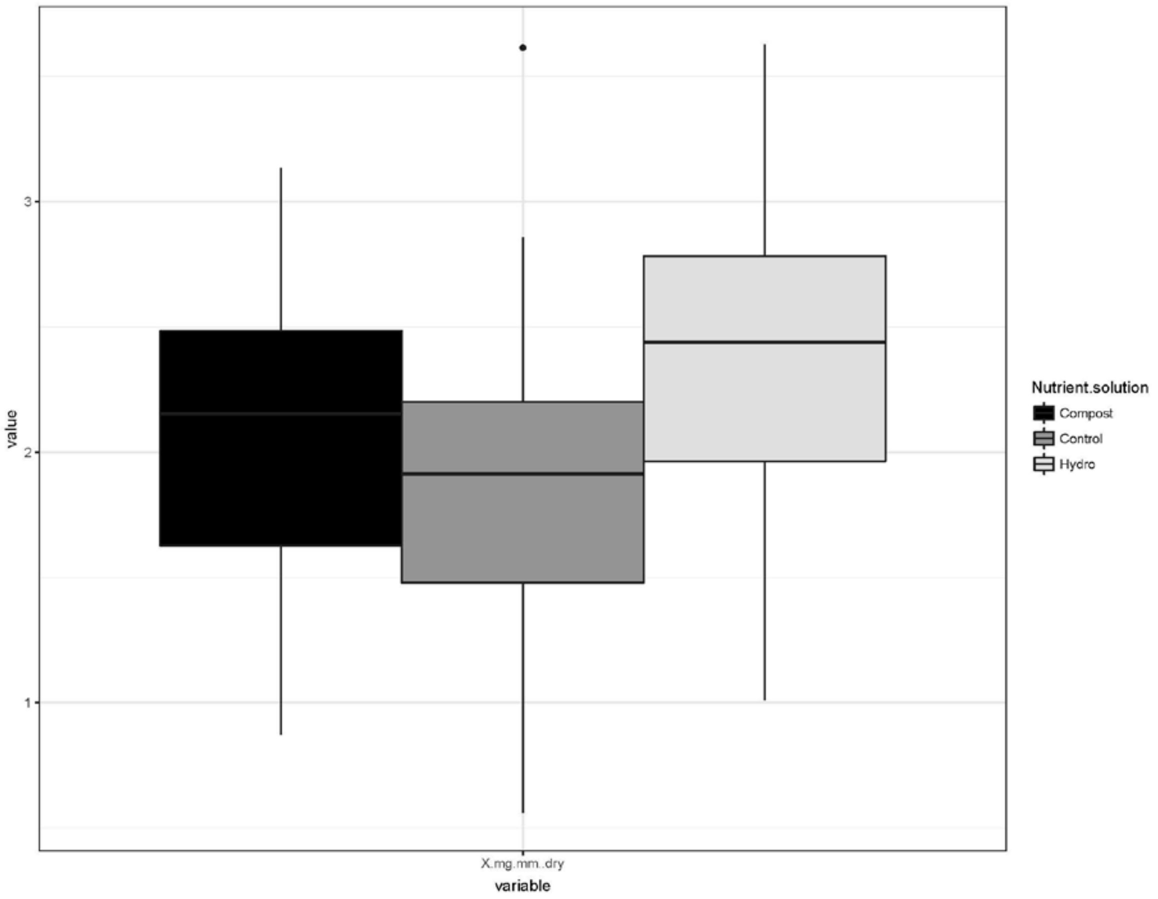

Figure E 13: Boxplot of mg/mm separated by biochar and nutrient.

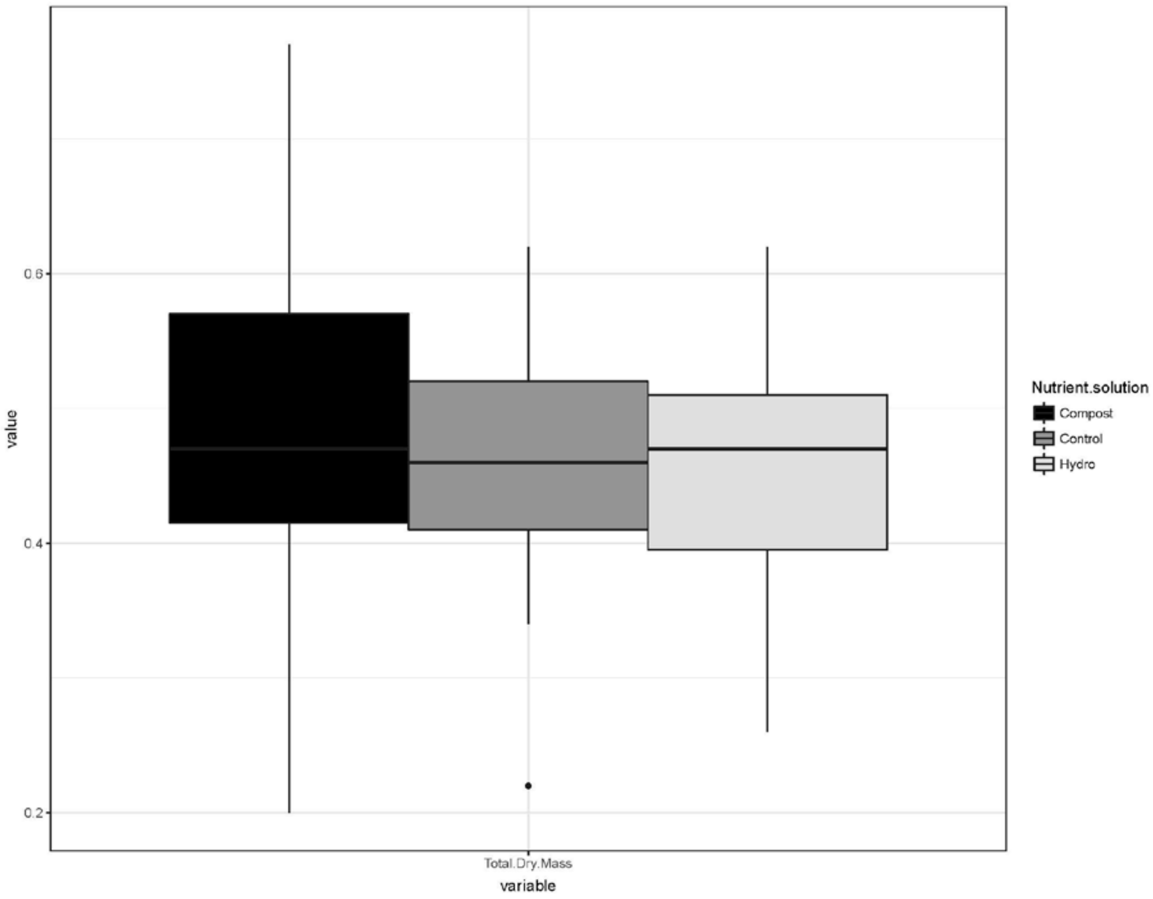

Figure E 14: Boxplot of total dry mass separated by biochar and nutrient.

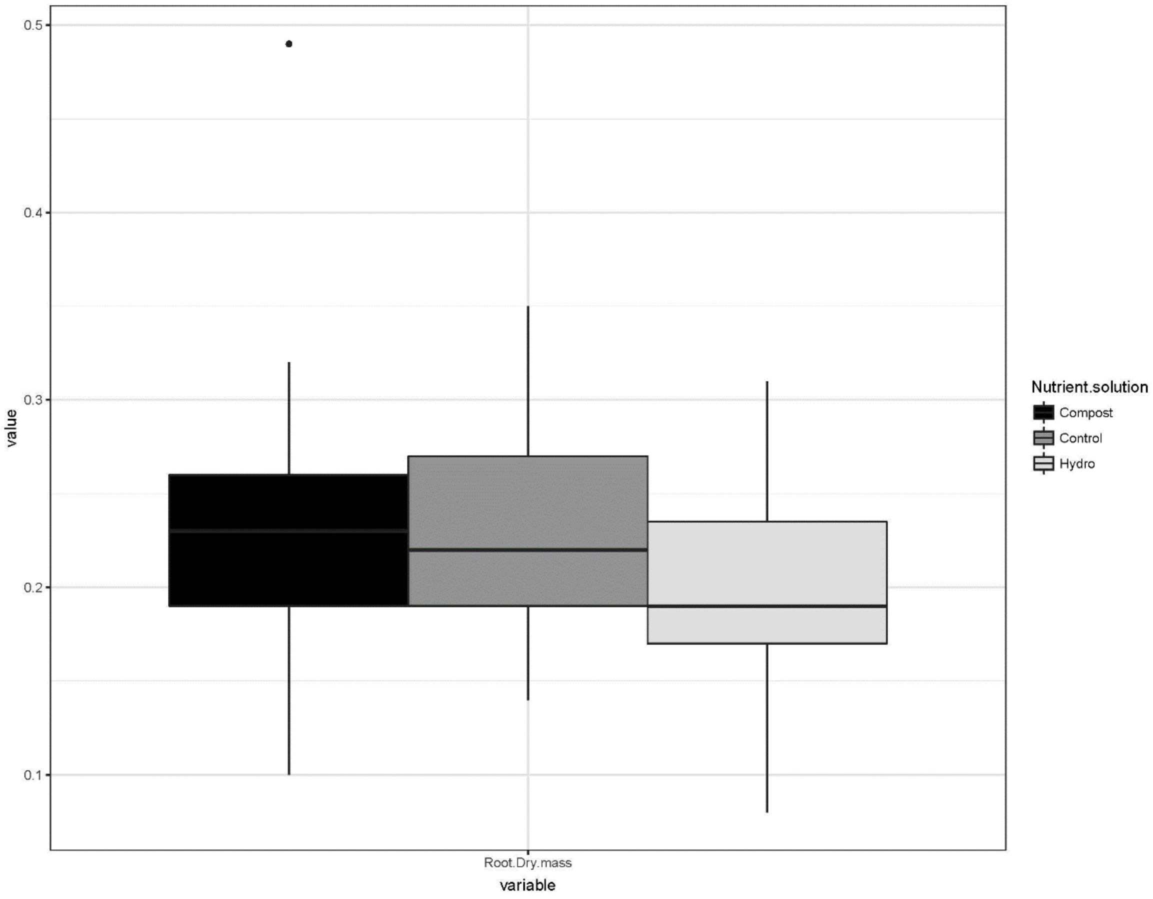

Figure E 15: Boxplot of root dry mass separated by biochar and nutrient.

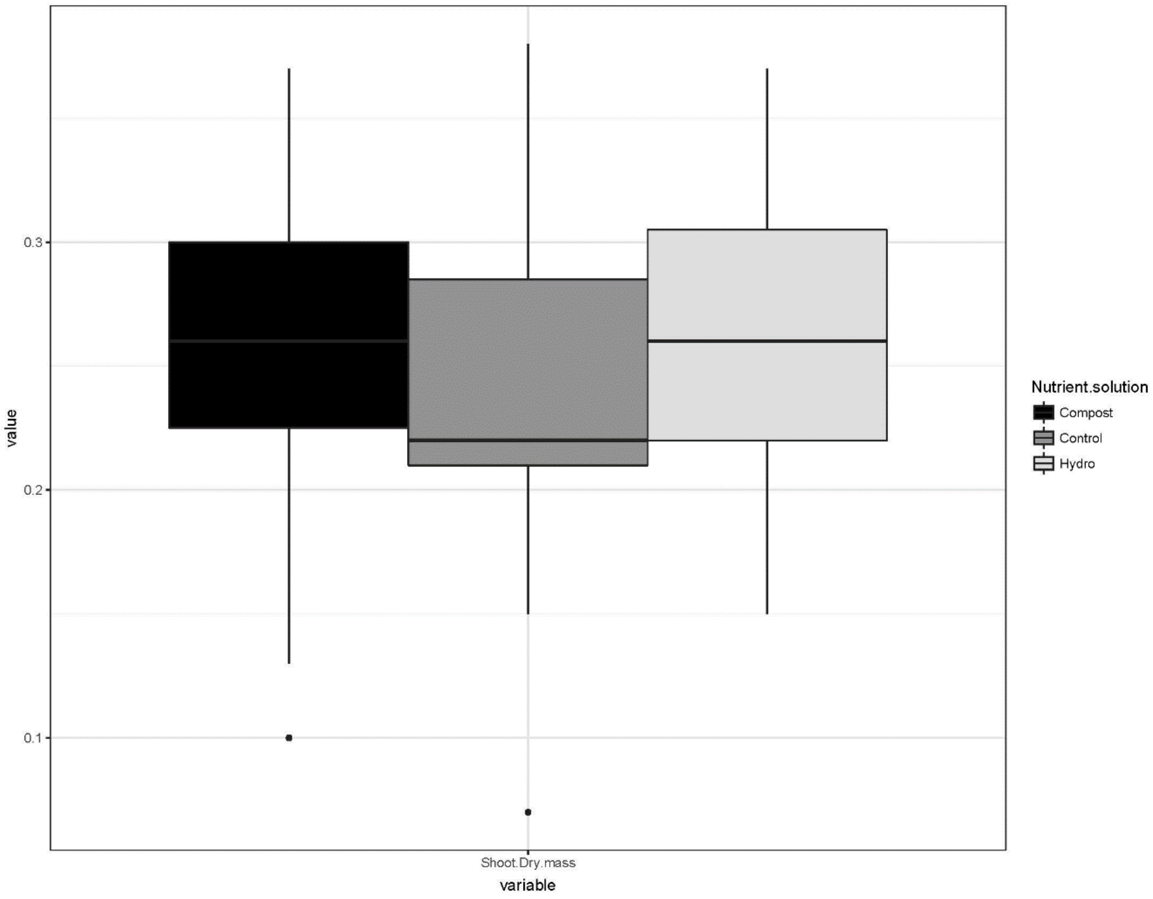

Figure E 16: Boxplot of shoot dry mass separated by biochar and nutrient.

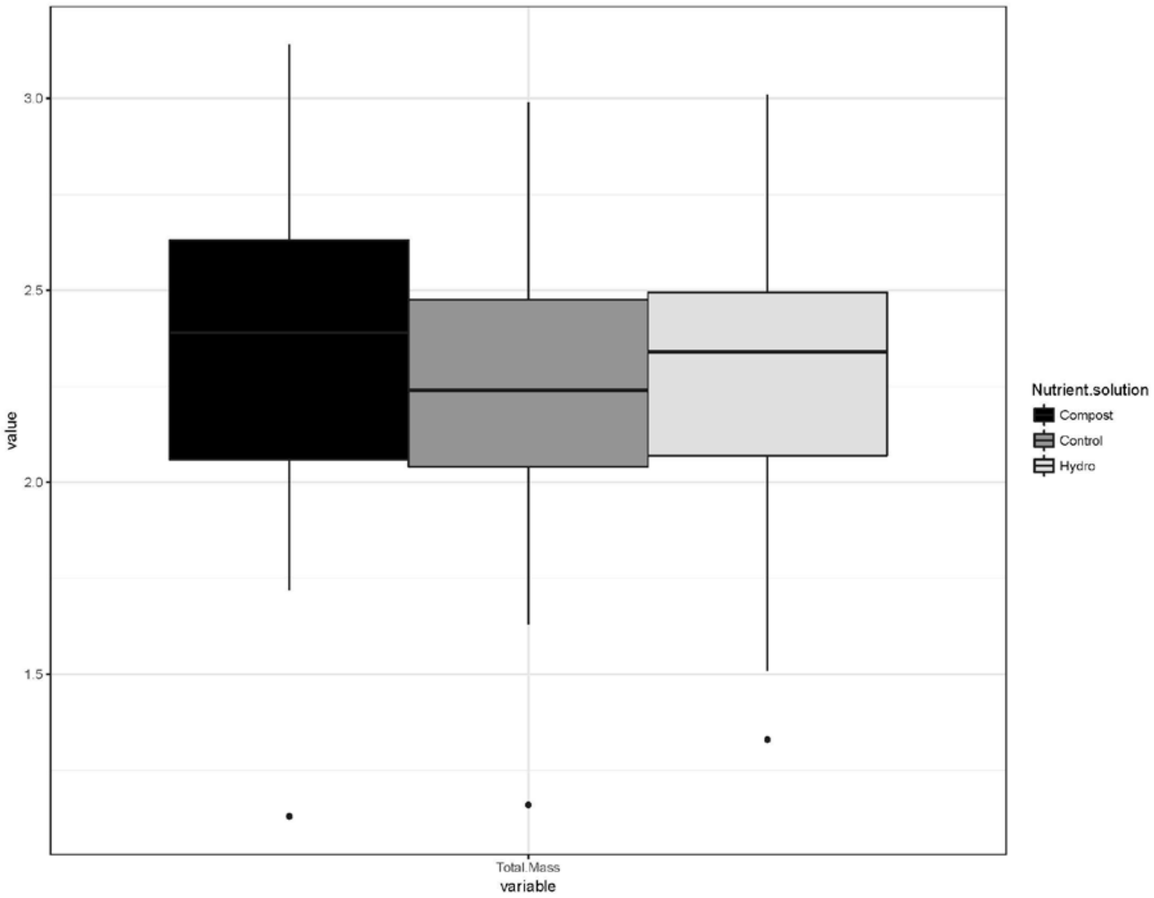

Figure E 17: Boxplot of total fresh mass separated by biochar and nutrient.

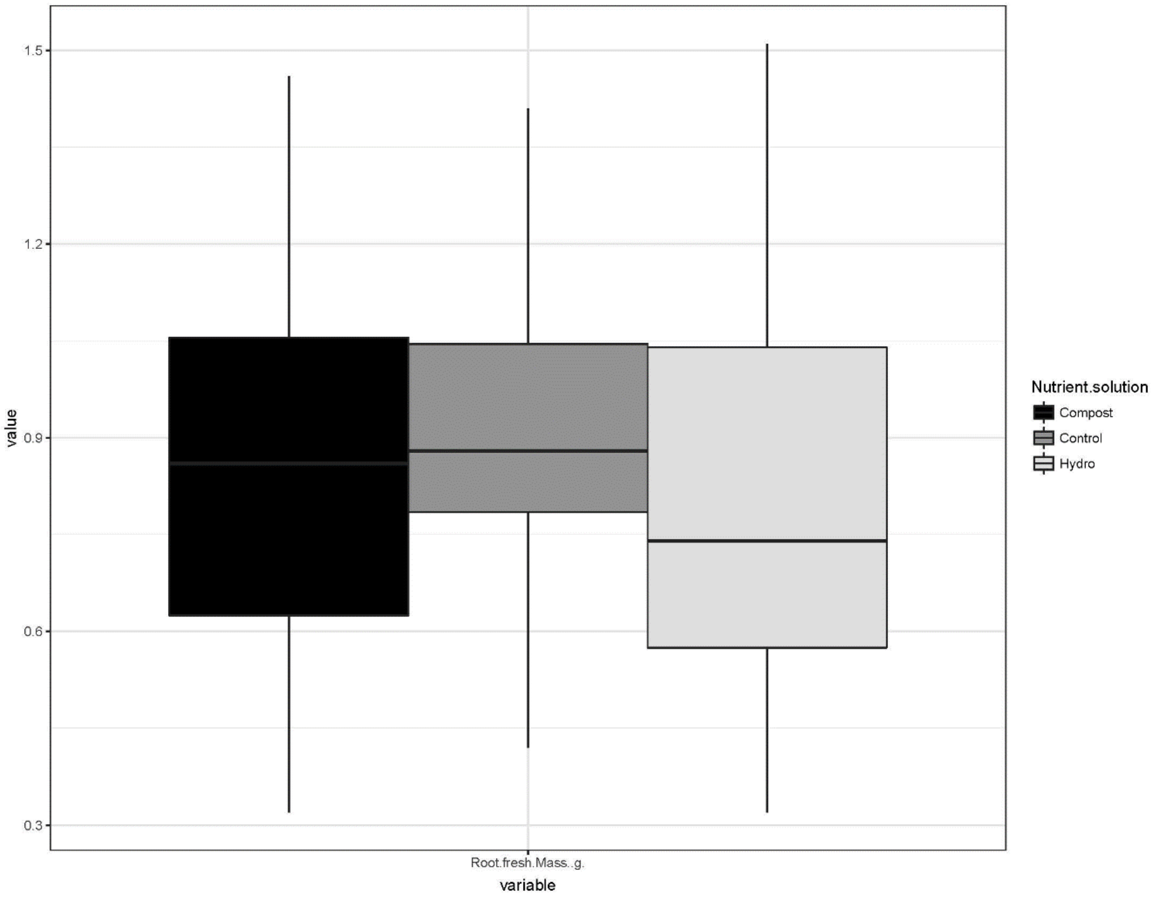

Figure E 18: Boxplot of root fresh mass separated by biochar and nutrient.

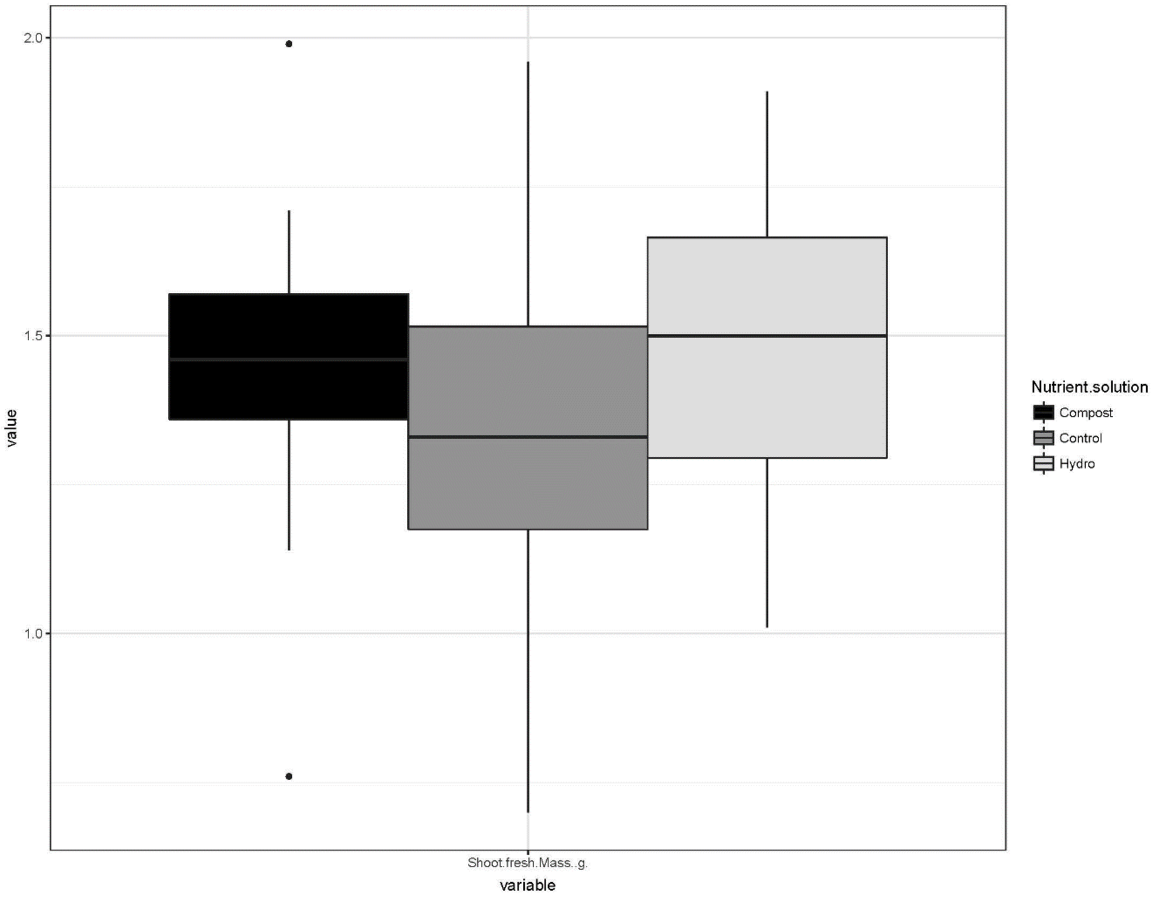

Figure E 19: Boxplot of shoot fresh map separated by biochar and nutrient.

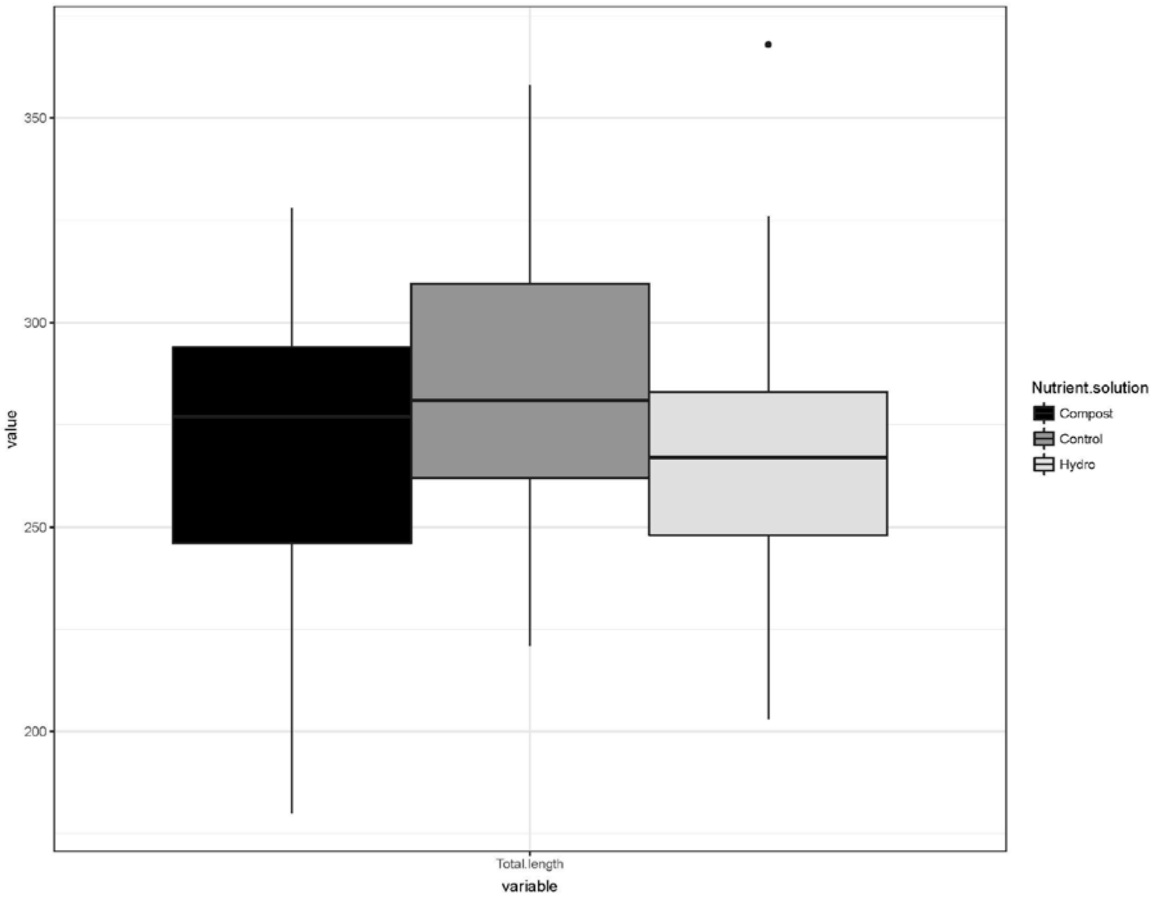

Figure E 20: Boxplot of total length separated by biochar and nutrient.

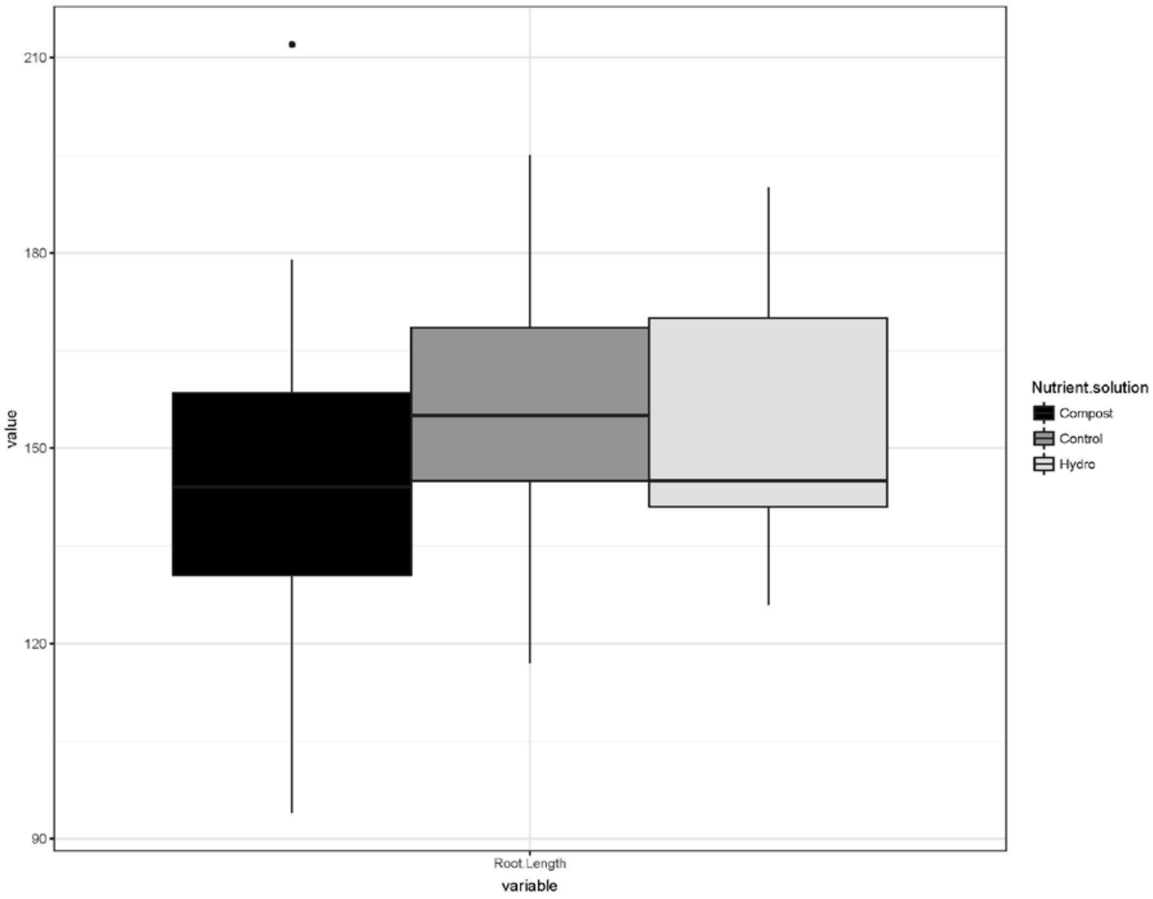

Figure E 21: Boxplot of root length separated by biochar and nutrient.

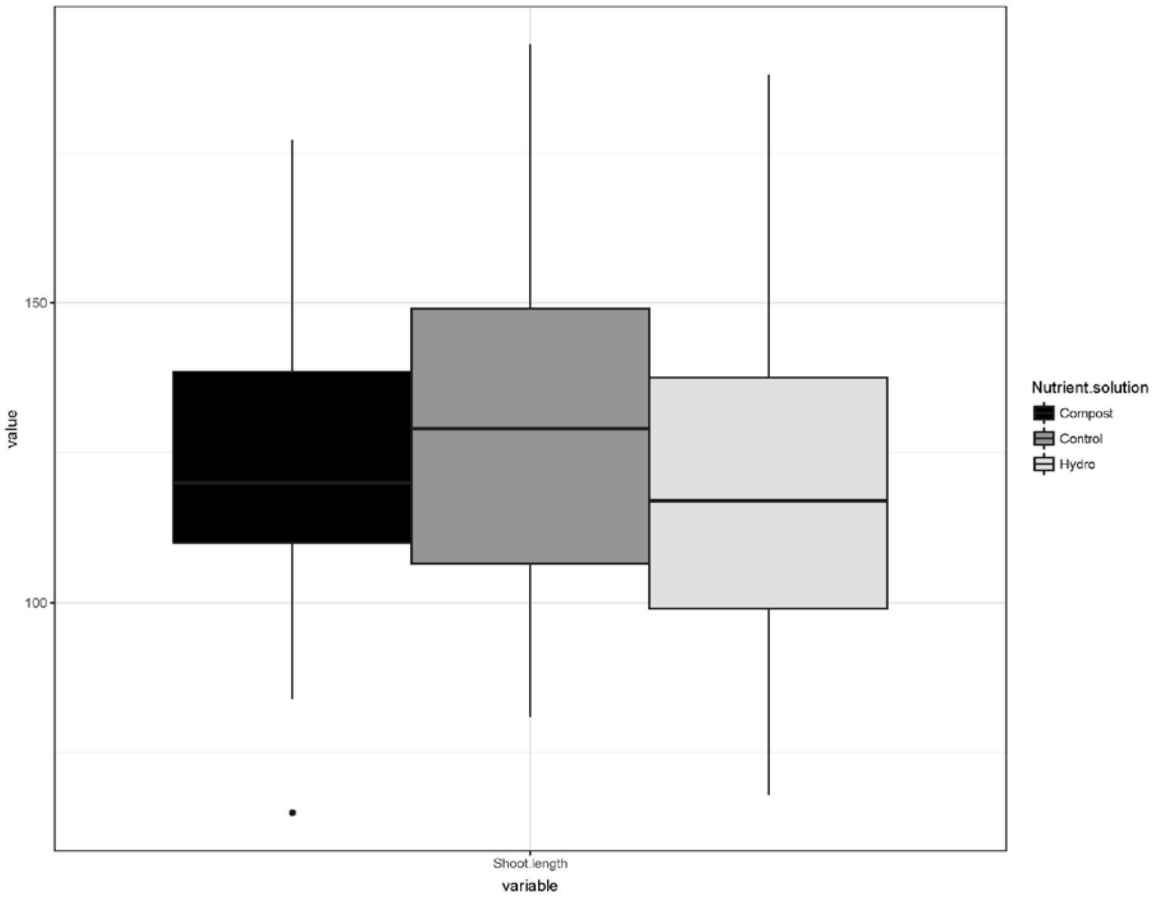

Figure E 22: Boxplot of shoot length separated by biochar and nutrient.

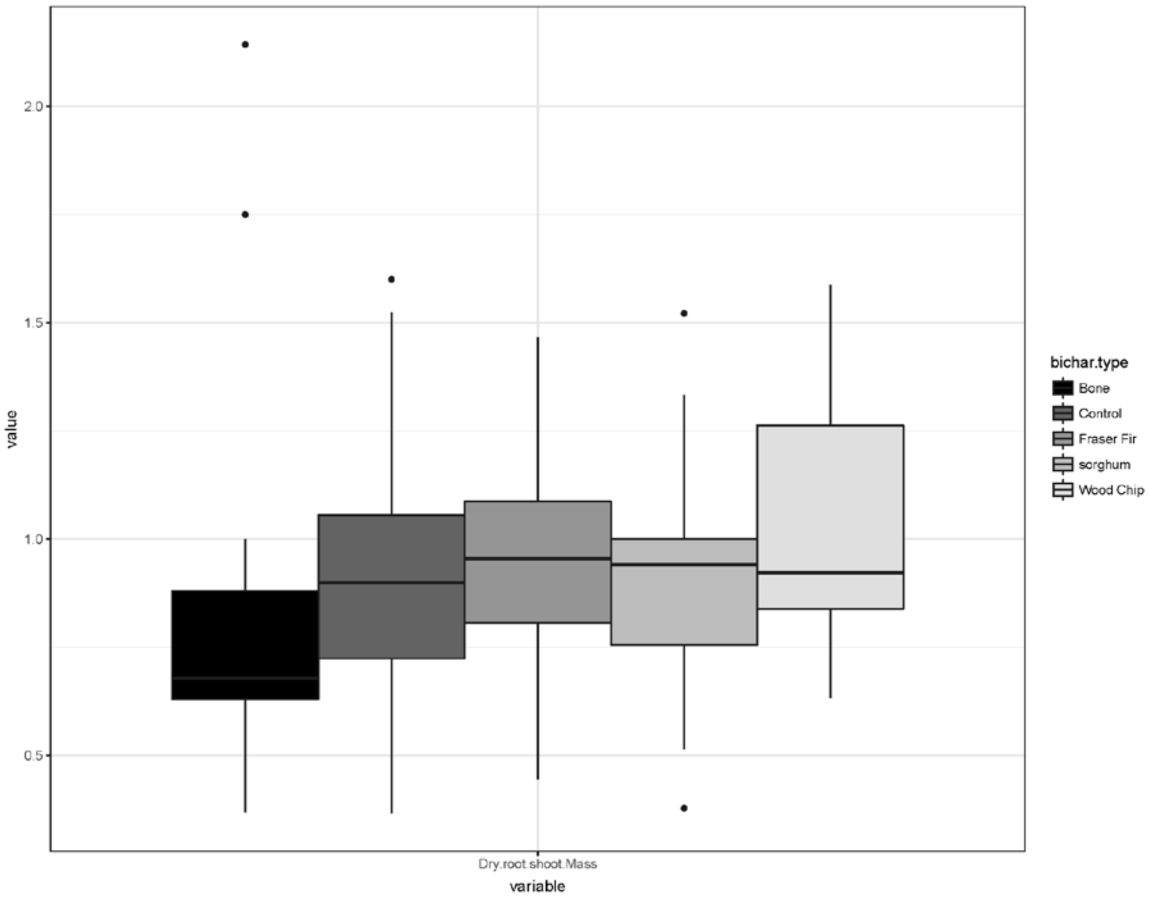

Figure E 23: Boxplot of RSR separated by biochar.

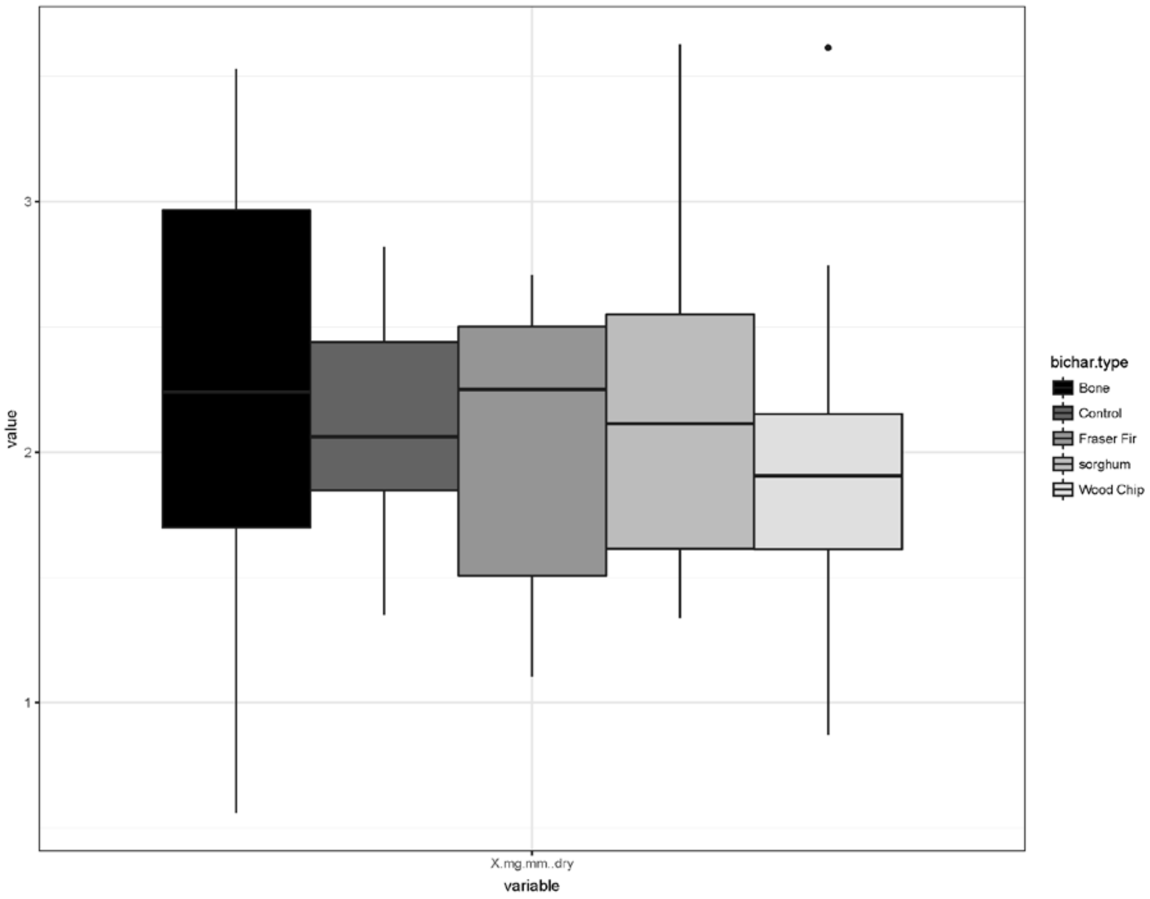

Figure E 24: Boxplot of mg/mm separated by biochar.

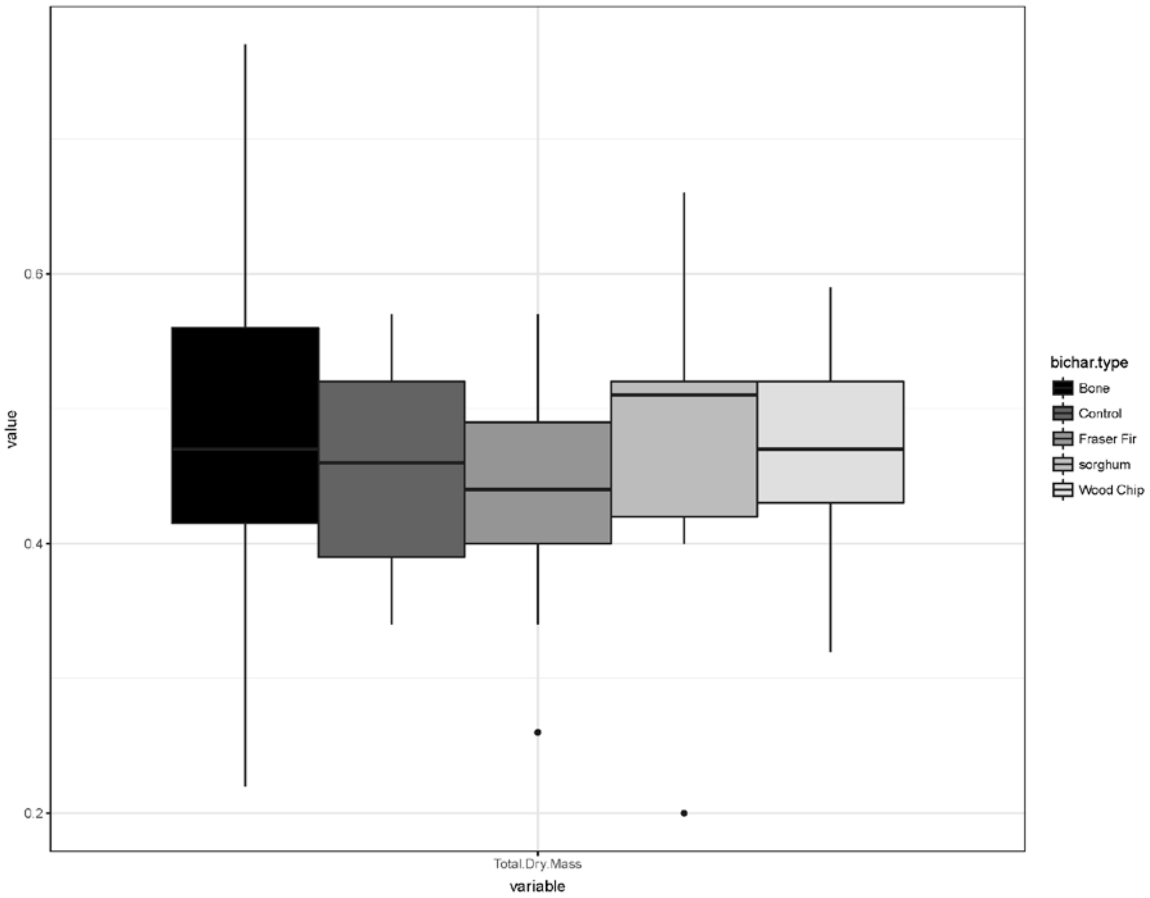

Figure E 25: Boxplot of total dry mass separated by biochar.

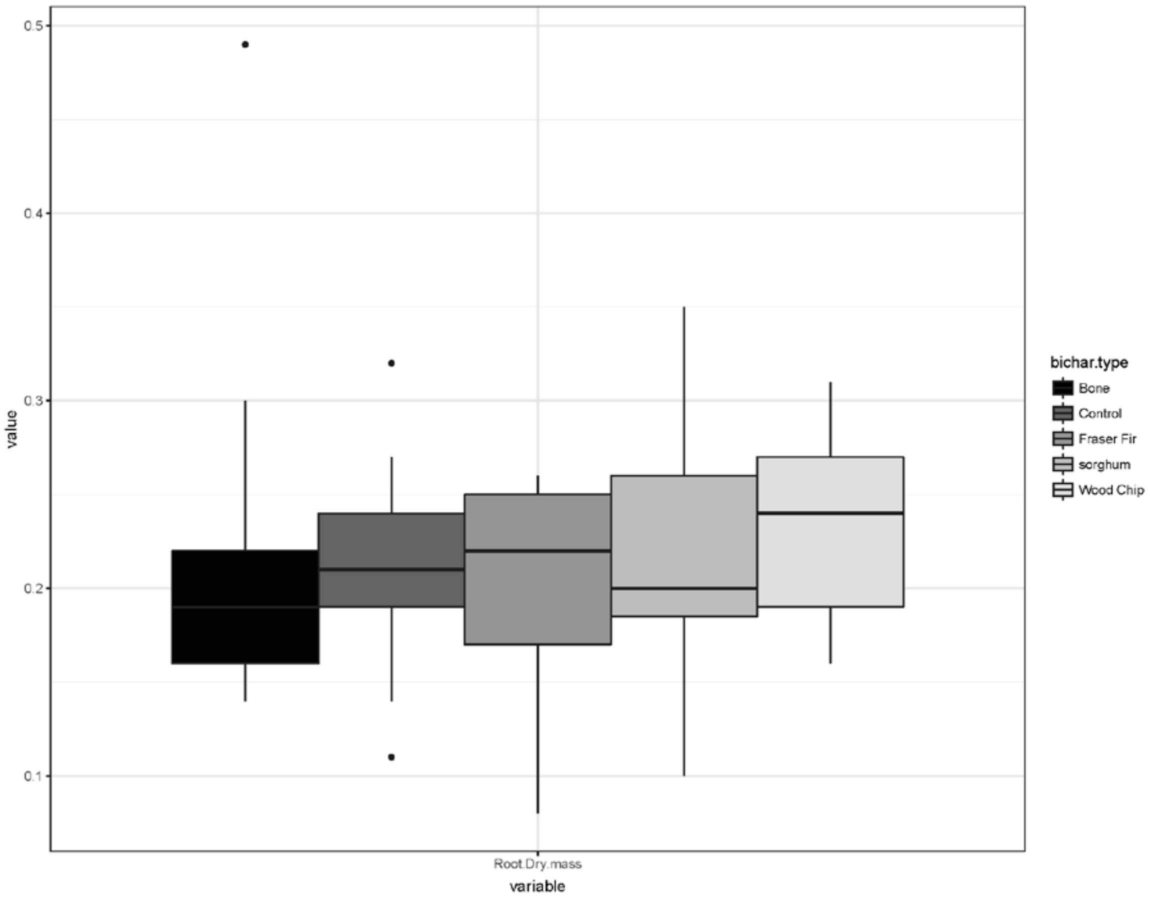

Figure E 26: Boxplot of root dry mass separated by biochar.

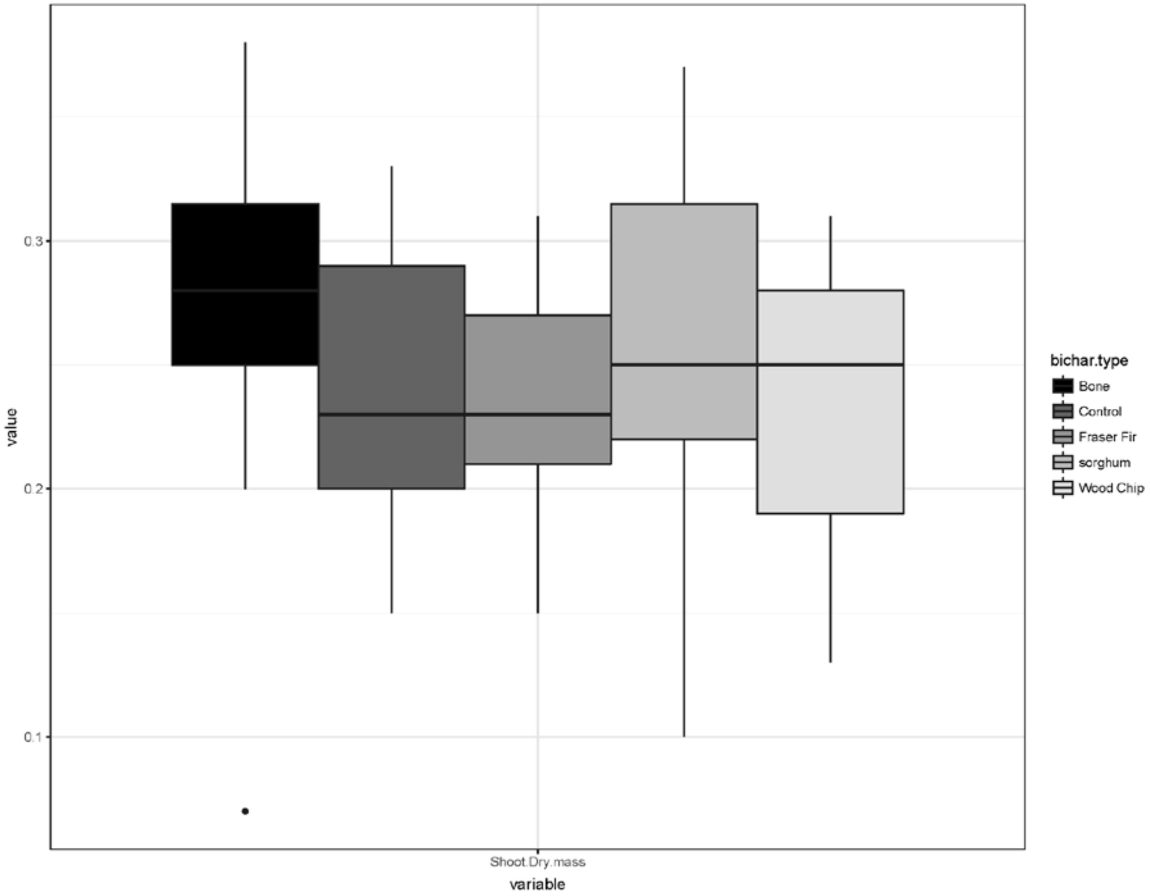

Figure E 27: Boxplot of shoot dry mass separated by biochar.

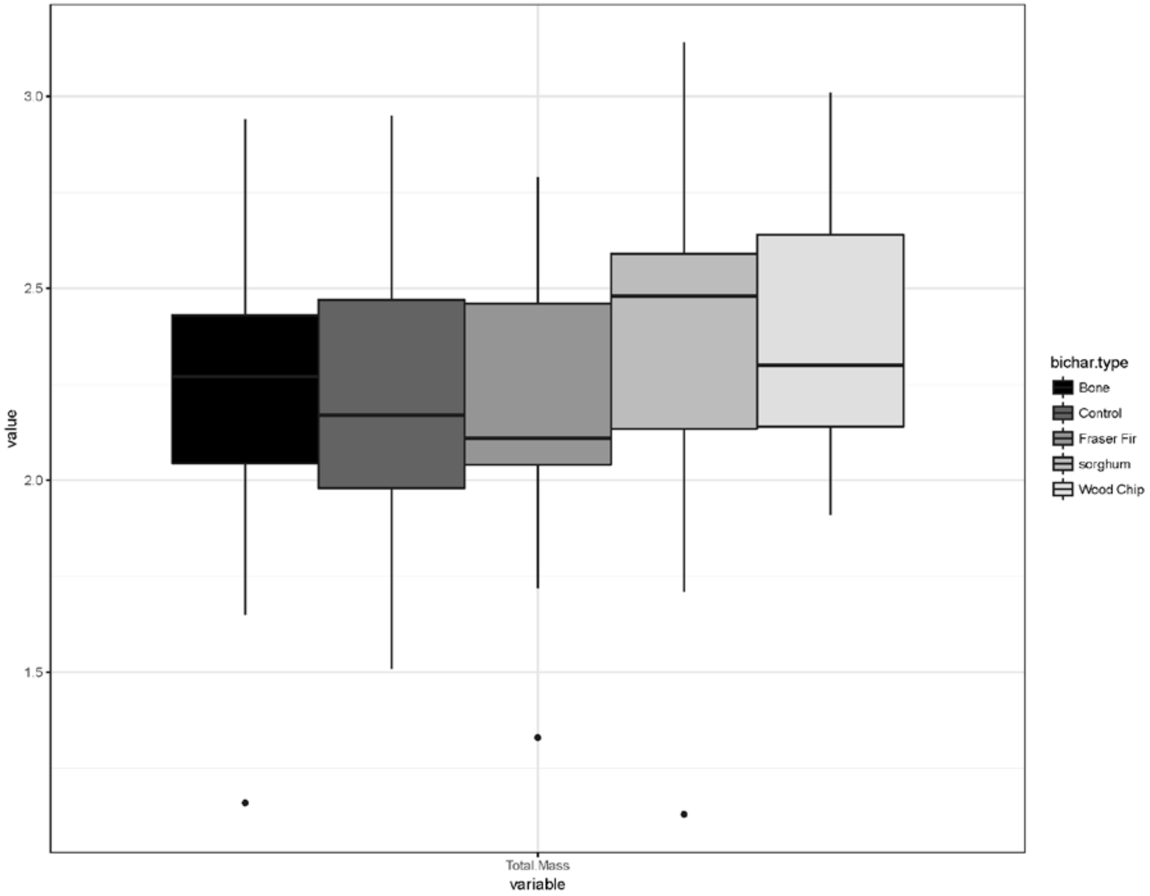

Figure E 28: Boxplot of total mass separated by biochar.

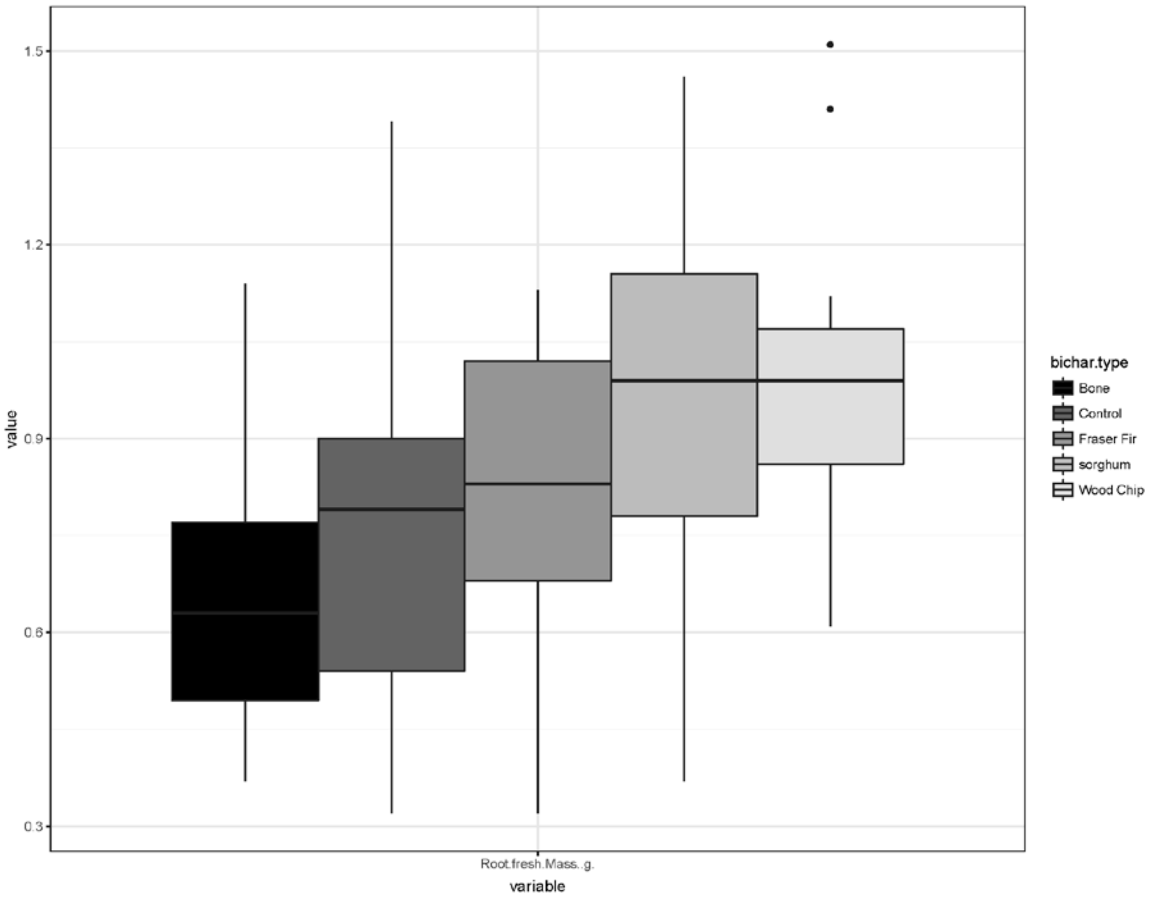

Figure E 29: Boxplot of root fresh mass separated by biochar.

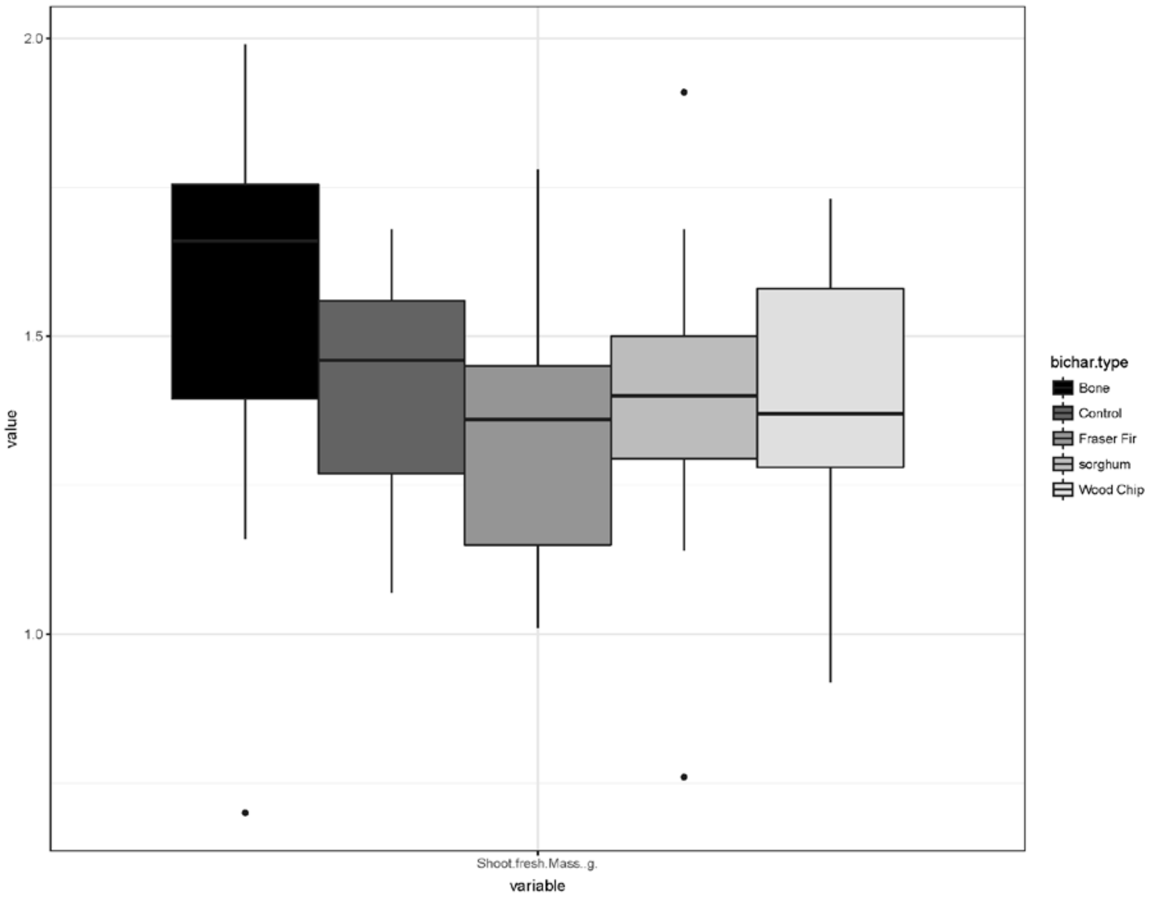

Figure E 30: Boxplot of shoot fresh mass separated by biochar.

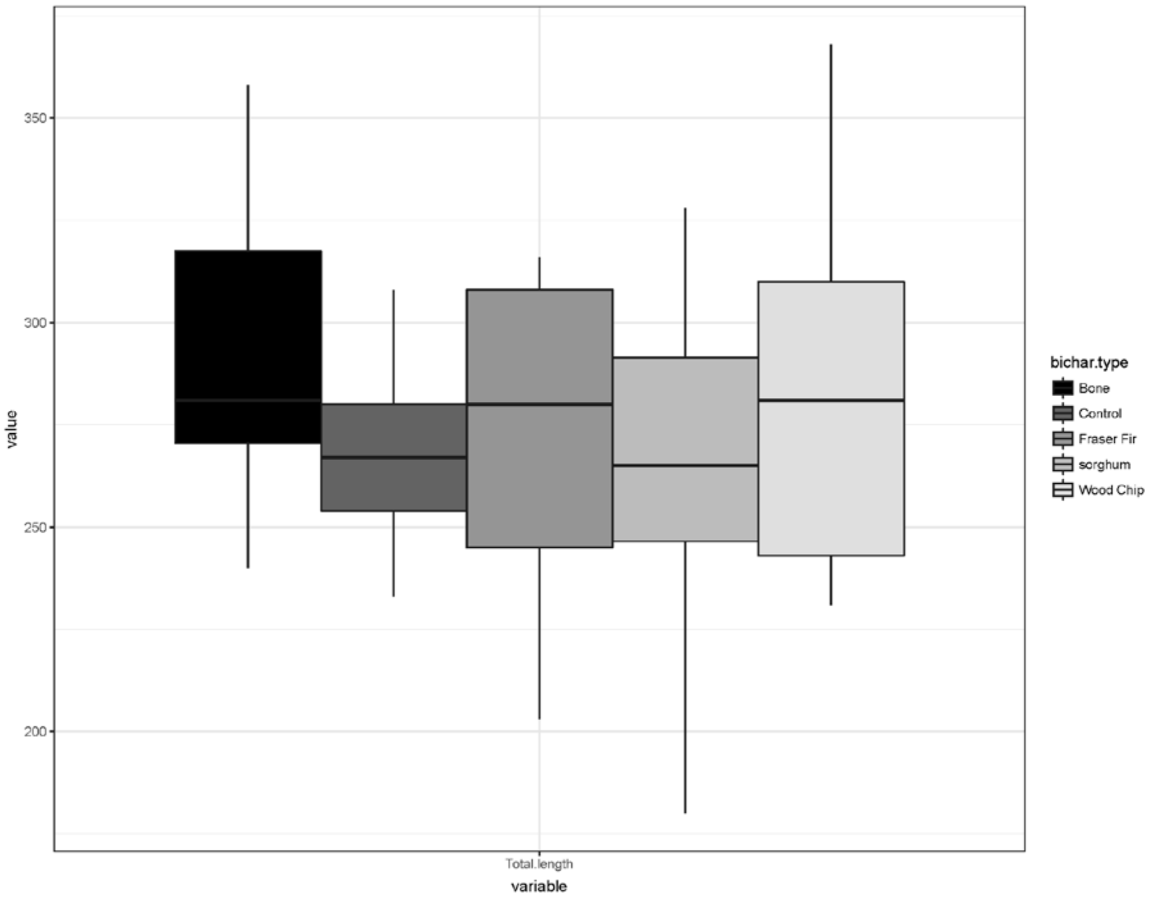

Figure E 31: Boxplot of total length separated by biochar.

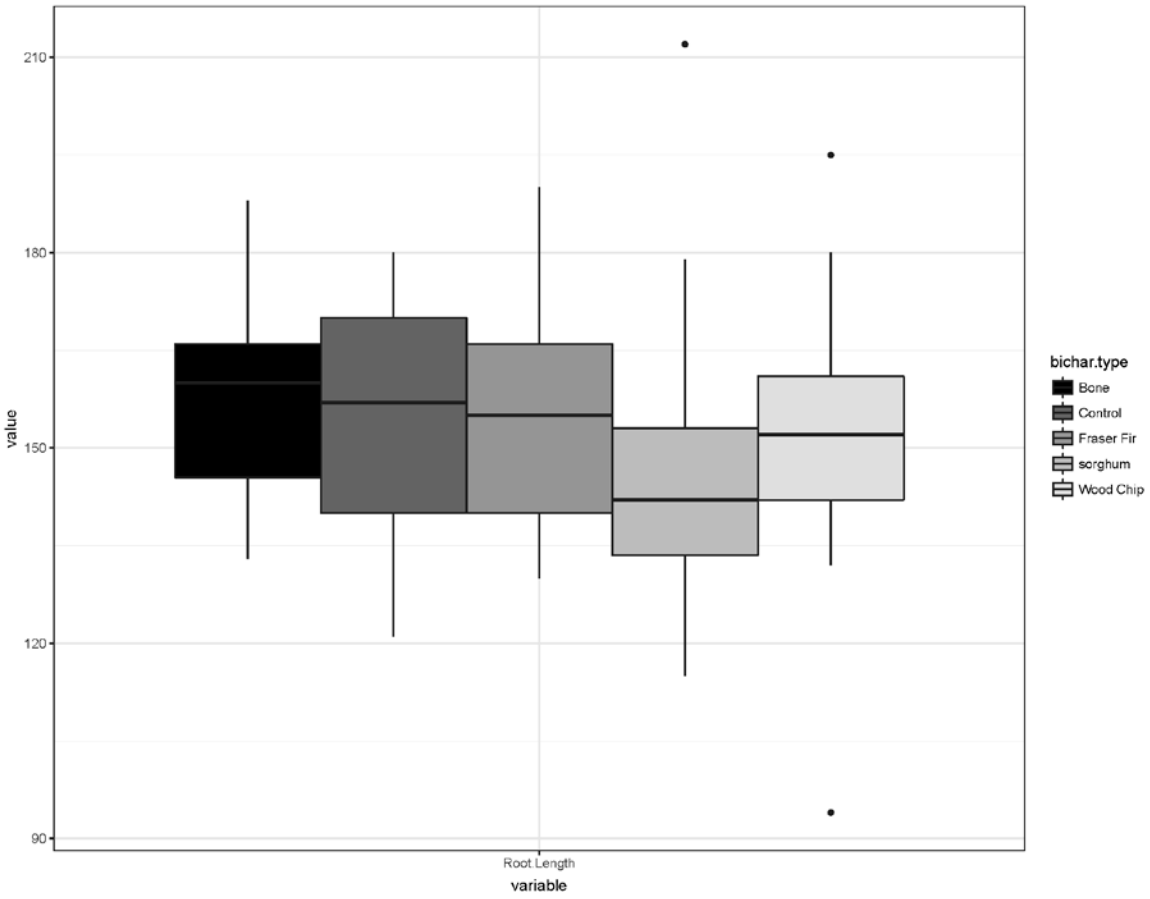

Figure E 32: Boxplot of root length separated by biochar.

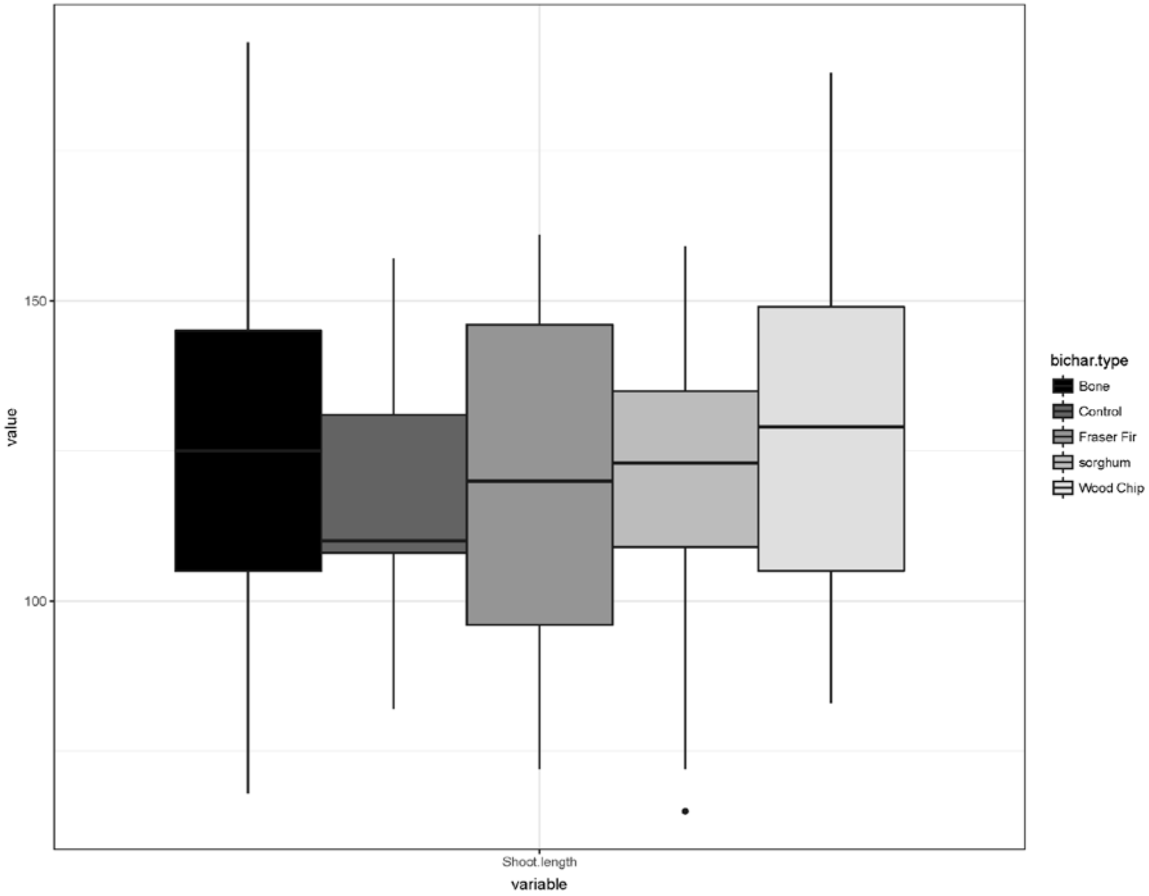

Figure E 33: Boxplot of shoot length separated by biochar.

Vita

Jared Weld Sanborn was born in Raleigh, NC to Hal and Cindy Sanborn. Jared attended Enloe High school in Raleigh before attending North Carolina State University. Jared Graduated from NCSU in 2014 with bachelors of science degrees in economics and philosophy, with a minor in mathematics. He enrolled at Appalachian State University as a master's candidate for the Master's of Science degree in Technology with a concentration in Appropriate Technology.

Jared Intends to pursue a doctorate degree in economics with a concentration in microeconomic theory and a focus on the economics of a changing energy landscape. Jared will continue to use the knowledge and experience he gained at Appalachian state university throughout his entire life.