Using Organic Amendments to Restore Degraded Mineland Soils

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Authorization to Submit Thesis

This thesis of Monica R. Ott, submitted for the degree of Master of Science with a Major in Soil and Land Resources and titled "**Using Organic Amendments to Restore Degraded Mineland Soils**," has been reviewed in final form. Permission, as indicated by signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

With over 30,000 abandoned mines on USDA Forest Service land, efficient and affordable reclamation methods are needed to restore site productivity. Surface applied amendments, biochar, biosolids, and woodchips, provide cheap, sustainable solutions to promote re-vegetation. We investigated amendment effects on soil quality at a dredge tailings site in Northeast Oregon. Experimental plots of the three amendments were sampled bi-annually for two years to measure changes in soil properties and plant success. Available nutrients were analyzed by both field and laboratory methods. Soil moisture and temperature were monitored *in-situ*, and soil water holding capacity was measured. Results show increases in soil pH, cation exchange capacity (CEC), organic carbon, macronutrients, and plant growth. Although changes are pronounced in single amendment applications, the combination treatments induce more stable plant growth by providing a combination of soil quality improvements. Results suggest that surface amendment of biochar, woodchips, and biosolids for land reclamation of disturbed forest soils may be a promising method for remediation in droughty areas of the Pacific Northwest.

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Chapter 1: Introduction and Literature Review

1.1 Abstract

Abandoned mines on public land in the western USA are numerous, and hazardous to both humans and the environment. Efficient and affordable reclamation methods are needed to restore soil function and productivity. Current reclamation strategies are both expensive and time consuming. Surface applied organic amendments, biochar, biosolids, and woodchips, provide inexpensive, local, sustainable solutions that will improve soil function and promote re-vegetation. This project investigated amendment effects on soil physical and chemical properties at an abandoned dredge tailings site in the Umatilla National Forest of northeastern Oregon. Experimental plots of the three amendments, applied singly and in combination, were sampled bi-annually over the course of two years. Project objectives were 1) determine which amendment or combinations promoted planted grass or seeded re-vegetation by looking at water holding capacity and nutrient availability over time, and 2) determine which amendment or combinations promote planted grass or seeded re-vegetation by looking at plant survival. Field research is needed to better understand how unincorporated organic amendments affect soil function in a natural setting.

1.2 Introduction

Mining in the Pacific Northwest, USA has been a staple industry throughout the history of development in the region. Mineral exploration and exploitation resulted in numerous operational and abandoned mine sites. Effective and cost efficient reclamation of these sites is of national concern (Mittal, 2011). In this project, we investigated the effects of surface applied amendments to soil chemical and physical properties of capped mine tailings in northeast Oregon. This field study measured the effectiveness of biochar, biosolids, and woodchips as amendments to restore soil function for the purpose of vegetation recovery.

1.2.1 Number of Abandoned Mine Sites

Exact numbers of abandoned mines in the USA are difficult to estimate because mine sites are broadly distributed, sites are on both public and private land, and often exist in hard to access locations (Mittal, 2011). In addition, assessment of the number of mine sites is confounded by the fact that there are inconsistent definitions of abandoned mines, limited information reported about land ownership of mines, and that some managing agencies do not keep data on land used for mining (Mittal, 2011).

In 1995, the USDA Forest Service (USFS) estimated the total abandoned mines on National Forests to be 38,991 (USDA, 2012). In 2011, the House Committee on Natural Resources: Subcommittee on Energy and Mineral Resources held a hearing concerning the problem of public abandoned mine land and how best to remediate these sites (AGI, 2011). Numbers reported by various agencies during this hearing show little change from twenty years ago, and reflect either a lack of reclamation or a lack of accurate data collection. The Department of Interior Bureau of Land Management (BLM) reported 31,000 abandoned mines on their land. The USFS abandoned mine land program reported between 27,000 and 39,000 abandoned mines. The United States Geological Survey (USGS), and the Government

Accountability Office reported that in the 12 western states, 161,000 abandoned mines were on public land (AGI, 2016). Today, according to the USGS, in Idaho, Oregon and Washington alone, there are approximately 38,500 mine sites (USGS, 2015). However, this number may not be only public land, as the USGS does not collect land ownership data (Mitta,l 2011). Clearly, the numbers of AML sites are large, and the reclamation needs are great.

1.2.2 Abandoned Mine Land Hazards

The hazards associated with public abandoned mine land are both physical and environmental (such as risks from the presence of toxic elements). Estimates have been made that eighty percent of mines pose physical hazards, and the other twenty percent pose both physical and environmental threats (AGI, 2016). Physical dangers to the public include concealed shafts and holes, decayed and unstable structures, and explosives. (Newton et al., 2000; AGI, 2016).

Environmental hazards include, but are not limited to, toxic soil, air, and water. The contaminants are introduced into the environment from both mining activities and chemicals used in the extraction and processing of ores. The contaminants degrade ecosystem stability and present toxicity risks to wildlife and humans. There are numerous examples of mining activity posing risks to humans, even long after the mines are shut down or abandoned (Grayson and Scott, 2003; Holzman, 2011; Koberstein, 2000). Areas surrounding abandoned mines are often barren of vegetation due to degraded or contaminated soils from tailings and extraction processes. Erosion often carries toxic elements off site and into surface and ground water (Duruibe et al., 2007). Site-point mining contamination easily and quickly becomes large scale. For example, the Bunker Hill Mine in Shoshone County of northern Idaho exhibits severe lead contamination has spread across a 21 square mile area (EPA, 2016).

1.2.3 Cost of Reclamation

Four government agencies (BLM, USFS, the Environmental Protection Agency (EPA), and the Office of Surface Mining (OSM)) have developed AML programs to mitigate both the hazards and cleanup costs of AML (BLM, 2014). According to the USFS, reclamation is defined as,

> “Returning disturbed land to a useful state, i.e., resource production, and limiting environmental impacts” (USFSc, 2015).

In 1977, the Surface Mining Control and Reclamation Act put in place laws that required reclamation bonds from operators before coal permits are obtained (OSMRE, 2015). Eventually, reclamation bonds and/or assurances were required for all types of mining on public land, with amounts varying based on product, period of operation, period of clean-up, and direct and indirect costs (USDA, 2004). Often, however, these assurances are not enough to cover the enormous cost of reversing mining damage done to site resources. If the operator cannot pay for full reclamation, the cost of reclamation falls to the government agencies, and ultimately the taxpayers. In the ten-year period from 1997 to 2008, the BLM, USFS, USGS, and OSM spent $2.6 billion dollars on hardrock mine reclamation (Mittal, 2011). This amount does not include all other types of mining reclamation, such as industrial and aggregate mining.

The Government Accountability Office and the Mineral Policy Center estimate that the cost of reclamation of abandoned mines (not already under reclamation) in the western 13 states, is between $9.6 and $21 billion (Weiss, 2015). These dollar amounts were determined by dividing abandoned mines into categories based on their respective cleanup costs, then multiplying by the amount of those types of abandoned mines (Table 1.1).

Table 1.1. Average cleanup cost by abandoned mine type nationally. Adapted from Center for Western Priorities Report, 2015.

Type of contamination	Average cleanup cost	Number of sites
Reclaimed and/or benign	$0	194,500
Landscape disturbance	$7,245	231,900
Safety hazard	$32,100	116,300
Surface water contamination	$1,646,678 - $4,940,035	14,400
Groundwater contamination	$8,233,391 - $24,700,173	500
Superfund	$411,699,550 - $576,337,370	50

In the Pacific Northwest, abandoned mine sites on National Forest lands cause a decrease in natural resources and profit generation for the USFS because site and vegetation production are reduced. Thus, it is imperative to develop efficient and affordable reclamation methods.

1.2.4 Methods of Reclamation

There are many mine land reclamation tools available, but their uses are site specific. Mining can affect water, air, soil and vegetation. Soil is a vital part of any disturbed site that interconnects other resources and is the foundation for plant growth (Sheoran et al., 2010). For example, contaminated air and wind can deposit undesirable elements onto the soil where soil water may leach these contaminants into groundwater or be taken up by plants. In the case of mine tailings and abandoned mine-land, re-vegetation is a main goal of reclamation, which requires healthy soil.

Common methods for reclaiming mine land and mitigating pollution include phytoremediation/revegetation, applying soil caps, adding amendments (organic or commercial), and removal/relocation of contaminated soil (EPA, 2000). Soil caps are frequently used as containment barriers for landfills (Handel et al., 1997), waste piles, and mine tailings (Hauser et al., 2001). If possible, topsoil is removed in the initial mining process, stockpiled, and reapplied after operations cease (Sheoran et al., 2010); otherwise a non-native soil cap is acquired. Availability of topsoil to cover the vast area of sites needing reclamation is limited. An interesting case occurred at the Superfund Site in Shoshone County, ID, where local farmers could no longer produce crops after selling 35-85 acres of their topsoil to cap contaminated mine waste, causing need for reclamation of the farmland (Silverman, 2001). To address limited topsoil availability, Brown et al. (2003) researched alternative methods, such as manufactured topsoil, to cap mine sites.

Sewage sludge (Asensio et al., 2013; Fosberg and Ledin, 2005), manure (Shrestha and Lal, 2009), and biosolids (Haering et al., 2000) have been shown to be effective on mine soils to increase organic matter content, neutralize soil acidity (pH), and increase N availability. Vegetative cover has been shown to increase organic matter and N through annual inputs of plant debris over a long period (Bendfeldt et al., 2000). Commercial fertilizers have also been used to alleviate nutrient deficiencies (, Steiner et al., 2007; Walsh and Redente, 2011).

1.2.5 Constraints of Reclamation Methods

Key concerns to be addressed when choosing or developing a reclamation method are time and money. Reclamation methods need to be both relatively fast acting and financially feasible for land managers to reclaim soil function to increase site productivity. Because many mine sites include massive amounts of tailings, natural pedogenesis and re-vegetation on rock material takes too long. Application of topsoil can be used to build a layer of soil conducive to plant growth. However, top dressed soil is often negatively impacted by the underlying tailings (such as acidity, heavy metals, or lack of water retention), and thus requires amendments to counter these factors.

1.2.6 Organic Versus Inorganic Amendments

Both organic and inorganic fertilizers have been used on mineland reclamation sites to increase soil chemical properties (Steiner et al., 2007; Walsh and Redente, 2011). In recent studies, inorganic fertilizers were effective at increasing nutrient concentrations, but needed yearly applications, whereas the organic fertilizers, chicken manure and compost, kept nutrient levels and organic matter elevated for the length of the study (4 years) (Steiner et al., 2007). Schoenholtz et al. (1992) found that although inorganic fertilizers increased biomass production on mine soils by 87% in the first year, measurements in subsequent years showed no significant biomass increase or long lasting effects. Steiner et al (2007) found that the application of inorganic fertilizers with charcoal derived from secondary forest wood doubled grain yields for four consecutive years, but soil nutrient levels were only elevated the first growing season. The same study found that application of chicken manure and charcoal not only increased crop production every year, but nutrient levels stayed elevated throughout the four-year study.

Some inorganic fertilizers must be tilled into the soil to avoid volatilization, and many need reapplications annually because they quickly degrade, mobilize, and leach. Even slow release commercial fertilizers, such as methylene urease, degrade within months, and are the most expensive (USDA, 2013; Kopec, 1994). Organic amendments are often waste materials (e.g., biosolids or manure) and are cheaper, typically environmentally healthy, and can be surface applied, thus eliminating incorporation costs. Manures, sewage sludge, sawdust, woodchips, and biochar have all been shown to be effective amendments that increase the rate of re-vegetation through changes in soil physical, chemical or biological enhancement (Brendfeldt et al., 2000; Forsberg and Ledin 2005; Tammeorg et al., 2013). Although mixing amendments into the soil may speed up changes to the soil, accessibility and getting equipment to most mine sites often makes this cost-prohibitive.

1.3 Experimental Site

1.3.1 Site Background and Research Needs

A mine tailings re-vegetation study is being conducted by the USFS Rocky Mountain Research Facility in Moscow, Idaho at an abandoned mine site on the Umatilla National Forest, Oregon. The Granite mining district of the Umatilla National Forest, on the eastern edge of Grant County, is part of the larger “Oregon Gold District” which produced millions of ounces of gold in the 19th and 20th centuries. Extensive hydraulic, lode, and dredge mining left tailings piles lining dredged waterways for miles (EOMA, 1999). Dredge gold mining is conducted by scooping rock and sediment up from the bottom of waterways and separating out gold from the waste materials. Large rocks and gravel that get carried through the dredge are then deposited on the shore in big rock heaps (Yannopoulos, 1991).

Figure 1.1. Map of Clear Creek experimental site

Clear Creek is a dredged waterway and is located approximately three miles west/southwest of the town of Granite, Oregon on Grant County Road 24 at an elevation of 1,439 meters above sea level. The site is a flattened tailings pile lining the north side of Clear Creek, leftover from dredging activities dating back as far as 1862 (EOMA, 1999). The tailings pile was capped in the 1970’s with roughly six inches of loam topsoil of unknown origin. Between 2001 and 2007, restoration work was done by USFS, including planting of shrubs, hardwoods, conifers, and the use of native plant seeding (Granite Creek Watershed EIS, 2015). These re-vegetation attempts had limited success. A few young ponderosa pines and few volunteer forbs are visible, but the overwhelming majority of the tailings cap is barren (Figure 1.2).

Figure 1.2. Pre-treatment Clear Creek reclamation site, Oct 2014 (USFS)

The Granite Creek Watershed, in which Clear Creek is a tributary, has been designated a “High Risk, High Value” area by the USFS because it provides habitat to steelhead and Chinook salmon, both of which are threatened species under the Endangered Species Act (NOAA Fisheries, 2016). Clear Creek specifically is home to steelhead, Chinook salmon, and bull trout (EIS 2015). In October 2014, experimental plots were installed, marked, and three soil amendments (biochar, biosolids, and woodchips) were surface applied. Application rates were as follows: Biochar- 11.2 Mg/ha, biosolids- 16.8 Mg/ha and woodchips- 22.7 Mg/ha. The plots are 10 x 10 feet with 3 replicates of each single amendment and combinations, plus controls, totaling 24 plots (Figure 1.3).

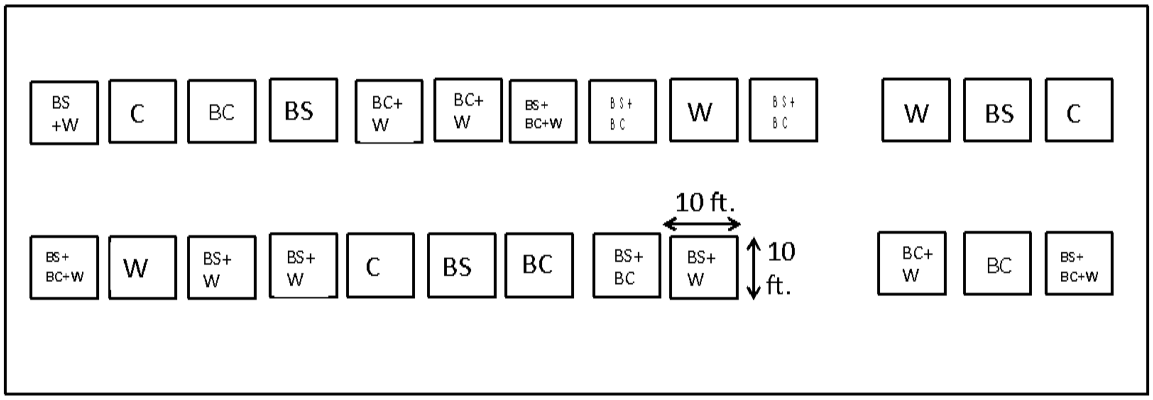

Figure 1.3. Clear Creek plot layout; bottom of figure faces south, runs parallel and is in close proximity to Clear Creek. C=control, BS=biosolid, BC=biochar, W=woodchip, BS+BC=biosolid + biochar, BS+W=biosolid+woodchip, BC+W=biochar+woodchip, and BS+BC+W=biosolid +biochar + woodchip.

At the time of application, half of each plot was seeded with a mixture of perennial grasses and native forbs (Table 1.2).

Table 1.2. Species and percentages of plants in seed mixture

Common name	**Scientific name**	**Relative percentage**
Western yarrow	*Achillea millefolium* L.	1.2%
Mountain brome	*Bromus marginatus* Nees es Steud.	35%
Bottlebrush squirreltail	*Elymus elymoide*s (Raf.) Swezey	9.4%
Blue wildrye	*Elymus glaucus* Buckley	25.9%
Idaho fescue	*Festuca idahoensis* Elmer	4.7%
Prairie junegrass	*Koeleria macrantha* (Ledeb.) Schult.	7.1%
Sandberg's bluegrass	*Poa secunda* J. Presl	4.7%
Bluebunch wheatgrass	*Pseudoroegneria spicata* (Pursh) A. Love	11.8%

These species are used by the National Resource Conservation Service in reclamation projects in the Pacific Northwest (NRCS, 2005), and known for their tolerance of degraded soils among other benefits. The other half of each plot was planted in April 2015 with greenhouse grown seedlings of the same grass species.

1.3.2. Site Limitations

The Clear Creek dredge site is located in Climate Division 8 (NOAA), with an average annual precipitation of 62.8 cm (averaged from the last 100 years). According to the Palmer Drought Severity Index (PDSI), the site is in a region of moderate drought (NIDIS), and according to the U.S. Drought Monitor is in a region of severe to extreme drought during 6 months of the year. Plant available water is likely a limiting soil factor at this location. Extending the growing season of plants by keeping moisture in the soil for a longer period could greatly aid re-vegetation attempts. Soil structure and soil texture are the two main components responsible for soil water retention and plant available water (Or, Tuller, and Wraith, 2009). The soil resting on top of the Clear Creek tailings is classified as a loam, with a rock content ranging from 28% to 52%, increasing from the surface down to 20 cm. As this soil cap is only 15.5 cm thick, it is important to maximize water retention quantity because water will quickly drain as soon as it percolates below the cap. Increasing silt and clay sized particles, organic matter, or particles with water retention characteristics (such as biochar) can aid in maximizing plant available water.

The second limiting factor on the experimental site is a commonly found issue at many tailing sites, a lack of plant-available nutrients (Hossner and Hons, 1992). Typical deficient soil nutrients in forest environments are N, P, and occasionally K, sulfur (S) and boron (B) (Coleman et al., 2014, Lehto et al., 2010, Kishchuk et al., 2002). Although this site is barren and not technically a forest environment, it is assumed that it was at one point and will be in the future following revegetation. Organic matter content, a major source of plant nutrients, is below typical percentages due to limited additions from vegetation litter and few soil organisms. Organic matter is also responsible for replenishing nutrients in soil solution, and organic C is positively correlated with P and K in the soil (Sheoran et al., 2010). Fifty to ninety percent of the CEC of mineral soils is from humus colloids found in soil organic matter (Brady and Weil, 1996). At Clear Creek, nutrients in the soil cap are either not sufficient for plant needs, or the combination of limited water and nutrients hinder growth. Once vegetation is established, additions of nutrients, mainly N, can meet plant demand over time. Establishing that vegetation requires soil amendments to get started.

1.4 Amendment Properties

1.4.1 Biochar as a Soil Amendment

In this study, three specific amendments were tested (biosolids, biochar woodchips). Biochar as an amendment has seen intensive research interests over the last few years (Atkinson et al., 2010; Beasley et al., 2007; Jeffery et al., 2011). The main applications of biochar have been to increase agricultural yield (Major et al., 2010; Sinclair et al., 2008), reduce risks at polluted sites (Fellet et al., 2011; Murano et al. 2009), sequester C in soils (Galinato et al., 2011; Steinbeiss et al., 2009) and restore degraded soils (Anawar et al., 2015; Stavi, 2012). Current interests in biochar can be traced to the Amazonian Terra Preta soils studied by Glaser (2001). Although the biochar of Terra Preta is not identical to pyrolysis-produced biochar, the soil quality enhancements from Terra Preta have promoted many researchers to test biochar as a soil amendment.

Biochar has been shown to influence soil chemical and physical properties by increasing soil nutrient retention and plant growth (Lehmann et al., 2003; Tammeorg et al., 2014), increasing soil water-holding capacity, and decreasing soil contaminant availability, usually heavy metals (Ojeda et al., 2015; Rodriguez-Vila et al., 201; Uchimiya et al., 2010). Particular nutrients that are found to be more bioavailable in biochar are P, K, calcium (Ca), magnesium (Mg), and molybdenum (Mo) (Atkinson et al., 2010). Biochar has also been shown to increase cation exchange capacity, which increases retention of cationic nutrients (namely K, Mg, Ca, NH_4) (Lehman, 2007; Liang, 2006), increases total organic C (Tammeorg et al., 2014; Unger et al., 2011), and increases soil pH (Chan et al., 2009).

Some studies have shown detrimental effects of biochar on soil health and plant growth. Kookana et al. (2011) found that biochar's sorption properties can hinder nutrient availability to plants by hindering N mineralization and increasing N immobilization. Yao et al. (2011) found that biochar absorbs phosphate, and when not applied with other nutrients can reduce already limited plant-available nutrients. There is also evidence suggesting that the pore space in biochar, one of its main benefits, becomes clogged over time (on a 100-year scale) with organic C and other adsorbed substances, reducing its sorption capacity by limiting the surface area of the inner pores (Hammes and Schmidt, 2012).

Properties of biochar that make it useful as a soil amendment are high macro- and micro-pore space, which are associated with its large surface area (Kookana et al., 2011; Lehman et al., 2012). Pore space is responsible for the high surface area and sponge-like characteristics of biochar. Although surface area is a physical property, it is directly related to chemical properties because increased surface area increases the solid solution interface, providing more exchange sites to accumulate nutrients for later use.

Biochar's surface charge allows for adsorption of water molecules and cation (NH_4^+, K^+) and anion nutrients (NO_3^-, PO_4^{3-}) (Downie et al., 2012). Different feedstocks and pyrolysis temperatures as well as how long the char has been in the soil greatly affect its surface charge (Uchimiya et al., 2010). Freshly produced biochar has less of an ability to adsorb ions because it has less surface charge. After aging and oxidation begins, which has been found to be a main component of biochar aging, the surface charge becomes increasingly negative due to formation of carbonyl, carboxyl, and phenolic groups (Cheng et al., 2006). These groups are believed to be the main sites of cation adsorption (Cheng et al., 2006; Pittman et al., 1999).

A second benefit of a more negative surface charge is water retention. Water molecules are polar, and therefore their slightly positive hydrogen atoms are attracted to the negatively charged functional groups on the surface of the char. Water retention is also a function of soil organic carbon content. Rawles et al. (2003) found that water retention increased in sandy soils specifically with increased additions of organic carbon. Biochar is composed of primarily organic carbon left over from pyrolysis (Kookana et al., 2011). However, some studies show that biochar does not increase soil water holding capacity. Recent studies show that rate of application and hydrophobicity of each biochar amendment, according to its original biomass, influences whether it will increase soil water retention (Hardie et al., 2013; Ojeda et al., 2014). Ojeda et al. (2014) found no change in water holding capacity in greenhouse studies of biochar, and Hardie et al. (2013) found that any change in water retention was dependent on the original feedstock of the biochar.

Table 1.3 Chemical analysis of the biochar applied to Clear Creek (USFS, 2014)

Biochar Analysis	
pH	7.9
	(%)
Total C	89
Total N	0.26
	(mg/kg)
Aluminum	1538
Barium	64.4
Boron	22.2
Calcium	4940
Copper	24.6
Iron	1224
Magnesium	998
Manganese	170
Phosphorus	248
Potassium	2220
Sodium	176
Strontium	28.8
Sulfur	160
Zinc	38.6

Depending on its feedstock and temperature of pyrolysis, biochar may have some hydrophobic character, and will repel water to different degrees (Ojeda et al., 2014). Biochar's hydrophobicity also depends on amount of water in the soil (Page-Dumroese et al., 2015). As a soil gets more saturated, the hydrophobic portions on the char edges are overcome, and water is held in the soil.

Breakdown of biochar over time influences its movement into the soil. Particle size of the biochar has an effect on how quickly it decomposes and mixes into the soil (Hammes and Schmidt, 2012). In this project, vertical distribution of nutrients were analyzed to determine rates of amendment incorporation into the soil profile. Because biochar is known to have many negative sites, biochar-amended soils may see lower levels of nutrients moving downward with solution than soils without biochar. Biosolids have high nutrient content and should release those nutrients into solution, yet may move quickly through the soil into the tailings. Building soil up in between the rocks of the tailings and providing roots with nutrients in those cracks should be a major benefit for revegetation and tailing stability, especially given the thin soil cap (12-15cm). Observing the time required for breakdown and natural incorporation, as seen by changes in soil properties over time, will aid in summarizing the effectiveness of surface application.

1.4.2 Biosolids as a Soil Amendment

Biosolids are commonly used for mine land reclamation, especially after the establishment of the Surface Mine Reclamation Act of 1977 (Haering et al., 2000). Mine soil deficiencies that are improved by biosolids are low organic matter, low CEC, and low nutrient levels (Ojeda et al., 2010). Nitrogen is the most common limiting soil nutrient (Brady and Weil, 1996). Biosolids contain between 1-6% N (Table 1.4), depending on the source and processing (Center for Urban Horticulture, 2002). For example, composted biosolids often have low mineralizable N, but high total organic N, which can be mineralized over time. Heat-treated sludge, on the other hand, has high levels of mineralizable N (Haering et al., 2000). Biosolids have been used to improve fertility of mine-impacted soil for many years and have been studied in comparison and combination with inorganic fertilizers on degraded soils (Sopper, 1992). Nutrient inputs from biosolids, along with their longer degradation time, have encouraged researchers to continue studying biosolids for reclamation purposes.

A concern with using biosolids for reclamation is the metal content. Multiple land applications could lead to potentially harmful metal loading in the soil, if applied at high rates. Metals in biosolids originate from many sources, such as dentist offices, construction sites, drain pipes, batteries, paints and pigments, to name a few (Holm, 2002). Treatment of biosolid waste determines the levels of such elements (similar to nutrient levels discussed above), and federal EPA regulations must be met to land-apply them (Brobst, 1994) (See Table 1.4). A benefit of using biosolids on mine sites is that only a single application may be necessary to support revegetation, and unlike an agricultural field, where repeated biosolids applications would be needed to meet nutrient demands of continuous cropping, with a single application undesirable metals will not build up. Additionally, forests are not used to grow food crops, thus decreasing risks of human exposure from the metals in biosolids. The USFS mine sites in the scope of this project are not located where humans will likely come into contact with them often, and the biosolids used from Bend, Oregon are well within EPA pollutant concentration limits (Table 1.3). At metals-contaminated mine sites, the trace element concentrations in biosolids are negligible compared to soil metal toxicity.

Table 1.4 Average values (n=3) of nutrients, metals and pH of the biosolids applied to Clear Creek (Bend wastewater treatment plant, Bend, OR) EPA ceiling concentration limits of trace elements for land-applied biosolids (Biosolid Management Handbook, Brost, 1994).

	Applied Biosolids	**Ceiling Concentrations**
	(mg/kg)	(mg/kg)
Kjeldahl Nitrogen	55,500	
Ammonia -N	1,940	
Nitrate -N	137	
Organic N	53,500	
Phosphorus	30,250	
Potassium	2,900	
pH	7.1	
Arsenic	3.8	75
Cadmium	1.1	85
Chromium	18	3,000
Copper	338	4,300
Lead	30	840
Mercury	<MDL=1	0
Molybdenum	8.1	75
Nickel	19	420
Selenium	3.4	100
Silver	4.1	
Zinc	478	7,500

1.4.3 Woodchips as a Soil Amendment

Woodchips, made from local wood sources, are a commonly used surface-applied amendment for mine site reclamation. Although woodchips do not change soil nutrient availability, they promote biological activity that degrades the woodchips, and eventually may increase soil organic matter content (Walsh and Redente, 2010). Woodchips can reduce surface evapotranspiration. For example, on a reclamation project on mine land in North Idaho, Walsh and Redente (2010) observed that woodchips increase organic matter, ammonium-N and nitrate-N after 4 years. Organic C content of soil affects water-holding capacity by changing the soil structure and increasing microbial activity (Edwards et al., 1999). Organic C can change water retention because its helps form polysaccharides that bind soil particles together causing aggregation and allowing infiltration. Microbial community populations in the soil effect mineralization rates of nutrients needed for plant growth (specifically N) among other functions.

Woodchips physically protect soil by sheltering the surface from erosive forces such as raindrop penetration and wind. Woodchips have also been shown to increase soil moisture on forest mine soils (Schoenholtz et al., 1992), especially after two growing seasons. Woodchips protect the soil surface from direct sunlight, keeping the soil moist and cool, reducing evaporation.

1.5 Recent Biochar Use

Murkerjee et al. (2014) applied biochar, water treatment residuals and coal derived humic acid at a rate of 0.5% (wt/wt) to a scalped silty clay loam and collected soil data over a period of two years. They found no effects for the first 1.5 years. This low application rate was chosen to represent what farmers were likely to apply, given manufacturing and transportation costs. The only significant changes seen to physiochemical soil properties were when comparing the first and second year. Available water increased from biochar application and electrical conductivity increased in all amendment applications. They suggested a higher rate of application for field studies may be required to see effects on revegetation.

Tammeorg et al. (2014) conducted a 3-year field study with two biochar application rates (5 and 10 ton dry matter ha^{-1}) along with a commercial N-P-K fertilizer tilled into a fertile sandy clay loam. The purpose of this study was to see if biochar, used for carbon sequestration, would have any adverse effects of already productive crop yields. No adverse effects were found, however, there was a marked increase in the soil moisture content at the end of the growing season in the biochar-amended soil.

At the Forest Service Hope Mine reclamation project in Aspen, Colorado, biochar was used in combination with compost to re-vegetate contaminated mine soil (As, Cd, Pb, and Zn) and prevent erosion on a steep hillside (ACES, 2011) (Figure 1.5). The first-year results showed increased soil moisture and native grass growth.

Hope Mine is an important case study for the USFS, demonstrating biochar's usefulness at remediation and stabilization. However, it was determined that biochar alone was not responsible for the reclamation success, and without compost (applied in quantities of up to 95% of total amendments by volume), the researchers postulate that it is likely there would have been a nutrient deficiency (USFSa, 2012). From the above studies, it appears biochar has a beneficial effect on soil moisture, but little to no effect on nutrient addition, and requires a nutrient rich substance to be applied simultaneously for revegetation to be achieved.

1.6 Research Objectives

1.6.1 Project Objectives

The overall site goals for the Clear Creek Project are 1) establish a best management practice for reclamation of dredge tailings, 2) determine if biochar, biosolids and woodchips used as amendments accelerate re-vegetation, and 3) measure how amendments affect long-term vegetation growth.

1.6.2 Reuse of Forest Waste

The USFS is interested in discovering whether biochar is a useful enough amendment to start a movement toward converting forest waste into biochar to be used for reclamation as well as sold commercially.

1.6.3 Reuse of Municipal Waste

Finding beneficial uses for the residuals from wastewater treatment plants is a public interest as people turn towards ways to reuse and recycle. In the past, biosolids were incinerated, put in landfills, used as covers for landfills, and land applied (Moller, 2007; EPA, 1999). Land application of Class B biosolids onto agricultural fields has been commonplace for the City of Bend, Oregon, yet more options are needed because of the anticipation of farmland conversion to alternative land uses (Thompson et al., 2015). The Forest Service has presented the City of Bend with an option for disposal through land applying these biosolids as a soil amendment on reclamation sites, provided the biosolids are treated to the stricter Class A pathogen requirements. The Clear Creek site is a case study to further this partnership and identify a safe, long-term use of biosolids in the state of Oregon.

1.6.4 Thesis Objectives

This master's research includes objectives that will integrate into the USFS Clear Creek reclamation project goals. The purpose of this research is to characterize the soil physical and chemical effects of various organic amendments when surface applied. Chemical effects of interest are nutrient enhancement, vertical nutrient distribution, and changes in pH, electrical conductivity, organic C, and CEC. The physical effects of interest are changes in plant available water, as determined by field capacity and permanent wilting point measurements. The two experimental objectives below will be used to guide measurements how the three amendments, biochar, biosolids and woodchips, alter soil properties and plant growth.

Objective 1. The first objective is to determine which amendment or combinations of amendments promote re-vegetation by looking at water holding capacity and nutrient availability over time.

Hypothesis 1: Soil water retention will be greater after application of soil amendments, extending the growing season and shortening the summer drought.

Water holding capacity of the plots will be measured at two sampling times: after the first growing season and after the second winter. As discussed above, there have been studies that show little or no effect of amendments on water retention (Odeja et al., 2015); depending on the hydrophobicity of the biochar, amount of amendments applied, and amount of water added to the soil (Page-Dumroese et al., 2015). Therefore, application amounts and precipitation will be observed to see how the amendments affect plant available water.

Hypothesis 2: Organic soil amendments will increase plant available nutrients and alter soil pH.

Samples taken at the two different sampling events will be analyzed for vertical distribution of nutrients, nutrient concentrations, pH, total organic carbon, and cation exchange capacity to see whether the amendments are changing these properties.

Additions of biosolids are expected to increase the main macronutrients N, P, and K because they contain high amounts of these elements, similar to adding a fertilizer (Table 1.4). Biochar has been shown to help retain nutrients in the soil; therefore, combination plots of biosolid+biochar are expected to have the highest continuous concentrations of plant-available nutrients in the soil. Steiner et al. (2007) found that combinations of charcoal and manure applied together greatly increased plant-available nutrients as opposed to these amendments applied alone.

Objective 2. Determine which amendment or combinations of amendments promote re-vegetation acceleration by increasing the number of plants significantly.

Hypothesis: there will be more plants in amended plots than the control plots.

1.7 Justification

The USFS has worked with private companies to develop a method of producing biochar at forest sites where biomass waste has either become a fire hazard or is left over from logging activity (USFSb, 2012). Portable, fast-pyrolysis units convert slash piles into bio-oil and biochar on site, retaining the carbon and nutrients of the woody biomass and eliminating the effort of transporting low-value, low-density biomass offsite. Biochar is applied to degraded soil of that site, and excess biochar can be used at other forest sites for reclamation. To support this method of biomass conversion, biochar effectiveness as an amendment to improve soil conditions must be researched. Aspects of its effectiveness are application quantities needed, persistence in the environment, effects on the physicochemical properties of the soil, and effects on plant cover.

The vast majority of studies done using biochar on mine sites have been for the purpose of remediation by reducing toxic metal uptake and immobilization of contaminants (Bakshi et al. 2014; Fellet et al., 2011; Strawn et al., 2015). Although biochar has been used as a soil amendment on degraded agricultural soils (Atkinson et al., 2010; Lehmann et al., 2012), and recently on rangeland soils (Stavi, 2012), it has not been widely used to increase soil quality on degraded mine soils without contamination. Many mine sites on USFS land in the Pacific Northwest are dredge sites where no chemicals were used or contaminants were not produced during extraction. At these sites, the major problem is lack of vegetation caused by conditions such as low OM, few micropores, or drough conditions.

In order to more widely use organic amendments as a tool to restore soil functions on degraded sites, affordable, replicable, field trials are needed. Although studies have found biochar to be hugely effective at improving soil quality and plant growth, most of these studies are in greenhouses and controlled environments (Bakshi et al., 2014; Fellet et al., 2011; Ojeda et al., 2015; Page-Dumroese et al., 2015; Schulz et al., 2013). To discover expected results of surface application of amendments in the forest environment, studies must be done under natural conditions. Of the field studies done, most methods involve mixing biochar and other amendments into the soil (Tammeorg et al., 2014; Jeffery et al., 2015). However, few studies have surface applied the amendments, as is being done at Clear Creek.

In a large-scale field setting, specifically on mine tailings, mixing in amendments is not always physically or financially possible. USFS abandoned mine sites are generally remote and inaccessible to large equipment. Other concerns are that tilling tailings piles exposes more pollution and hazardous elements to air and water, and if vegetation is growing there, it may turn over the existing organic horizon, leading to increased erosion and loss of nutrient cycling. Research into surface applied amendments on mine soil in field settings (breakdown rates, application rates, and overall effectiveness) is necessary for developing economic, practical means of reclaiming forest mine sites.

1.8 Literature Cited

Anawar, H. M., F. Akter, Z. M. Solaiman, and V. Strezov. 2015. Biochar: An emerging panacea for remediation of soil contaminants from mining, industry and sewage wastes. Pedosphere. 25(5): pp. 654–665.

ACES (Aspen Center for Environmental Studies). 2011. Hope mine biochar project. July 2010–August 2011, Aspen, Colorado, USA.

AGI (American Geosciences Institute). 2011. House committee on natural resources subcommittee on energy and mineral resources oversight hearing on "Mining in America: The Administrations use of Claim Maintenance Fees and Cleanup of Abandoned Mine Lands". Available at: http://www.americangeosciences.org/policy/house-committee-natural-resources-subcommittee-energy-and-mineral-resources-oversight-heari-0.

Atkinson, C. J., J. D. Fitzgerald, and N. A. Hipps. 2010. Potential mechanisms for achieving agriculture benefits from biochar application to temperate soils: a review. Plant Soil 337:1-18.

Bakshi, S., Z. L. He, and W. G. Harris. 2014. Biochar amendment affects leaching potential of copper and nutrient behavior in contaminated sandy soils. J. Environ. Qual. 43:1894-1902.
BLM. 2014. Abandoned mine lands. U.S. Department of the Interior. Available at: https://www.blm.gov/wo/st/en/prog/more/Abandoned_Mine_Lands.html.

Brady, C. N., and R.R. Weil. 1996. The Nature and Property of Soils. Prentice Hall Inc., New Jersey.

Bray, R. H. and L. T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39-45.

Brobst, R. 1994. Biosolids management handbook: Section 1. Environmental protection agency. Available at: http://www2.epa.gov/region8/biosolids-management-handbook-section-1.

Brown, S., C .Henry, R. Chaney, H. Compton and P. DeVolder. 2003. Using municipal biosolids in combination with other residuals to restore metal-contaminated mining areas. Plant and Soil 249: 203-215.

Burt, R. 2011. Soil Survey Lab Information Manual. NRCS. Lincoln, Nebraska. Pp 247.

Center for Urban Horticulture, University of Washington. 2002. Using biosolids for reclamation and remediation of disturbed soils. Plant Conservation Alliance, Bureau of Land Management, US Dept of Interior.

Cheng, C., J. Lehmann, J. E. Thies, S. D. Burton, and M. H. Engelhard. 2006. Oxidation of black carbon by biotic and abiotic processes. Org. Geochemistry 37:1477-1488.

Coleman, M. D., T. M. Shaw, M. J. Kimsey, and J. A Moore. 2014. Nutrition of douglas-fir in the Inland Northwest. Soil Sci. Soc. Am. J. 78(1):S11-S22.

DeLuca, T. H., D. MacKenzie, M. Gundale, and S. Joseph. 2012. Biochar effects on soil nutrient transformations. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Taylor and Francis, Hoboken. p. 251-71.

Downie, A., A. Crosky, and P. Munroe. 2012. Physical properties of biochar. In: J. Lehmann and S. Joseph, editors. Biochar for environmental management: Science and technology. Taylor and Francis, Hoboken. p. 22-25.

Duruibe, J.O., M.O.C. Ogwuegbu and J.N. Egwurugwa. 2007. Heavy metal pollution and human biotoxic effects. Int. J. Phys. Sci.. 2(5):112-118.

EOMA (Eastern Oregon Mining Association). 1999. Oregon gold mining: Grant county gold districts. Available at http://www.h2oaccess.com/articles.php/19991202.

Edwards J.H., C.W. Wood, D.L. Thurlow, and M.E. Ruf. 1999. Tillage and crop rotation effects on fertility status of a Hapludalf soil. Soil Sci. Soc. Am. J. 56:1577-1582.

EPA. 2016. Bunker Hill Mining and Metallurgical Superfund Site (Coeur d’ Alene Basin). Site Summary. Available at: http://www.epa.gov.

EPA. 1999. Biosolid generation, use, and disposal in the United States. Municipal and Industrial Waste Division. Available at: http://www.epa.gov/sites/production/files/2015-07/documents/biosolids_generation_use_disposal_in_u.s_1999.pdf.

Fellet, G., L. Marchiol, G. Delle Vedove, and A. Peressotti. 2011. Application of biochar on mine tailings: Effects and perspectives for land reclamation. Chemosphere 83:1262-1267.

Gericke, M., A. Pinches, and J.V. van Rooyen. 2000. Bioleaching of chalcopurite concentrate using an extremely thermophilic culture. Int. J. Miner. Process. 62:243-255.

Gupta, S.C. Larson, W.E. 1979. Estimating soil water characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res. 15(6):1633-1635.

Haering, K. C., W. L. Daniels, and S. E Feagley. 2000. Reclaiming mined lands with biosolids manures and papermill sludges. ASA, CSSA, SSSA, Agronomy monograph. 41:615-644.

Hammes, K. and W. Michaeol and I. Schmidt. 2012. Changes in biochar in soil. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Taylor and Francis, Hoboken. p. 169-181.

Hardie, M., B. Clothier, S. Bound, G. Oliver, and D. Close. 2014. Dous biochar influence soil physical properties and soil water availability? Plant Soil 376:347-361.

Holm, O., E. Hansen, C. Lassen, F. Stuer-Lauridsen and J. Kjolholt. 2002. Heavy metals in waste: Final report. European Commission. Available at http://ec.europa.eu/environment/waste/studies/pdf/heavy_metalsreport.pdf.

Holzman, D. C. 2011. Mountaintop removal mining: Digging into community health concerns. Environ. Health Perspec. 119 (11): a476–a483.

Hossner, L. R. and F. M. Hons. 1992. Reclamation of mine tailings. In: Rattan Lan and B.A. Stewart, editors, Soil restoration. Advances in soil science volume 17. Braun-Brumfield, Ann Arbor, MI. p. 311-350.

Jeffery, S., M. Meinders, C. Stoof, T. Bezemer, T. vande Voorde, L. Mommer and J. W. van Groenigen. 2015. Biochar application does not improve the soil hydrological function of a sandy soil. Geoderma 251(252):47-54.
Kishchuk, B. E. and R. P. Brockley. 2002. Sulfur availability on lodgepole pine sites in British Colombia. Soil Sci. Soc. Am. J. 66:1325-1333.

Koberstein, P. 2000. Out of the Earth, into our lungs. The Cascadia Times. Available at http://www.times.org/archives/2000/november2000/bunkerhill.htm.

Kookana, R. S., A. K. Sarmah, L. van Zwieten, E. Krull, and B. Singh. 2011. Biochar application to soil: Agronomic and environmental benefits and unintended consequences. Advances in agronomy. 112:103-143.

Kopec, D. M. 1994. Easing the roller coaster ride with slow release fertilizers. Cooperative Extension University of Arizona.1(10). Available at http://turf.arizona.edu/tips1094.html.

Lehmann et al. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferrasol of the central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249:343-357.

Lehto, T., T. Ruuhola, and B. Dell. 2010. Boron in forest trees and forest ecosystems. Forest Ecol. Manage. 260:2053-2069.

Liang, B, J. Lehmann, J. Kinyangi, J. Grossman, B. O'Neill, J.O. Skjemstad, J. Petersen, J. Theis, F.J. Luizao, and E.G. Neves. 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70:1719-1730.

Major J., M. Rondon, D. Molina, S.J. Riha, and J. Lehmann. 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil. 333(1):117-128.

Mariano, E., P. Trivelin, J. Leite, M. Magda, R. Otto, and H. Franco. 2013. Incubation methods for assessing mineralizable nitrogen in soils under sugarcane. R. Bras. Ci. Solo 37:450-461.

Mittal, A. K. 2011. Abandoned Mines: Information on the number of hardrock mines, cost of ceanup and value of financial assurances. Testimony before the subcommittee on energy and mineral resrouces, committee on natural resources, House of Representatives. United States Government Accountability Office.

Murano et al. 2009. Effects of the application of carbonaceous absorbents on pumpkin (Cucurbita maxima) uptake of heptachlor epoxide in soil. Soil Sci. Plant Nutr.. 55(2):325-332.

Mukherjee A, and R. Lal. 2013. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy. 3:313–339.

Nelson, S. 2015. Editor's notes. Mountain West News Newsletter. University of Montana. Available at http://mountainwestnews.org/Index.aspx.

Newton et al. 2000. California's Abandoned Mines: A report on the magnitude and scope of the issue in the state. Department of Conservation. Abandoned mines lands unit. Available at www.conservation.ca.gov/omr/abandoned_mine_lands/AML_Report/Documents/volume1textonly.pdf.

NOAA (National Oceanic and Atmospheric Administration). 2016. Office of Protected Resources: Steelhead trout. National Oceanic and Atmospheric Administration. Available at: www.fisheries.noaa.gov/pr/species/fish/steelhead-trout.html.

Ojeda, G., S. Mattana, J.M. Alcaniz, G. Marando, M. Bonmati, S.K. Woche, and J. Bachmann. 2010. Wetting process and soil water retention of a mine soil amended with composted and thermally dried sludges. Geoderma 156:399-409.

Ojeda, G., S. Mattana, A. Avila, J. M. Alcaniz, M, Volkmann, and J. Bachmann. 2015. Are soil-water functions affected by biochar application? Geoderma 1(11):249-250.

Or, D., M. Tuller, J. M. Wraith. 2009. Agricultural and Environmental Soil Physics. Published by authors.

OSMRE (Office of Surface Mining, Reclamation, and Enforcement). 2016. Laws, Regulations, and Guidance: Surface Mining Control and Reclamation Act. Available at: https://www.osmre.gov/lrg.shtm.

Page-Dumroese D. S., Coleman M., Thomas S. C. 2016. Opportunities and uses of biochar on forest sites in North America. In: Biochar: a regional supply chain approach in view of climate change mitigation. Chapter 15. Cambridge University Press.

Page-Dumroese, D., P.R. Robichaud, R.E. Brown, and J.M. Tirocke. Water repellency of two forest soils after biochar addition. Am. Soc. Agric. Bio. Engi. 85(2):335-342.

Page-Dumroese, D., A. Harvey, and M. Jurgensen. 1995. A guide to soil sampling and analysis on the national forests of the inland northwest United States. Soil quality monitoring and long term ecosystem sustainability. Rocky Mountain Research Station. USDA Forest Service. Available at: www.forest.moscowfsl.wsu.edu/smp/solo/documents/GTRs/INT_326/GTR326.php#anchor 168738.

Pierzynski, Gary M., Editor. 2000. Methods of phosphorus analysis for soils, sediments, residuals, and waters. Southern cooperative series bulletin no. #396. SERA-IEG.
Rawls, W.J., Y.A. Pachepsky, J.C. Ritchie, T.M. Sobecki, and H. Bloodworth. 2003. Effect of soil organic carbon on soil water retention. Geoderma 116:61-76.

Robertson, S. J., P. M. Rutherford, J. C. Lopez-Gutierrez, and H. B. Massicotte. 2011. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. Can. J. Soil Sci. 92:329-340.

Robichaud, P. R, S. A. Lewis, and L. E. Ashmun. 2008. New procedure for sampling infiltration to assess post-fire soil water repellency. Res. Note. RMRS-RN-33. Fort Collins, CO: U.S. Dep. of Ag., Forest Service, Rocky Mountain Research Station. p.14.

Rodriguez-Vila, A., E F. Covelo, R. Forjan, and V. Asensio. 2014. Phytoremediating a copper mine soil with Brassica juncea L., compost and biochar. Environ. Sci. Pollut. 21:11293-11304.

Salehi, M. H., O. Hashemi Beni, H. Beigi Harchegani, I. Esfandiarpour Borujeni, and H. R. Morghian. 2011. Refining soil organic matter determination by loss-on-ignition. Pedosphere 21(4):473-82.

Schoenholtz, S. H., J. A. Burger, and R. E. Kreh. 1992. Fertilizer and organic amendment effects on mine soil properties and revegetation success. Soil Sci. Soc. Amer. J. 56:1177-1184.

Scott, D.F., R.L. Grayson. 2003. Selected health issues in mining. Center for Disease Control. Available at: www.cdc.gov/niosh/mining/UserFiles/works/pdfs/shiim.pdf.

Sheoran, V., A.S. Sheoran, and P. Poonia. 2010. Soil reclamation of abandoned mine land by revegetation: A review. International journal of soil, sediment and water 3(2):article 13.

Shultz, H., G. Dunst, and B. Glaser. 2013. Positive effects of composted biochar on plant growth and soil fertility. Agron. Sustain. Dev. 33:817-827.

Sopper, W.E. 1992. Reclamation of mine land using municipal sludge. In: Rattan Lan and B.A. Stewart, editors, Soil restoration. Advances in soil science volume 17. Braun-Brumfield, Ann Arbor, MI. pp.351-431.

Stavi, I,. 2012. The potential use of biochar in reclaiming degraded rangelands. Journal of Environmental Planning and Management 55(5):657-665.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macedo, J.L.V., Blum, W.E.H., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and Soil 291:275.

Strawn, D. G., A. C. Rigby, L. L. Baker, M. D. Coleman, and I. Koch. 2015. Biochar soil amendment effects on arsenic availability to mountain brome. J. Environ. Qual., short communications.

Strawn, D. G., H. L. Bohn, and G. A. O'Connor. 2015. Soil Chemistry. John Wiley & Sons, West Sussex, UK.

Sparks, D.L. 1996. Methods of Soil Analysis. Part 3. Soil Science Society of America Book Series. 5:1001.

Tammeorg, P., A. Simojoki, P. Makela, F. L. Stoddard, L. Alakukku, and J. Helenius. 2014. Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil 374:89-107.

Thompson, S., D. S. Page-Dumroese, J. G. Archuleta, J. Wodrich. 2015. Bend, Oregon's unlikely path to class "A" biosolids. Draft of presentation paper. City of Bend, Oregon.

Uchimiya, M., I. M. Lima, K. T. Klasson, and L. H. Wartelle. 2010. Contaminant immobilization and nutrient release by biochar soil amendment: Roles of natural organic matter. Chemosphere 80:935-40.

Unger, R., R. Killorn, and C. Brewer. 2011. Effects of soil application of different biochar on selected soil chemical properties. Communications in Soil Science and Plant Analysis 42-19:2310-321

USDA. 2014. Soil quality indicators: Potentially mineralizable nitrogen (PMN). USDA natural resource conservation science. Available at www.nrcs.usda.gov/wps/PA_NRCSConsumption.

USDA. 2004. Training guide for reclamation bond estimation and administration. USFS Mineral and Geology Management Program. Available at: www.fs.fed.us/geology/bond_guide_042004.pdf.

USDA. 2013. Fertilizer use and price. Economic Research Service. Available at: www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26718.

USDA. USFS. 2012. Abandoned mine lands. Minerals and geology management. Available at: www.fs.fed.us/geology/aml.html.

USFSa. 2012. Hope Mine Project - Aspen Ranger District-White River National Forest. Watershed, Fish, Wildlife, Air and Rare Plants: Soil. Available at: www.fs.fed.us/biology/soil/photos.html

USFSb. 2012. Using Woody Biomass to Produce Bio-oil and BioChar. Watershed, Fish, Wildlife, Air and Rare Plants: Soil. Available at: www.fs.fed.us/biology/soil/index.html.

USFSc. 2015. Reclamation. Minerals and geology management. Available at: https://www.fs.fed.us/geology/reclamation.html.

USGS. 2015. Mineral resources on-line spatial data. Available at: http://mrdata.usgs.gov.

United States. 2015. Department of Agriculture. Draft environmental impact statement: Granite Creek watershed mining project. Wallowa-Whitman NF and Umatilla NF, Oregon.

Wos, B., and M. Pietrzykowski. 2015. Simulation of birch and pine litter influence on early stage of reclaimed soil formation process under controlled conditions. J. Environ. Qual. 44(4):1091-1098.

Yannopoulos, J.C. 1991. The extractive metallurgy of gold. Van Nostrand Reinhold, New York.

Chapter 2: Plant Survival on Dredge Mine Tailings After Applying Biochar, Biosolid, and Woodchip Soil Amendments

2.1 Abstract

The challenge of reclaiming the numerous abandoned mines in National Forests of the Pacific Northwest calls for new methods and cost-effective strategies. Soil function must be restored in order to establish vegetation and forest productivity. Biochar, biosolids and woodchips are organic waste byproducts that have been shown to increase soil productivity by increasing water holding capacity and nutrient concentrations. To test the effectiveness of these amendments in a forest environment, a field study was established in northeastern Oregon in 2014 with amendments applied singly and in combinations. Soil sampling was conducted at the start and end of each growing season for two years. Soil chemical properties (pH, organic matter (OM), cation exchange capacity (CEC), electrical conductivity (EC)), key nutrients (nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg)) and soil-water properties (plant available water, soil moisture and temperature) were measured. Results indicate the most effective treatments for increased plant counts were biosolids+woodchips and biosolids+biochar+woodchips combination treatments. Although soil properties were significantly altered by individual treatments, the combination treatments improved nutrient availability and soil moisture, resulting in up to six times more plants than in the control plots. Forest managers can produce biochar and woodchips from the abundant forest waste generated during harvest operations, and class “A” biosolids are available in Oregon from local municipalities. Using these

three amendments to reclaim disturbed mine soils can provide an affordable and effective reclamation strategy.

2.2. Introduction

Within the last decade, reclamation of abandoned mine land (AML) in the United States has gained government attention and public concern. In the 12 Western states, over 161,000 abandoned mines exist. Cost of this widespread cleanup is substantial (Mineral Policy Center 2015, USGS 2012). In 2011, the Office of Accountability estimated the cost of reclaiming abandoned mines on public land in the 12 Western states to be in the range of \$10-\$21 billion dollars. In the state of Idaho, there are many abandoned hardrock and dredge mine sites on National Forest land (USFS 2013). Much of the unproductive AML is in forested areas, reducing forest productivity and timber harvest potential. Finding inexpensive reclamation methods is the first step toward restoring soil function in order to establish vegetation at impacted sites in National Forests.

In the Pacific Northwest, abandoned mine sites are located in rural areas and often have rugged terrain and limited access. Eighty percent of abandoned mines on public land contain physical hazards, but no environmental hazard or contamination (AGI 2016). Physical hazards include waste rock piles and disturbed landscapes that often lack vegetation. Combined costs of equipment, transportation, and re-application of needed nutrients rules out many common reclamation strategies. Surface applied amendments with minimal disturbance are an inexpensive solution to increase soil function and accelerate re-vegetation. Three possible amendments that have shown some success in soil restoration are biochar, municipal biosolids, and woodchips.

Biochar, as a soil amendment, has seen intense research interests recently (Atkinson et al., 2010; Beesley et al., 2010, 2011; Jeffery et al., 2011). Proposed uses of biochar applied to the soil have been to increase agricultural yield (Major et al., 2010; Sinclair et al., 2008), reduce risks at polluted sites (Fellet et al., 2011; Murano et al., 2009), sequester C in soils (Galinato et al., 2011; Steinbeiss et al., 2009), and restore organic matter to degraded soils (Anawar et al., 2015; Stavi, 2012).

Biochar has been shown to influence soil chemical and physical properties, resulting in increased available nutrients and plant survival (Lehmann et al., 2003; Tammeorg et al., 2014), water-holding capacity, and decreasing soil contaminants, usually heavy metals (Ojeda et al., 2015; Rodriguez-Vila et al., 2014; Uchimiya et al., 2010). Biochar has been shown to increase CEC and retention of cationic nutrients (namely K^+, Mg^{2+}, Ca^{2+}, NH_4^+) (Lehman, 2007; Liang, 2006), increase total organic C (Tammeorg et al., 2014; Unger et al. 2011), and raise soil pH (Chan et al., 2009). Biochar properties are greatly affected by feedstock and pyrolysis temperatures (Gundale and DeLuca 2006, Uchimiya et al. 2010) and therefore their effects on soil parameters vary.

At the Hope Mine reclamation project in the White River National Forest in Colorado, biochar was applied at varying rates in combination with compost, erosion control webbing, and hydromulching to re-vegetate contaminated mine soil (arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn)) and prevent erosion on a steep hillside (ACES, 2011). Due to the slope, amendments were not incorporated into the mine rock.

Within the first year, the combined amendments increased soil moisture and native grass growth. The success of the revegetation was not only due to the biochar because the compost, applied in quantities of up to 95% of total amendments, provided nutrients and organic matter (USFSa 2012). The optimal biochar application rate was determined to be 5.44 Mg/ha at a 12.5% v/v biochar-compost cover (Peltz and Harley 2016).

Recent studies have also found adverse effects of biochar on soil health and plant growth, such as hindering N mineralization and increasing N immobilization (Kookana et al. 2011), absorbing P (Yao et al. 2011), and clogged pore spaces over time, which decreases its surface area and therefore sorption properties (Hammes and Schmidt 2012).

The majority of studies conducted with biochar on mine sites have been for the purpose of remediation by reducing toxic metal uptake and immobilization of contaminants (Fellet et al. 2011, Bakshi et al. 2014, Strawn et al. 2015). Although biochar has been used as a soil amendment on degraded agricultural soils (Lehmann et al. 2012, Atkinson et al. 2010), and recently on rangeland soils (Stavi 2012), it has not been widely used to alter soil function on degraded mine soils that are not contaminated.

Biosolids are commonly used for reclamation of disturbed mine land, especially after the establishment of the Surface Mine Reclamation Act of 1977 (Haering et al. 2000; Sopper 1993; https://www.osmre.gov/lrg.shtm). Mine soil deficiencies that are improved by biosolids are low organic matter, CEC, pH and nutrients (Fosberg and Ledin, 2006; Ojeda et al., 2010). Biosolids contain between 1-6% N, depending on the source and processing (Center for Urban Horticulture, 2002). Recent mine land reclamation research with biosolids and sewage sludge show they can be used as a manufactured topsoil (Brown et al., 2003) or incorporated into unproductive soils to increase vegetation growth.

Woodchips are another frequently used surface-applied amendment on mine sites. Woodchips add few soil nutrients, but they promote biological activity that degrades the woodchips, thereby increasing the soil organic matter content (Walsh and Redente 2010). Woodchips also reduce surface evapotranspiration. In a reclamation project on mine land in North Idaho, Walsh and Redente (2010) found woodchips increase organic matter, ammonium-N and nitrate-N after 4 years. Organic C content of soil affects water-holding capacity by changing the soil structure and increasing microbial activity (Edwards et al., 1999). Organic C can change water retention because it forms polysaccharides that bind soil particles together, causing aggregation and allowing infiltration. Microbial community populations in the soil effect mineralization rates of nutrients needed for plant growth. Woodchips have been shown to increase soil moisture on mine-impacted sites within forested areas (Schoenholtz et al., 1992), especially after two growing seasons. A reason for the increased moisture retention is that woodchips on the soil surface protect from direct sunlight, keeping the soil cool and reducing evaporation.

The United States Forest Service (USFS), in cooperation with the City of Bend, Oregon, initiated a mine tailings reclamation project in the Umatilla National Forest in northeastern Oregon to determine the benefits of surface applied organic amendments. The purpose of the cooperation is the use of AML as a beneficial disposal option for biosolids. The USFS also worked with Biochar Solutions Inc. (Anderson et al., 2016) to produce biochar near forest sites where biomass waste has either become a fire hazard, or is left over from logging activity (Page-Dumroese et al., 2016; USFSb 2012). Portable, fast-pyrolysis units convert slash piles into bio-oil and biochar on site, retaining the carbon and nutrients of the woody biomass and eliminating the effort of transporting low-use, low-density biomass offsite. Biochar can be applied to recently harvested or other degraded sites. To support this method of biomass conversion, biochar's effectiveness as an amendment to improve soil conditions must be researched on a variety of soils and conditions. This includes application rates, persistence in the environment, and effects on soil properties.

Although studies have found biochar to be extremely effective at improving biological, chemical and physical soil properties, as well as plant growth, most of these studies are in greenhouses and controlled environments (Bakshi et al., 2014; Fellet et al., 2011; Page-Dumroese et al., 2016; Schulz et al., 2013; Ojeda et al., 2015). To understand how surface application of amendments affect soil health and plant growth in forests, field studies must be conducted. Most field study methods involve mixing biochar and other amendments into the mineral soil (Jeffery et al., 2015; Tammeorg et al., 2014). However, few studies have surface applied the amendments, as was done in this study. In a large-scale field setting, specifically on mine tailings, mixing in amendments is not always possible. USFS abandoned mine lands generally are remote, making access for large equipment to till the soil caps difficult and costly. Other concerns with integration of amendments in soils are that tilling tailings piles exposes hazardous elements to air and water and destroys whatever plant and soil structure does exist, leading to increased erosion and loss of nutrients. Thus, to develop effective and economical reclamation strategies for forest soils, research into surface applied amendments on mine soils in field settings (breakdown rates, application rates, and overall effectiveness) is necessary.

The objectives of this research were to: 1) Determine if surface applied soil amendments affect soil water holding capacity, plant available nutrients, pH, CEC, and OC and 2) determine if surface applied soil amendments affect plant success.

2.3. Materials and Methods

2.3.1. Experimental Site and Soil Characteristics

The study site is in the Granite mining district of Grant County, Oregon and is part of the larger "Oregon Gold District," which produced gold throughout the 18th and 19th centuries. Clear Creek is a dredged creek located approximately three miles west/southwest of Granite, Oregon (44.780541,-118.459623; Figure 2.1.). The site is a flattened tailings pile left over from dredging activities dating as far back as 1862, lining the north side of Clear Creek (EOMA 1999). The tailings pile was capped in the 1970's with roughly six inches of a loam topsoil from an unknown source. Between 2001 and 2007, plantings were installed by USFS including planting of shrubs, hardwood, conifers and seeding with native grasses and forbs (Granite Creek Watershed EIS 2015). These re-vegetation attempts had limited success, resulting in <10% ground cover of grasses and forbs and only 2-3 surviving ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson).

Figure 2.1. Map of Clear Creek Reclamation project in NE Oregon.

The site is in located in Climate Division 8 (NOAA) with an annual precipitation of 62.8 cm per year. According to the Palmer Draught Severity Index (PDSI) the site is in a region of moderate draught (NIDIS) and in a region of severe to extreme drought during 6 months of the year (July-Oct) (https://www.drought.gov/drought/dews/pacific-northwest). The soil cap on top of the tailings pile is extremely rocky with the fine fraction (< 2mm) classified as a loam. Rock fragment content of the soil ranges from 28% to 52%, increasing from the surface down to 20 cm (Table 2.1.). Soil physicochemical properties are listed in Table 2.1.

Table 2.1. Analysis of the fine-fraction and rock content of the topsoil cap (n=6).

Property	Soil (%)
Rock fragment	28-52
Sand	47 ± 5
Silt	35 ± 3
Clay	18 ± 2
Textural class (USDA)	Loam
Total soil bulk density	1.82 g m^2
pH	5.47 ± 0.38
Organic carbon	3.76 ± 0.44
Organic nitrogen	<0.008

2.3.2. Experimental Design

In October 2014, experimental plots were constructed in a randomized design. The plots were 10 x 10 feet with 3 replicates of each single amendment and combination, plus controls, totaling 24 plots. Biochar, biosolids, and woodchips, were surface applied. Application rates were as follows: biochar- 11.2 Mg/ha, biosolids- 16.8 Mg/ha and woodchips- 22.7 Mg/ha. The application rates were chosen to standardize the amount of C being applied depending on each amendment’s percent C. Maximum tree growth response to applied carbon in an Inceptisol and Andisol was previously seen at the application rate of 25 Mg-C/ha (Page-Dumroese et al., 2015). Amendments were applied as close to this rate of C as possible. Table 2.2 gives the nutrient and metal content of the Class A biosolids applied.

Table 2.2 Average values of elements and pH of the biosolids applied to Clear Creek (Bend wastewater treatment plant, Bend, OR) EPA ceiling concentration limits of trace elements for land-applied biosolids (Biosolid Management Handbook, Brost, 1995).

	Applied Biosolids	Ceiling Concentrations
	(mg/kg)	(mg/kg)
Kjeldahl Nitrogen	55,500	
Ammonia as N	1,940	
Nitrate as N	137	
Organic N	53,500	
Phosphorus	30,250	
Potassium	2,900	
pH	7.1	
Arsenic	3.8	75
Cadmium	1.1	85
Chromium	18	3,000
Copper	338	4,300
Lead	30	840
Mercury	<MDL=1	0
Molybdenum	8.1	75
Nickel	19	420
Selenium	3.4	100
Silver	4.1	
Zinc	478	7,500

At the time of application, half of each plot received a seed mixture comprised of 7 grasses and 1 forb native to the area (Table 1.2). This mixture is commonly used by the USFS on reclamation sites. The other half of each plot was planted in April 2015 with greenhouse grown seedlings of *Bromus carinatus* Hook. & Arn. and *Elymus glaucus* Buckl., which are known for their tolerance in degraded soils (USDA-NRCS 2012, 2013). Twenty-five seedlings of each species were planted on half of every plot.

2.3.3. Sampling

Soil samples were collected from the experimental plots in September 2015, eleven months after amendment application, and May 2016, 19 months after amendment application. These sampling times were chosen to capture soil conditions after a growing season (fall), and after a winter of weathering (spring). Due to the small size of the plots and deconstructive nature of soil sampling, plots were divided into a 4-block grid, and samples were excavated in a different block at each sampling event. Soils were collected from the 0 to 3 cm and 3 to 12 cm depths. The soil surface was brushed free of amendments in order to sample only the top 3 cm of mineral soil. With such high rock content, use of core samplers was not possible and all samples were unconsolidated. Samples were sealed in plastic bags, placed in a cooler to minimize biological nutrient cycling, and transported to the lab where they were kept refrigerated.

2.3.4. *In Situ* Measurements

Bulk density was measured using excavation and polyurethane foam method on site (Page-Dumroese et al. 1999). Excavated soil was weighed for a total soil mass and also sieved through a 2-mm sieve to separate the fine fraction. The hardened foam volume was determined by water displacement and both a total bulk density and a fine fraction bulk density were calculated.

Unibest resin capsules (Unibest International LLC, Walla Walla, WA) were installed in each plot in October 2014 following application of amendments. Resin capsules absorb bioavailable cations and anions from soil solution, and concentrations reflect available nutrients that could be used by plants. The resin membrane ions were H^+ and OH^- that exchange readily with soil solution ions due to the resin's higher affinity for soil ions (Johnson et al., 2005, Warrington and Skogley (UNIBEST) 1996). Ion resin capsules have been shown to be an effective method of capturing bioavailable nutrient concentrations over time (Schoenau and Huang 1991, Qian et al 1992, Drohan et al 2005), and have been used to measure charcoal amended or burned soils (Gundale and DeLuca 2005, Blank et al 2007). Elements are reported as mass of analyte per volume of extraction solution (mg/L) for the time period that the resin capsules were left in the soil. The resin capsules were replaced with new capsules in May 2015, September 2015, and June 2016, at which time data from the data loggers was downloaded as well. The resin capsules were sent to Unibest Int. to obtain NO_3, NH_4, Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, and Zn concentrations that had absorbed to the capsule since the time of installation.

Temperature and moisture sensor data loggers (Onset Computer Corp., Bourne, MA) were installed on October 14, 2014 into one plot of each amendment type to record soil moisture and temperature. Measurements were recorded every 2 hours.

2.3.5. Laboratory Chemical Methods

The collected soil samples were kept cold until reaching the lab, at which time an ammonium and nitrate extraction (Keeney and Nelson 1982) was performed (within 24 hrs). The purpose of an immediate extraction is to see how much of the N pool is available to plants as NH_4^+ and NO_3^- at a single point in time. A 1:2 soil to 2M KCl slurry was shaken for 1 hour and filtered through No. 2 Whatman filter paper (St. Louis, MO). Extracts were frozen until analysis by flow injection (FIA2500, FIAlab Instruments, Bellevue, WA).

To measure potentially mineralizable N, anaerobic digestion of soil samples (Powers 1980) was conducted with field-wet soil using 8 grams of soil and 16mL of DI water placed into 50mL tubes. Tubes were hand agitated and placed in a dark incubation chamber at 40 to 42 °C for 1 week. Upon removal from the incubation chamber, 16 mL of 2 M KCl was added to the centrifuge tubes to extract the mineralized ammonium and nitrate. Samples were shaken for 1 hour and filtered through No. 2 Whatman filter paper and analyzed by FIA2500 flow injection analyzer (FIAlab Instruments, Bellevue, WA). Soil moisture content of the field-wet samples was measured on a mass basis by oven drying the subsamples at 105 °C for 24 hrs. The remaining samples were spread out evenly in tins or on butcher paper to air-dry.

Soil pH and electrical conductivity were measured on each air-dry sample in a 1:1 DI water slurry using a pH probe (250 Denver Instruments, Bohemia, NY) and EC meter (Oakton Instruments, Vernon Hills, IL). Total carbon and nitrogen were measured by dry combustion at 950 °C on a CN analyzer (Leco TruSpec, St. Joseph, MI, USA). Sample sizes ranged from 0.2002 g to 0.2098 g.

Cation exchange capacity was measured for the non-combination plots using an ammonium acetate method (Miller and Sumner 1996). Samples were allowed to sit overnight in ammonium acetate, then washed with ethanol using a Buchner funnel and

No. 42 Whatman filter paper. Ammonium was extracted from the exchange sites using 10% acidified (HCl) sodium chloride. Extracts were analyzed for ammonium with an NH_3 gas-sensing ion selective probe (Orion Research, Inc., Boston, MA) (Banwart et al. 1972, Mulvaney 1996). Accuracy and quality control of the ammonia probe were checked using standards and reference soil.

2.3.6. Soil Water Retention

Initial soil moisture content was measured by oven-dry method using subsamples of 10-15 g (see O'Kelly, 2004). Field capacity and permanent wilting point were measured as water retention by pressure plate extraction (Klute 1986). Duplicate unconsolidated soil samples that had been sieved to the 2-mm fine fraction, ranging in mass from 20 g to 40 g, were saturated and equilibrated overnight before being placed on a fully saturated 1 bar ceramic plate. The accepted field capacity pressure of -0.03 MPa was applied to the pressure chambers (Soil Moisture Equipment, Santa Barbara, CA) for 48 hrs. After equilibration, the chambers were opened and samples were oven dried to obtain the gravimetric water content. Similar sample preparation was followed as above, applying -1.5 MPa pressure for 96 hrs on a 15-bar ceramic plate to obtain the water content at permanent wilting point. The duration of pressure exertion was determined by trial runs, checking the reference soil for consistency with the soil's known water content ranges at specified pressures.

2.3.7. Plant Density

Plants were systematically tagged using digital images of a 3ft x 4ft representative section of the plots. One photo per side (seeded and planted) of every plot was analyzed to measure plant counts. Species were divided into two groups, 1) the planted grass species and 2) volunteer forbs and grasses.

2.3.8 Statistical Analysis

Results from all experiments were analyzed using SAS (SAS Institute, Cary, NC) to determine statistical significance. The data was first analyzed by univariate tests to choose appropriate transformations if necessary to normalize the distributions. A pooled generalized linear mixed model using log, beta, and Poisson transformations, in accordance with data distributions, was used for analysis of variance tests between treatments and between years (Stroup 2015). P-values less than 0.05 were considered significant.

2.4. Results

2.4.1. Soil Properties

Significant differences in pH, EC, CEC, OC, and OM were seen between treatments, primarily in the surface soil layer (0-3 cm). Time and treatment were both significant factors in the top 3 cm. In the subsurface soils, time and treatment had much less effect on total pH, EC, CEC and organic matter (Table 2.3). Influences of biosolids, biochar and woodchips on soil physical and chemical properties for the top 12 cm are presented in Tables 2.4 and 2.5. Soil pH in the 0-3 cm soils was within one pH unit between the two sampling events (Table 2.1 and Tables 2.4). Treatments containing biosolids had the largest initial increase in pH compared to the control in fall 2015, but in spring 2016, pH had decreased to below the pH values of fall 2015 (Table 2.4). Soil pH in the woodchip and biochar treatments were not significantly different from the control in fall 2015, but by spring 2016, both treatments had higher pH values than the control.

Table 2.3. Summary statistics showing p-values of year (2015 and 2016) and treatment effects for each measured soil parameter. P-values below 0.05 are significant.

0-3cm	**df**	**pH**	**EC**	**CEC**	**OC**	**OM**
Source		***p-values***				
Year	1	***0.001***	***<.0001***	***0.0008***	***0.0007***	***0.0007***
Treatment	7	***0.0002***	***<.0001***	***0.0001***	***<.0001***	***<.0001***
Year*Treatment	7	***<.0001***	***<.0001***	0.0487	0.1285	0.1263

3-12cm	**df**	**pH**	**EC**	**CEC**	**OC**	**OM**
Source		***p-values***				
Year	1	0.1212	***<.0001***	***<.0001***	0.1332	0.1334
Treatment	7	0.0827	***<.0001***	0.2942	0.8	0.7993
Year*Treatment	7	***0.0029***	***0.0097***	0.0732	0.8821	0.8826

Table 2.4. Mean values of soil parameters (±) standard deviation of 3 replicate plots from treatments sampled in 2015 and 2016 for the surface soil (0-3 cm).

Treatment	**Year**	**pH**	**EC** (dS/cm)	**OC** (%)	**CEC** (cmolc/kg)
Control	2015	5.44 ± 0.07 *fg*	956.0 ± 643.3 *a*	3.71 ± 0.23 *gh*	17.7 ± 0.5 *e*
	2016	5.61 ± 0.18 *defg*	40.5 ± 2.4 *fg*	3.61 ± 0.17 *h*	22.2 ± 1.7 *cd*
Biosolids	2015	6.48 ± 0.04 *a*	584.7 ± 27.1 *a*	8.15 ± 1.67 *a*	28.1 ± 0.8 *a*
	2016	5.93 ± 0.05 *bcd*	254.5 ± 64.8 *bc*	5.57 ± 0.56 *bcde*	27.1 ± 2.2 *ab*
Biochar	2015	5.73 ± 0.09 *cdef*	66.3 ± 14.7 *ef*	4.40 ± 0.16 *defgh*	18.7 ± 1.4 *de*
	2016	5.99 ± 0.06 *bcd*	40.8 ± 5.7 *fg*	4.26 ± 0.33 *fgh*	24.8 ± 1.2 *abc*
Woodchips	2015	5.44 ± 0.07 *fg*	835.0 ± 261.7 *a*	4.42 ± 0.55 *defgh*	17.2 ± 0.7 *e*
	2016	5.90 ± 0.05 *bcde*	38.5 ± 6.9 *fg*	4.32 ± 0.22 *efgh*	23.8 ± 1.6 *bc*
Biosolids + Woodchips	2015	5.92 ± 0.15 *bcde*	458.7 ± 54.9 *ab*	5.86 ± 0.66 *bc*	
	2016	5.55 ± 0.12 *efg*	133.8 ± 14.3 *cd*	5.63 ± 0.21 *bcd*	
Biosolids + Biochar	2015	6.19 ± 0.22 *efg*	449.7 ± 116.0 *ab*	8.08 ± 3.08 *a*	
	2016	5.55 ± 0.14 *efg*	188.1 ± 23.7 *cd*	5.50 ± 0.20 *bcde*	
Biochar +Woodchips	2015	5.95 ± 0.05 *bcd*	36.8 ± 3.1 *fg*	5.45 ± 0.48 *cde*	
	2016	5.44 ± 0.05 *fg*	32.5 ± 3.9 *g*	4.72 ± 0.23 *cdefg*	
Biosolids +	2015	6.03 ± 0.15 *bc*	561.0 ± 56.5 *a*	6.86 ± 0.39 *ab*	
Biochar + Woodchips	2016	5.31 ± 0.17 *g*	127.7 ± 43.3 *de*	5.38 ± 0.61 *cdef*	

Table 2.5. Mean values of soil parameters (±) standard deviation of 3 replicate plots from treatments sampled in 2015 and 2016 for the subsurface soil (3-12 cm).

Treatment	**Year**	**pH**	**EC** (dS/cm)	**OC** (%)	**CEC** (cmolc/kg)
Control	2015	5.61 ± 0.06 *abc*	324.2 ± 90.9 *ab*	3.69 ± 0.34 *ab*	19.2 ± 2.5 *c*
	2016	5.71 ± 0.20 *abc*	32.3 ± 4.33 *ghij*	3.79 ± 0.17 *ab*	20.87 ± 0.94 *bc*
Biosolids	2015	5.3 ± 0.04 *bcd*	301.3 ± 15.4 *ab*	3.82 ± 0.08 *ab*	18.1 ± 1.0 *c*
	2016	5.32 ± 0.10 *bcd*	120.8 ± 23.01 *cdef*	3.74 ± 0.16 *ab*	24.38 ± 1.31 *ab*
Biochar	2015	5.23 ± 0.22 *cd*	62.2 ± 17.3 *efghi*	3.78 ± 0.47 *ab*	19.1 ± 1.1 *c*
	2016	5.82 ± 0.18 *a*	27.0 ± 1.56 *hij*	3.79 ± 0.16 *ab*	25.95 ± 2.81 *a*
Woodchips	2015	5.61 ± 0.06 *abc*	350.3 ± 83.2 *a*	4.04 ± 0.23 *ab*	17.4 ± 0.4 *c*
	2016	5.84 ± 0.07 *ab*	25.2 ± 2.48 *ij*	3.71 ± 0.18 *ab*	27.90 ± 1.02 *a*
Biosolids + Woodchips	2015	5.98 ± 0.12 *a*	183.5 ± 88.3 *bcde*	3.88 ± 0.40 *ab*	
	2016	5.11 ± 0.06 *cd*	75.0 ± 15.76 *defg*	3.61 ± 0.57 *b*	
Biosolids + Biochar	2015	5.33 ± 0.38 *bcd*	246.3 ± 79.1 *abc*	4.14 ± 0.21 *a*	
	2016	5.00 ± 0.06 *d*	143.2 ± 11.11 *abcd*	3.92 ± 0.02 *ab*	
Biochar +Woodchips	2015	5.58 ± 0.26 *abc*	106.5 ± 74.9 *fghi*	3.92 ± 0.27 *ab*	
	2016	5.24 ± 0.07 *cd*	23.8 ± 0.81 *j*	3.69 ± 0.18 *ab*	
Biosolids +	2015	5.98 ± 0.38 *a*	228.0 ± 16.8 *abc*	3.72 ± 0.52 *ab*	
Biochar + Woodchips	2016	5.13 ± 0.07 *cd*	69.3 ± 15.91 *defgh*	3.71 ± 0.15 *ab*	

The highest electrical conductivity (EC) values for samples in fall 2015 were in the control and woodchip treatments (Tables 2.4 and 2.5). The EC of the biochar and biochar+woodchip treatments were significantly less than the control. In spring 2016, treatments containing just biosolids had significantly higher EC's than any other treatment. All treatments in spring 2016, except biochar, had much lower EC values than in fall 2015. Biochar maintained a low EC for the entire study.

Cation exchange capacity was significantly greater for the biosolid treatment than any other treatment in fall 2015 (Figure 2.2). In the subsurface, CEC increased significantly in all treatments from fall 2015 to spring 2016, except for the control.

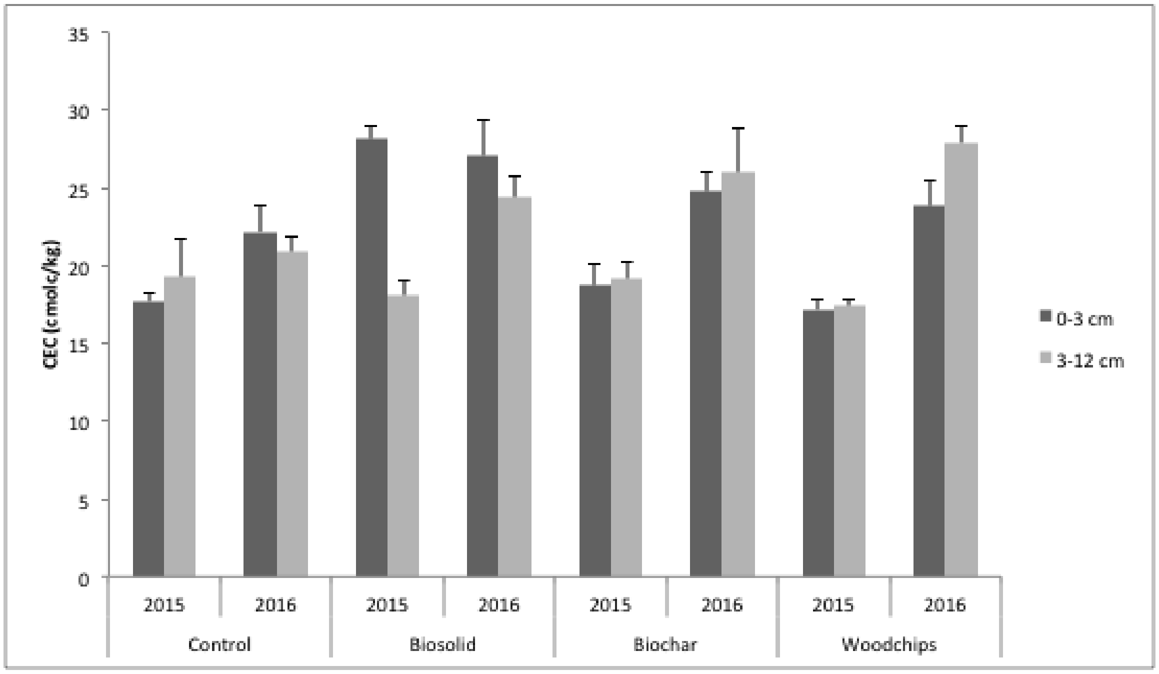

Figure 2.2. Mean cation exchange capacity of surface (0-3cm) and subsurface (3-12cm) soils from Fall 2015 and Spring 2016. Error bars indicate one standard error.

Organic carbon in the surface (0-3 cm) soil was significantly greater in biosolid and all combination treatments in fall 2015 compared with the control (Figure 2.3).

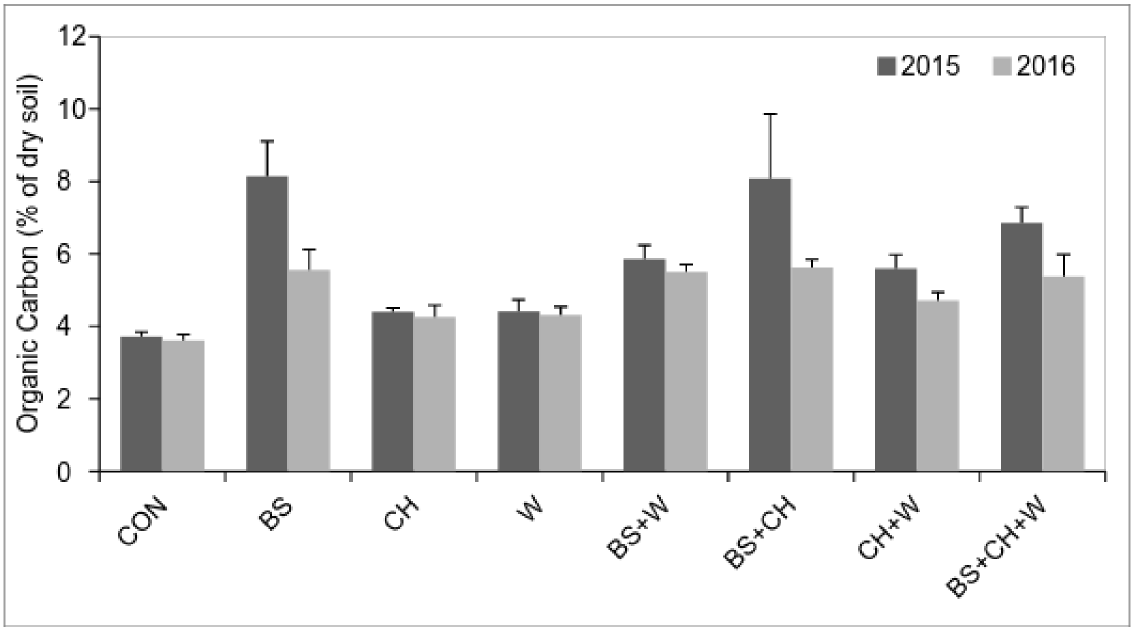

Figure 2.3. Mean organic carbon percentages for the surface layer (0-3 cm) of soil from Fall 2015 and Spring 2016 samplings. Error bars indicate one standard error. C=control, BS=biosolid, BC=biochar, W=woodchip, BS+BC=biosolid + biochar, BS+W=biosolid+woodchip, BC+W=biochar+woodchip, and BS+BC+W=biosolid +biochar + woodchip.

Biosolids alone and the biochar+biosolids combination had 4.4% more organic carbon than the control. Biochar and woodchips applied alone did not have a significant effect on OC compared to the control or each other. Organic carbon percentages in the surface soils decreased from fall 2015 to spring 2016 in all treatments (Figure 2.3), with significant differences in the biosolids alone and biosolid combination treatments. The subsurface soils of all plots had no significant change in OC across treatments or in any specific treatment from fall 2015 to spring 2016.

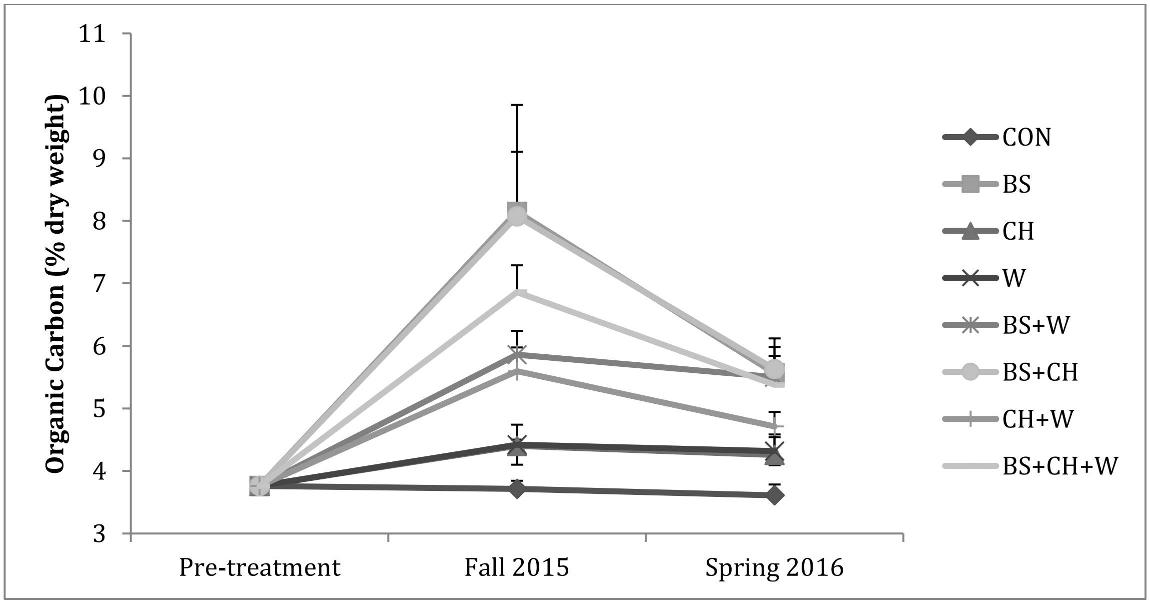

Figure 2.4. Surface (0 – 3 cm) organic carbon percentages of treatments from pre-treatment, Fall 2015 and Spring 2016 samplings. Error bars indicate one standard error.

2.4.2. Nutrient Availability

2.4.2.1. Laboratory Nitrogen Results

The highest N concentrations at both sampling events occurred in the treatments containing biosolids. NH_4^+ and NO_3^- concentrations were combined to determine the total, plant available, inorganic nitrogen content for each treatment type at both sampling events (Table 2.6 and Table 2.7). In the biosolid plots, nitrogen levels decreased after the first year to much lower concentrations the following spring (Figure 2.5). The subsurface layer (3-12 cm) had less inorganic-N than the surface (0-3 cm); the biosolids treatment was greatest among all the subsurface soils. There was less inorganic-N in all combination treatments containing woodchips than treatments with only a single amendment. For example, biosolid+woodchips had less inorganic-N than biosolids alone. At both sampling events and depths, woodchip and biochar+woodchip plots had lower inorganic-N concentrations than the control plots.

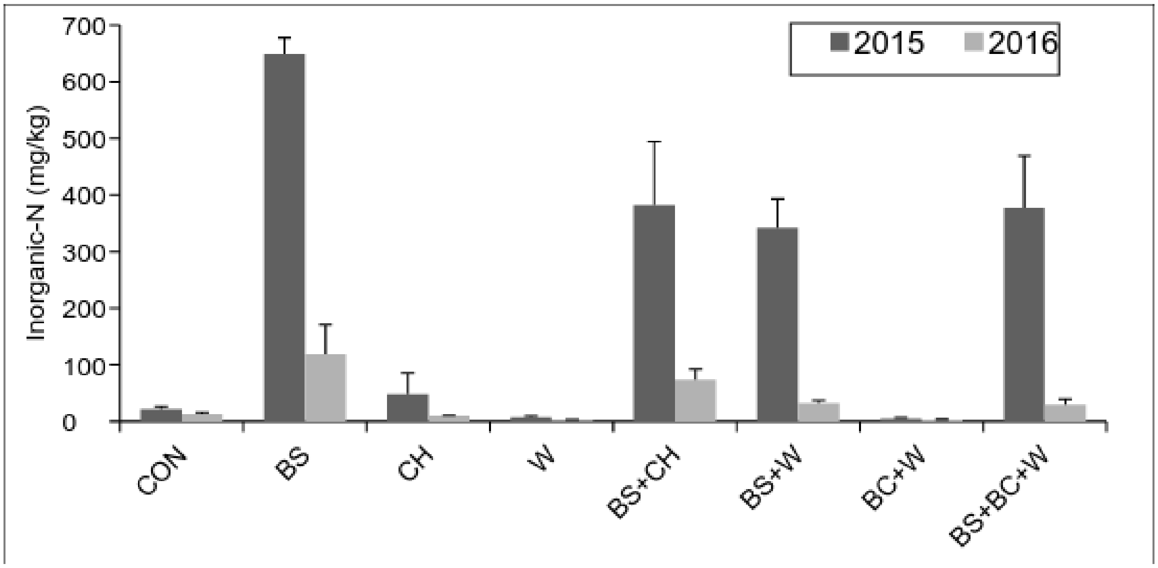

Figure 2.5. Extractable inorganic nitrogen concentration in the surface (0-3 cm) soil from the two sampling events, 2015 and 2016. Error bars indicate one standard error.

Table 2.6. Mean values of nitrogen of the 0-3 cm layer for fall 2015 and spring 2016(±) standard deviation.

Treatment	Year	Total N (%)	NH4-N (mg/kg)	NO3-N (mg/kg)	Mineralizable-N (mg/kg)
Control	2015	0.02 ± 0.02 *de*	1.22 ± 0.37 *bcd*	1.33 ± 0.46 *ef*	51.70 ± 2.37 *fgh*
	2016	0.03 ± 0.02 *e*	7.92 ± 1.79 *de*	5.62 ± 0.74 *efg*	40.50 ± 2.15 *gh*
Biosolids	2015	0.70 ± 0.23 *a*	540.3 ± 31.01 *a*	108.9 ± 3.71 *ab*	527.2 ± 134.26 *a*
	2016	0.31 ± 0.07 *abc*	56.24 ± 25.40 *b*	62.00 ± 27.96 *bc*	156.47 ± 49.50 *cde*
Biochar	2015	0.04 ± 0.06 *cde*	38.7 ± 34.36 *cde*	9.3 ± 3.45 *e*	71.8 ± 24.74 *fgh*
	2016	0.02 ± 0.02 *e*	3.86 ± 0.47 *defg*	6.24 ± 1.08 *ef*	37.15 ± 3.54 *h*
Woodchips	2015	0.06 ± 0.02 *abcde*	3.9 ± 0.91 *efg*	3.5 ± 1.38 *fgh*	83.2 ± 17.93 *fgh*
	2016	0.01 ± 0.01 *e*	1.22 ± 0.37 *gh*	1.33 ± 0.46 *i*	51.70 ± 2.37 *gh*
Biosolids + Woodchips	2015	0.33 ± 0.08 *abc*	244.9 ± 68.92 *a*	97.8 ± 18.82 *ab*	178.0 ± 34.77 *bc*
	2016	0.27 ± 0.03 *abc*	34.39 ± 10.71 *cde*	20.35 ± 5.41 *d*	139.25 ± 12.02 *de*
Biosolids + Biochar	2015	0.50 ± 0.39 *ab*	277.7 ± 102.82 *a*	104.6 ± 16.20 *ab*	No value
	2016	0.27 ± 0.05 *abc*	11.43 ± 3.02 *bc*	39.23 ± 8.24 *cd*	118.84 ± 45.56 *def*
Biochar +Woodchips	2015	0.05 ± 0.03 *bcde*	2.1 ± 0.74 *fgh*	3.0 ± 1.16 *gh*	56.7 ± 8.22 *gh*
	2016	0.03 ± 0.01 *de*	1.04 ± 0.28 *h*	2.12 ± 0.13 *hi*	59.29 ± 8.36 *gh*
Biosolids + Biochar + Woodchips	2015	0.36 ± 0.01 *ab*	230.4 ± 76.21 *a*	146.6 ± 23.13 *a*	276.9 ± 17.05 *ab*
	2016	0.19 ± 0.07 *abcd*	6.37 ± 2.05 *def*	23.03 ± 8.14 *d*	97.70 ± 28.73 *efg*

Table 2.7. Mean values of measured nitrogen of the 3-12 cm layer, for at two fall 2015 and spring 2016 (±) standard deviation.

Treatment	**Year**	**Total N** (%)	**NH4-N** (mg/kg)	**NO3-N** (mg/kg)	**Mineralizable-N** (mg/kg)
Control	2015	0.02 ± 0.01 *ab*	0.9 ± 0.34 *d*	4.8 ± 1.14 *ef*	26.1 ± 0.37 *cd*
	2016	0.04 ± 0.03 *ab*	0.67 ± 0.10 *d*	2.91 ± 0.33 *fg*	24.89 ± 6.16 *cd*
Biosolids	2015	0.06 ± 0.02 *a*	100.2 ± 29.50 *a*	46.6 ± 2.26 *a*	10.3 ± 0.72 *ab*
	2016	0.04 ± 0.02 *ab*	33.29 ± 16.17 *ab*	17.11 ± 4.97 *bc*	17.43 ± 1.58 *bc*
Biochar	2015	0.02 ± 0.02 *ab*	2.6 ± 1.97 *cd*	8.3 ± 4.48 *def*	22.7 ± 6.82 *de*
	2016	0.03 ± 0.02 *ab*	0.98 ± 0.12 *cd*	3.38 ± 0.66 *fg*	19.25 ± 0.35 *cd*
Woodchips	2015	0.04 ± 0.02 *ab*	0.9 ± 0.03 *cd*	1.7 ± 0.40 *gh*	26.4 ± 0.37 *cd*
	2016	0.02 ± 0.02 *b*	0.61 ± 0.03 *d*	0.81 ± 0.17 *h*	19.32 ± 0.34 *cd*
Biosolids + Woodchips	2015	0.06 ± 0.03 *ab*	88.0 ± 59.25 *a*	36.2 ± 10.46 *ab*	45.2 ± 11.72 *ab*
	2016	0.08 ± 0.08 *ab*	28.21 ± 8.13 *bc*	12.11 ± 3.66 *cd*	19.46 ± 4.22 *cd*
Biosolids + Biochar	2015	0.06 ± 0.02 *a*	57.2 ± 29.90 *ab*	31.9 ± 10.57 *ab*	319.5 ± 274.03 *a*
	2016	0.02 ± 0.01 *ab*	5.92 ± 2.09 *a*	15.26 ± 6.23 *bc*	8.64 ± 1.88 *bcd*
Biochar +Woodchips	2015	0.04 ± 0.01 *ab*	0.7 ± 0.12 *d*	1.5 ± 0.00 *gh*	26.9 ± 0.41 *cd*
	2016	0.03 ± 0.02 *ab*	0.70 ± 0.03 *d*	1.02 ± 0.22 *h*	21.39 ± 1.94 *cd*
Biosolids + Biochar + Woodchips	2015	0.03 ± 0.02 *ab*	22.8 ± 7.05 *ab*	40.1 ± 2.95 *a*	62.5 ± 9.03 *ab*
	2016	0.02 ± 0.01 *ab*	1.59 ± 0.16 *cd*	9.32 ± 1.70 *cde*	5.05 ± 2.50 *e*

The most significant difference in total nitrogen in fall 2015 was between control and biosolid treatments. After 19 months, (sampling event 2), biosolid treatments still had more total-N than the control or other amendments (Figure 2.6).

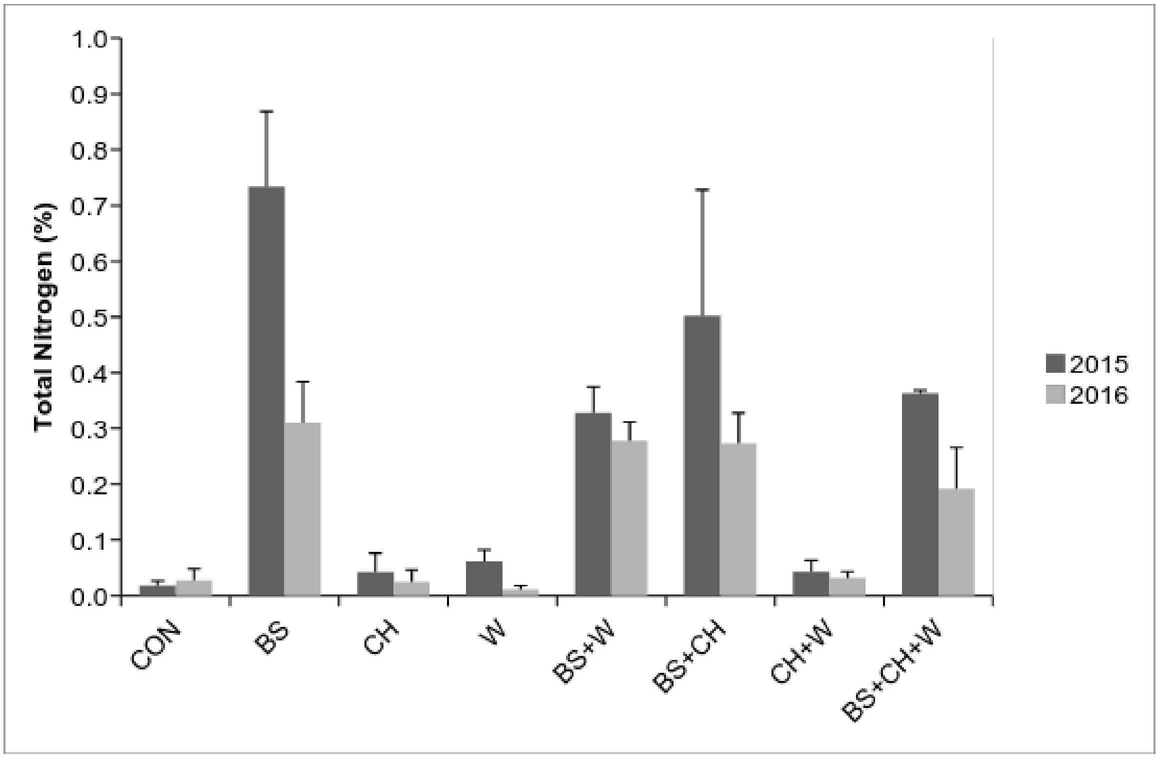

Figure 2.6. Total nitrogen percentages in the top three centimeters from fall 2015 and spring 2016. Error bars indicate one standard error.

To assess N that would be available in one week, anaerobic digestions were done. After one week of anaerobic incubation, nitrate concentrations were below method detection limits, and ammonium concentrations in all treatments containing biosolids increased significantly above the control for both sampling events (Table 2.6 and Table 2.7). At both sampling events, the elevated ammonium concentrations, termed potentially mineralizable nitrogen (PMN), were highest in the biosolid alone treatment, and decreased from fall 2015 to significantly lower concentrations in spring 2016. In the biochar and woodchips treatments, along with their combinations, ammonium concentrations were not statistically different from the control at both sampling events.

2.4.2.2. In-Situ Nutrient Results

Nutrient data from the in-situ ion resin capsules show nutrient release over time from amendment application. Similar to plant roots, ion resin capsules are dependent on diffusion rates for nutrient capture, and diffusion rates increase with soil moisture (Blank et al 2007). The resin capsules were retrieved and replaced three times during this study (April 2015, September 2015, June 2016), resulting in the three data events (Table 2.9). Total nutrient values received from Unibest were divided by the amount of time the resin capsules were left in the soil to show results on a per month basis. The highest nutrient concentrations (N, P, K, Ca, and Mg) were found in the biosolid plots (Table 2.9). In agreement with the laboratory results, biochar and woodchip nitrogen concentrations remain low. Amendments were applied in October 2014 and results from spring 2015 show an increase of nutrients in biosolid treatments compared to the control, suggesting nutrients were released from the biosolid over the winter. During the 2015 growing season, concentrations of P, K, Ca, Mg and S decreased, and then increased after the 2015-2016 winter (Table 2.9). Resin-recovered nutrient concentrations in the biosolid treatments were higher than the control plots.

Nitrogen and P trends in the different treatments differed over time (Figures 2.7 and 2.8). During the summer, inorganic nitrogen increased in the biosolid and biosolid+woodchips treatments, and decreased in these plots over the winter. Conversely, in biosolids+biochar plots, inorganic nitrogen continued to increase over the winter months.

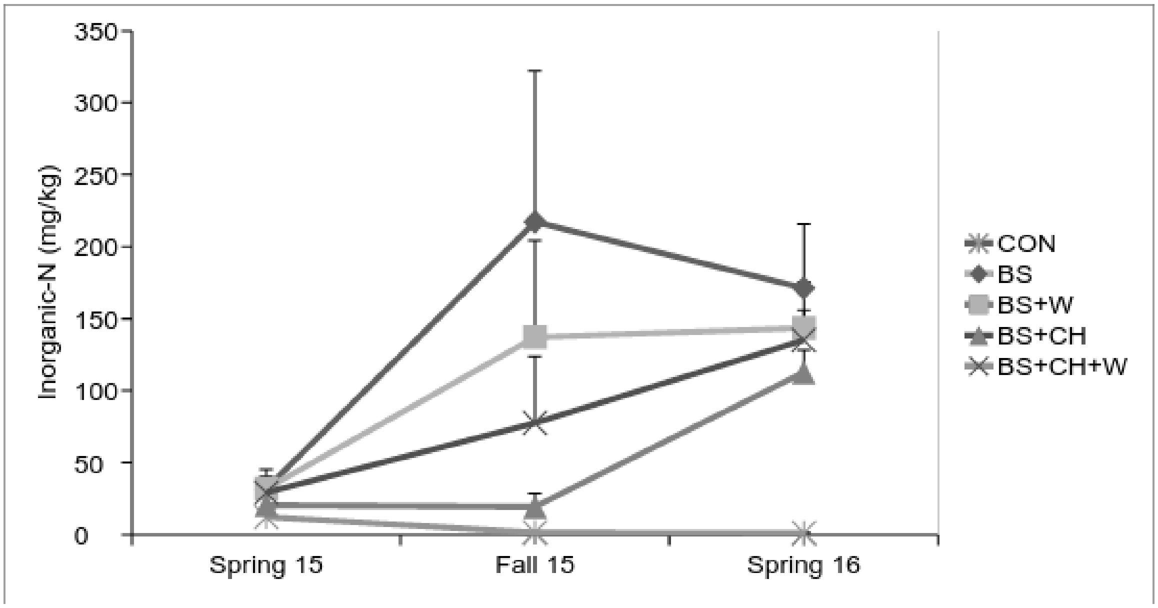

Figure 2.7. Plant available N from resin capsule results for treatments containing biosolids. Values at each time represent total inorganic-N adsorbed to resin capsules at that time. Error bars indicate one standard error.

Phosphorus concentration trends in biosolid treatments were opposite nitrogen, showing high concentrations after winter (spring 2015 and spring 2016), and lower concentrations following the summer season (fall 2015); the biosolid+woodchip plots were an exception (Figure 2.7).

The ion resin capsule results have high standard deviations (Table 2.9), which is inherent of variability present in field settings, and has been documented in previous studies using resin capsules (Gundale and DeLuca, 2005). Ion capsule results can be used as an indicator of relative plant nutrient availability (Qian, 1992), and in this study, relative comparisons show treatment effects.

Table 2.8. Summary statistics showing p-values of time (spring 2015, fall 2015 and spring 2016) and treatment effects for ion resin capsule nutrient concentrations. P-values below 0.05 are significant. (See Appendix A-3 for analysis results).

10 cm depth	**df**	**Total-N**	**NH4**	**NO3**	**P**	**K**	**Ca**	**Mg**	**S**
Source					***p-values***				
Year	2	0.1722	***0.0002***	***0.0057***	***0.0004***	***0.0004***	***<.0001***	***<.0001***	***<.0001***
Treatment	7	***<.0001***	***0.0208***	***<.0001***	***<.0001***	***0.0032***	***<.0001***	***<.0001***	***<.0001***
Year*Treatment	14	***0.0024***	0.3649	***<.0001***	0.5232	0.1189	0.082	0.0799	0.2943

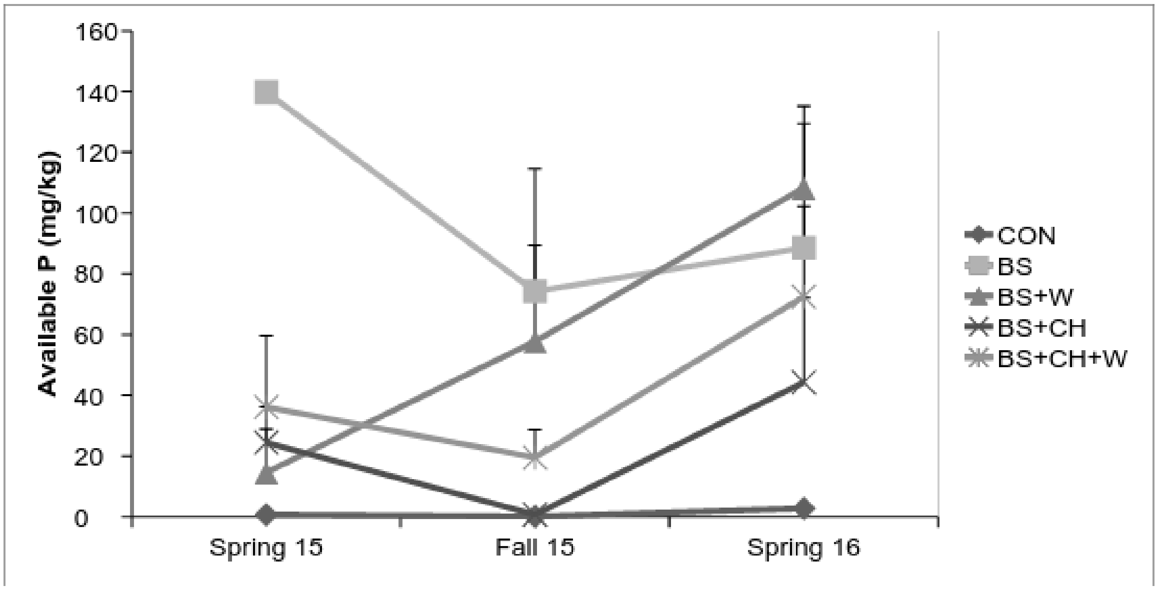

Figure 2.8. Available phosphorus from resin capsule results for treatments containing biosolids. Values at each time represent total P adsorbed to resin capsules at that time. Error bars indicate one standard error.

Table 2.9. Selected nutrient means from the ion resin capsule for the three rounds of data collection (±) standard deviation. Inorganic-N is a combination of NH_4^+ and NO_3^-. NA - Spring 2015 biosolid results reflect only one rep, not an average of three.

Treatment		**Inorganic-N**	**P**	**K**	**Ca**	**Mg**	**S**	**Al**	**Fe**
					(mg/L per month)				
Control									
	* Spring 2015	2.04 ± 1.05 *def*	0.13 ± 0.09 *ef*	1.23 ± 0.78 *abcd*	6.96 ± 2.96 *cdefgh*	3.32 ± 1.68 *cdefgh*	1.80 ± 0.87 *efg*	0.23 ± 0.08 *ef*	0.16 ± 0.02 *ef*
	** Fall 2015	0.29 ± 0.32 *gh*	0.03 ± 0.01 *f*	0.15 ± 0.55 *f*	1.35 ± 0.27 *i*	0.55 ± 0.25 *i*	0.96 ± 0.04 *ghi*	0.13 ± 0.04 *f*	0.13 ± 0.06 *ef*
	*** Spring 2016	0.12 ± 0.06 *h*	0.31 ± 0.05 *abcde*	0.84 ± 0.30 *bcde*	5.60 ± 2.13 *defgh*	2.73 ± 1.06 *defgh*	0.67 ± 0.55 *ihj*	0.36 ± 0.24 *def*	0.24 ± 0.19 *def*
Biosolids									
	Spring 2015	5.32 ± NA *abcd*	23.30 ± NA *a*	1.81 ± NA *abcd*	56.83 ± NA *a*	22.91 ± NA *a*	31.44 ± NA *a*	0.12 ± NA *f*	0.06 ± NA *f*
	Fall 2015	43.44 ± 36.29 *a*	14.83 ± 14.00 *abc*	5.91 ± 4.74 *ab*	23.25 ± 18.30 *abcde*	14.81 ± 11.94 *abcd*	6.82 ± 7.25 *bcde*	0.60 ± 0.34 *bcde*	0.63 ± 0.35 *bc*
	Spring 2016	19.02 ± 8.54 *a*	9.84 ± 2.63 *a*	2.58 ± 2.63 *abcd*	30.82 ± 16.40 *ab*	12.88 ± 4.59 *ab*	6.74 ± 3.67 *bc*	0.34 ± 0.09 *def*	0.28 ± 0.13 *cde*
Biochar									
	Spring 2015	2.18 ± 1.16 *de*	0.09 ± 0.06 *f*	2.27 ± 1.17 *abcd*	11.78 ± 8.62 *bcdefg*	5.58 ± 3.94 *abcdefg*	2.26 ± 0.39 *cdefg*	0.75 ± 0.70 *bcde*	0.43 ± 0.26 *bcd*
	Fall 2015	1.08 ± 0.86 *defg*	0.03 ± 0.03 *f*	0.30 ± 4.56 *ef*	3.42 ± 1.63 *hi*	1.59 ± 0.84 *ih*	1.03 ± 0.16 *fghi*	0.22 ± 0.14 *f*	0.15 ± 0.07 *ef*
	Spring 2016	0.75 ± 1.00 *fgh*	0.30 ± 0.31 *def*	1.83 ± 2.54 *abcde*	4.91 ± 3.23 *fgh*	2.53 ± 1.88 *efgh*	0.68 ± 0.61 *ij*	0.29 ± 0.09 *def*	0.20 ± 0.09 *def*
Woodchips									
	Spring 2015	2.84 ± 0.05 *abcde*	0.16 ± 0.16 *def*	1.20 ± 0.40 *abcd*	6.77 ± 1.12 *cdefgh*	3.15 ± 0.72 *cdefgh*	2.11 ± 0.22 *cdefg*	0.24 ± 0.05 *def*	0.19 ± 0.07 *def*
	Fall 2015	0.51 ± 0.33 *efgh*	0.24 ± 0.19 *def*	0.52 ± 0.97 *def*	4.05 ± 2.32 *gih*	2.07 ± 1.18 *fgh*	0.98 ± 0.04 *ghi*	0.66 ± 0.27 *bcd*	0.59 ± 0.13 *bc*
	Spring 2016	0.14 ± 0.02 *gh*	0.15 ± 0.15 *def*	1.07 ± 0.54 *abcd*	4.73 ± *efgh*	2.26 ± 0.69 *efgh*	1.20 ± 0.85 *fghi*	0.26 ± 0.06 *def*	0.17 ± 0.04 *def*
Biosolid+									
woodchips	Spring 2015	5.31 ± 3.87 *bcde*	2.43 ± 4.12 *abcd*	3.25 ± 2.43 *ab*	20.54 ± 16.59 *bcdef*	10.92 ± 9.58 *abcdef*	16.10 ± 18.03 *bcd*	0.31 ± 0.10 *cdef*	0.18 ± 0.03 *def*
	Fall 2015	27.42 ± 23.24 *ab*	11.55 ± 10.98 *ab*	4.12 ± 1.99 *a*	23.10 ± 14.75 *abc*	14.83 ± 10.59 *ab*	3.19 ± 1.75 *cdefg*	1.04 ± 0.57 *ab*	0.85 ± 0.40 *ab*
	Spring 2016	15.95 ± 6.15 *abc*	12.03 ± 4.06 *abc*	3.24 ± 1.11 *abc*	18.09 ± 7.26 *abcd*	9.17 ± 2.17 *abcd*	1.78 ± 1.02 *defg*	0.29 ± 0.07 *def*	0.22 ± 0.11 *ef*
Biosolid+									
biochar	Spring 2015	3.42 ± 2.32 *abcd*	4.07 ± 3.43 *bcdef*	2.47 ± 1.01 *ab*	12.82 ± 8.47 *abc*	6.89 ± 4.85 *abc*	7.74 ± 8.42 *ab*	0.28 ± 0.03 *def*	0.20 ± 0.04 *def*
	Fall 2015	3.88 ± 3.25 *cde*	0.15 ± 0.11 *def*	0.73 ± 0.98 *cdef*	5.11 ± 4.98 *hi*	2.67 ± 2.61 *igh*	1.23 ± 0.34 *fghi*	0.37 ± 0.35 *def*	0.24 ± 0.14 *de*
	Spring 2016	12.53 ± 2.98 *a*	4.92 ± 5.37 *a*	2.29 ± 0.55 *ab*	15.09 ± 2.24 *abc*	8.01 ± 1.56 *abc*	2.13 ± 0.53 *efg*	0.34 ± 0.20 *def*	0.16 ± 0.06 *def*
Biochar+									
woodchips	Spring 2015	1.26 ± 0.56 *def*	0.09 ± 0.05 *f*	1.46 ± 0.84 *abcd*	7.36 ± 4.29 *cdefgh*	3.66 ± 2.10 *cdefgh*	1.98 ± 0.47 *defg*	0.38 ± 0.17 *cdef*	0.24 ± 0.12 *de*
	Fall 2015	0.80 ± 0.38 *defg*	0.14 ± 0.04 *def*	1.87 ± 0.44 *abcd*	8.46 ± 4.39 *cdefgh*	4.67 ± 2.87 *bcdefgh*	1.51 ± 0.34 *efgh*	2.54 ± 2.75 *a*	2.09 ± 2.09 *a*
	Spring 2016	0.14 ± 0.03 *gh*	0.30 ± 0.22 *cdef*	0.86 ± 0.24 *abcde*	4.47 ± 1.56 *fgh*	2.14 ± 0.80 *fgh*	0.33 ± 0.09 *j*	0.34 ± 0.17 *def*	0.20 ± 0.11 *def*
Biosolid+									
biochar+	Spring 2015	4.88 ± 3.14 *abcd*	6.02 ± 6.80 *abcd*	2.43 ± 1.20 *abc*	12.64 ± 3.34 *bcdef*	6.70 ± 1.17 *abcde*	9.75 ± 3.30 *ab*	0.26 ± 0.15 *ef*	0.15 ± 0.05 *ef*
woodchips	Fall 2015	15.51 ± 15.97 *abcd*	3.90 ± 3.15 *abcde*	2.10 ± 2.30 *abcd*	15.18 ± 1.84 *abcde*	7.93 ± 1.26 *abcd*	2.42 ± 0.83 *cdefg*	1.47 ± 1.52 *ab*	1.13 ± 1.03 *ab*
	Spring 2016	15.01 ± 4.00 *ab*	8.05 ± 12.08 *abc*	1.82 ± 1.28 *abcd*	17.13 ± 7.45 *abc*	9.56 ± 4.42 *abc*	3.10 ± 2.14 *cdefg*	0.25 ± 0.06 *def*	0.14 ± 0.05 *ef*

* Spring 2015 represents 6 month in soil **Fall 2015 represents 5 month in soil ***Spring 2016 represents 9 month in soil

2.4.3. Available Water

For plant available water (PAW), both year and treatment were significant factors in the surface layer, but only treatment was significant in the subsurface (Table 2.10).

Table 2.10 Summary statistic p-values for field capacity (FC), permanent wilting point (PWP) and plant available water (PAW) across year (2015, 2016) and treatment. P-values below 0.05 are significant.

0-3cm Source	**df**	**FC**	**PWP**	**PAW**
Year	1	0.8832	0.1363	***0.0047***
Treatment	7	***<.0001***	***0.0003***	***0.0009***
Year*Treatment	7	0.1928	0.3437	***0.0283***

3-12cm Source	**df**	**FC**	**PWP**	**PAW**
Year	1	0.1699	0.2442	0.2426
Treatment	7	***0.0401***	0.1446	***0.0009***
Year*Treatment	7	***0.0174***	0.1001	***0.0001***

The top 3 cm of soil had the greatest changes in PAW. The most PAW was detected in the surface soil biochar+woodchip treatment in fall 2015 (5.4% more than the control (Table 2.11)). Similar results were found for the biosolid treatments (5.3% more than control) (Figure 2.9). All amended plots had higher surface soil PAW than the control plots in fall 2015, but in spring 2016, only biosolids and the biosolids+biochar+woodchip treatments had a significant difference from the control plots (Table 2.11). Biochar+woodchips treatments and the control had significant change in PAW from 2015 to 2016. While the control increased over time, the biochar+woodchips significantly decreased.

Table 2.11. Measured values of water content at two pressures (-0.03 MPa) and (-1.5 MPa) and initial moisture content for the 0-3 cm soil depth at the two sampling events (±) standard deviation. Calculated PAW is the difference in water content between the two pressures.

Treatment	**Year**	**Water Content (%)**			
		(Initial MC)	(-0.03 MPa)	(-1.5MPa)	PAW
Control	2015	3.55 ± 1.06 *ij*	23.94 ± 0.85 *g*	13.39 ± 0.82 *edf*	10.55 ± 0.22 *f*
	2016	2.74 ± 0.95 *j*	26.80 ± 2.60 *efg*	12.77 ± 1.40 *f*	14.02 ± 1.43 *ebdc*
Biosolids	2015	4.91 ± 1.97 *ghi*	34.80 ± 4.52 *a*	18.87 ± 3.48 *ab*	15.94 ± 1.07 *ab*
	2016	5.62 ± 0.35 *efghi*	32.85 ± 4.19 *ab*	15.90 ± 2.27 *bcdef*	16.95 ± 1.93 *a*
Biochar	2015	3.66 ± 0.49 *ij*	25.78 ± 2.45 *fg*	12.85 ± 1.62 *f*	12.92 ± 1.00 *e*
	2016	4.27 ± 2.07 *hij*	28.05 ± 2.62 *def*	12.93 ± 1.88 *f*	15.12 ± 1.00 *abcde*
Woodchips	2015	5.06 ± 0.93 *fghi*	28.29 ± 4.19 *bcdef*	13.83 ± 1.12 *cdef*	14.46 ± 3.14 *bcde*
	2016	7.56 ± 1.18 *cdef*	29.01 ± 0.26 *cdef*	13.57 ± 0.40 *def*	15.44 ± 0.13 *abcd*
Biosolids + Woodchips	2015	6.07 ± 0.43 *bcde*	29.91 ± 2.44 *bcde*	16.26 ± 0.78 *abcde*	13.65 ± 2.41 *de*
	2016	7.67 ± 2.96 *ab*	32.38 ± 1.61 *ab*	15.62 ± 1.87 *abc*	15.40 ± 1.08 *abcd*
Biosolids + Biochar	2015	7.97 ± 2.72 *efgh*	34.85 ± 6.20 *a*	20.80 ± 9.32 *a*	14.05 ± 3.15 *bcde*
	2016	10.80 ± 2.75 *def*	31.02 ± 3.21 *abcd*	17.16 ± 0.55 *bcdef*	15.22 ± 1.46 *abcd*
Biochar +Woodchips	2015	6.70 ± 0.33 *defg*	29.35 ± 2.19 *bcdef*	13.41 ± 1.02 *ef*	15.98 ± 1.73 *ab*
	2016	10.67 ± 4.13 *bc*	28.18 ± 1.86 *def*	14.44 ± 1.28 *cdef*	13.73 ± 0.76 *cde*
Biosolids + Biochar + Woodchips	2015	9.13 ± 0.69 *bcd*	32.06 ± 1.96 *abc*	16.51 ± 0.72 *abcd*	15.56 ± 1.60 *abcd*
	2016	13.86 ± 3.23 *a*	30.56 ± 1.22 *bcde*	14.63 ± 0.60 *cdef*	15.93 ± 1.82 *abc*

Table 2.12. Measured values of water content at two pressures (-.03MPa) and (-1.5MPa) and initial moisture content for the 3-12 cm depth at the two sampling events (±) standard deviation. Calculated PAW is the difference in water content between these two pressures.

Treatment	**Year**	**Water Content (%)**			
		(Initial MC)	(-0.03 MPa)	(-1.5MPa)	PAW
Control	2015	14.43 ± 0.72 *bcd*	23.71 ± 0.37 *abc*	13.57 ± 0.19 *abc*	10.15 ± 0.19 *f*
	2016	14.163 ± 2.63 *bcd*	26.93 ± 2.20 *de*	13.70 ± 1.35 *abc*	13.23 ± 0.86 *ab*
Biosolids	2015	14.01 ± 2.02 *bcd*	24.30 ± 1.19 *cde*	12.30 ± 0.85 *c*	12.00 ± 0.61 *bcd*
	2016	13.758 ± 1.03 *bcd*	26.43 ± 0.44 *abcd*	13.27 ± 0.23 *abc*	13.15 ± 0.29 *ab*
Biochar	2015	13.33 ± 1.85 *cd*	25.65 ± 1.54 *abcd*	13.52 ± 1.38 *abc*	12.13 ± 0.73 *abcd*
	2016	16.107 ± 2.89 *abc*	27.91 ± 2.95 *ab*	14.38 ± 1.38 *a*	13.52 ± 1.74 *ab*
Woodchips	2015	16.21 ± 1.88 *abc*	27.69 ± 1.56 *ab*	15.01 ± 0.88 *a*	12.68 ± 0.92 *abc*
	2016	16.266 ± 1.77 *abc*	26.85 ± 1.56 *abc*	14.15 ± 0.82 *ab*	12.70 ± 0.94 *abc*
Biosolids + Woodchips	2015	15.10 ± 1.14 *bcd*	25.45 ± 0.26 *abcd*	13.79 ± 0.82 *abc*	11.56 ± 0.56 *cde*
	2016	14.57 ± 1.98 *d*	22.77 ± 4.08 *e*	12.39 ± 2.03	10.38 ± 2.05 *e*
Biosolids + Biochar	2015	14.72 ± 3.91 *bc*	25.08 ± 0.52 *bcde*	13.52 ± 0.45 *abc*	11.66 ± 0.42 *cde*
	2016	11.418 ± 0.64 *bcd*	24.24 ± 1.66 *cde*	13.43 ± 1.40 *abc*	10.81 ± 0.32 *edf*
Biochar +Woodchips	2015	15.22 ± 1.37 *bc*	26.20 ± 2.36 *abcd*	13.37 ± 1.18 *abc*	12.75 ± 1.37 *abc*
	2016	17.233 ± 4.31 *ab*	25.27 ± 1.24 *bcd*	14.66 ± 1.66 *a*	10.62 ± 0.61 *ef*
Biosolids + Biochar + Woodchips	2015	15.72 ± 4.33 *bc*	24.83 ± 3.99 *cde*	12.58 ± 2.53 *bc*	12.24 ± 1.47 *a*
	2016	19.331 ± 2.89 *a*	28.27 ± 1.59 *a*	14.64 ± 0.24 *a*	13.63 ± 1.67 *a*

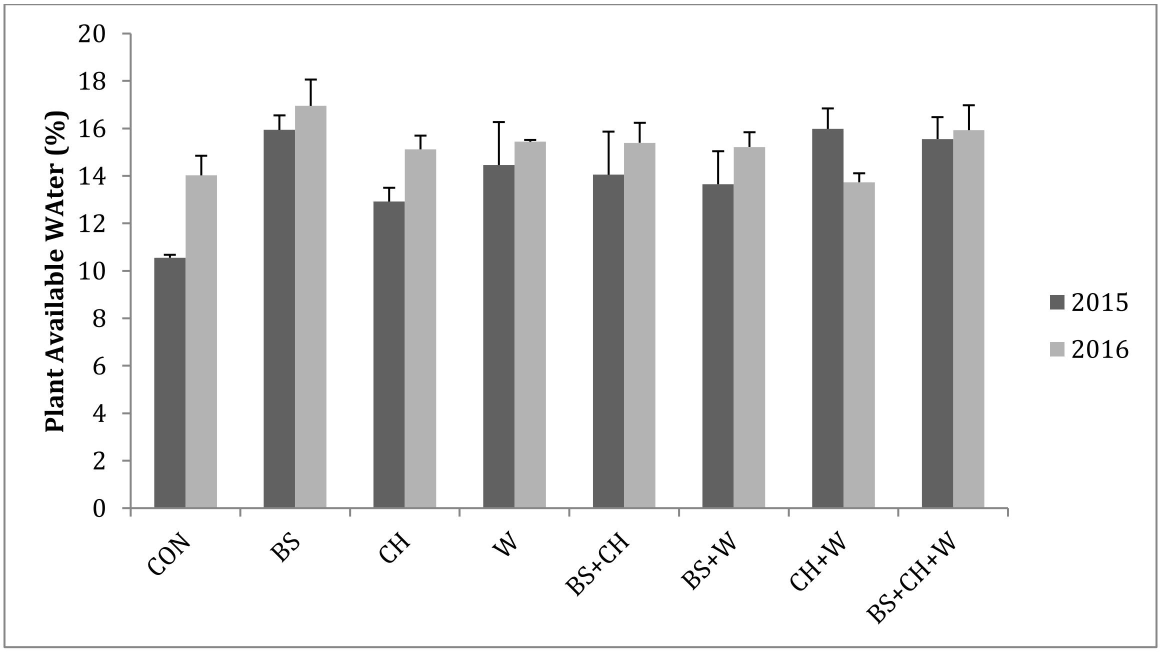

Figure 2.9 PAW as determined by the difference between field capacity (-.03MPa) and permanent wilting point (-1.5MPa) in the surface soil for 2015 and 2016. Error bars indicate one standard error.

The subsurface soil layer of all amended plots had a significant increase in PAW compared to the control in fall 2015 (Figure 2.10). However, in the spring 2016, no increases were seen, and three combination plots (BS+CH, CH+W, and BS+W) had significantly lower PAW percentages than the control.

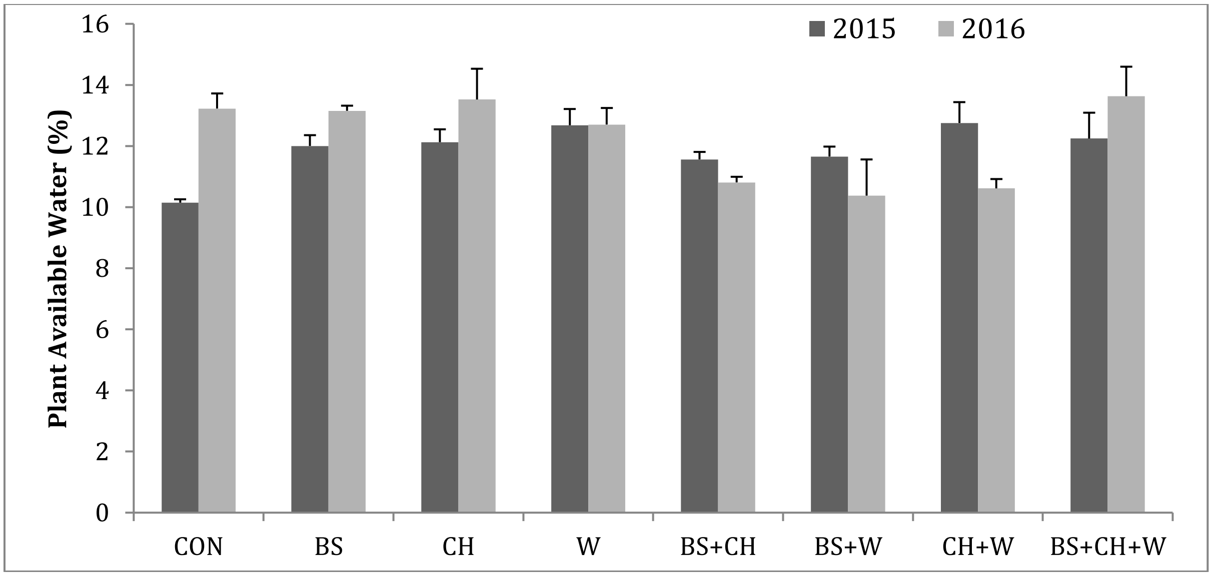

Figure 2.10 PAW as determined by the difference between field capacity (-0.03 MPa) and permanent wilting point (-1.5 MPa) in the subsurface soil for 2015 and 2016. Error bars indicate one standard error.

2.4.4. Soil Temperature and Moisture

Soil temperature and moisture were different in the various treatments. Comparing the biosolid, biochar, woodchips and biosolid+biochar+woodchip treatments, during the 2015 growing season, biosolids had the greatest soil moisture (Figure 2.11). There were very small differences in soil moisture between the biochar, woodchips, and biosolid+biochar+woodchips treatments as compared to the control soil.

Soil temperature was greatest in the biochar treated plots, followed by biochar+woodchips (Figure 2.12). These results support the soil moisture results, as biochar seemed to be warmer and dryer, and biosolids were cooler and wetter. Interestingly, the laboratory soil water holding capacity results showed biochar+woodchips and biosolids alone as having the highest plant available water (Figure 2.9). Although biochar may have the capacity to influence water retention when mixed with the soil, in the field, they may cause temperature increases when applied to the soil surface.

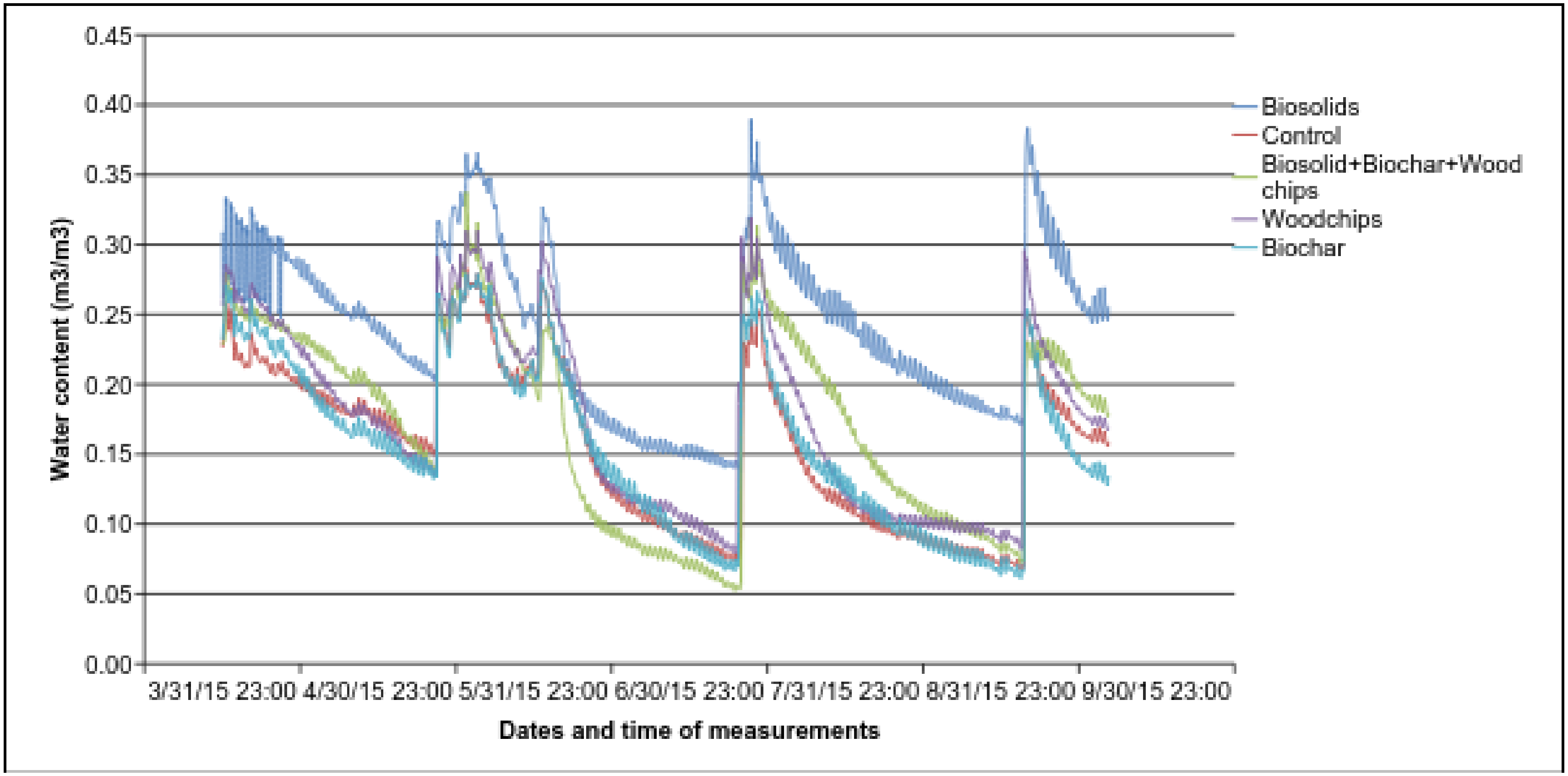

Figure 2.11 Daily soil moisture measurements from April 2015 to September 2015, recorded by in-situ sensors.

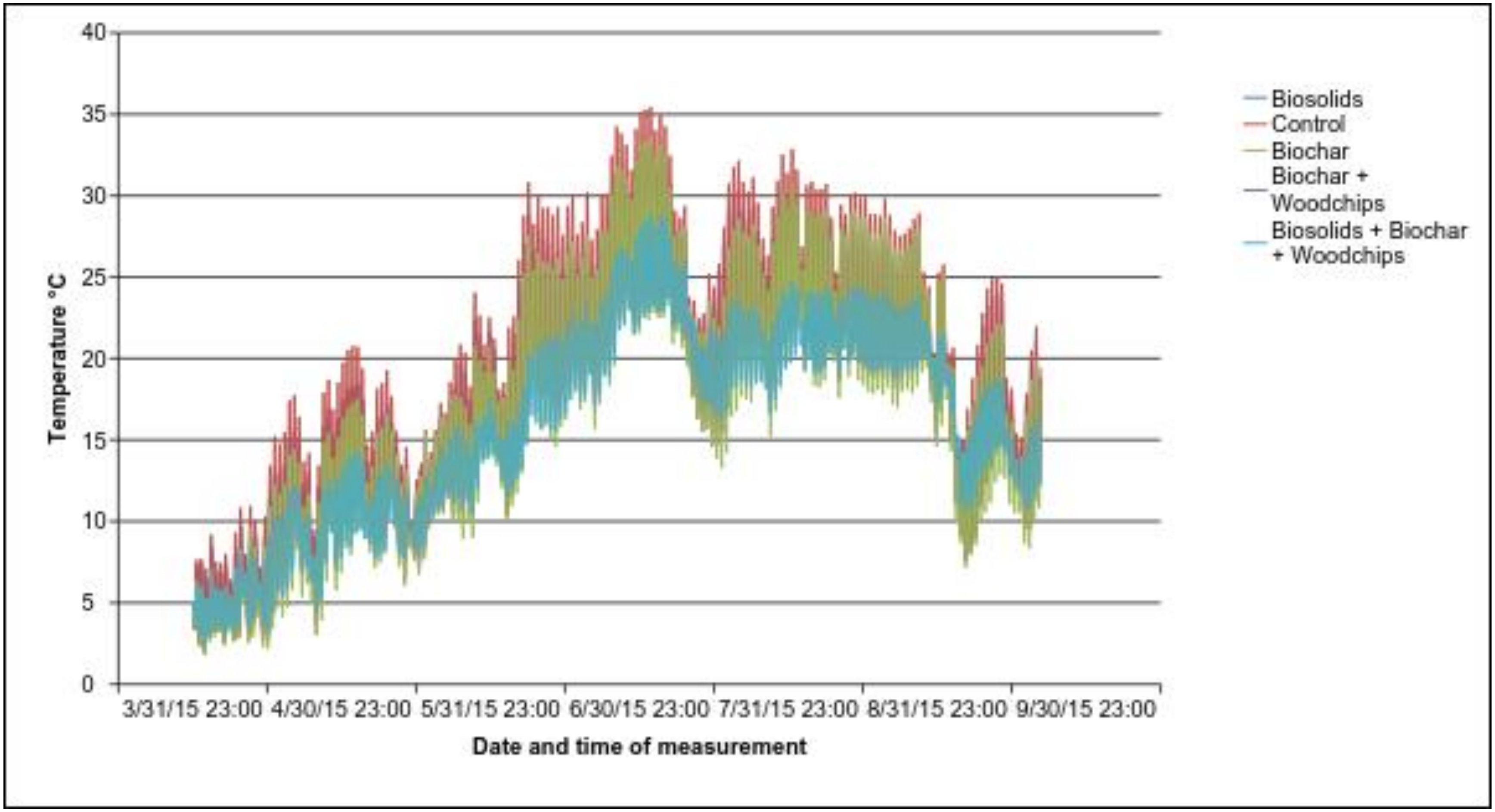

Figure 2.12 Daily soil temperature measurements from April 2015 to September 2015, recorded by in-situ sensor. Treatments not visible on graph are similar enough values to the visible colors to not be seen.

2.4.5. Plant Success

Plant cover was significantly different from fall 2015 to spring 2016 (Table 2.13). Woodchips had the most visible impact on increases of vegetation between the sampling events in both planted and seeded sides (Figure 2.12). The first sampling event was at the end of a dry summer, and the second, after a wet spring. In the control plots, there was an increase in plants from fall 2015 to spring 2016. Treatments containing woodchips had significantly greater quantities of plants, up to five times more plants, than the other treatments or the control.

Table 2.13 P-values for total plant counts as affected by year and treatment. P-values below 0.05 are significant (See Appendix A-5 for analysis results).

Seeded Source	**df**	**Grasses**	**Forbs**
Year	1	***<.0001***	***<.0001***
Treatment	7	***<.0001***	***<.0001***
Year*Treatment	7	0.4317	***<.0001***

Planted Source	**df**	**Grasses**	**Forbs**
Year	1	***<.0001***	***<.0001***
Treatment	7	***0.0001***	***0.0043***
Year*Treatment	7	0.2666	0.2224

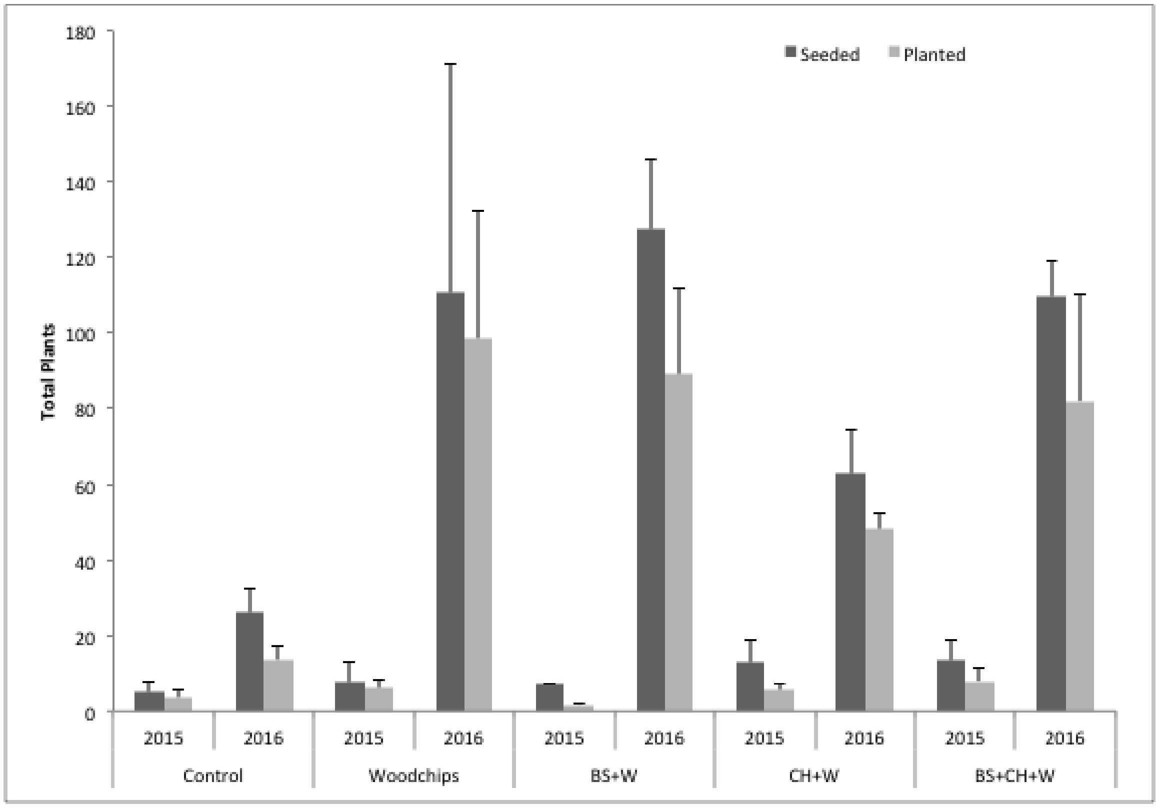

Figure 2.13. Total plant counts of woodchip treatments from fall 2015 and spring 2016, categorized according to planting strategy. Error bars indicate one standard error.

By the second survey (2016), the seeded half of each plot contained more total plants than the planted half in all treatments (Figure 2.12). This is also a function of which types of plant species were growing in either half. By the end of 19 months, volunteer forbs were much more plentiful than the chosen grass species (sampling event 2). In the fall 2015, after a dry summer, there were either more grasses present or no significant difference between the two groups of plants, indicating a higher drought tolerance of *Bromus carinatus* and *Elymus glaucus* than the native forbs (Figure 2.13).

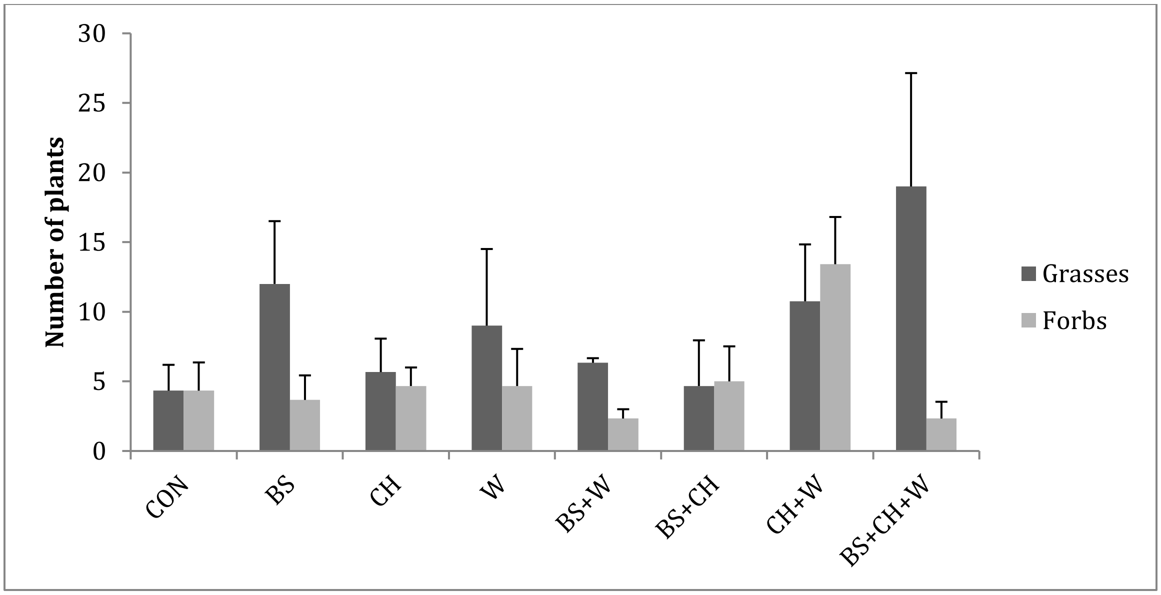

Figure 2.14. Combined plant counts of both sides of treatment plots in fall 2015. Error bars indicate one standard error.

2.5. Discussion

2.5.1. Soil Properties

In this study, the biochar treatment had small, non-significant pH changes. Many studies have observed soil pH changes after biochar amendment (Fellet et al. 2011, Hardie et al. 2014) however, other studies point out a lack of soil pH change with biochar amendment. For example, Murkharjee et al. (2014) conducted a 2-year study with 0.5% biochar by weight amendment and observed no significant increase in soil pH. Kelly et al. (2014) performed a 65-day column study on hardrock mine tailings with biochar application rates of 10%, 20%, and 30% biochar by weight; the maximum change in pH was observed in the 30% application rate, but was only a 0.3 increase.

In this study the most effective treatment for increasing topsoil pH was biosolids (Table 2.3). The initial biosolid pH (7.1) was greater than the pre-treatment soil pH

(5.47), thus the increased pH of the amended soil is caused by some pH buffering of the biosolids. However, over time, exchangeable acidity and buffering capacities of soils cause the pH to return to its original value (Brady and Weil 1996), which occurred in the biosolids treatment in the spring 2016 (Table 2.3). Nutrient uptake by plant roots also contributes to pH buffering because as the roots absorb cation nutrients, they release protons to maintain electrical neutrality, thereby decreasing the surrounding soil pH (Marschner 1995a, Hedley et al. 1982).

Electrical conductivity was affected by both biosolids and biochar treatments. Biosolids had the highest EC of all treatments, even in the spring 2016, due to biosolids adding soluble salts. Sidhu et al. (2016) found similar increases in EC from applying biosolids to copper mine tailings at application rates of 2.5%, 5%, 10%, and 20% of the dry weight, where maximum EC occurred in the 20% amendment rate (EC was increased by 27 times the control). The lowest values of EC at both sampling events were in the biochar treatments, which may have been caused by adsorption of soluble salts to biochar’s charged surface. Fellet et al, (2011, 2014) found that biochar increases EC in proportion to increasing application rates of 1%, 5%, and 10% by dry weight. These two studies were laboratory experiments with time periods of 15 days and 90 days. Murkharjee et al. (2014) found biochar to have no effect on EC after two years in the field at 0.5% dry weight application.

An important soil property for reclamation of disturbed soils is organic matter and OC content. Since amendments in this study were only applied once, treatments that sustained elevated OC percentages over time should be beneficial to plant cover. The greatest OC increase occurred in the biosolids treatment during the first sampling event. Combination treatments did not increase OC as much as biosolids during this first year and biochar and woodchips applied alone only raised OC by <1% (Tables 2.4 and 2.5). In the spring 2016 sampling, all treatments containing biosolids, including combinations, had similar OC contents. Differences in OC results between treatments can be attributed to three factors: 1) amendment particle size, 2) amendment decomposition rates, and 3) soil water content.

Biosolids are small, readily decomposed particles, with accessible surface area for microbial attack, whereas the woodchips and biochar are more durable and have larger particle sizes. Biosolids have a much lower C:N ratio than woodchips, supporting rapid decomposition and net mineralization (Schroth and Sinclair 2003). As biosolids decompose and release available N, biological activity is stimulated, leading to further degradation. The woodchips and biochar have very high C:N ratios (46.5:0.11 and 89:0.26 respectively) with biochar containing little to no N, and thus microbial activity is not expected to be stimulated by these amendments. In fact, because they contain so much C, soil N concentrations in the soil were depleted in biochar and woodchip treatments (Figure 2.5). Each sample date was separated by a winter and spring, so the soil environment at the times of sampling were very different. Biosolids break down faster during the first year of application, releasing the easily accessible organic materials and nutrients, explaining the high percentages of OM in fall 2015 (Sullivan et al., 2015). At the second sampling event, nearly two years after amendment, some of the soluble organic matter could have leached out of the soil.

In the biosolids treated soils, the greater amount of organic C is partly caused by the fact that most biosolid particles fit through the 2-mm sieve, which is not the case with biochar and woodchips. The biochar applied was a mixture of small and large particle sizes. The extremely light-weight fine particles are easily picked up by wind and quickly disappear, leaving the heavier biochar pieces. Larger biochar particles do not break down quickly and therefore the majority of what is left on the plots gets sieved out during the sample preparation process. It should be noted that this is an appropriate representation of field soil conditions, as these larger particles of biochar and woodchips are not integrated with the soil below the surface.

2.5.2. Nutrient Availability

Biosolids significantly increased plant available N and P. The biosolids applied were 5.5% nitrogen by weight. According to the application rate of 16.8 Mg/ha, 374 kgs of total nitrogen were applied per acre or 0.9 kg-N/plot. Ninety-seven percent of the total nitrogen was organic-N, requiring mineralization for plant use, and three percent, equaling 11.22 kgs of nitrogen, was plant available at the time of application. *Bromus carinatus* and *Elymus glaucus* have fertilization requirements of 14-23 kgs of N/acre and 9-14 kgs of N/acre respectively when planted on infertile soils (USDA, 2012; USDA-NRCS, 2013). The immediately available-N portion of the biosolids at the time of application met nearly all nitrogen requirements.

Fall 2015 results show elevated levels of available-N after the first year in biosolid treatments. Although it was an unusually dry summer and plant growth was hindered by lack of moisture, the required nitrogen for growth was present from the biosolid application, as can be seen in the KCl extraction results (Table 2.6 and Table 2.7). Drought not only inhibits plant available water, but nutrient availability as well because diffusion is the main mechanism for nutrient transport in soil (Marschner, 1995).

The nitrogen decrease from fall 2015 to spring 2016 is likely caused by the weather differences at these two sampling times. The summer of 2015, prior to the first sampling event, had record high temperatures and drought. Lack of moisture in the soil can allow soluble salts to build up, which would normally have leached with periodic rain events (Barber 1984). Very little plant growth was observed in fall 2015 in any of the treatments (Figure 2.13). During the growing season, as plants uptake nutrients for new growth, soil nitrogen decreases (Schroth and Sinclair 2003). The steep decrease in total-N and available-N at sampling event 2 (Table 2.6 and Table 2.7) may be attributed to the large amount of plant cover (uptake), also seen at sampling event 2 (Figure 2.15), as well as possible nitrate leaching and nitrogen use by other soil organisms.

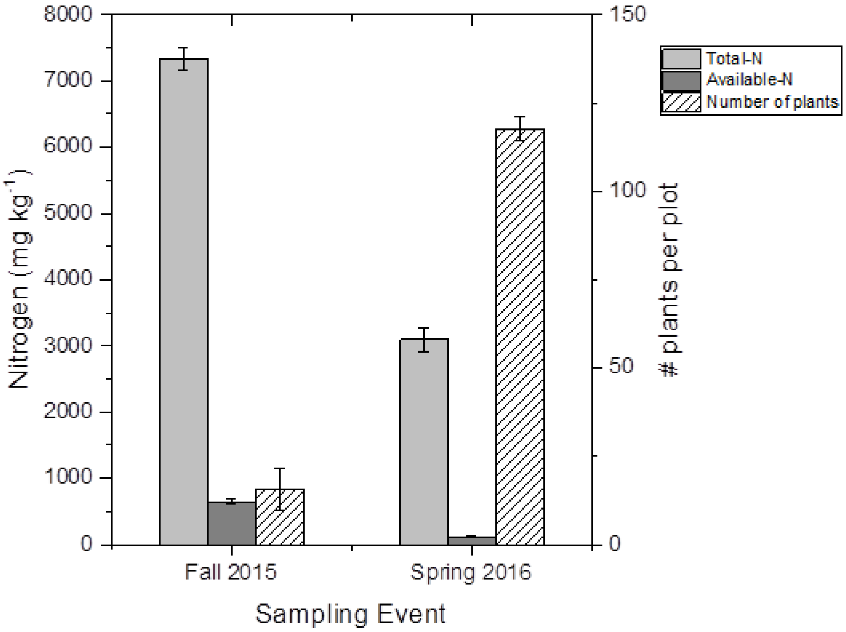

Figure 2.15 Plant available nitrogen, total nitrogen, and plant counts from fall and spring samplings in the biosolid treatment. Lab soil test were from the 0-3 cm layer. Error bars indicate standard error.

In the fall, after the growing season, precipitation increased, as the large store of organic-N is converted to bioavailable forms via mineralization, available-N (ammonium and nitrate) will increase (Table 2.6 and 2.7). This excess of plant available nitrogen could then be readily used by the new plants in the early growing season of 2016 (Table A-9 and A-10).

At both sampling events, biochar and woodchips, along with their combination, caused a decrease in the amount of N in the soil, as compared to the control. As discussed above, this is a short-term effect of applying high C materials to a N-limited soil. With an added carbon source, increased microbial activity would use up more available nitrogen and be in competition with plants, completely depleting readily available N.

From fall 2015 to spring 2016, (Table 2.9), recovery of P on the ion resin capsules increased. The original biosolids contain 3.03% total phosphorus by weight. Unlike nitrogen, which is mobile in soils, phosphorus is mineralized to the plant available form, and is immobile, remaining in the soil through a wet season (e.g., Spring 2016) (Stevenson, 1986). In previous biosolid application studies, available phosphorus has been found to remain in the surface soil, above 10 cm (McGuire et al., 2000; Shober et al., 2003; Sidhu et al., 2016). McGuire et al. (2000) found that at 11 different test sites of varying application rate, iron and aluminum-bound phosphorus was the dominant form of P below 10 cm, which caused decreased plant available-P. Shober et al. (2003) found no increase in available P below 10 cm after up to 18 years of annual biosolid application (53.71 Mg/ha). In the present study, the ion resin capsules are located at a depth of 10 cm, meaning that all increases seen in biosolid treatments represented the soil at that depth, thus suggesting vertical movement of available-P.

The lack of significant effects of biochar on nutrient enhancement is consistent with other biochar field studies. Kelly et al. (2014) found no increase in P for biochar at any application rate. However, in combination plots of biochar with biosolids, nutrients were released, showing higher concentrations of all measured nutrients (N, P, K, Ca and Mg) than biochar alone (Table 2.9). The rate of application of biosolids was the same in the single and mixed treatments, so the rate of nutrient release from biosolid alone and biosolid combination plots (biochar+biosolids) should be similar. Although available nutrient concentrations were higher in the biochar+biosolid treatment than in biochar alone, they were still lower than biosolids alone. This could be indicative of adsorption of nutrients from solution to biochar surfaces, which are then available to plants through diffusion. Another explanation is that during the sieving process, any biochar particles larger than 2 mm were sieved out, and thus any nutrients adsorbed to the surfaces of these particles are not represented in the results.

2.5.3. Available Water

Plant available water was not significantly altered by the application of biochar. Hardie et al. (2014) and Odeja et al. (2015) observed similar results. Hardie et al. (2014) incorporated 47 Mg/ha of biochar to plots in a field study and reported no significant effects on soil water retention. Odeja et al. (2015) found that PAW was not modified after a one-year column study at an application rate of 10 g C/kg soil using six types of biochar. They suggested that the effects of biochar on soil water retention may be soil and biochar specific, as supported by Struebel et al. (2011), who found less than half of sixty different application types, varying by soil type, biochar type, and application rate, had any increase in water holding capacity. However, in some studies biochar has been shown to increase plant available water. Murkherjee et al. (2014) found that in a one year field study on a silt loam amended at a rate of 7.5 Mg/ha oak wood biochar, PAW increased by 63%. In this study, spring 2016 PAW in the control soil was greater than

PAW in the fall 2015 for both the surface and subsurface layers. Such a result is difficult to explain, but may be due the high variability in the field plots (Tables 2.11 and 2.12).

More research is required to understand how surface applied biochar changes soil surface and subsurface temperatures and how these temperature changes may affect soil moisture. Because data logger locations were not replicated or in all treatment combinations, the results from the single treatment monitoring data loggers have limitations for interpreting effects of treatments on soil moisture and temperature. In addition, future experimental design, such as measuring the albedo of the surface amendments to see if the darker colored amendments absorb more heat than the bare soil, could be used to interpret soil moisture results.

2.5.4 Plant Cover

Biosolids and woodchips both had significant effects on plant cover (Table A-9 and A-10). By addressing the nutrient and water limitations at the same time, woodchips and biosolids produced five times the amount of vegetation than was found on untreated soil (combining plant counts from both seeded and planted halves). Schoenholtz et al. (1992) measured soil water potential and tree growth after woodchip application on mine soils and found that woodchips were directly related to better survival and growth because of increased soil water potential. The drought tolerant species of grasses, combined with the native forbs, allowed for total vegetation in the biosolid, woodchips, and combination treatments to be a better environment in the the long, dry growing season.

2.5.5. Limitations

Short observation time, lack of incorporation, plot size, and instrumentation were limitations of this study. Nineteen months is a relatively short field study for mine land reclamation, and with continued sampling of these treatments, further effects from biochar and woodchips may become apparent. Allowing more time for amendment decomposition may reveal more nutrient distribution into the lower levels of the soil and rock material, establishing soil between rocks for plant roots to utilize.

To improve reclamation using amendments, the amendments could be incorporated into the soil to prevent loss by erosion (wind and raindrop) from the soil. Biochar has very little mass and much is lost to wind or raindrop erosion, as noted in previous biochar studies (Anawar et al 2015). Effects of biochar may be more prominent when placed under heavier amendments such as woodchips, or lightly incorporated.

Another important factor is the plot size. Larger study plots would allow more thorough sampling by doing composites across each plot. Danger of too much destruction limited the sampling area to one sample per plot, which caused both large variation and very small representation of the larger area of each plot. With larger experimental plots producing more vegetation, destructive sampling of plants for tissue and root analysis would also be possible.

Lastly, if using in-situ methods of measuring soil and moisture, placing at least one instrument per plot, as well as at different depths, would provide a better assessment of the variability in measuring in-situ soil moisture and temperature.

2.6. Conclusions

The most successful treatments for re-vegetation in this study were the combinations of biosolid+woodchips and biosolid+woodchips+biochar. This conclusion is based on the combined improvement of soil physical and chemical properties (OC, available N and P, and moisture retention). Although many soil properties were measured to identify soil improvements that would typically lead to increased plant growth, the end goal of establishing ground cover vegetation was determined by plant counts and density.

Figure 2.16 Photos of treatment plots from the second sampling event in spring 2016. Top: Control treatment Bottom: Biosolid+biochar+woodchp treatment. Photo taken by author.

The application rates of 18.5 ton/ha of biosolids and 25 ton/ha of woodchips were sufficient to accelerate re-vegetation. Further research is needed to discover the effects of biochar on re-vegetation of degraded forest soils in field conditions.

2.7. Literature Cited

ACES (Aspen Center for Environmental Studies). 2011. Hope Mine Biochar Project. July 2010–August 2011, Aspen, Colorado, USA.

Anawar, H. M, F. Akter, Z. M. Solaiman, and V. Strezov. 2015. Biochar: An emerging panacea for remediation of soil contaminants from mining, industry and sewage wastes. Pedosphere. 25(5):654–665.

Anderson, N., D. Mitchell. Forest operations and woody biomass logistics to imporove efficiency, value, and sustainability. Bioenerg. Res. 9(2):518-533.

Atkinson, C. J., J. D. Fitzgerald, and N. A. Hipps. 2010. Potential mechanisms for achieving agriculture benefits from biochar application to temperate soils: a review. Plant Soil 337:1-18.

Bakshi, S., Z. L. He, and W. G. Harris. 2014. Biochar amendment affects leaching potential of copper and nutrient behavior in contaminated sandy soils. J. Environ. Qual. 43:1894-1902.

Banwart, W. L., M. A. Tabatabai, and J. M. Bremner. 1972. Determination of ammonium in soil extracts and water samples by an ammonia electrode. Commun. Soil Sci. Plant Anal. 3:449.

Barber, S. A. 1984. Soil Nutrient Bioavailability: A Mechanistic Approach. John Wiley & Sons, Inc. New York: pp 44.

Beesley, L., Moreno-Jimenez, E. and J.L. Gomez-Eyles. 2010. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ. Pollut. 158:2282–2287.

Beesley, L., E. Moreno-Jiménez, J.L. Gomez-Eyles, E. Harri, B. Robinson and T. Sizmur. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ. Pollut. 159:3269–3282.

Blank, R.R., Chambers, J., Roundy, B., Whittaker, A., 2016. Nutrient availability in rangeland soils : influence of prescribed burning , herbaceous vegetation removal , overseeding with bromus tectorum, season, and elevation. Rangeland Ecol. Manage. 60:644–655.

Brady, C. N., and R.R. Weil. 1996. The Nature and Property of Soils. Prentice Hall Inc., New Jersey.

Brost, R. 1995. Biosolid Management Handbook: EPA region viii. Environmental Protection Agency. Denver, Colorado.

Brown et al. 2003. Using municipal biosolids in combination with other residuals to restore metal-contaminated mining areas. Plant and Soil 249: 203-215.

Center for urban horticulture, University of Washington. 2002. Using biosolids for reclamation and remediation of disturbed soils. Plant Conservation Alliance, Bureau of Land Management, US Dept. of Interior.

Chan, K.Y., and Z. Xu. 2009. Biochar: Nutrient properties and their enrichment. pp.67-84. In J. Lehmann and S. Joseph (eds.) Biochar for environmental management: Science and technology. Earthscan, London.

Drohan, P.J., Merkler, D.J., Buck, B.J., 2005. Suitability of the Plant Root Simulator Probe for Use in the Mojave Desert. Soil Sci. Soc. Am. J. 69:1482.

Edwards J.H., C.W. Wood, D.L. Thurlow, and M.E. Ruf. 1999. Tillage and crop rotation effects on fertility status of a Hapludalf soil. Soil Sci. Soc. Am. J. 56:1577-1582

Fellet, G., Marchiol, L., Delle Vedove, G., Peressotti, A., 2011. Application of biochar on mine tailings: Effects and perspectives for land reclamation. Chemosphere. 83:1262–1267.

Fellet, G., Marmiroli, M., Marchiol, L., 2014. Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. Sci. Total Environ. 468-469, 598–608.

Forsberg, L.S., Ledin, S., 2006. Effects of sewage sludge on pH and plant availability of metals in oxidising sulphide mine tailings. Sci. Total Environ. 358:21–35.

Galinato, S.P., Yoder, J.K., Granatstein, D., 2011. The economic value of biochar in crop production and carbon sequestration. Energy Policy. 39:6344–6350.

Gundale, M. and T. DeLuca. 2006. Temperature and source material influence ecological attributes of ponderosa pine and Douglas-fir charcoal. Forest Ecology and Management. 231(1-3):86-93.

Haering, K.C., Daniels, L.W., Feagley, S.E., 2000. Reclaiming mined lands with biosolids, manures, and papermill sludges, in: Reclamation of Drastically Disturbed Lands. Soil Sci. Soc. Am., Madison, Wisconsin, pp. 615–644.

Hammes, K. and W.I. Michaeol. Schmidt. 2012. Changes in biochar in soil. In: J. Lehmann and S. Joseph, editors, Biochar for environmental management: Science and technology. Taylor and Francis, Hoboken. p. 169-181.

Jain, T. B., Graham, R. T. and Adams, D. L. 1997. Carbon to organic matter ratios for soils in Rocky Mountain coniferous forests. Soil Sci. Am. J. 61:1190-1195.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144:175–187.

Johnson, Dale W., P. S. J. Verburg, and J. A. Arnone. 2005. Soil extraction, ion exchange resin, and ion exchange membrane measure of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Sci. Soc. Am. J. 69:260–265

Keeney and Nelson. 1982. Nitrogen-inorganic forms in: Methods of soil analysis. Part two. Argon. 9:643-693.

Kelly, C.N., Peltz, C.D., Stanton, M., Rutherford, D.W., Rostad, C.E., 2014. Biochar application to hardrock mine tailings: Soil quality, microbial activity, and toxic element sorption. Appl. Geochemistry. 43:35–48.

Klute, A. 1986. Water retention: Laboratory methods. In. A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agron. Monogr. 9 Am. Soil Ass. and Soil Sci. Soc. Am., Madison, WI. P 635-662.

Kookana, R. S., A. K. Sarmah, L. van Zwieten, E. Krull, and B. Singh. 2011. Biochar application to soil: Agronomic and environmental benefits and unintended consequences. Advances in agronomy 112:103-143.

Lehmann et al. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferrasol of the central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249:343-357.
Liang, B. et al., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70:1719-1730.
Major J., M. Rondon, D. Molina, S.J. Riha, and J. Lehmann. 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil. 333(1):117-128.

Marschner, H. 1995b. Mineral Nutrition of Higher Plants. 2nd ed. Elsevier Ltd. Pp 486.
Miller, W. P., M. E. Sumner. 1996. Cation exchange capacity and exchange coefficients. In D. L. Sparks (ed.) Methods of soil analysis. Part 3. Chemical methods. No. 5. Am. Soil Ass. and Soil Sci. Soc. Am., Madison, WI. P. 1201-1229.

Mineral Policy Center. 2015. In The Mining Burdern 2015 Report. Center for Western Priorities. Available at www.westernpriorities.org.

Mukherjee A, and R. Lal. 2013. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy. 3:313–339

Mulvaney, R.L. 1996. Nitrogen – Inorganic forms. In D.L. Sparks (ed.) Methods of soil analysis. Part 3. Chemical Methods. No. 5. Am. Soil Ass. and Soil Sci. Soc. Am., Madison, WI. pp. 1201-1229.

Murano et al. 2009. Effects of the application of carbonaceous absorbents on pumpkin (Cucurbita maxima) uptake of heptachlor epoxide in soil. Soil Science and Plant Nutrition. Vol 55: 2. Pp325-332.

Nelson, D.W. and L.E. Sommers. 1996. Total Carbon, Organic Carbon, and Organic Matter. In D. L. Sparks (ed.) Methods of soil analysis. Part 3. Chemical methods. No. 5. Am. Soil Ass. and Soil Sci. Soc. Am., Madison, Wisconsin. P. 1201-1229.

Ojeda G., S. Mattana and J. Alcaniz et al. 2010. Wetting process and soil water retention of a minesoil amended with composted and thermally dried sludges. Geoderma 156:399-409.

Ojeda, G., S. Mattana, A. Avila, J. M. Alcaniz, M. Volkmann, and J. Bachmann. 2015. Are Soil-water Functions Affected by Biochar Application? Geoderma. 1(11): 249-250.

O'Kelly, B. 2004. Accurate determination of moisture content of organic soils using the oven drying method. Drying Technology 22(7):1767-1776.

Page-Dumroese, D.S., P.R. Robichaud, R.E. Brown, and J.M. Tirocke. 2015. Water repellency of two forest soils after biochar addition. ASABE 85(2):335-342.

Page-Dumroese D.S., M. Coleman and S.C. Thomas. 2015. Opportunities and uses of biochar on forest sites in North America. In: Biochar: a regional supply chain approach in view of climate change mitigation. Chapter 15. Cambridge University Press.

Page-Dumroese D.S., M.F. Jurgensen, R.E. Brown, and G.D. Mroz. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil. Sci. Soc. Am. J. 63:379-383.

Eastern Oregon Mining Association. 1999. Oregon gold mining: Grant county gold districts. Accessed at www.h2oaccess.com/articles.php/19991202.

Peltz, C.D., Harley, A., Guo, M., He, Z., Uchimiya, S.M., 2016. Biochar Application for Abandoned Mine Land Reclamation Soil Sci. Soc. Am. 80439: 325–340.

Powers, RF. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Soc. Am. J. 44:1314-1320.

Pribyl, D. 2010. A critical review of the conventional SOC to SOM conversion factor. Geoderma: 156(3/4):75-83.

Qian, P., J.J. Schoenau, and W.Z. Huang. 1992. Use of ion exchange membranes in routine soil testing. Commun. Soil Sci. Plant Anal. 23:1791–1804.

Rodriguez-Vila, A., E. F. Covelo, R. Forjan, and V. Asensio. 2014. Phytoremediating a copper mine soil with Brassica juncea L., compost and biochar. Environ. Sci. Pollut. Res. 21:11293-11304.

Schoenau, J.J. and W.Z. Huang. 1991. Anion-exchange membrane, water, and sodium bicarbonate extractions as soil test for phosphorus. Commun. Soil Sci. Plant Anal. 22(5-6):465-492.

Schoenholtz, S.H., Burger, J. a., Kreh, R.E., 1992. Fertilizer and Organic Amendment Effects on Mine Soil Properties and Revegetation Success. Soil Sci. Soc. Am. J. 56:1177.

Schroth, G. and F. L. Sinclair. 2003. Trees, Crops, and Soil Fertiity: Concepts and Research Methods. Wallingford, Oxon, UK: CABI Publishing.

Shober, A. L., R.C. Stehouwer and K.E. Macneal. 2003. On- farm assessment of biosolids effects on soil and crop tissue quality. J. of Env. Quality, 32:1873–1880.

Shultz, H., G. Dunst, and B. Glaser. 2013. Positive effects of composted biochar on plant growth and soil fertility. Agron. Sustain. Dev. 33:817-827.

Sidhu, V., D. Sarkar and R. Datta. 2016. Effects of biosolids and compost amendment on chemistry of soils contaminated with copper from mining activities. Environ. Monit. Assess. 188:176.

Sinclair, K., P. Slavich, L. Zwieten, and A. Downie. 1994. Productivity and nutrient availability on a Ferrosol: biochar , lime and fertiliser. Society 119–122.

Steinbeiss, S., G. Gleixner and M. Antonietti, M. 2009. Effect of biochar amendment on soil carbon balance and soil microbial activity. Soil Biol. Biochem. 41:1301–1310.

Strawn, D. G., H. L. Bohn, and G. A. O'Connor. 2015. Soil Chemistry. John Wiley & Sons, West Sussex, UK.

Stroup, W.W., 2015. Rethinking the analysis of non-normal data in plant and soil science. Agron. J. 107:811–827.

Sims, T. J. 2000. Soil test phosphorus: Mehlich 3 in: Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. Southern Cooperative Series Bullatin No. #396: 17-19.

Sopper, W.E. 1992. Reclamation of mine land using municipal sludge. In: Rattan Lan and B.A. Stewart, editors, Soil restoration. Advances in soil science volume 17. Braun-Brumfield, Ann Arbor, Michigan. p. 351-431.

Stavi, I. 2012. The potential use of biochar in reclaiming degraded rangelands. Journal of Environmental Planning and Managemet. 55(5):657-665.

Tammeorg, P., A. Simojoki, P. Makela, F. L. Stoddard, L. Alakukku, and J. Helenius. 2014. Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil. 374:89-107.

Uchimiya, M., I. M. Lima, K. T. Klasson, and L. H. Wartelle. 2010. Contaminant immobilization and nutrient release by biochar soil amendment: Roles of natural organic matter. Chemosphere. 80:935-40.

Unger, R., R. Killorn, and C. Brewer. 2011. Effects of Soil Application of Different Biochar on Selected Soil Chemical Properties. Commun. Soil. Sci. and Plant Anal. 42(19):2310-321.

Warrington, G.E. and E.O. Skogley. 1996. UNIBEST PST-1 resin capsule adsorbs chemical elements (as ions) from the soil solution (the water in a moist soil) like a plant root. Available at http://www.wecsa.com/Refrence/Pst_wrk.htm.

USDA Natural Resources Conservation Service. 1996. Soil Survey Laboratory Methods Manual. USDA-NRCS Soil Survey Investigations Report No. 42. U.S. Govt. Print. Office, Washington D.C pp. 431-432.

USDA Natural Resources Conservation Service. 2012. Cucamonga' California Brome. Lockeford Plant Materials Center. Lockeford, California.

USDA-NRCS. 2013. Release brochure for 'Elkton' blue wildrye (Elymus glaucus ssp. jepsonii). USDA-Natural Resources Conservation Service, Corvallis Plant Materials Center, Corvallis, Oregon.

USDA. USFS. 2013. Abandoned mine lands. Minerals and geology management. http://www.fs.fed.us/geology/aml.html.

USDA. USFSa. 2012. Hope Mine Project - Aspen Ranger District-White River National Forest. Watershed, Fish, Wildlife, Air and Rare Plants: Soil. http://www.fs.fed.us/biology/soil/photos.html

USDA. USFSb. 2012. Using Woody Biomass to Produce Bio-oil and BioChar. Watershed, Fish, Wildlife, Air and Rare Plants: Soil. http://www.fs.fed.us/biology/soil/index.html.

Walsh, J.R., E.F. Redente. 2011. Comparison of Reclamation Techniques to Re-establish Western White Pine on Smelter-impacted Hillsides in Idaho. Restor. Ecol. 19, 141–150.

Westman,C.J., J. Hytonen and A. Wall. 2006. Loss-on- ignition in the detremination of pools of organic carbon in soils of forests and afforested arable fields. Commun. Soil. Sci. and Plant Anal. 37(7-8):1059-1075.

Chapter 3: Broader Implications

3.1. Abstract

Results of the Clear Creek reclamation project suggest that the organic amendments biochar, biosolids, and woodchips have broader applications based on their separate contributions to soil enhancement. Biochar's multiple applications include long-term carbon (C) storage, greenhouse gas reduction, agricultural soil amendment to improve productivity, and barren land amendment to encourage re-vegetation. Costs of biochar have decreased the likelihood of large-scale agricultural use, but use on smaller reclamation sites is also feasible. This project has shown biosolids to be effective at increasing soil nutrients and consequently plant growth. Negative public perception of biosolids hinders its broad application in populated areas. Forest application of biosolids for reclamation of nutrient poor sites needs further investigation. The mulch effect from the woodchip treatments in this project can apply to many environments such as: arid and abandoned agricultural land where erosion is prevalent or forest sites disturbed by logging and livestock. Organic amendments and methods of re-use of municipal and forest byproducts should be considered as alternatives to conventional reclamation methods in the constant effort to reduce contributions to climate change.

3.2. Introduction

Over the past decade, organic byproducts have been heavily studied as possible amendments for degraded and contaminated lands (Chaney et al. 1999, Larney and Angers, 2012). Depending on the environment of the degraded soil, land managers are responsible for choosing an appropriate amendment to target the individual site problems. The research done in this study on biochar, biosolids, and woodchips shows that each amendment provides unique benefits to ameliorate detrimental properties of degraded soil. The amendments show promise to be used on their own and in combinations. This chapter examines the broader implications of research presented in this thesis, and provides some discussion of specific cases and general environments suitable for potential use of the amendments for reclamation purposes.

3.3. Amendment Potential

3.3.1 Biochar

One major use for biochar as an amendment that is currently under consideration is its ability to reduce the rate and impacts of climate change. Biochar has been labeled a carbon sink when applied to soil due to its stable, aromatic forms of organic carbon that have relatively long resident times (Sohi et al., 2010). Since biochar is formed through pyrolysis, much less carbon is emitted as CO_2 than ordinary combustion (Sohi et al., 2010). In fact, according to the International Energy Agency (2016), 30-40% of pyrolysis feedstock mass may be recovered in the form of biochar, especially when using lower temperature pyrolysis.

To date, biochar is being investigated as a carbon sink, but not widely used as such because of opposing research results. Another proposed benefit of biochar application for soil is improved soil quality in agricultural fields (Jeffery et al., 2011). Improving agricultural productivity is considered an indirect contributor to reducing our greenhouse gas emissions because it reduces the conversion of forests to farmland in order to meet rising food demands (Galinato et al., 2011).

The recent use of biochar as a soil amendment for degraded sites in varying environments (forest, rangeland, waste piles, etc.) is a third use with potentially global effects. Reclaiming un-vegetated sites in forests through amendment application not only adds a stable form of carbon back to the soil, but increases the filtration that vegetation naturally performs through converting CO_2 to oxygen. A leading problem for all three of these uses for biochar is the cost of acquiring large enough biochar quantities to induce the desired effects, whether they be storage of C, increased crop productivity, or accelerated re-vegetation of disturbed sites.

The quantitative review of biochar's effectiveness for increasing crop productivity by Jeffery et al. (2011) cross-referenced 16 biochar studies in the past decade. They found that positive results for crop productivity from biochar application ranged from application rates of 7 - >73 ton ha^{-1} with the higher quantities having greater effects. In the 2014 State of the Biochar Industry report published by the International Biochar Initiative, the average retail price of biochar was US $3.08 kg or $2,794 ton. For large farm owners, these costs accelerate quickly. Much of the cost of biochar stems from the quality of the feedstock that was used to make it.

National forests have a surplus of woody biomass waste that could be used to produce biochar. As is, forests already contribute to carbon storage, but on a much shorter time scale than biochar. Fallen trees in the majority of inland Northwest forests take between 21-111 years to fully degrade depending on tree species and microclimate (Edmonds 1990) and carbon is then re-introduced to the carbon cycle. If this same wood was transformed to biochar, the carbon cycle is put on hold for up to 1600 years depending on biochar type, environment and pyrolysis method (Singh et al., 2012, Sohi et al., 2010) until the recalcitrant char is degraded.

3.3.2. Biosolids

Total available nutrients were greatest in the biosolids treated soils. Figure 3.1 shows the sum of the nutrient availability recovered from the resin capsules (see section 2.9) from three sampling times over 19 months. The available nutrients from biosolids were sufficient to promote dense plant cover on a six-inch soil cap that had been un-vegetated for over thirty years. These results show that biosolids are an effective method for restoring plant cover, if seed and plants are also introduced at the same time, on nutrient-poor forest soils. This conclusion has been presented in other biosolid studies of forest soils (Logsdon 1993, Brown et al. 2003, Haering et al. 2000, Bendfeldt et al. 2001).

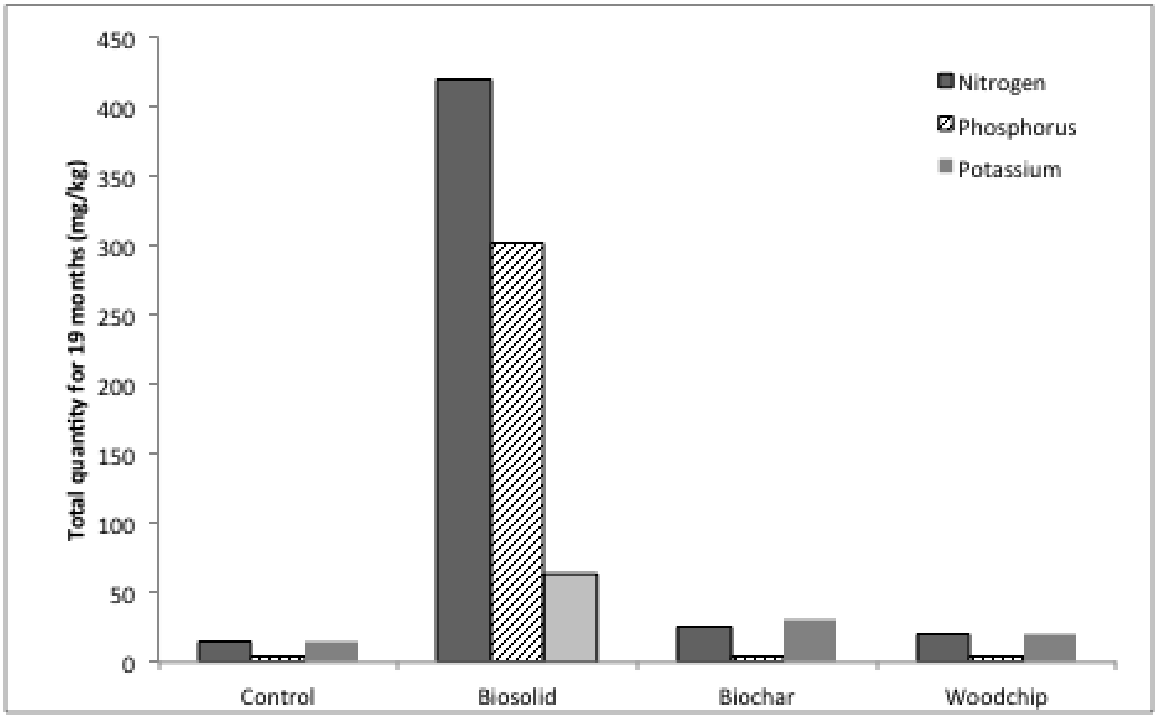

Figure 3.1. Summed available nitrogen, phosphorus and potassium from ion resin capsule from three sampling times during the 19 months of study.

Class A biosolids meet pathogen reduction requirements from the EPA as having virtually no pathogens (Walker et al. 1994). These are considered the Exceptional Quality (EQ) biosolids, as compared to the Pollutant Concentration (PC) biosolids of Class B. Class A biosolids use is unregulated; they may be sold or given away and land applied in bulk with no monitoring of metal loading. Oregon National Forests can use local city biosolid waste for reclamation of their disturbed sites and cities can better dispose of their biosolids without fighting the social stigmas about the byproduct being land applied to agricultural fields. As forests land is not used for crops and metal loading is not as much of a concern, multiple applications may be possible. More research into how many applications cause buildup of immobile elements is needed in forest ecosystems as well as nutrient loading that may become toxic to the forest plants, wildlife, and grazing cattle.

3.3.3. Woodchips

In this study, woodchips had a significant effect on plant growth (Figure 2.12) although they added very little plant available nutrients in the first two years. Pressure plate results did not show a significant effect on soil water holding capacity at either sampling depths in the woodchip-treated soils. In woodchip treatments, it was observed that nitrogen was nearly depleted, suggesting that both plants and microbes were using available nitrogen (Cardoso et al., 2013).

The improvements seen in increased plant cover from the biosolid and woodchip treatments apply to other environments where reclamation of degraded soil is needed. For example, in areas of the arid Great Basin region of the U.S., abandoned agricultural fields have increased steadily since the early 1990's due to low fertility (USDA National Agricultural Statistics Service, 2012). Problems from abandoned farmland include substantial wind erosion and exotic plant invasion (Porensky et al., 2014). Soil remediation measures must be taken to preserve soil and maintain ecosystem stability. Studies have been done using irrigation measures to try to counter the lack of natural precipitation required to re-establish vegetation (Porensky et al., 2014, Roundy et al., 2001). Surface applied woodchips have the potential to not only increase soil moisture, but also reduce erosion by providing protection and increasing plant growth and root systems.

Surface application is an important aspect of a woodchip reclamation strategy to increase soil moisture. A reclamation pot study done by Gebhardt (2015) on arid Arizona soils revealed that woodchips, when incorporated into the soil at 4% and 8%, significantly increased drainage and decreased plant growth. Avoiding this would be important when reclaiming abandoned mine land or tailings piles with little soil cover where water loss from drainage is prevalent.

Erosion can be a common problem in forest environments after logging, road building and livestock movement (Belsky and Blumenthal 1997). Cattle grazing alone can reduce the forest floor litter layer by 40% to 60%, and expose up to 400% more bare ground than ungrazed areas (Tucker and Leininger, 1990), greatly reducing soil organic matter and nutrients. With reduced nutrients, plant recovery from grazing is slowed. Compaction from grazing reduces infiltration and increases run-off, greatly increasing erosion (Belsky and Blumenthal 1997). Surface applied biosolids and woodchips address the issues of lowered nutrient and protection of bare soil. They are an easily applied amendment strategy that is cheap, effective and natural.

3.4. Conclusions

As climate change continually gains awareness, and research focuses on ways to lower the global carbon footprint, alternative methods to established practices are needed in all areas of land management. The research presented in this thesis showed that biosolids, woodchips and biochar, in combination, create an improved soil environment for increasing plant cover. Each of these products is an organic waste that, when recycled and put to beneficial use, directly and indirectly lower the overall contribution to global warming. For example, both biosolids and woody biomass from forests are commonly burned as a means of disposal, releasing greenhouse gasses into the atmosphere (EPA 1999). Using them as organic amendments retains carbon in a stable form and provides nutrients and physical benefits when applied to soils. By re-vegetating barren land with biosolids, biochar and woodchips, forest managers have the opportunity to increase forest productivity with reduced cost, re-use waste materials, and bolster the forests' contribution to reducing CO_2 in the atmosphere.

3.5. Literature Cited

Belsky, A.J. and D. M. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior west. Conserv. Biol. 11(2):315–327.

Cardoso et al. 2013. Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? Sciencia Agricola. 70(4):274-289.

Chaney, D.E., L.E. Drinkwater, and G.S. Pettygrove. 1999. Organic soil amendments and fertilizers. University of California, Oakland, CA.

Collins, H, D. Granatstein, C. Kruger, M. Garcia-Perez and J. Yoder. 2009. Use of biochar from the pyrolysis of waste organic material as a soil amendment: laboratory and greenhouse analyses: Final Report. Center for Sustaining Agriculture and Natural Resources. Washington State University.

Das, K. C., M. Garcia-Perez, B. Bibens, and N. Melear. (2008). Slow pyrolysis of poultry litter and pine woody biomass: Impact of chars and bio-oils on microbial growth. J. Environ. Sci. Health: Part A 43:714–724.

Edmonds, R. L. 1990. Organic matter decomposition in western United States forests. Symposium on Management and Productivity of Western-Montana Forest Soils. Boise, ID. Accessed at: SOLO: USFS Rocky Mountain Research Station.

EPA. 1999. Biosolids generation, use, and disposal in The United States.
Office of Solid Waste. Washington, DC.

Gebhardt, M.M. 2015. Soil amendment effects on degraded soils and consequences for plant growth. MS Thesis. University of Arizona. Tucson, Arizona.

Jeffery, S., F.G.A. Verheijen, M. Van der Velde and A.C. Bastos. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144:175–187.

Larney, F. J. and D. A. Angers. 2012. The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science. 92(1):19-38.

Logsdon, G. 1993. Thirty years of land reclamation with biosolids. Biocycle. 34(10):51.

Porensky, L.M., E.A. Leger, J. Davison, W.W. Miller, E.M. Goergen, E.K. Espeland and E.M. Carroll-Moore. 2014. Arid old-field restoration: Native perennial grasses suppress weeds and erosion, but also suppress native shrubs. Agric. Ecosyst. Environ. 184:135–144.

Roundy, B. A., H. Heydari, C. Watson, S.E. Smith, B. Munda and M. Pater. 2001. Summer establishment of sonoran desert species for revegetation of abandoned farmland using line source sprinkler irrigation. Arid L. Res. Manag. 15:23–39.

Schulz, H.,G. Dunst and B. Glaser, B. 2013. Positive effects of composted biochar on plant growth and soil fertility. Agron. Sustain. Dev. 33:817–827.

Singh, B.P., Cowie, A.L., Smernik, R.J., 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environ. Sci. Technol. 46:11770–11778.

International Biochar Initiative. 2014. State of the Biochar Industry. [Online] Available at www.biochar-international.org/State_of_industry_2014.

Appendix A: Raw Data

Table A-1: 2015 Soil Properties

Treatment	Rep	Depth	pH	EC (uS/cm)	CEC (cmolc/kg)	OC (%)
Control	1	0-3 cm	5.6	384	18.7	3.5
		3-12 cm	5.6	307	17.1	3.6
Control	2	0-3 cm	5.3	244	17.1	3.9
		3-12 cm	5.6	491	24.3	3.7
Control	3	0-3 cm	5.4	2240	17.3	3.8
		3-12 cm	5.7	177.7	16.3	3.7
Biosolids	1	0-3 cm	6.4	586	28.3	6.3
		3-12 cm	5.3	288	20.0	3.7
Biosolids	2	0-3 cm	6.5	537	29.4	8.8
		3-12 cm	5.4	284	16.9	3.8
Biosolids	3	0-3 cm	6.6	631	26.7	9.4
		3-12 cm	5.2	332	17.4	3.9
Biochar	1	0-3 cm	5.6	95.7	21.4	4.6
		3-12 cm	4.9	94.6	21.1	4.3
Biochar	2	0-3 cm	5.7	52.5	17.3	4.2
		3-12 cm	5.2	56.5	18.7	3.5
Biochar	3	0-3 cm	5.9	50.7	17.4	4.4
		3-12 cm	5.7	35.5	17.6	3.6
Woodchips	1	0-3 cm	5.6	1337	15.9	3.9
		3-12 cm	5.6	505	16.6	3.8
Woodchips	2	0-3 cm	5.3	712	17.9	5.0
		3-12 cm	5.6	220	17.7	4.2
Woodchips	3	0-3 cm	5.4	456	17.9	4.4
		3-12 cm	5.7	326	17.9	4.1
Biosolids+Biochar	1	0-3 cm	6.4	630		11.5
		3-12 cm	5.6	383		4.4
Biosolids+Biochar	2	0-3 cm	6.2	486		7.2
		3-12 cm	5.2	247		4.0
Biosolids+Biochar	3	0-3 cm	5.9	233		5.5
		3-12 cm	5.2	109		4.1
Biosolids+Woodchips	1	0-3 cm	5.6	494		5.6
		3-12 cm	5.5	346		4.3
Biosolids+Woodchips	2	0-3 cm	5.9	531		5.4
		3-12 cm	5.7	162.3		3.9
Biosolids+Woodchips	3	0-3 cm	6.3	351		6.6
		3-12 cm	6.7	42.2		3.5
Biochar+Woodchips	1	0-3 cm	5.8	32.4		6.7
		3-12 cm	4.8	28.2		4.0
Biochar+Woodchips	2	0-3 cm	5.9	31.2		5.9
		3-12 cm	5.9	33.7		4.3
Biochar+Woodchips	3	0-3 cm	6.0	44.2		4.3
		3-12 cm	5.5	331		3.7
Biochar+Woodchips	4	0-3 cm	6.2	39.4		5.0
		3-12 cm	6.1	32.9		3.7
Biosolids+Biochar+ Woodchips	1	0-3 cm	5.9	542		7.7
		3-12 cm	5.5	226		3.1
Biosolids+Biochar+ Woodchips	2	0-3 cm	5.9	474		6.6
		3-12 cm	5.7	200		3.9
Biosolids+Biochar+ Woodchips	3	0-3 cm	6.3	667		6.3
		3-12 cm	6.7	258		4.1
Reference	1				18.6	7.25
Reference	2				21.3	7.13
Reference	3				18.3	7.19
Reference	4				21.1	7.30
Reference	5				22.4	7.25
Reference	6				22.6	7.25
Reference	7					7.20
Reference	8					7.26

Table A-2: 2015 Nitrogen Measurements

Treatment	Rep	Depth	NO3 (mg/kg)	NH4 (mg/kg)	Mineralized NO3 (mg/kg)	Mineralized NH4 (mg/kg)	Total-N (%)
Control	1	0-3 cm	10.34	19.58	<BMDL	78.11	0.0012
		3-12 cm	6.65	0.54	<BMDL	27.30	0.0116
Control	2	0-3 cm	5.08	9.85	<BMDL	66.07	0.0327
		3-12 cm	2.73	0.54	<BMDL	26.52	0.0379
Control	3	0-3 cm	5.16	14.63	<BMDL	46.56	0.0194
		3-12 cm	5.09	1.57	<BMDL	27.05	0.0138
Biosolids	1	0-3 cm	108.65	316.24	0.40	825.16	0.4655
		3-12 cm	43.06	68.86	<BMDL	79.07	0.0251
Biosolids	2	0-3 cm	102.66	601.54	0.85	1,382.40	0.8332
		3-12 cm	50.79	159.13	0.60	170.75	0.0709
Biosolids	3	0-3 cm	115.50	518.44	0.19	995.00	0.9011
		3-12 cm	45.81	72.53	<BMDL	81.66	0.0805
Biochar	1	0-3 cm	16.16	107.28	<BMDL	228.56	0.1098
		3-12 cm	17.03	6.54	1.15	25.18	0.0717
Biochar	2	0-3 cm	5.06	0.88	<BMDL	47.86	0.0031
		3-12 cm	5.49	0.64	<BMDL	4.13	0.0000
Biochar	3	0-3 cm	6.77	7.85	<BMDL	54.99	0.0149
		3-12 cm	2.28	0.59	<BMDL	27.36	0.0034
Woodchips	1	0-3 cm	2.18	2.30	<BMDL	67.92	0.0324
		3-12 cm	1.76	0.94	<BMDL	26.64	0.0057
Woodchips	2	0-3 cm	6.26	5.45	<BMDL	124.52	0.1011
		3-12 cm	2.31	0.85	<BMDL	27.54	0.0748
Woodchips	3	0-3 cm	2.09	3.90	<BMDL	68.85	0.0498
		3-12 cm	0.92	0.89	<BMDL	27.77	0.0564
Biosolids+Biochar	1	0-3 cm	133.69	299.52	0.19	177.54	0.9002
		3-12 cm	39.50	102.32	<BMDL	969.23	0.0992
Biosolids+Biochar	2	0-3 cm	102.49	443.87	0.27	78.17	0.4878
		3-12 cm	45.19	68.66	0.22	136.30	0.0570
Biosolids+Biochar	3	0-3 cm	77.68	89.69	0.21	1,065.07	0.1186
		3-12 cm	9.45	0.65	<BMDL	24.47	0.0241
Biosolids+Woodchips	1	0-3 cm	106.92	220.55	0.39	405.54	0.2955
		3-12 cm	56.51	55.27	0.20	116.34	0.1212
Biosolids+Woodchips	2	0-3 cm	124.79	139.55	0.27	373.91	0.2681
		3-12 cm	21.61	5.69	<BMDL	28.05	0.0332
Biosolids+Woodchips	3	0-3 cm	61.56	374.54	<BMDL	489.05	0.41997
		3-12 cm	30.60	202.95	0.21	255.22	0.010335
Biochar+Woodchips	1	0-3 cm	2.55	2.42	<BMDL	79.52	0.084885
		3-12 cm	1.30	0.98	<BMDL	27.35	0.049675
Biochar+Woodchips	2	0-3 cm	2.10	1.26	<BMDL	55.19	0.07041
		3-12 cm	1.27	0.78	<BMDL	27.58	0.0678
Biochar+Woodchips	3	0-3 cm	5.93	3.82	<BMDL	55.80	0.005155
		3-12 cm	1.84	0.57	<BMDL	28.559	0.04229
Biochar+Woodchips	4	0-3 cm	1.42	1.03	<BMDL	44.99	0.01268
		3-12 cm	1.54	0.51	<BMDL	27.15	0
Biosolids+Biochar+ Woodchips	1	0-3 cm	138.61	336.05	0.99	583.65	0.35475
		3-12 cm	45.53	33.71	2.69	86.33	0
Biosolids+Biochar+ Woodchips	2	0-3 cm	111.07	82.40	0.65	358.93	0.37231
		3-12 cm	35.36	9.63	<BMDL	90.12	0.0395
Biosolids+Biochar+ Woodchips	3	0-3 cm	190.01	272.59	0.34	579.25	0.36363
		3-12 cm	39.41	25.16	<BMDL	79.44	0.05076
Reference	1		120.992344	37.4617157	<BMDL	21.43	0.0567
Reference	2				<BMDL	20.83	0.0625
Reference	3						0.0603
Reference	4						0.0757
Reference	5						0.0691
Reference	6						0.0611
Reference	7						0.0516
Reference	8						0.0723

Table A-3: 2015 Mehlich-3 Nutrient Results

Treatment	Rep	Depth	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	S (mg/kg)	Al (mg/kg)	Fe (mg/kg)
Control	1	0-3 cm	8.69	129.55	1590.00	707.43	8.41	631.19	156.34
		3-12 cm	17.76	190.84	1501.50	644.06	4.70	674.26	116.63
Control	2	0-3 cm	10.72	160.69	1645.50	605.94	5.78	778.22	158.61
		3-12 cm	5.75	105.52	1646.00	628.22	5.31	750.00	177.77
Control	3	0-3 cm	14.50	177.16	1662.00	660.89	3.89	684.65	136.29
		3-12 cm	5.60	123.93	1703.50	707.92	4.69	667.33	178.51
Biosolid	1	0-3 cm	976.73	312.73	2656.00	956.93	25.89	522.77	160.69
		3-12 cm	95.40	137.11	1512.00	679.21	12.09	617.33	174.85
		3-12 cm	95.40	134.37	1497.50	672.77	11.55	615.35	168.91
		3-12 cm	95.79	136.46	1520.00	682.18	11.74	617.33	169.01
Biosolid	2	0-3 cm	1273.76	313.58	3334.50	1107.92	30.26	524.75	160.89
		3-12 cm	120.99	141.84	1264.50	518.81	14.31	750.50	214.36
Biosolid	3	0-3 cm	1479.70	415.07	3306.00	1130.20	37.36	513.37	180.40
		3-12 cm	179.85	158.90	1635.50	687.62	14.47	736.14	212.52
Biochar	1	0-3 cm	72.23	231.04	1830.50	575.74	7.57	753.47	156.29
		3-12 cm	7.76	110.04	1573.00	557.92	6.52	859.90	217.67
Biochar	2	0-3 cm	22.50	159.20	1444.00	587.13	4.20	718.32	128.51
		3-12 cm	6.03	112.23	1383.00	630.20	3.18	610.40	140.05
		3-12 cm	5.75	119.00	1441.00	668.81	3.13	597.03	133.86
		3-12 cm	6.23	122.88	1430.50	658.91	3.39	605.45	142.28
Biochar	3	0-3 cm	12.40	190.54	1420.50	616.83	3.48	645.05	126.44
		3-12 cm	5.23	126.76	1607.50	715.35	3.17	625.74	161.93
Woodchip	1	0-3 cm	11.84	178.55	1437.50	629.21	5.48	636.14	131.73
		3-12 cm	5.67	123.28	1526.00	676.24	4.34	611.88	175.20
Woodchip	2	0-3 cm	14.23	220.19	1518.00	569.31	4.06	749.50	132.52
		3-12 cm	6.56	130.99	1514.50	571.78	2.95	775.25	180.59
Woodchip	3	0-3 cm	11.19	171.39	1456.50	605.94	5.12	710.89	153.17
		3-12 cm	5.11	120.64	1584.00	645.54	5.07	735.64	207.67
BS/BC	1	0-3 cm	1656.44	347.41	3726.00	1253.96	34.82	507.43	156.78
		0-3 cm	1810.40	353.48	4026.00	1327.72	36.83	485.99	159.95
		0-3 cm	1714.85	350.04	3814.00	1286.14	35.36	480.45	154.55
		3-12 cm	389.65	229.00	1797.50	736.63	17.84	745.54	198.96
BS/BC	2	0-3 cm	886.14	352.48	2851.00	964.36	26.24	709.41	184.50
		3-12 cm	45.97	125.42	1422.50	556.44	11.99	820.79	207.87
BS/BC	3	0-3 cm	205.99	218.60	1795.50	660.89	9.78	747.52	159.60
		3-12 cm	7.04	119.05	1556.50	595.54	27.35	795.05	200.15
W/BS	1	0-3 cm	510.40	240.04	2366.00	777.23	20.32	790.10	193.12
		3-12 cm	193.56	130.94	1702.50	601.98	14.89	760.40	191.83
W/BS	2	0-3 cm	543.07	325.07	2292.50	849.50	13.28	700.50	180.64
		3-12 cm	51.78	119.90	1644.50	674.26	6.80	710.40	191.44
W/BS	3	0-3 cm	840.59	242.13	2370.50	855.94	16.03	630.69	172.48
		3-12 cm	4.54	136.46	1574.00	680.69	3.15	718.32	169.16
W/BC	1	0-3 cm	14.39	210.54	1575.50	564.85	5.46	853.47	169.65
		3-12 cm	5.01	137.31	1477.00	571.78	5.23	836.63	196.78
W/BC	2	0-3 cm	8.94	189.60	1603.50	556.44	10.47	848.51	184.06
		3-12 cm	3.58	124.82	1773.00	648.51	5.15	884.65	219.46
W/BC	3	0-3 cm	17.16	187.91	1501.50	603.47	3.08	787.13	141.78
		3-12 cm	238.71	183.63	1490.50	621.29	9.86	680.69	191.09
		3-12 cm	243.12	186.81	1528.00	639.11	9.86	683.66	188.22
		3-12 cm	234.36	189.65	1497.50	624.26	10.01	673.27	183.96
W/BC	4	0-3 cm	13.64	199.10	1620.00	639.11	4.00	746.04	154.41
		3-12 cm	5.83	141.94	1719.00	714.36	4.55	728.22	178.81
W/BS/BC	1	0-3 cm	639.60	272.43	2438.50	783.66	23.74	763.37	179.01
		3-12 cm	38.03	108.65	1011.00	418.27	10.78	664.85	161.53
W/BS/BC	2	0-3 cm	646.53	287.41	2378.50	830.20	15.39	598.51	169.95
		3-12 cm	138.27	164.72	1769.50	745.54	9.50	699.01	185.69
W/BS/BC	3	0-3 cm	900.99	380.79	2547.00	903.96	22.12	644.06	178.61
		3-12 cm	89.65	147.76	1667.00	669.80	12.26	727.72	202.03
		3-12 cm	88.96	150.34	1731.50	692.57	11.70	750.50	198.66
		3-12 cm	83.07	139.10	1608.50	638.61	10.75	705.45	187.18
Blank			0.00	0.71	0.00	0.00	0.00	0.00	0.00
Blank			0.00	0.70	0.00	0.00	0.00	0.00	0.00
Blank			0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A-4: 2015 Pressure Plate Results

Treatment	Rep	Depth	FC (%)	Average-FC (%)	PWP (%)	Average-PWP (%)	PAW (%)
Control	1	0-3 cm	23.05	23.26	12.58	12.58	10.68
			23.46		12.58		
		3-12cm	23.95	24.00	13.82	13.67	10.33
			24.05		13.52		
Control	2	0-3 cm	24.83	24.89	14.01	14.22	10.67
			24.95		14.43		
		3-12cm	23.38	23.30	13.15	13.35	9.95
			23.21		13.54		
Control	3	0-3 cm	24.10	23.67	13.33	13.37	10.3
			23.24		13.42		
		3-12cm	23.65	23.84	13.85	13.69	10.15
			24.03		13.53		
Biochar	1	0-3 cm	29.31	28.53	14.94	14.65	14.37
			27.75		14.36		
		3-12cm	27.52	27.39	15.15	15.05	12.37
			27.26		14.95		
Biochar	2	0-3 cm	25.23	23.86	11.92	12.02	13.31
			22.49		12.12		
		3-12cm	25.14	25.07	12.06	11.96	13.09
			25.00		11.86		
Biochar	3	0-3 cm	25.32	24.94	11.92	11.81	13.41
			24.55		11.71		
		3-12cm	25.11	24.48	13.40	13.16	11.72
			23.84		12.93		
Biosolid	1	0-3 cm	29.89	30.40	15.56	15.60	14.33
			30.91		15.64		
		3-12cm	23.56	24.28	12.98	12.77	10.59
			25.00		12.57		
Biosolid	2	0-3 cm	39.33	39.43	23.29	23.16	16.04
			39.53		23.03		
		3-12cm	21.87	23.12	11.10	11.32	10.76
			24.37		11.53		
Biosolid	3	0-3 cm	34.63	34.59	18.51	18.48	16.12
			34.55		18.45		
		3-12cm	24.02	25.50	12.62	12.81	11.41
			26.98		13.01		
Woodchips	1	0-3 cm	25.75	24.81	12.45	12.68	12.13
			23.87		12.91		
		3-12cm	26.46	26.39	13.84	14.02	12.37
			26.33		14.19		
Woodchips	2	0-3 cm	32.47	32.93	14.71	14.91	18.03
			33.40		15.11		
		3-12cm	28.63	29.42	15.56	15.70	13.72
			30.21		15.84		
Woodchips	3	0-3 cm	26.45	27.12	13.76	13.90	13.22
			27.80		14.04		
		3-12cm	26.96	27.24	15.60	15.30	11.95
			27.53		14.99		

Table A-4 Continued

Biosolid+Biochar	1	0-3 cm	40.26	41.38	32.98	30.85	10.53
			42.50		28.72		
		3-12cm	24.95	24.93	14.05	13.82	11.1
			24.90		13.59		
Biosolid+Biochar	2	0-3 cm	34.52	34.13	18.99	19.12	15.02
			33.74		19.24		
		3-12cm	25.54	25.66	14.00	13.72	11.94
			25.79		13.44		
Biosolid+Biochar	3	0-3 cm	29.35	29.03	12.63	12.43	16.6
			28.71		12.24		
		3-12cm	24.66	24.65	13.10	13.00	11.64
			24.63		12.91		
Biosolid+Woodchips	1	0-3 cm	32.06	31.64	16.78	17.07	14.57
			31.22		17.37		
		3-12cm	25.40	25.24	14.16	13.50	11.96
			25.09		12.84		
Biosolid+Woodchips	2	0-3 cm	31.11	30.98	15.46	15.51	15.47
			30.85		15.56		
		3-12cm	25.31	25.74	13.74	14.34	11.01
			26.17		14.94		
Biosolid+Woodchips	3	0-3 cm	28.38	27.12	16.07	16.21	10.91
			25.86		16.35		
		3-12cm	25.77	25.36	13.50	13.36	12.01
			24.96		13.21		
Biochar+Woodchips	1	0-3 cm	28.27	28.30	14.22	14.11	14.36
			28.33		14.00		
		3-12cm	24.97	25.20	13.66	13.64	11.55
			25.43		13.62		
Biochar+Woodchips	2	0-3 cm	31.69	32.61	14.26	14.21	18.4
			33.52		14.15		
		3-12cm	29.86	29.58	14.91	14.89	14.69
			29.30		14.86		
Biochar+Woodchips	3	0-3 cm	28.91	28.17	11.94	11.99	16.97
			27.43		12.04		
		3-12cm	27.24	25.19	12.19	12.02	15.04
			24.85		11.85		
			23.49				
Biochar+Woodchips	4	0-3 cm	28.08	28.08	13.39	13.36	14.69
			29.22		13.32		
		3-12cm	26.17	26.17	13.24	13.21	12.93
			25.50		13.18		
Biosolid+Biochar+ Woodchips	1	0-3 cm	34.42	34.42	16.71	17.18	17.71
			34.06		17.66		
		3-12cm	19.56	19.56	9.59	9.66	9.97
			20.89		9.73		
Biosolid+Biochar+ Woodchips	2	0-3 cm	31.39	31.39	15.86	15.75	15.53
			31.59		15.64		
		3-12cm	27.79	27.79	13.90	14.13	13.89
			26.99		14.36		
Biosolid+Biochar+ Woodchips	3	0-3 cm	30.09	30.09	16.83	16.58	13.26
			30.81		16.32		
		3-12cm	26.08	26.08	13.99	13.95	12.91
			27.64		13.91		
Reference	1	Top	29.31		10.47		
		Bottom	28.41		10.29		
Reference	2	Top	29.73		10.92		
			28.79		10.61		
		Bottom	27.08				
			29.77				
Reference	3	Top	29.97		11.07		
			29.72		11.03		
		Bottom	29.99				
			29.53				

Table A-5: 2016 Soil Properties

Treatment	Rep	Depth	pH	EC (uS/cm)	CEC (cmolc/kg)	OC (%)
Control	1	0-3 cm	5.74	37.7	5.4	3.50
		3-12 cm	6.05	28.2	4.0	3.58
Control	2	0-3 cm	5.35	45.3	6.5	3.95
		3-12 cm	5.41	41	5.9	4.13
Control	3	0-3 cm	5.95	38.4	5.5	3.38
		3-12 cm	5.97	27.8	4.0	3.65
Biosolids	1	0-3 cm	5.93	176.4	15.7	5.11
		3-12 cm	5.37	109.8	54.7	3.52
Biosolids	2	0-3 cm	6.01	383	23.6	6.67
		3-12 cm	5.16	165	29.1	4.05
Biosolids	3	0-3 cm	5.85	204	12.5	4.92
		3-12 cm	5.49	87.6	7.5	3.64
Biochar	1	0-3 cm	5.94	52.3	4.9	4.91
		3-12 cm	5.54	28.3	3.4	4.12
Biochar	2	0-3 cm	6.12	34.4	5.1	3.89
		3-12 cm	6.07	23.9	4.1	3.59
Biochar	3	0-3 cm	5.94	35.8	7.4	3.97
		3-12 cm	6.08	28.8	4.3	3.67
Woodchips	1	0-3 cm	5.83	52	3.4	4.04
		3-12 cm	5.90	29.9	4.2	3.59
Woodchips	2	0-3 cm	6.00	33.9	3.1	4.15
		3-12 cm	5.93	24.1	21.8	3.49
Woodchips	3	0-3 cm	5.88	29.6	17.3	4.76
		3-12 cm	5.72	21.5	25.6	4.06
Biosolids+Biochar	1	0-3 cm	5.62	152.3		5.45
		3-12 cm	4.90	121		3.56
Biosolids+Biochar	2	0-3 cm	5.34	179		5.39
		3-12 cm	5.03	152.9		3.63
Biosolids+Biochar	3	0-3 cm	5.81	233		6.05
		3-12 cm	5.09	155.6		3.63
Biosolids+Woodchips	1	0-3 cm	5.36	118.2		5.13
		3-12 cm	5.01	49.5		3.17
Biosolids+Woodchips	2	0-3 cm	5.65	120.9		5.57
		3-12 cm	5.14	71.8		3.54
Biosolids+Woodchips	3	0-3 cm	5.75	162.4		5.81
		3-12 cm	5.20	103.8		5.04
Biochar+Woodchips	1	0-3 cm	5.49	26.6		5.06
		3-12 cm	5.22	26		3.98
Biochar+Woodchips	2	0-3 cm	5.41	33.4		4.78
		3-12 cm	5.1	22.1		3.99
Biochar+Woodchips	3	0-3 cm	5.56	26.9		4.05
		3-12 cm	5.46	23.7		3.30
Biochar+Woodchips	4	0-3 cm	5.34	43.1		4.97
		3-12 cm	5.26	23.4		3.48
Biosolids+Biochar+ Woodchips	1	0-3 cm	5.58	214		6.18
		3-12 cm	5.03	82.1		4.00
Biosolids+Biochar+ Woodchips	2	0-3 cm	5.04	79		5.76
		3-12 cm	5.13	88.2		3.62
Biosolids+Biochar+ Woodchips	3	0-3 cm	5.53	90		4.19
		3-12 cm	5.26	37.7		3.50
Ref	1				18.6	7.19
Ref	2				21.3	7.17
Ref	3				18.3	7.20
Ref	4				21.1	7.22
Ref	5				22.4	7.16
Ref	6				22.6	

Table A-6: 2016 Nitrogen Measurements

Treatment	Rep	Depth	NO3 (mg/kg)	NH4 (mg/kg)	Mineralized NO3 (mg/kg)	Mineralized NH4 (mg/kg)	Total-N (%)
Control	1	0-3 cm	4.35	5.55	<BMDL	45.87	0.01
		3-12 cm	2.90	0.48	<BMDL	18.83	0.01
Control	2	0-3 cm	6.93	11.43	0.28	55.73	0.07
		3-12 cm	2.34	0.71	<BMDL	37.90	0.09
Control	3	0-3 cm	5.57	6.77	<BMDL	43.64	0.00
		3-12 cm	3.49	0.84	<BMDL	19.95	0.01
Biosolids	1	0-3 cm	25.77	41.09	0.18	158.42	0.25
		3-12 cm	9.48	54.58	1.52	73.81	0.04
Biosolids	2	0-3 cm	117.01	105.81	<BMDL	360.59	0.46
		3-12 cm	26.45	43.73	0.59	58.00	0.07
Biosolids	3	0-3 cm	43.21	21.83	<BMDL	119.13	0.22
		3-12 cm	15.39	1.55	<BMDL	20.33	0.01
Biochar	1	0-3 cm	7.41	4.06	<BMDL	47.07	0.07
		3-12 cm	4.18	1.18	<BMDL	20.99	0.07
Biochar	2	0-3 cm	4.08	4.56	<BMDL	42.22	0.01
		3-12 cm	2.57	0.75	<BMDL	19.36	0.00
Biochar	3	0-3 cm	7.23	2.97	<BMDL	33.74	0.00
		3-12 cm	2.58	1.00	<BMDL	20.33	0.01
Woodchips	1	0-3 cm	0.43	0.85	<BMDL	53.99	0.00
		3-12 cm	0.57	0.57	<BMDL	19.59	0.00
Woodchips	2	0-3 cm	1.90	1.96	<BMDL	56.85	0.01
		3-12 cm	1.15	0.59	<BMDL	20.58	0.00
Woodchips	3	0-3 cm	1.67	0.84	<BMDL	47.92	0.02
		3-12 cm	0.72	0.68	<BMDL	19.63	0.05
Biosolids+Biochar	1	0-3 cm	24.82	16.01	<BMDL	70.03	0.25
		3-12 cm	9.04	18.25	1.78	30.66	0.01
Biosolids+Biochar	2	0-3 cm	39.52	34.04	<BMDL	129.83	0.20
		3-12 cm	21.49	38.17	<BMDL	45.01	0.02
Biosolids+Biochar	3	0-3 cm	53.35	53.11	10.54	259.82	0.38
		3-12 cm	27.99	39.20	6.97	45.88	0.03
Biosolids+Woodchips	1	0-3 cm	23.84	5.40	<BMDL	154.48	0.21
		3-12 cm	7.01	2.02	0.25	13.20	0.00
Biosolids+Woodchips	2	0-3 cm	9.74	14.23	<BMDL	129.58	0.30
		3-12 cm	10.13	6.57	<BMDL	28.78	0.02
Biosolids+Woodchips	3	0-3 cm	27.47	14.66	<BMDL	168.00	0.33
		3-12 cm	19.20	9.16	<BMDL	34.15	0.23
Biochar+Woodchips	1	0-3 cm	2.22	0.53	<BMDL	47.66	0.05
		3-12 cm	0.59	0.68	<BMDL	20.31	0.05
Biochar+Woodchips	2	0-3 cm	2.37	0.68	<BMDL	78.03	0.04
		3-12 cm	1.25	0.80	<BMDL	21.78	0.05
Biochar+Woodchips	3	0-3 cm	1.74	1.22	<BMDL	44.39	0.00
		3-12 cm	1.40	0.66	<BMDL	18.70	0.00
Biochar+Woodchips	4	0-3 cm	2.14	1.74	<BMDL	71.27	0.03
		3-12 cm	1.23	0.67	<BMDL	27.59	0.00
Biosolids+Biochar+ Woodchips	1	0-3 cm	38.65	10.27	<BMDL	154.18	0.29
		3-12 cm	7.36	1.78	<BMDL	9.89	0.04
Biosolids+Biochar+ Woodchips	2	0-3 cm	19.19	5.56	<BMDL	109.74	0.24
		3-12 cm	12.70	1.39	<BMDL	3.38	0.01
Biosolids+Biochar+ Woodchips	3	0-3 cm	11.25	3.29	<BMDL	48.31	0.05
		3-12 cm	7.91	----	<BMDL	6.85	0.00
Reference	1		117.4378	40.8392	<BMDL	20.06	0.07581
Reference	2				<BMDL	19.84	0.05296
Reference	3						0.06688
Reference	4						0.05173
Reference	5						0.05330

Table A-7: 2016 Mehlich-3 Nutrient Results

Treatment	Rep	Depth	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	S (mg/kg)	Al (mg/kg)	Fe (mg/kg)
Control	1	0-3 cm	15.50	184.10	1670.50	670.00	4.12	911.00	153.90
		3-12 cm	7.83	175.00	2104.50	874.00	2.85	980.00	210.00
Control	2	0-3 cm	12.09	149.95	1794.50	624.00	5.32	962.50	207.60
		3-12 cm	5.51	123.30	2052.00	721.50	5.68	968.00	232.40
Control	3	0-3 cm	18.15	170.35	1560.00	609.50	2.57	860.00	149.50
		3-12 cm	6.86	126.85	1621.50	648.00	1.61	741.50	160.45
Biosolid	1	0-3 cm	1000.50	296.75	3246.00	1009.00	12.84	826.50	238.35
		3-12 cm	207.10	193.35	1665.50	698.50	4.57	795.00	214.10
		3-12 cm	267.95	264.50	2243.50	966.00	6.66	1092.50	296.50
		3-12 cm	246.90	233.15	2011.00	850.00	5.94	992.50	269.45
Biosolid	2	0-3 cm	1176.00	280.75	3952.50	983.50	15.60	705.00	185.65
		3-12 cm	286.20	219.55	1921.00	783.50	7.08	970.00	249.65
Biosolid	3	0-3 cm	634.00	219.75	2796.00	815.50	8.59	802.50	218.05
		3-12 cm	94.65	98.65	1820.00	725.50	3.25	777.00	201.50
Biochar	1	0-3 cm	34.92	276.10	2042.00	686.50	3.32	934.00	171.45
		3-12 cm	8.12	164.75	2186.50	826.00	4.05	1186.00	267.80
Biochar	2	0-3 cm	3.75	140.70	1752.00	720.00	1.89	774.00	187.40
		3-12 cm	21.62	239.95	2230.00	883.50	3.21	1121.50	237.75
		3-12 cm	4.73	163.30	2040.50	833.00	2.30	879.00	214.30
		3-12 cm	3.76	136.15	1707.50	687.50	1.86	768.00	191.55
Biochar	3	0-3 cm	14.86	165.25	1623.50	632.00	2.22	928.00	177.90
		3-12 cm	4.29	120.50	1848.50	720.50	1.78	865.00	213.55
Woodchip	1	0-3 cm	26.20	229.90	2095.50	833.00	11.32	1112.00	218.35
		3-12 cm	5.63	135.35	1769.50	713.50	2.36	774.00	177.15
Woodchip	2	0-3 cm	15.93	241.00	2074.50	801.50	2.70	1031.50	186.65
		3-12 cm	3.28	159.70	2359.00	981.00	2.19	1068.00	257.15
Woodchip	3	0-3 cm	9.54	180.95	1732.00	637.50	2.05	903.00	184.35
		3-12 cm	5.05	156.50	2053.50	771.00	2.50	1045.00	242.60
Biosolid+Biochar	1	0-3 cm	781.00	227.60	2599.00	853.50	9.69	825.50	218.55
		0-3 cm	829.00	233.25	2726.50	871.00	10.30	857.50	230.65
		0-3 cm	928.00	265.70	3124.50	1008.00	11.33	997.00	270.60
		3-12 cm	266.10	216.30	2103.50	1007.00	5.34	1114.50	308.05
Biosolid+Biochar	2	0-3 cm	275.70	180.35	1506.00	637.50	7.36	813.00	244.35
		3-12 cm	812.00	267.30	2524.00	896.50	11.74	920.00	258.85
Biosolid+Biochar	3	0-3 cm	1272.50	260.75	3952.00	921.50	15.03	824.00	258.70
		3-12 cm	202.95	157.15	1774.50	747.00	6.71	890.00	253.65
Biosolid+Woodchips	1	0-3 cm	528.50	231.95	2743.00	814.50	7.67	984.50	247.30
		3-12 cm	104.20	131.45	1250.50	474.80	4.19	853.50	244.05
Biosolid+Woodchips	2	0-3 cm	1035.50	265.20	3641.50	1079.50	9.02	946.50	289.75
		3-12 cm	170.30	129.45	1715.50	755.50	4.02	877.50	251.00
Biosolid+Woodchips	3	0-3 cm	1130.50	295.65	3733.00	962.50	12.50	1041.50	266.65
		3-12 cm	303.45	223.20	2038.00	871.50	6.23	1005.00	262.15
Biochar+Woodchips	1	0-3 cm	10.61	224.30	1751.50	569.00	1.81	915.50	178.00
		3-12 cm	3.84	122.20	1778.50	629.00	1.71	901.00	203.45
Biochar+Woodchips	2	0-3 cm	20.88	284.15	2019.00	698.00	2.42	1083.50	195.45
		3-12 cm	6.19	185.85	2360.50	871.00	2.82	1254.50	278.15
Biochar+Woodchips	3	0-3 cm	20.03	182.25	1743.00	659.00	1.60	926.00	175.80
		3-12 cm	6.98	163.25	1958.00	798.50	1.97	961.50	201.75
		3-12 cm	6.74	167.90	1969.00	819.00	1.71	955.00	197.50
		3-12 cm	6.97	161.75	1955.50	798.50	1.90	959.00	201.15
Biochar+Woodchips	4	0-3 cm	20.16	217.15	1946.00	725.00	2.25	992.00	184.50
		3-12 cm	3.98	125.05	1798.00	715.50	1.29	834.00	198.10
Biosolid+Biochar+ Woodchips	1	0-3 cm	1114.00	360.70	3009.00	964.00	12.00	847.00	260.25
		3-12 cm	165.75	160.55	2085.00	912.50	7.04	1139.50	328.85
Biosolid+Biochar+ Woodchips	2	0-3 cm	788.50	291.95	2347.50	823.50	8.19	707.00	202.75
		3-12 cm	211.05	236.15	1777.00	805.00	5.10	883.50	249.90
Biosolid+Biochar+ Woodchips	3	0-3 cm	291.80	224.65	1902.50	758.00	6.65	840.00	206.15
		3-12 cm	42.33	130.40	1824.00	822.00	3.23	833.50	197.90
		3-12 cm	43.47	129.05	1791.50	799.50	3.02	849.00	201.95
		3-12 cm	45.90	125.90	1808.50	809.50	2.94	842.00	199.95
Blank			-1.61	-6.54	0.47	-0.02	-0.70	0.19	-0.39
Blank			-1.58	-6.19	1.70	0.10	-0.84	0.12	-0.53
Blank			-1.42	-8.51	1.43	0.01	-0.81	-0.08	-0.25

Table A-8: 2016 Pressure Plate Results

Treatment	Rep	Depth	FC (%)	Average-FC (%)	PWP (%)	Average-PWP (%)	PAW (%)
Control	1	0-3 cm	27.03	27.16	12.29	12.29	14.86
			27.28		12.35		
		3-12cm	26.46	26.09	12.88	12.88	13.21
			25.72		13.33		
Control	2	0-3 cm	28.83	29.20	14.45	14.45	14.75
			29.57		14.23		
		3-12cm	29.59	29.43	15.38	15.38	14.04
			29.26		15.11		
Control	3	0-3 cm	24.36	24.03	11.59	11.59	12.43
			23.70		11.73		
		3-12cm	25.42	25.27	12.86	12.86	12.41
			25.12		12.63		
Biochar	1	0-3 cm	31.16	30.99	15.12	15.12	15.88
			30.83		15.08		
		3-12cm	31.22	31.19	16.11	16.11	15.08
			31.15		15.84		
Biochar	2	0-3 cm	26.41	25.97	12.20	12.20	13.77
			25.54		11.76		
		3-12cm	25.66	25.48	13.66	13.66	11.82
			25.30		13.84		
Biochar	3	0-3 cm	26.80	27.19	11.62	11.62	15.57
			27.58		11.83		
		3-12cm	26.90	27.07	13.79	13.79	13.27
			27.24		13.07		
Biosolid	1	0-3 cm	31.31	30.94	14.30	14.30	16.64
			30.57		15.32		
		3-12cm	25.06	26.01	12.96	12.96	13.05
			26.96		13.41		
Biosolid	2	0-3 cm	37.77	37.66	18.11	18.11	19.55
			37.56		18.92		
		3-12cm	26.61	26.39	12.78	12.78	13.60
			26.17		13.41		
Biosolid	3	0-3 cm	29.64	29.96	14.47	14.47	15.49
			30.28		14.32		
		3-12cm	27.44	26.88	13.39	13.39	13.49
			26.32		13.66		
Woodchips	1	0-3 cm	29.16	28.71	12.88	12.88	15.83
			28.26		13.35		
		3-12cm	26.47	26.22	13.19	13.19	13.04
			25.97		13.66		
Woodchips	2	0-3 cm	28.84	29.20	13.96	13.96	15.23
			29.56		13.68		
		3-12cm	25.78	25.70	14.08	14.08	11.62
			25.61		13.88		
Woodchips	3	0-3 cm	30.10	29.12	14.30	14.30	14.82
			28.14		13.24		
		3-12cm	28.59	28.63	15.13	15.13	13.50
			28.67		14.95		

Table A-8 Continued

Biosolid+Biochar	1	0-3 cm	28.23	28.09	13.93	13.93	14.16
			27.95		14.61		
		3-12cm	24.68	24.69	13.47	13.47	11.22
			24.71		13.76		
Biosolid+Biochar	2	0-3 cm	30.50	30.52	14.90	14.90	15.62
			30.54		14.78		
		3-12cm	22.14	22.41	11.68	11.68	10.74
			22.68		12.23		
Biosolid+Biochar	3	0-3 cm	34.84	34.45	18.26	18.26	16.19
			34.05		17.25		
		3-12cm	25.35	25.63	14.79	14.79	10.84
			25.91		14.68		
Biosolid+Woodchips	1	0-3 cm	32.24	32.44	17.04	17.04	15.40
			32.64		17.12		
		3-12cm	18.15	18.19	9.99	9.99	8.20
			18.23		10.15		
Biosolid+Woodchips	2	0-3 cm	31.15	30.74	16.70	16.70	14.04
			30.33		16.63		
		3-12cm	23.67	24.09	13.07	13.07	11.02
			24.51		13.35		
Biosolid+Woodchips	3	0-3 cm	34.04	33.96	17.96	17.96	16.00
			33.89		17.53		
		3-12cm	25.96	26.02	13.61	13.61	12.41
			26.07		14.16		
Biochar+Woodchips	1	0-3 cm	29.69	29.69	15.15	15.15	14.54
			29.69		15.37		
		3-12cm	26.23	26.44	16.11	16.11	10.33
			26.65		16.64		
Biochar+Woodchips	2	0-3 cm	27.70	27.66	14.52	14.52	13.14
			27.62		14.85		
		3-12cm	26.26	26.23	15.89	15.89	10.35
			26.20		15.31		
Biochar+Woodchips	3	0-3 cm	26.12	25.76	12.60	12.60	13.16
			25.40		12.55		
		3-12cm	24.25	25.86	12.81	12.81	13.05
			23.94		12.46		
Biochar+Woodchips	4	0-3 cm	29.40	27.78	15.20	15.20	12.59
			29.79		15.30		
		3-12cm	24.16	26.27	13.71	13.71	12.56
			24.46		14.30		
Biosolid+Biochar+ Woodchips	1	0-3 cm	30.20	29.51	14.56	14.56	14.95
			29.91		15.30		
		3-12cm	28.41	28.64	14.86	14.86	13.78
			27.59		14.98		
Biosolid+Biochar+ Woodchips	2	0-3 cm	29.90	28.74	14.99	14.99	13.75
			29.43		15.05		
		3-12cm	26.88	28.44	14.93	14.93	13.51
			26.77		14.12		
Biosolid+Biochar+ Woodchips	3	0-3 cm	31.66	31.81	13.73	13.73	18.07
			32.24		14.15		
		3-12cm	31.51	30.30	14.21	14.21	16.09
			28.45		14.74		
Refernce	1	top	30.94		11.12		
		bottom	30.60		10.55		
Reference	2	top	29.15		11.83		
		bottom	29.99		10.31		
Ref	3	top	30.97		11.57		
		bottom			11.28		

Table A-9: 2015 Plant Counts

Treatment	Rep	Side	Grass	Forbe
Control	1	Seeded	2	7
		Planted	6	1
Control	2	Seeded	2	4
		Planted	0	0
Control	3	Seeded	0	0
		Planted	3	1
Biosolids	1	Seeded	5	2
		Planted	2	5
Biosolids	2	Seeded	7	0
		Planted	1	3
Biosolids	3	Seeded	9	1
		Planted	12	0
Biochar	1	Seeded	7	3
		Planted	2	3
Biochar	2	Seeded	0	2
		Planted	7	0
Biochar	3	Seeded	1	5
		Planted	0	1
Woodchips	1	Seeded	16	2
		Planted	4	0
Woodchips	2	Seeded	1	1
		Planted	2	1
Woodchips	3	Seeded	0	3
		Planted	4	7
Biosolids+Biochar	1	Seeded	0	7
		Planted	0	3
Biosolids+Biochar	2	Seeded	10	1
		Planted	1	2
Biosolids+Biochar	3	Seeded	2	2
		Planted	1	0
Biosolids+Woodchips	1	Seeded	6	1
		Planted	0	2
Biosolids+Woodchips	2	Seeded	7	0
		Planted	0	1
Biosolids+Woodchips	3	Seeded	5	2
		Planted	1	1
Biochar+Woodchips	1	Seeded	4	5
		Planted	1	6
Biochar+Woodchips	2	Seeded	4	9
		Planted	2	1
Biochar+Woodchips	3	Seeded	10	7
		Planted	6	1
Biochar+Woodchips	4	Seeded	13	22
		Planted	9	1
Biosolids+Biochar+ Woodchips	1	Seeded	15	2
		Planted	2	1
Biosolids+Biochar+ Woodchips	2	Seeded	2	1
		Planted	4	3
Biosolids+Biochar+ Woodchips	3	Seeded	20	0
		Planted	14	0

Table A-10: 2016 Plant Counts

Treatment	Rep	Side	Grass	Forbe
Control	1	Seeded	0	14
		Planted	6	10
Control	2	Seeded	8	27
		Planted	5	2
Control	3	Seeded	0	29
		Planted	3	15
Biosolids	1	Seeded	14	63
		Planted	4	46
Biosolids	2	Seeded	9	23
		Planted	10	56
Biosolids	3	Seeded	25	45
		Planted	18	40
Biochar	1	Seeded	9	6
		Planted	9	48
Biochar	2	Seeded	0	14
		Planted	7	26
Biochar	3	Seeded	0	58
		Planted	1	5
Woodchips	1	Seeded	42	189
		Planted	7	157
Woodchips	2	Seeded	8	51
		Planted	6	46
Woodchips	3	Seeded	10	32
		Planted	4	76
Biosolids+Biochar	1	Seeded	2	77
		Planted	2	46
Biosolids+Biochar	2	Seeded	18	54
		Planted	5	57
Biosolids+Biochar	3	Seeded	4	57
		Planted	2	77
Biosolids+Woodchips	1	Seeded	20	88
		Planted	15	39
Biosolids+Woodchips	2	Seeded	12	98
		Planted	7	74
Biosolids+Woodchips	3	Seeded	14	150
		Planted	6	126
Biochar+Woodchips	1	Seeded	18	64
		Planted	3	34
Biochar+Woodchips	2	Seeded	17	12
		Planted	19	32
Biochar+Woodchips	3	Seeded	22	45
		Planted	9	50
Biochar+Woodchips	4	Seeded	18	55
		Planted	18	27
Biosolids+Biochar+ Woodchips	1	Seeded	4	125
		Planted	6	124
Biosolids+Biochar+ Woodchips	2	Seeded	8	93
		Planted	11	73
Biosolids+Biochar+ Woodchips	3	Seeded	50	49
		Planted	20	12

Table A-11: Bulk Pre-treatment Soil Particle Size Analysis

Sample ID	Depth	Sand (%)	Silt (%)	Clay (%)
Bulk 1	0-3 cm	43	38	19
	3-12 cm	42	36	22
Bulk 2	0-3 cm	45	36	19
	3-12 cm	48	35	17
Bulk 3	0-3 cm	48	35	17
	3-12 cm	57	28	15

Table A-12: Organic Matter LOI Reference Samples

Year	Type	Rep	Depth	LOI (%)	Calculated OM (%)
	Bulk	1	0-3cm	3.63	3.99
			3-12cm	3.77	4.15
	Bulk	2	0-3cm	5.65	6.22
			3-12cm	5.34	5.87
	Bulk	3	0-3cm	5.75	6.32
			3-12cm	2.98	3.28
2015	**Control**	1	0-3cm	3.73	4.11
			3-12cm	4.00	4.40
2015	**Control**	2	0-3cm	5.35	5.89
			3-12cm	5.14	5.66
2015	**Control**	3	0-3cm	4.51	4.96
			3-12cm	4.06	4.47
2016	**Control**	1	0-3cm	3.64	4.00
			3-12cm	3.94	4.33
2016	**Control**	2	0-3cm	5.33	5.86
			3-12cm	5.83	6.42
2016	**Control**	3	0-3cm	3.46	3.80
			3-12cm	3.64	4.00

Table A-15: Spring 2015 Resin Capsule Results

Treatment	Rep	Total N	NO3	NH4	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn
Control	1	5.16	5.16	0.00	0.88	0.06	22.93	0.01	0.99	2.31	8.96	0.40	1.45	0.32	4.78	0.11
Control	2	17.13	16.99	0.14	1.88	0.03	58.21	0.10	1.13	11.57	28.80	0.25	18.03	1.38	13.74	0.07
Control	3	14.43	14.43	0.00	1.34	0.02	44.21	0.05	0.84	8.24	22.02	0.10	15.26	0.60	13.87	0.10
Biosolids	1															
Biosolids	2	31.93	17.60	14.33	0.70	0.03	340.96	0.96	0.37	10.86	137.47	0.07	2.22	139.77	188.64	0.05
Biosolids	3															
Biochar	1	7.35	7.35	0.00	1.56	0.05	35.44	0.05	1.42	5.79	15.49	0.75	9.81	0.36	12.95	0.07
Biochar	2	11.03	11.03	0.00	9.30	0.02	130.07	0.14	4.35	19.36	60.28	0.66	18.87	0.94	11.56	0.10
Biochar	3	20.85	20.85	0.00	2.59	0.02	46.53	0.16	2.00	15.80	24.76	0.17	27.96	0.34	16.11	0.02
Woodchips	1	17.27	17.27	0.00	1.66	0.06	35.86	0.04	1.41	5.50	15.85	0.46	8.19	0.25	11.71	0.09
Woodchips	2	16.82	16.82	0.00	1.20	0.02	45.40	0.07	0.84	8.93	21.94	0.24	13.29	1.62	13.59	0.02
Woodchips	3															
Biosolids+Biochar	1	9.03	9.03	0.00	1.15	0.04	53.68	0.03	0.98	4.99	25.25	0.44	10.26	0.26	42.56	0.08
Biosolids+Biochar	2	31.12	31.12	0.00	2.10	0.03	78.80	0.12	1.29	19.28	39.99	0.23	29.61	0.39	26.06	0.08
Biosolids+Biochar	3	55.42	54.46	0.96	2.26	0.01	237.31	0.18	1.03	34.20	131.34	0.47	50.16	43.18	221.18	0.03
Biosolids+Woodchips	1	31.22	16.92	14.30	1.68	0.02	60.87	0.04	0.89	12.48	29.98	1.16	8.46	36.19	18.30	0.09
Biosolids+Woodchips	2	25.57	25.57	0.00	1.89	0.02	133.79	0.11	1.32	21.75	74.40	0.33	31.36	36.39	104.76	0.10
Biosolids+Woodchips	3	4.77	4.77	0.00	1.48	0.03	36.08	0.07	1.32	10.28	19.62	0.19	14.33	0.63	16.24	0.02
Biochar+Woodchips	1	4.32	4.32	0.00	1.22	0.04	23.43	0.03	0.93	3.46	10.54	0.39	3.73	0.25	8.63	0.09
Biochar+Woodchips	2	7.34	7.34	0.00	3.23	0.03	72.96	0.08	1.13	13.54	35.50	0.36	13.51	0.61	13.87	0.10
Biochar+Woodchips	3	11.06	11.06	0.00	2.39	0.02	36.13	0.06	2.25	9.27	19.80	0.18	10.25	0.82	13.09	0.02
Biochar+Woodchips	4															
Biosolids+Biochar+Woodchips	1	48.53	17.83	30.70	2.56	0.03	98.22	0.16	1.22	22.61	47.76	1.77	24.47	80.57	80.81	0.13
Biosolids+Biochar+Woodchips	2	10.88	10.88	0.00	0.94	0.01	69.63	0.10	0.66	8.76	38.95	0.11	27.32	27.42	51.71	0.09
Biosolids+Biochar+Woodchips	3	28.40	28.40	0.00	1.11	0.02	59.61	0.05	0.88	12.32	33.84	0.16	18.78	0.36	43.06	0.02

Table A-16: Fall 2015 Resin Capsule Results

Treatment	Rep	Total N	NO3	NH4	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn
Control	1	0.17	0.17	0.00	0.53	0.02	5.83	0.01	0.56	0.52	1.43	0.08	1.20	0.19	4.68	0.02
Control	2	0.94	0.94	0.00	0.88	0.01	6.10	0.02	0.97	1.02	2.98	0.07	0.59	0.12	5.03	0.02
Control	3	3.25	3.25	0.00	0.51	0.01	8.26	0.01	0.43	0.64	3.86	0.04	0.92	0.09	4.72	0.02
Biosolids	1	342.40	183.65	158.75	3.54	0.02	176.80	0.15	4.10	61.76	101.54	3.23	21.59	139.43	74.57	0.07
Biosolids	2	9.09	9.09	0.00	1.14	0.01	10.96	0.02	1.14	1.31	5.55	0.08	0.86	0.22	4.61	0.02
Biosolids	3	300.11	245.95	54.16	4.40	0.02	160.93	0.13	4.17	25.58	115.00	0.77	7.46	82.85	23.17	0.07
Biochar	1	0.81	0.81	0.00	0.65	0.01	8.32	0.01	0.59	0.23	3.33	0.09	0.59	0.08	4.36	0.01
Biochar	2	6.12	6.12	0.00	1.93	0.01	24.43	0.01	1.16	2.63	11.58	0.18	1.55	0.31	6.00	0.02
Biochar	3	9.28	9.28	0.00	0.77	0.02	18.60	0.01	0.55	1.58	8.94	0.05	1.31	0.07	5.16	0.01
Woodchips	1	2.41	0.97	1.44	2.70	0.02	9.76	0.03	3.45	2.02	4.98	0.47	1.31	2.06	5.00	0.02
Woodchips	2	4.26	4.26	0.00	4.85	0.02	32.74	0.04	3.18	3.43	16.68	0.35	1.90	0.22	4.65	0.02
Woodchips	3	0.97	0.97	0.00	2.33	0.02	18.19	0.03	2.20	2.37	9.45	0.23	1.72	1.34	5.03	0.01
Biosolids+Biochar	1	1.89	1.89	0.00	0.58	0.01	3.70	0.01	0.67	0.87	1.51	0.11	0.40	0.40	4.32	0.01
Biosolids+Biochar	2	34.01	34.01	0.00	3.88	0.02	52.63	0.04	2.01	6.59	27.36	0.36	4.75	0.44	7.67	0.03
Biosolids+Biochar	3	22.26	22.26	0.00	1.16	0.02	20.33	0.03	0.93	3.46	11.24	0.10	1.90	1.34	6.50	0.01
Biosolids+Woodchips	1	167.25	146.25	21.00	4.51	0.02	135.13	0.11	3.52	28.30	73.80	0.92	9.79	61.61	14.62	0.06
Biosolids+Woodchips	2	8.77	8.77	0.00	8.34	0.02	33.93	0.07	6.52	6.81	21.42	0.75	4.25	1.00	7.91	0.03
Biosolids+Woodchips	3	235.22	192.55	42.67	2.82	0.03	177.46	0.14	2.74	26.71	127.29	1.22	9.87	110.61	25.29	0.08
Biochar+Woodchips	1	4.51	4.51	0.00	3.50	0.02	25.26	0.03	3.71	7.65	11.50	0.81	3.81	0.51	5.60	0.02
Biochar+Woodchips	2	1.94	1.94	0.00	28.49	0.01	67.07	0.17	22.50	11.58	39.28	1.51	6.13	0.87	8.77	0.06
Biochar+Woodchips	3	5.61	5.61	0.00	6.05	0.02	34.53	0.06	5.19	8.87	19.21	0.33	7.96	0.67	8.21	0.02
Biosolids+Biochar+Woodchips	1	162.25	121.20	41.05	2.69	0.03	80.26	0.07	3.00	15.69	39.08	2.53	7.33	29.73	14.70	0.06
Biosolids+Biochar+Woodchips	1	11.46	11.46	0.00	2.17	0.03	45.21	0.04	2.08	6.53	21.27	0.60	9.38	0.66	15.09	0.03
Biosolids+Biochar+Woodchips	2	66.66	62.25	4.41	3.18	0.03	82.13	0.06	2.39	7.20	46.22	0.32	6.80	27.44	14.32	0.02
Biosolids+Biochar+Woodchips	3	3.68	3.68	0.00	16.14	0.02	65.37	0.12	11.56	8.54	33.65	0.81	5.73	1.34	7.32	0.04

Table A-17: Spring 2016 Resin Capsule Results

Treatment	Rep	Totat N	NO3	NH4	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn
Control	1	1.77	0.00	1.77	5.73	0.02	48.43	0.06	4.11	9.81	21.92	2.31	4.93	2.97	2.25	0.03
Control	2	0.86	0.00	0.86	2.10	0.02	32.38	0.06	1.48	4.52	16.64	0.15	6.82	3.09	4.23	0.01
Control	3	0.69	0.00	0.69	1.78	0.02	70.51	0.05	0.83	8.36	35.17	0.15	18.71	2.28	11.69	0.01
Biosolids	1	83.53	73.30	10.23	4.05	0.03	122.13	0.20	3.79	48.47	68.51	1.05	20.14	74.00	32.17	0.04
Biosolids	2	227.30	227.30	0.00	2.78	0.02	415.83	0.44	2.14	1.49	144.12	2.27	1.12	75.76	96.80	0.12
Biosolids	3	202.71	201.05	1.66	2.43	0.02	294.18	0.21	1.50	19.79	135.22	0.58	28.63	115.84	52.97	0.08
Biochar	1	2.29	1.28	1.01	3.21	0.02	19.65	0.04	2.77	2.10	8.97	0.60	2.06	0.40	1.75	0.02
Biochar	2	0.75	0.00	0.75	2.93	0.02	36.74	0.05	1.59	4.59	17.71	0.34	4.93	1.85	4.37	0.02
Biochar	3	17.09	16.25	0.84	1.74	0.02	76.28	0.11	1.11	42.80	41.58	0.14	25.33	5.80	12.30	0.01
Woodchips	1	1.20	0.00	1.20	2.88	0.02	42.30	0.03	1.92	4.08	17.01	0.43	5.59	0.55	6.29	0.02
Woodchips	2	1.09	0.00	1.09	2.38	0.03	53.39	0.11	1.37	12.27	27.50	0.16	18.00	0.62	19.62	0.01
Woodchips	3	1.44	0.00	1.44	1.75	0.03	32.03	0.06	1.27	12.60	16.55	0.17	16.18	2.89	6.39	0.01
Biosolids+Biochar	1	108.70	79.40	29.30	3.34	0.03	124.20	0.11	3.07	38.37	69.68	1.94	5.25	131.83	8.51	0.04
Biosolids+Biochar	2	207.33	206.10	1.23	2.26	0.02	238.28	0.26	1.28	30.52	105.04	1.46	4.89	126.77	26.32	0.04
Biosolids+Biochar	3	114.54	109.20	5.34	2.19	0.03	126.00	0.10	1.59	18.59	72.81	0.77	6.13	66.13	13.32	0.03
Biosolids+Woodchips	1	140.79	135.20	5.59	1.51	0.03	123.93	0.09	0.80	15.95	61.18	2.12	8.12	19.37	13.74	0.04
Biosolids+Woodchips	2	87.36	86.05	1.31	5.04	0.03	124.42	0.14	1.87	20.17	67.16	0.39	27.25	13.40	22.93	0.03
Biosolids+Woodchips	3	110.12	108.45	1.67	2.71	0.02	159.11	0.15	1.61	25.73	87.95	0.51	23.02	99.96	20.74	0.04
Biochar+Woodchips	1	1.52	0.00	1.52	2.01	0.03	29.14	0.03	1.26	6.48	12.70	0.40	3.44	2.04	2.38	0.02
Biochar+Woodchips	2	1.24	0.00	1.24	2.24	0.02	35.47	0.04	1.16	6.55	18.09	0.22	4.89	1.04	3.87	0.01
Biochar+Woodchips	3	1.02	0.00	1.02	4.83	0.02	55.98	0.07	2.85	10.29	26.91	0.32	8.60	4.91	2.66	0.02
Biosolids+Biochar+Woodchips	1	93.73	92.45	1.28	1.77	0.02	84.94	0.03	0.96	6.19	43.82	0.37	4.12	4.27	6.51	0.03
Biosolids+Biochar+Woodchips	2	152.03	151.10	0.93	2.85	0.02	158.95	0.10	1.71	14.06	91.53	0.18	41.25	15.28	33.56	0.02
Biosolids+Biochar+Woodchips	3	159.50	150.55	8.95	2.14	0.02	218.71	0.22	1.03	28.89	122.86	3.01	22.37	197.77	43.72	0.05