BIOCHAR EFFECT ON SOIL PHYSICAL AND CHEMICAL PROPERTIES AND BERMUDAGRASS GROWTH

A Thesis

by

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ABSTRACT

As population continues to rise and development continues, there is increasing pressure for the production of food on a decreasing amount of land as well as an increased need for combustible fuel. Biofuels produced from agricultural products may be able to alleviate some of the demands on foreign oil, and the byproduct, biochar, is reported to have positive effects on soil properties and crop growth when applied to soils. To test this, biochar produced from sorghum (*sorghum bicolor*) was field tested on sandy loam soil at rates of 0, 4, 8, 12, and 16 Mg ha^{-1}. Biochar was applied to soil using two different methods, surface applied and incorporated down to 15 cm, and bermudagrass (*cynodon dactylon*) was grown from seed. Runoff, sediment loss, biomass yield, saturated hydraulic conductivity, water holding capacity, bulk density, porosity, and soil nutrients were tested in a randomized block design. Biochar did not have a significant effect on physical parameters, biomass, or runoff and sediment loss ($\alpha=0.05$). Biochar application to soils produced a significant linear increase on certain soil chemical parameters six months after application (pH and K). Soil test K continued to show a linear increase 22 months after biochar application; however the linear trend was reversed for pH with incorporated biochar.

Additionally, a greenhouse study was conducted using the same biochar source with identical application rates and application methods. Three soils were tested, an acidic fine sandy loam (Rader fine sandy loam), an acidic clay (Burleson clay), and an alkaline clay (Ships). Soil temperature, water loss, emergence rates, biomass yields, nutrient mass export, and bulk density were tested. Surface applied biochar enchanced bermudagrass emergence, increasing the germination index ($\alpha=0.05$) for Burleson clay and Ships clay soils. Biochar application increased biomass yields for 8 and 12 Mg ha^{-1} rates for Burleson soils compared to other application rates. Moreover, rates above 12 Mg ha^{-1} decreased biomass yield, indicating a quadratic response to biochar application. There was not a significant difference in nutrient uptake in bermudagrass tissue, nor was there a significant change in soil bulk density in response to biochar application.

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NOMENCLATURE

μmhos cm^{-1}	Micromhos per centimeter
ANOVA	Analysis of variance
BC	Biochar
CEC	Cation exchange capacity
cm	Centimeter
EC	Electrical Conductivity (μmhos cm^{-1})
g m^{-2}	Gram per meter squared
g	Gram
INC	Incorporated
kPa	Kilopascal
K_{sat}	Saturated Hydraulic Conductivity
Mg ha^{-1}	Megagram per hectare
SA	Surface applied
w	Gravimetric Water Content

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1. INTRODUCTION

With increasing population pressure, global climate change, and diminishing fossil fuel reserves, increasing interest in alternative sources to fossil fuels has promoted the pursuit of technologies to convert biomass into sustainable, refine-able oils. One of several conversion technologies proposed is pyrolysis. Pyrolysis is well suited to utilize agricultural biomass, post-industrial commercial and consumer waste, and high lignin wastes from cellulosic ethanol conversion platforms. While the primary goal of pyrolysis is to obtain refine-able oils, the process produces a carbonaceous byproduct known as biochar. Biochar (BC) is a solid charcoal-like substance that can be combusted as an additional energy source or disposed of through land application. Biochar may provide additional economic and agronomic benefit to bioenergy systems due to its physical and chemical properties, which may increase soil fertility and productivity when added to soil (Laird, 2008). It is estimated that 5 to 15% of the fertile Midwestern prairie soils consists of charcoal from centuries of prairie fires, due to the half-life of carbon in soil charcoal which is estimated to be greater than 1,000 years (Glaser, Lehmann, et al., 2002, Laird, 2008). Thus, biochar potentially could be used as a carbon sequestration technique due to the biological stability of the carbon compounds in biochar (Glaser, Lehmann, et al., 2002, Spokas, Cantrell, et al., 2012).

It is believed that charcoal was intentionally used as a soil amendment in highly weathered soils of the Amazon to improve their chemical and physical properties (Glaser and Birk, 2012, Lehmann, da Silva, et al., 2003). Pyrolysis-derived biochar may have similar beneficial applications when applied to low productivity soils in temperature regions. Benefits of soil-applied charcoal or biochar have long been observed but the mechanisms that are responsible for the benefits have not been fully studied (Lehmann 2003). Multiple studies have identified positive effects of biochar on soil properties, including increased water holding capacity (Kinney, Masiello, et al., 2012), liming effect (Laird 2010), and nutrient availability (Schulz and Glaser, 2012).

This project investigates the practical use of biochar on marginal cropland soils to improve the overall soil health as well as production capacity over time. Section 2 will introduce the physical and chemical limitations of marginal soils to crop growth for which biochar may be a solution and the properties of biochar that make it a potential remedy. Section 3 will detail the field study that was conducted to test application rates (0, 4, 8, 12, 16 Mg ha^{-1}) and methods of application (surface applied and incorporated) on soil properties, runoff and bermudagrass growth. Soil properties tested were saturated hydraulic conductivity, bulk density, water holding capacity, porosity, and nutrient content. Section 4 will detail the greenhouse study that was conducted to further investigate these application rates and methods of application on the emergence, growth, and nutrient dynamics in three different soils. Section 5 will discuss the implications of the results found in these studies and explain how the data collected will add to understanding the practical use of biochar in agronomic settings.

2. LITERATURE STUDY

2.1 What is Biochar?

Biochar is the carbon-rich solid byproduct of heating biomass such as wood, manure, stalks, or leaves in the absence or near absence of air. It is organic matter that is heated at relatively low temperatures (<700°C) in a thermal decomposition process that takes place with little to no oxygen present (Lehmann and Joseph, 2012, Verheijen, Jeffery, et al., 2010). According to the International Biochar Initiative, biochar is simply "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" (Initiative, 2012). Biochar is difficult to classify based on its properties, both chemical and physical, because of the variability imparted to it by the production conditions (time, temperature) and feedstock. Biochar can have a variety of particle and pore sizes and size distributions, and nutrient content based on several production conditions, which will be discussed in section 2.3. Biochar may be used to mitigate some problems associated with the need to accommodate increasing energy production as well as food production (Laird, 2008).

2.2 Need for Improving Marginal Cropland

According to its 2007 report, the NRCS estimates that approximately 14 million acres of prime farmland have been lost to development in the United States since 1982 (NRCS, 2007). Prime farmland is fertile, productive soil with favorable drainage and soil texture that is generally used for growing valued food crops. Losing this prime farmland is enough cause for alarm on its own, however, when taking into account predictions of human population increase the disparity between food energy needed and the capacity to produce it is more pronounced. More food and feed will be needed from a decreasing amount of prime farmland, which necessarily involves increasing productivity in the already existing farmland or expanding to marginal or poor cropland (Bessou, Ferchaud, et al., 2011). Thus, sustainable sources of fuels are currently being pursued and will be increasingly pursued in the future as pressures inevitably increase. As previously stated, biomass provides a source of refine-able oils that can be adapted for use as a replacement for fossil fuels in furnaces, boilers, and engines modified to handle bio-oil (Boerrigter and Rauch, 2006).

The crucial problem with the future of sustainable biomass production and the meeting of increasing needs for food and feed is the simultaneous push to increase production of both food crops and bio-energy crops. Biochar may be able to fit into this unique environmental niche and improve marginal cropland, enabling the increased production of future bio-energy crops without sacrificing food for energy (Woolf, Lehmann, et al., 2014). Pyrolysis is one such technology that may be the key to producing a positive feedback loop that produces energy while improving soil health (through biochar addition) and thus increasing the ability to produce more biomass and more energy.

2.3 Pyrolysis and Biochar Production

Pyrolysis is a thermo-chemical process, which involves the heating of biomass above temperatures of 300°C in absence of oxygen in order to liberate chemical energy from the organic matter (Crombie and Mašek, 2015, Demirbas, 2007, van der Stelt, Gerhauser, et al., 2011). Torrefaction is a similar process but occurs at lower temperatures, generally accepted to be from around 200 to 300°C (Prins, Ptasinski, et al., 2006, van der Stelt, Gerhauser, et al., 2011). Pyrolysis produces three main substances: non-condensable gases, bio-oil, and biochar, all of which have beneficial uses (Crombie and Mašek, 2015, Spokas, Cantrell, et al., 2012). The non-condensable gases are flammable hydrocarbons and can be used in energy generation, in fact, they are often burned within the pyrolysis process to keep it functioning (Crombie and Mašek, 2015). The bio-oil portion of the product can be used as a liquid fuel source and is the most widely applicable constituent of pyrolysis products due to its potential for integration into current fossil fuel infrastructure (gasoline-based systems). Biochar is the residual solid stabilized carbon that is left over when the fluids are liberated.

Different production temperatures and different feedstocks may be used to produce unique biochars for a variety of goals (Qian, Kumar, et al., 2015, Sohi, 2013). The time of applied heat and the temperature of heating are used to classify the pyrolysis process as either fast, moderate, slow, or gasification (Brown, 2009). Based on temperature and residence time, the liquid:char:gas ratio significantly changes. The spectrum ranges from fast pyrolysis (75:12:13) all the way to gasification (5:10:85), with intermediate steps producing proportionally lower amounts liquids and proportionally increasing char and gas fractions (with the exception of gasification, which produces a lower fraction of char even than fast pyrolysis) (Brown, 2009).

Fast pyrolysis (FP) occurs at a higher temperature and shorter residence times and produces more liquids and less rich solids (biochar). Slow pyrolysis (SP) in turn occurs at a lower temperature and at a longer residence time and stabilizes more carbon in biochar from and produces less oil and gas (Crombie and Mašek, 2015, Ronsse, van Hecke, et al., 2013, Stewart, Zheng, et al., 2013). Depending on the goals of the producer either type of pyrolysis might have more value in a specific instance, although it is likely that both are necessary for the sustainable future of bio-energy crops (Pituello, Francioso, et al., 2015). Biochar has been shown to improve the fertility of poor soils and also sequester carbon due to the recalcitrance of biochar (Bessou, Ferchaud, et al., 2011, Spokas, Cantrell, et al., 2012). Focusing on slow pyrolysis, which produces higher proportions of solid products, would provide more biochar for application to soil and any associated benefits. Focusing on fast pyrolysis, which produces higher proportions of liquid products, would produce more fuel for heating and energy production.

2.4 Biochar Application to Soil

Historical application and incorporation of charcoal to and into soils have shown long-lasting improvements to the fertility of weathered soils. This is attributed to the ancient practice of "slash-and-char" agriculture in the Amazon, where forests were burned and charred residue mixed into the highly weathered soils (Lehmann, da Silva, et al., 2003). This is in contrast to "slash-and-burn" agriculture where vegetation is cleared and burned. Slash and burn involves the clearing of biomass but not the long-term incorporation residues resulting in steep declines of soil fertility in those areas leading to more land clearing and forest loss (Crombie and Mašek, 2015, Lehmann, da Silva, et al., 2003). More recent studies have also reported positive improvements from the incorporation of biochar into poor soils, including: decreased bulk density (-4.5% with addition of 2.25 Mg ha^{-1}, -6% with addition of 4.50 Mg ha^{-1} according to Chen 2015), increased water holding capacity (25 to 36% increase with 7% biochar by weight addition, according to Kinney 2012), liming effect (20 g kg^{-1} biochar increased soil pH by almost 1 pH unit, according to Laird 2010), and enhanced nutrient availability (significant increases in N (up to 7%), organic C (up to 69%), and P K, Mg and Ca, according to Laird 2010).

Other studies, however, have revealed that charcoal/biochar addition to soil is not always beneficial and can in fact be harmful to soil health. For example, historic sites of charcoal production in Zambia have been found to have slower plant regeneration rates than nearby native soils (Chidumayo, 1988). Historic pyrolysis at wood production plants and charcoal leachate addition to soil have led to these sites actually being included in the EPA Superfund site list for having high levels of organic chemicals (Edenborn and Severson, 2007, Erstfeld and Snow-Ashbrook, 1999). Clearly biochar addition to soils may have significant benefits but must be monitored and conducted in the proper way or there may be adverse effects (Spokas, Cantrell, et al., 2012).

2.5 Physical Biochar Effect

2.5.1 Saturated Hydraulic Conductivity

In the recent literature, there has not been a conclusive stance on the effects of biochar addition to soils on the rate at which water can move through soil. This is due to the variability of different biochar products as well as the soils to which they are added. Rates of 16 t ha^{-1} (16 Mg ha^{-1}) incorporation of teak and rosewood biochar into a clay loam soil produced a significant increase in K_{sat}, which was reported as an improvement in this context (Asai, Samson, et al., 2009). Githinji 2014 tested the effect of adding significant amount of biochar by weight to a sandy soil, by adding 0, 25, 50, 75, and 100% biochar. They stated that the K_{sat} values decrease approximately linearly (R^2=0.840) as the rate of biochar application increased. Initial K_{sat} values for the soil (0.45 cm min^{-1}) decreased by 33% (to 0.30 cm min^{-1}) when 25% biochar was added (Githinji 2014). At 100% biochar, the K_{sat} value was about 0.20 cm min^{-1}, less than half of the sandy soil itself. This study demonstrated the damping effect that biochar addition can have on K_{sat} in a sandy soil, if there already existed a high K_{sat} value in that soil relative to the biochar. Thus, it is likely that soils and biochar with large disparities in between Ksat values have the highest potential for significant biochar influence.

Another study observed increased K_{sat} as a result of adding charcoal to native soils over an extended period of time (Ayodele, Oguntunde, et al., 2009). These studies provide a good example of the different ways in which biochar effects can be viewed, based on the goals and antecedent conditions. Other studies have reported no significant change in K_{sat} due to interaction of biochar application and a variety of soils (Hardie, Clothier, et al., 2014, Jeffery, Meinders, et al., 2015, Laird, Fleming, et al., 2010). It appears that for clay soils, biochar may enhance (increase) K_{sat} by increasing the number and/or connectivity of macropores, while sandy soils may have decreased K_{sat} due to the absorptive capacity of the biochar. Changes in K_{sat} are linked to changes in soil porosity, aggregation, and water holding capacity (Nelissen, Ruysschaert, et al., 2015).

2.5.2 Water Holding Capacity

One of the primary benefits of biochar additions to soils is the reported increase in water holding capacity of the soil, which is attributed to its high porosity and/or capacity for promoting soil aggregation (Herath, Camps-Arbestain, et al., 2013, Laird, Fleming, et al., 2010). In a study conducted on Midwestern agricultural soils, soils retained increasing percentages of water at field capacity with increasing biochar application rates, relative to un-amended soils (Laird, Fleming, et al., 2010). Kinney 2012 observed a 25-36% increase in field capacity of soils amended with 7% biochar by weight, regardless of differences in production temperature (Kinney, Masiello, et al., 2012). In a 5-year pilot study conducted in Finland, biochar was found to increase water holding capacity by 11% (Karhu, Mattila, et al., 2011). It should be noted, however, that increased water holding capacity does not necessarily translate directly to plant available water, especially if the specific biochar used has a high proportion of micropores, which hold water at a tension that is not necessarily accessible by plants.

2.5.3 Bulk Density and Porosity

Bulk density, the ratio of soil mass when dry to volume, and porosity, the ratio of pore space in a soil to the bulk volume of the soil, are intrinsically related, and can thus be engaged simultaneously in discussion. Biochar itself has a very low density and high porosity, so the effect on the soil to which it is added is similar, though the mean is stretched by the higher bulk density and lower porosity of the soil (Lehmann and Joseph, 2012). Many studies have observed decreases in bulk density and increases in porosity as a result of biochar application (Chan, Van Zwieten, et al., 2008, Chen, Du, et al., 2011, Githinji, 2014, Mukherjee and Lal, 2013, Nelissen, Ruysschaert, et al., 2015). Roughly 2% (by weight) of biochar in soil is enough biochar addition to show a significant decrease in bulk density in amended soils (Chen, Du, et al., 2011, Mukherjee and Lal, 2013). The rate of biochar application as well as the density and porosity of the original soil are critical in predicting the effects of biochar addition to any soil. In same study referenced previously, in which Githinji 2014 tested saturated hydraulic conductivity at 0, 25, 50, 75, and 100% biochar application rates, the response of bulk density and porosity were also tested in the same soil under the same rates. The results of these bulk density and porosity measurements followed a strong linear trend for both porosity (R^2=0.994) and bulk density (R^2=0.994) (Githinji 2014). There was an increase in porosity with increasing biochar addition and a decrease in bulk density with increasing biochar addition. The relationship is almost perfectly linear, which indicates that the soil and biochar interacted with each other in a direct way, without the interaction of soil aggregation factors. This is unlike saturated hydraulic conductivty, which seemed to be disproportionate affected by biochar, that is, biochar had a larger effect on K_{sat} values than soil did (at 50% biochar by weight, the K_{sat} value was almost that of pure biochar, instead of being an average of the K_{sat} of the native soil and biochar) (Githinji 2014). The rates of biochar addition used in this example are not feasible and this study serves more to confirm the physical effect of increasing biochar addition. Ideally, enhanced soil aggregation should lead to decreased bulk density, since the pore distribution form raw biochar addition does not necessarily indicate increased soil productivity.

2.6 Chemical Biochar Effect

2.6.1 Nutrient Retention and Release

Nutrient leaching is a large problem associated with agricultural production, necessitating the application of additional synthetic fertilizers, which can lead to soil acidification, increased cost, loss of crop yield, and increased environmental pollution (Anderson, Condron, et al., 2011). Thus, the potential ability of biochar to enhance nutrient retention is of high interest. Several studies have found an increased ability of biochar to limit the leaching of ammonium and nitrate, with the mechanisms being cation exchange capacity and increased water holding capacity, respectively (Yao, Gao, et al., 2012, Zheng, Wang, et al., 2013). Phosphorous in plant wastes can also be conserved and released through the addition of certain types of biochar in plant available forms (Qian, Zhang, et al., 2013). In a greenhouse study testing the addition of compost, fertilizer, and biochar combination, however, there was no evidence of decreased ammonium, nitrate, or phosphate leaching, though there was a decrease in nitrification (Schulz and Glaser, 2012).

Biochar itself generally contains high densities of nutrients, but also may improve the performance of added fertilizers due to its cation exchange capacity. Biochar addition in tandem with fertilizer (biochar plus fertilizer) has been shown to outperform fertilizer and biochar that were applied independently (Schulz and Glaser, 2012). This indicates a clear interaction between biochar and fertilizer. This is likely due to the high porosity and surface area of biochar, which facilitates the adherence of nutrient molecules to the many exchange sites on the biochar particle. Biochar applied to soil without added fertilizer also increased plant yield and nutrient availability (particularly K) where biochar was applied to agronomic systems (rice production with rice-husk biochar, durum wheat production with hardwood biochar) (Ogawa and Okimori, 2010, Vaccari, Baronti, et al., 2011).

2.6.2 Biochar Effect on pH

Biochar has been shown to have a significant liming ability due to its intrinsically high pH (true for most biochars, though some may be acidic) and concentration of basic cations retained from the initial feedstock, including Ca, Mg, and K (Beesley, Moreno-Jimenez, et al., 2011, Laird, Fleming, et al., 2010, Lehmann, Rillig, et al., 2011). Biochar has also been shown to increase cation exchange capacity (CEC) which increases the potential for sorption of many organic and inorganic substances, including essential plant nutrients (Beesley, Moreno-Jimenez, et al., 2011, Liang, Lehmann, et al., 2006). In a study of Anthrosols with biochar amendments, the CEC was found to be 1.9 times higher in biochar amended soils relative to adjacent soils and was attributed to high charge density and large surface area of biochar particles (Liang, Lehmann, et al., 2006). In another field study conducted in the North China Plain, CEC was shown to increase by 24.5% with the addition of 4.5 Mg ha^{-1} biochar (Chen 2015).

2.7 Biochar Effect on Plant Growth

While biochar has been shown to improve some physical and chemical properties of soil, those improvements may not translate to the improvement of crop production for soils in general (Nelissen, Ruysschaert, et al., 2015). Biochar derived from plant material sources are often lower in N content relative to biochar produces from animal materials (manure) and even application rates of 100 Mg ha^{-1} have failed to produce plant production responses (Chan, Van Zwieten, et al., 2008, Lehmann, da Silva, et al., 2003). In a meta-analysis of biochar studies relating to crop production, however, biochar addition has been show to increase crop production in multiple crops, including an overall increase in crop production, though there is large variability among individual crops (Jeffery, Verheijen, et al., 2011). It is clear from this grouping of studies that there is no consistent linear increase in crop production based on biochar application rate, but the data does show a marked increase in crop production with certain biochar addition situations. In this meta-analysis, the grand mean of studies showed a positive significant increase of approximately 10%. However, most of the rates tested were not significant, and the only rates that showed significance on their own were 10, 25, 50, and 100 Mg

ha^{-1}. The rates tested in this study were closely matched by some of those in the meta-analysis (1.5, 3, 5, 8 Mg ha^{-1}). These rates did not show significant changes due to biochar application, though this meta-analysis combines multiple types of soils and crops.

Not only can it increase gross biomass production, biochar addition has also been shown to increase plant health, measured by metrics such as leaf production, plant height, and grain production (Uzoma, Inoue, et al., 2011). Specifically in regards to bermudagrass production, biochar addition has been shown to increase biomass harvest values relative to untreated soil (Artiola, Rasmussen, et al., 2012, Sheng, Adeli, et al., 2014). In a greenhouse study similar to the one conducted in this study in which biochar was applied to greenhouse soil at 0, 2, and 4% (by weight), biomass yield was significantly increase under normal moisture conditions with 2% application and significantly increased for both 2 and 4% under moisture stress (Artiola, Rasmussen, et al., 2012). It was also measured in this study that volumetric water content at -30 kPa increased by 8% relative to the control with the addition of 4% biochar. Thus, it was likely the increased moisture retention in the soil due to biochar addition that produced increased bermudagrass yields during moisture stress.

3. FIELD STUDY

3.1 Objectives

The objective of this study was to evaluate soil properties, runoff and bermudagrass (*cynodon dactylon*) growth in response to biochar application rate and method over a two-year period under field conditions.

3.2 Materials and Methods

To evaluate soil properties, runoff and bermudagrass growth in response to biochar application rate and method, a two-year field study was initiated during summer 2013 at College Station, TX. The field site located at Texas A&M University included four replications of nine treatments arranged in a randomized complete block design (Figure 3.1). Treatments included soil with surface applied or incorporated biochar at 0, 4, 8, 12, and 16 Mg ha^{-1} (Figure 3.4). Soil was a Booneville fine sandy loam previously used for pasture and forage, control soil analysis (Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis) are listed the table below (Table 3.1). Plots were maintained under limited irrigation.

Table 3.1. Booneville fine sandy loam soil analysis.

Nutrient	Booneville fine sandy loam
pH	6.21
	µmhos cm^{-1}
EC	223.5
	mg kg^{-1}
NO_3-N	0.62
P	293.6
K	318.7
Ca	1214.2
Mg	127.3
S	32.1
Na	107.9

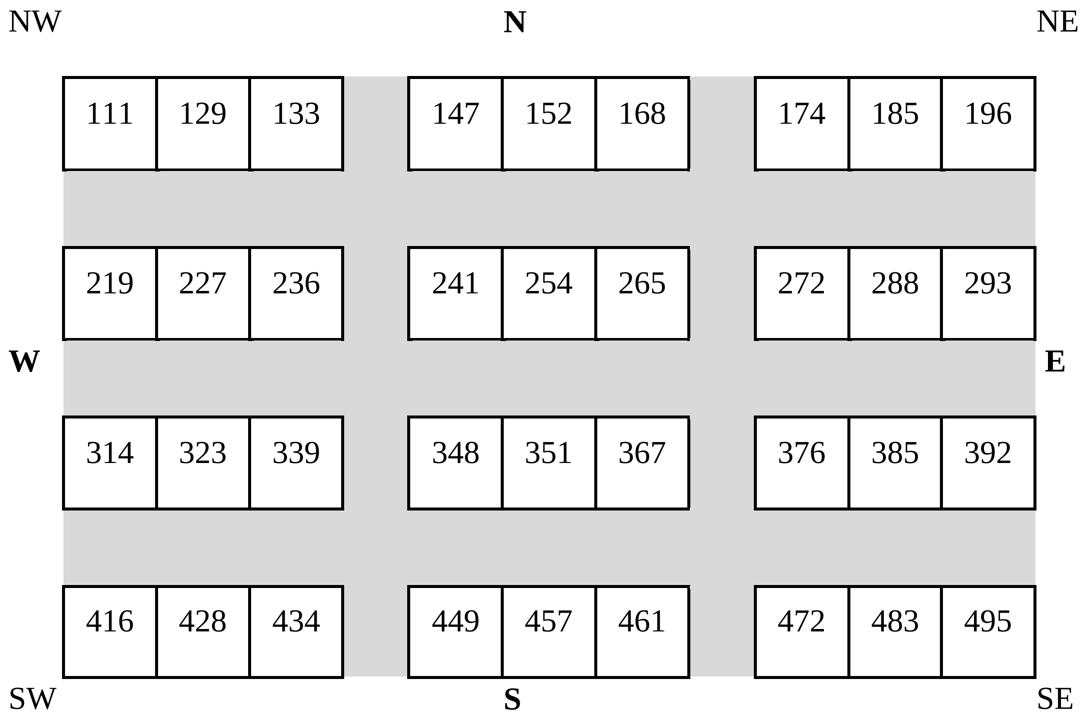

Figure 3.1. Plot locations in the field. The first digit indicates the block (1 to 4), the second digit refers to the plot number in the block (left to right 1 to 9), and the third number refers to the treatment for that plot (Table 3.2).

Table 3.2. Biochar treatment codes for field study plots.

KEY	
1	Control - 0 Mg ha^{-1}
2	Surface Applied - 4 Mg ha^{-1}
3	Surface Applied - 8 Mg ha^{-1}
4	Surface Applied - 12 Mg ha^{-1}
5	Surface Applied - 16 Mg ha^{-1}
6	Incorporated - 4 Mg ha^{-1}
7	Incorporated - 8 Mg ha^{-1}
8	Incorporated - 12 Mg ha^{-1}
9	Incorporated - 16 Mg ha^{-1}

3.2.1 Plot Installation

Soil was prepared by tilling to a depth of 15 cm and weeds that emerged after initial tillage was treated with Roundup (4.8 L Glyphosate ha^{-1}). Pressure treated lumber (3 m by 10 cm by 5 cm) was used to delineate 3 m by 3 m plots in 4 rows of 9 plots, for a total of 36 plots. Each plot border was positioned to provide a 1% slope for collection of surface runoff. Drainage ditches were used to prevent overland flow across plot area.

The center portion of the plot was separated hydrologically from the remainder of the plot by installing sheet metal to a depth of 10 cm to prevent run-on or subsurface flow (Figure 3.2). The center portion was installed after application of biochar and seeding of bermudagrass. Two pieces of sheet metal were hammered into the soil 30 cm apart along the whole length of the plot to make a center plot that was 3 m by 30 cm.

Figure 3.2. The center runoff/biomass collection plot, weir, and the buried buckets (which contain plastic bags to catch runoff).

The junctions between sheet metal and boards were sealed using aluminum flashing and silicon. In the center of the board at the lowest side of the plots, a notch was cut to fit a metal weir which led directly into a 26.5 L (30 cm diameter by 50 cm tall) bucket. A hole was cut into the side of each bucket so that the weir, constructed out of a 15 cm wide x 25 cm long to 15 cm diameter straight register vent boot (Imperial Manufacturing Group, Richibucto, NB) fit into the bucket and capture only surface runoff from plots (Figure 3.3).

Figure 3.3. The runoff catchment device: 30 cm diameter by 50 cm tall bucket with embedded weir (before being sealed together and buried).

The junctions between the bucket and the weir were sealed with silicone caulk to prevent water from the soil entering the bucket and filling it. At the junction between the soil of the plots and the weir, a small trench was dug along the front edge of the weir (30 cm long by 3 cm wide and 10 cm deep) and filled with bentonite clay to prevent infiltration and water loss. A 30 cm diameter auger was used to dig the holes for each bucket.

Precipitation data for College Station, TX, was measured and recorded at the Easterwood Airport weather station (3.5 km from the site), which is maintained by Texas A&M University and the Office of the State Climatologist (http://climatexas.tamu.edu/). The cumulative rainfall data over the course of the study is shown below (Figure 3.4).

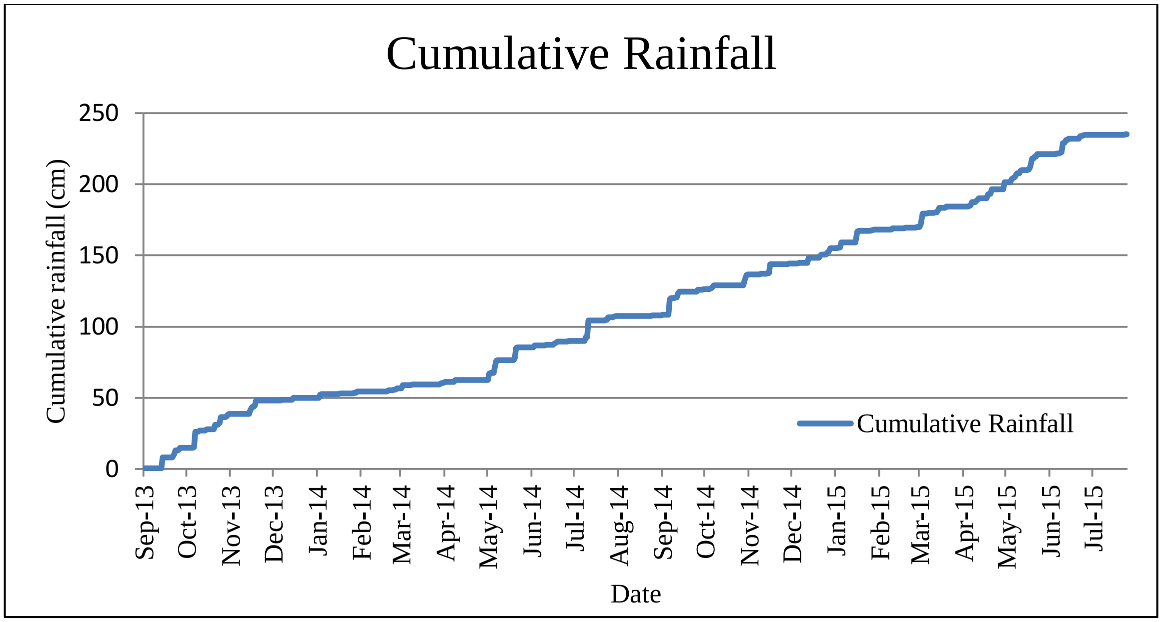

Figure 3.4. Cumulative rainfall at Easterwood Airport weather station (3.5 km from field site) over the course of the runoff study (9/7/13 to 7/31/15).

3.2.2 Biochar Application and Berdmudagrass Seeding

Biochar was applied at rates of 0, 4, 8, 12, and 16 Mg ha^{-1}. Actual biochar application rates were determined by correcting for moisture content. To find the moisture content of the biochar, representative samples were taken from the biochar source, weighed, and dried at 105 °C for 24 hours. Weights of biochar application were calculated using the formula below:

$$\text{Gravimetric water content (w)} = \frac{\text{mass of water (g)}}{\text{mass of dry biochar (g)}}$$

The rates of biochar application were calculated using this pre-obtained *w* value. Grab samples were taken during weighing and bagging of treatments to be applied in the field calculate the actual moisture content at the time of application. Biochar in a bulk bag was mixed in a horse trough by hand to homogenize before samples were removed to apply to the plots (Section 3.2.1). The *w* contents at the time of weighing are recorded in table along with the actual application rates for each block (Table 3.3).

Table 3.3. Actual rates of biochar application by block (a separate bulk bag was used for each block). Rates refer to both surface-applied and incorporated biochar.

	Average Moisture Corrected Application Rate (kg ha^{-1})			
Application Rate (kg ha^{-1})	Block 1 (w = 0.82 kg kg^{-1})	Block 2 (w = 1.54 kg kg^{-1})	Block 3 (w = 1.25 kg kg^{-1})	Block 4 (w = 1.30 kg kg^{-1})
4000	3912	3652	3355	4220
8000	7824	7309	6710	8440
12000	11736	10962	10061	12660
16000	15648	14614	13416	16881

w = gravimetric water content

Four replications of two application methods, surface applied (SA) and incorporated biochar (INC) were used, in addition to 1 control were arranged in a randomized block design (9 treatments per block). After all plots were graded to 1% slope, the biochar was applied to the plots where the biochar was to be incorporated and then spread out evenly using a landscaping rake (8/30/13 to 9/3/13). All biochar was applied with a two week period in late August/early September of 2013. The dates of biochar application were:

- 8/22/13: Block 4, treatments 6 through 9 applied
- 8/23/13: Block 1 through 3, treatments 6 through 9 applied)
- 8/30/13: Block 1 through 2, treatments 2 through 5 applied)
- 8/30/13: Blocks 1 through 2 seeded
- 9/3/13: Block 3 through 4, treatments 2 through 5 applied)
- 9/3/13: Block 3 through 4 seeded

All of the plots were then tilled using a gas-powered rototiller to a depth of 15 cm. This assured that all of the plots received the same amount of tillage, not just the incorporated plots. After tilling, the biochar was applied to the surface applied plots and spread evenly with a landscaping rake. After all biochar was applied, the plots were broadcast seeded by hand at a rate of 10 g m^{-2} and then irrigated twice daily with approximately 0.25 cm of municipal tap water until emergence was achieved (7 days). After the first winter, bermudagrass was reseeded at the same rate as the initial seeding (5/26/14). Two days later (5/28/14), nitrogen fertilizer (ammonium sulfate) was applied to all plots at a rate of 50 kg ha^{-1} to satisfy N requirements that were not met by biochar.

3.2.3 Biochar Production and Characterization

Sorghum (*Sorghum bicolor*) grown in College Station, TX was used as feedstock for fixed-bed pyrolysis by Agri-Tech Producers (Columbia, SC). Biomass was stored in silage bags after harvest until shipping for pyrolysis. For pyrolysis by Agri-Tech, a hammermill fed biomass at a rate of 130 to 180 kg hr^{-1} into a chamber at 400°C, heated for 3 minutes and cooled for 2 minutes. The pressure was near ambient atmospheric pressure and no inert gasses were added. After biochar was cooled, it was bagged and shipped to College Station, TX. The nutrient concentration in biochar was used to estimate nutrients application rates of field plots (Table 3.4 and 3.5).

Table 3.4. Feedstock and biochar analysis.

	Sorghum feedstock	Biochar
Nutrient	Nutrient concentration (g kg^{-1})	
C	407.9	486.8
N	16.7	13.7
P	3.2	5.3
K	35.0	57.7
Ca	13.3	26.3
Mg	3.6	7.3
Na	1.0	2.8
Fe	4.5	7.7
S	2.9	4.1
	Nutrient concentration (mg kg^{-1})	
Zn	131	453
Cu	17.8	98.0
Mn	105.9	258.3
B	10.8	12.8

Table 3.5. Mean biochar application rates with corresponding nutrient application rates.

	Moisture Corrected Mean Biochar Application Rate ($Mg\ ha^{-1}$)			
	3.79	7.57	11.36	15.14
Nutrient	Nutrient Application Rate ($kg\ ha^{-1}$)			
N	51.9	103.7	155.6	207.5
P	20.2	40.4	60.6	80.8
K	218.3	436.7	654.9	873.2
Ca	99.4	198.8	298.2	397.5
Mg	27.5	55.1	82.6	110.1
Na	10.4	20.8	31.2	41.6
Zn	1.7	3.4	5.1	6.9
Fe	29.1	58.1	87.2	116.3
Cu	0.4	0.7	1.1	1.5
Mn	1.0	2.0	2.9	3.9
S	15.5	31.1	46.6	62.1
B	0.0	0.1	0.1	0.2

To characterize physical properties of biochar, biochar was sieved to determine the proportion of particle sizes (Figure 3.5). A Ro-Tap was fitted with sieves (2, 1, 0.85, 0.3, and 0.075 mm) and 100 g of biochar was shaken (150 strokes/min) for 10 minutes. Biochar particles that remained on each sieve were brushed off of each sieve and weighed.

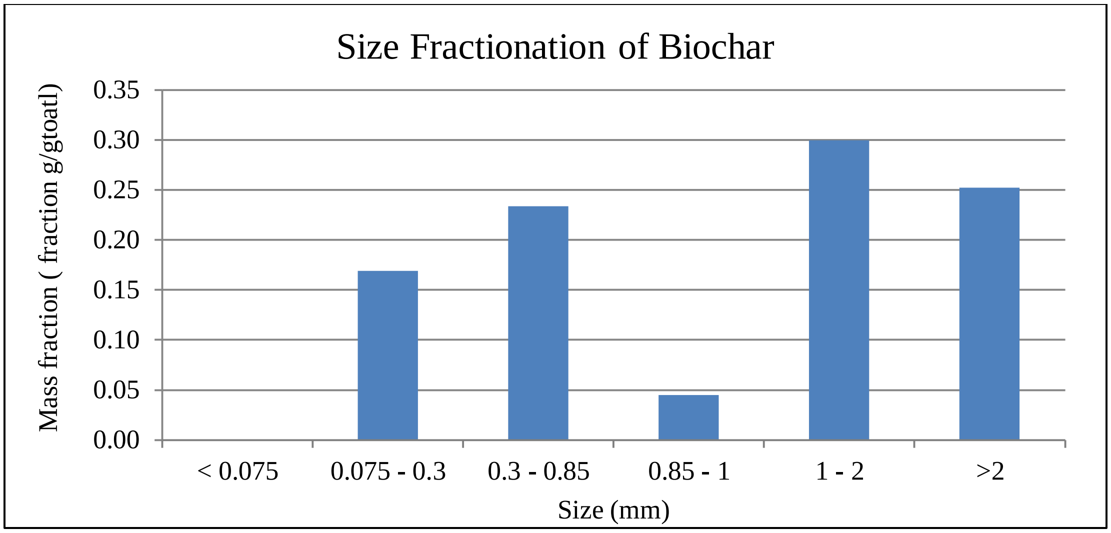

Figure 3.5. Size fraction of biochar particles separate by sieves fitted to a Ro-Tap sieve shaker.

3.2.4 Runoff and Sediment Capture

Runoff was captured by attaching plastic bags to the weir so that only runoff from the plots was captured, which were taken to the lab for quantification and sub sampling. Bags used were 56 cm by 91 cm by 4 mil polyethylene bags produced by International Plastics (Greenville, SC). Bags were secured on to the weirs using 15 cm hose clamps. After each rainfall event, plots were checked and bags collected if runoff was present and then bags were immediately replaced. Total runoff was quantified by weighing (0.1 g resolution) the runoff volume collected in each bag. Runoff volume was calculated by obtaining the mass of water and sediment (measured in subsample) and subtracting the mass of the sediment. The mass less sediment was used to estimate runoff water volume at 1 g mL^{-1}.

Sub-samples were taken (120 mL) using 4 oz clear plastic cups (ULINE, Pleasant Prairie, WI) from the runoff collected from each plot to quantify the amount of sediment that was lost for each runoff-producing rainfall event. If the runoff produced less than 120 mL, then the full amount of captured runoff was used in the following step. The sediment sub-samples were weighed (0.001 g resolution), dried in a 65 °C oven for 48 hours, and then weighed again to quantify the sediment transported off of the plots with the runoff. Sediment weights and runoff plot area were used to estimate sediment loss per unit area (g m^{-2}).

3.2.5 Soil Sampling and Analysis

Two sets of soil samples were collected, the first during January & February of 2014, and the second taken in June of 2015. For measurement of soil physical properties, soil was sampled using a 5 cm by 15 cm AMS Soil Core Sampler with sliding hammer and clear plastic AMS Soil Core Sampler liners, two soil cores were taken from each of the 36 research plots, one from each side of the plots outside of the center research plot, for a total of 72 independent samples (Figure 3.6). The core liners were transparent, allowing research technicians to observe any channeling down the side of the cores. Channeling in the soil core would provide preferential water flow down the side of the core during saturated hydraulic conductivity testing. If a channel was observed, the sample was discarded and another sample was taken. A second set of samples was taken

(06/04/15) using AMS Step probe with a 2.2 cm by 33 cm probe. Ten soil samples (15 cm depth) were taken from each plot, five on either side of the center plot, and composited for analysis.

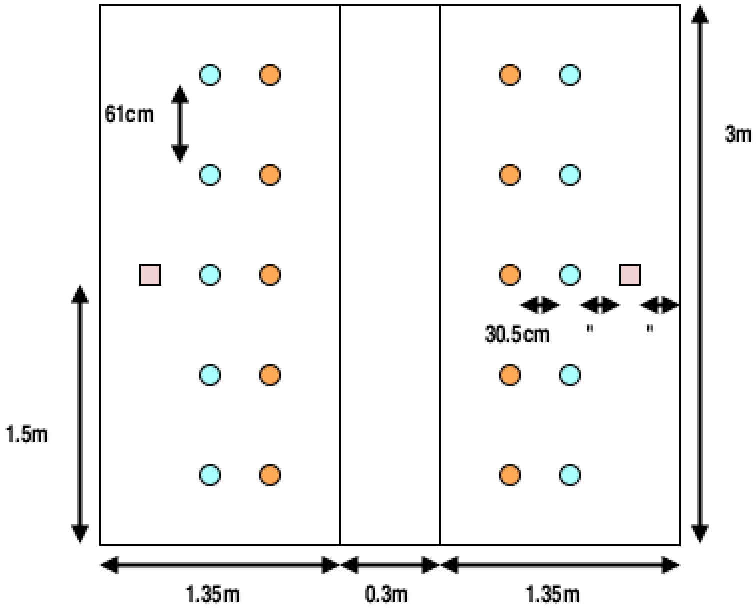

Figure 3.6. Diagram of a research plot. Pink squares: location of soil sampling for physical property testing. Blue circles: location of first set of samples for analysis of nutrients. Orange circles: location of second set of samples for nutrient analysis.

Soil was submitted to the Texas A&M AgriLife Extension Soil, Water, Forage Testing Laboratory in College Station, TX, for nutrient analysis (pH, NO3-N, EC and Mehlich III P, K, Ca, Mg, Na, and S, http://soiltesting.tamu.edu/). Electrical conductivity and pH were determined using a 1:2 soil: de-ionized water ratio, left to equilibrate for 30 minutes, and measured with a conductivity or hydrogen sensitivity probe, respectively (Rhoades, 1982, Schofield 1955). Mehlich-III solution was used to extract P, K, Ca, Mg, Na and S from soil samples and analyzed using ICP (Mehlich, 1978, Mehlich, 1984). The NO_3–N in KCl extracts of soil was analyzed through cadmium reduction (Kachurina, Krenzer, et al., 2000, Keeney, 1982).

3.2.6 Bermudagrass Harvest

Bermudagrass was harvested from the center-isolated portion of the plot (3 m by 30 cm) using Makita XMU02Z 18V Cordless LXT grass shear to determine biomass yields. Vegetation was sheared 5 cm above the soil surface. The harvested biomass was bagged and weighed, and a representative sub-sample was taken to determine moisture content. The sub-sample was weighed to obtain a wet weight, dried at 65 °C for 72 hours and weighed again. Moisture content was calculated on a dry mass basis. The moisture content was used to calculate the dry biomass for each plot using the following formula:

$$\text{Biomass per plot (g m}^{-2}\text{)} = \frac{\frac{\text{wet mass of total sample (g)}}{(1+\text{w})}}{\text{plot area (m}^{2}\text{)}}$$

3.2.7 Soil Saturated Hydraulic Conductivity

For soil saturated hydraulic conductivity (K_{sat}), bulk density, water holding capacity, and porosity testing, the 5 cm diameter by 15 cm long soil cores collected from side plots were used. Soil cores were prepared for saturated hydraulic conductivity testing by first securing cheese cloth across the bottom to prevent soil loss. Using sections of motorcycle inner tube, an extra 5 cm of core liner was added to the top of each 15cm core to provide a reservoir for a constant head to be maintained during testing. Samples were saturated from the bottom up using reverse osmosis water with $CaCl_2$ containing 1.47 g L^{-1} to minimize soil dispersion that can affect K_{sat} (Zimmie, 1981). Once the columns were saturated, they were tested by block (*n*=18) using a constant head infiltrometer (Figure 3.7).

Figure 3.7. Constant head infiltrometer bench. Left: shown with sample columns being tested for K_{sat}. Right: front view of infiltrometer.

The procedure used to measure K_{sat} was as follows. The samples were taken from the tank they were saturated in and placed on the device, where a constant head was maintained for 40 minutes to allow for steady state flow to be established. Immediately after constant head was established, the soil height and head were measured with a ruler. Leachate was collected for a period of 20 minutes and weighed. This process was repeated 2 additional times for a total of 3 measurements per column. After the 3 repeated measurements, the soil height and head were measured. Ksat was determined using data collected and the formula below.

$$K_{sat} = \frac{VL}{At\Delta H}$$

Where:

V = volume of leachate (cm^3)

L = length of the soil in the column (cm)

A = area of column surface (cm^2)

t = time (sec)

H = height of hydraulic head (cm)

3.2.8 Soil Bulk Density

After the 72 columns were tested for saturated hydraulic conductivity, they were dried at 105 °C for 24 hours. To find the bulk density without the influence of vegetation and top-dress biochar the top 1.5 cm of each column were removed with a coping saw. The new dimensions of each column were measured with a ruler and the volume was calculated. The dry mass of the soil was measured and the bulk density calculated using the following formula.

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{\text{dry soil (g)}}{\text{volume of column (cm}^{3}\text{)}}$$

3.2.9 Soil Water Holding Capacity

After the bulk density was calculated, the same soil, now dried, was used to calculate water holding capacity by pressure plate extraction using a Soilmoisture Equipment Corp. (Goleta, California) pressure plate and pressure vessel (Figure 3.8). Pressures used were 10, 33, 100, and 300 kPa. A ½ bar (50 kPa) high flow, 1 bar (100 kPa) (2 separate plates and vessels), and 5 bar (500 kPa) pressure plate was used.

Figure 3.8. Pressure plate extraction vessels (-10,- 33, -100 kPa pressure vessels).

Samples were tested 9 at a time (one half of the samples per replication) at all 4 different pressures simultaneously. The procedure, repeated 8 times total (2 per rep by 4 reps), is as follows. Soils were taken from the drying oven after bulk density testing, to ensure that there was no separation due to differences in density, the soil was rewet with distilled water and stirred to ensure a representative sample was placed on the pressure plate for moisture extraction. Nine 1 cm by 5 cm polyvinylchloride rings were placed on each of 4 pressure plates and filled with the homogenous mixture from each soil core. The plate was covered with reverse osmosis water and the samples were left to saturate completely for 24 hours. After 24 hours, the pressure vessels were closed and the proper pressures were applied for an additional 24 hours. The samples were then transferred using a spatula into a container and the weight recorded. The containers were placed back into the drying oven (105 °C) for 24 hours then weighed again. Water content was calculated as:

$$\text{w}= \frac{\text{mass of sample after pressure chamber (g)-mass of dry soil (g)}}{\text{mass of dry soil (g)}}$$

3.2.10 Porosity

Porosity was calculated by finding particle density using a Micromeritics helium pycnometer (Norcross, GA) with the formula:

$$\text{Porosity } \left(\frac{\text{pore volume}}{\text{total volume}}\right) = 1 - \frac{\text{bulk density (g cm}^{-3}\text{)}}{\text{particle density (g cm}^{-3}\text{)}}$$

After soil was weighed to find dry soil mass for water holding capacity calculation, the entire sample was placed into the pycnometer (Figure 3.9). Particle density was calculated using Micromeritics particle density procedures. The soil sample was placed into the pre-weighed cup used in the device. This was repeated 3 times for each sample. Particle density was calculated using these pressure readings using the formulas provided by Micromeritics for the device.

Figure 3.9. Micromeritics helium pycnometer used to calculate particle density.

3.3 Statistical Analysis

Results from the runoff, sediment, biomass, K_{sat}, water holding capacity, bulk density, and porosity were analyzed for normality and homogeneity of variance (Levene's HOV test treatment vs affected parameter e.g. runoff) before being analyzed with ANOVA at a significant level of $\alpha=0.05$ to test for treatment effects (SAS). When normality was violated, data was transformed using either a square root function or natural log. This was necessary for soil nutrients (square root), which were not normally distributed. When significant treatment effects were observed, treatment means were separated using the least squared means (LSMEANS) function of SAS with the Tukey adjustment.

Soil nutrients and pH were also tested using for linear and quadratic relationships, based on the observed trends in means. The regression was done using SAS and the GLM function and the trend line function of Excel. The testing treated nutrient concentration (or pH) as the dependent variable and biochar application rate as the independent variable. Application method was not analyzed against concentration in the field nutrient analyses because they showed no significant application method effect (with the exception of NO_3-N in the 2/14/14, which is analyzed by method and rate).

3.4 Results and Discussion

3.4.1 Soil Physical Properties

Soil saturated hydraulic conductivity (K_{sat}) was measured six months after biochar application. Values of K_{sat} were log (natural) transformed to improve normality and equality of variance before ANOVA and treatment means and standard errors were back transformed for reporting. Soil hydraulic conductivity treatment mean rates ranged from 1.3×10^{-3} mm s^{-1} to 2.8×10^{-3} mm s^{-1} and did not differ ($p=0.1125$) across treatments (Figure 3.10) or compared to the control (1.8 x 10-3 mm s^{-1}).

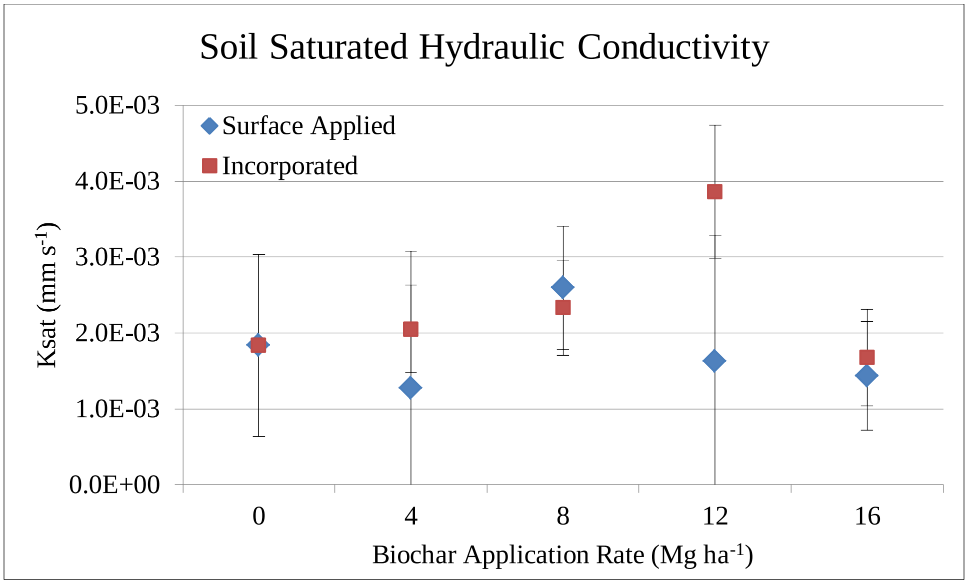

Figure 3.10. Soil saturated hydraulic conductivity (mm s^{-1}) for soil with surface applied or incorporated biochar at increasing rates. Vertical lines indicate standard error of the mean (*n*=4).

Root growth may have influenced soil saturated hydraulic conductivity rates, masking potential impacts of biochar. A similar field study conducted on a sandy soil to which 1, 5, 10, and 50 Mg ha^{-1} of hay biochar were applied also found a lack of effect on K_{sat} values (unamended soil=0.15 mm s^{-1}) due to biochar application (Jeffery, Meinders, et al., 2015). The native soil in the aforementioned study had a K_{sat} value much higher than the control value of this study, and used rates both higher and lower than those used in this study, yet found no significant change in K_{sat} using a double ring infiltrometer. Similarly, a study testing biochar addition (0, 5, 10, 20 Mg ha^{-1}) fine sandy loam soil found no change in K_{sat} values using the constant head method (Laird, Fleming, et al., 2010). Biochar addition to soil may either predominately slow K_{sat} due to water filling the high porosity of biochar particles, or may predominately increase K_{sat} by improving soil structure (Castellini, Giglio, et al., 2015, Uzoma, Inoue, et al., 2011). For these studies and for the soil used in this study, which had a natural K_{sat} value of 1.8×10^{-3} mm s^{-1}, biochar addition did not predominately have an effect either way. It is logical that the low K_{sat} values would not be significantly affected by introducing the high porosity of biochar, which is reported to be responsible for increasing the amount of space to be filled as water flows through the soil, thus slowing hydraulic conductivity (Uzoma, Inoue, et al., 2011). Additionally, the influence of vegetation may have influenced soil structure more than biochar addition.

Similar to saturated hydraulic conductivity, the addition of biochar to soil did not significantly affect bulk density ($p=0.2324$). Mean soil bulk density values ranged from 1.18 to 1.35 g cm^{-3} for soil with increasing biochar application rates (Figure 3.11).

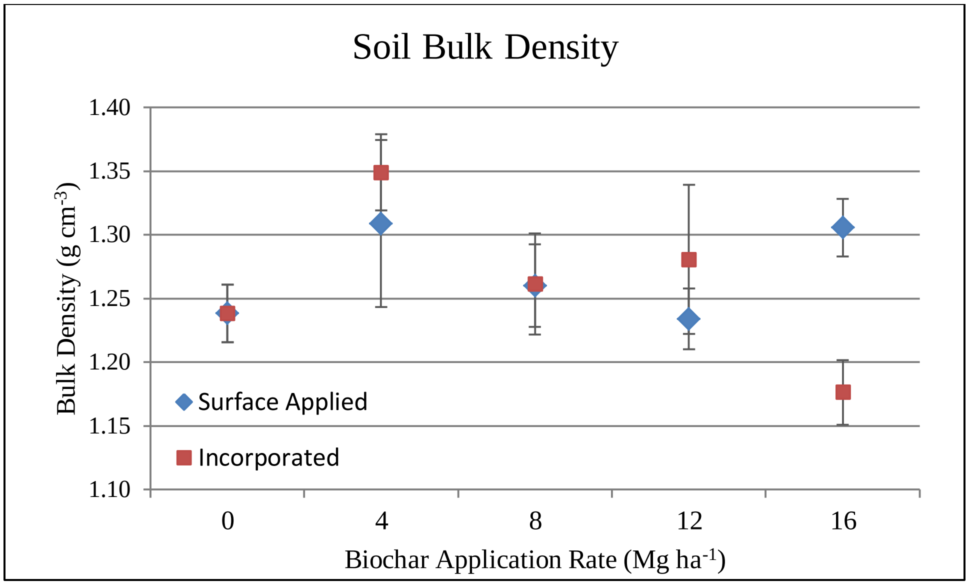

Figure 3.11. Soil bulk density (g cm^{-3}) measured on soil with increasing biochar application rates and contrasting methods of application. Vertical lines indicate standard error of the mean (*n*=4).

The amount of biochar added to the soil was equivalent to 1% of soil by weight and 7.5% by volume at the highest biochar application rate. The physical change in bulk density, that is, in the absence of structure-building processes achieved by biota, can be predicted by using the bulk densities of the soil and biochar and the application rates. The table below shows the anticipated effect of incorporated biochar addition to soil in the absence of biotic influence (Table 3.6).

Table 3.6. Predicted and observed bulk densities (g cm^{-3}) for soil with incorporated biochar at increasing rates.

	Biochar Application Rate (Mg ha^{-1})				
Bulk density (g cm^{-3})	**0**	**4**	**8**	**12**	**16**
Predicted	--	1.23	1.21	1.19	1.17
Observed*	1.24	1.35	1.26	1.28	1.18

*Mean bulk density calculated from field samples (*n*=4). Calculated using measured field bulk density of 1.24 g cm^{-3} and measured biochar density of 0.14 g cm^{-3}.

Therefore, potential for change in soil bulk density was minimal even without the influence of flora or fauna. According to previous studies, roughly 2% (by weight) of biochar to soil percentage is enough to produce a measurably significant decrease in bulk density in amended soils (Chen 2011, Mukherjee 2013). It is likely, then, that the rate of biochar application was not high enough to produce the type of linear, physically-induced decrease in bulk density as seen in studies like Githinji 2014, where there was almost a direct linear relationship when biochar was added in 25% (by weight) increments. There was actively growing vegetation present at all the sampling sites, and thus there was significant rooting activity within the samples analyzed for physical properties even though the aboveground vegetation in each sample was removed prior to the determination of bulk density. This rooting activity necessarily affected bulk density, due to the low density of typical bermudagrass roots and the variation of rooting volume inherently present in field samples. The influence of the macropores and channels created by biotic activity, the greatest factor in the formation of macropores, may have overshadowed any observable effects caused by biochar application, as macroporosity is most affected by the preferential flow in macropores (Jeffery, Meinders, et al., 2015).

Building upon the bulk density data collected, the results for porosity are consistent with the overall trend of physical responses to biochar application. That is, there did not exist a significant change in porosity values with respect to biochar application rate or method (p=0.1422). The measurements obtained for block one of particle density were discarded due to instrument error. Porosity values ranged from 0.48 to 0.54, with the unamended soil having a porosity of 0.51 (Figure 3.12).

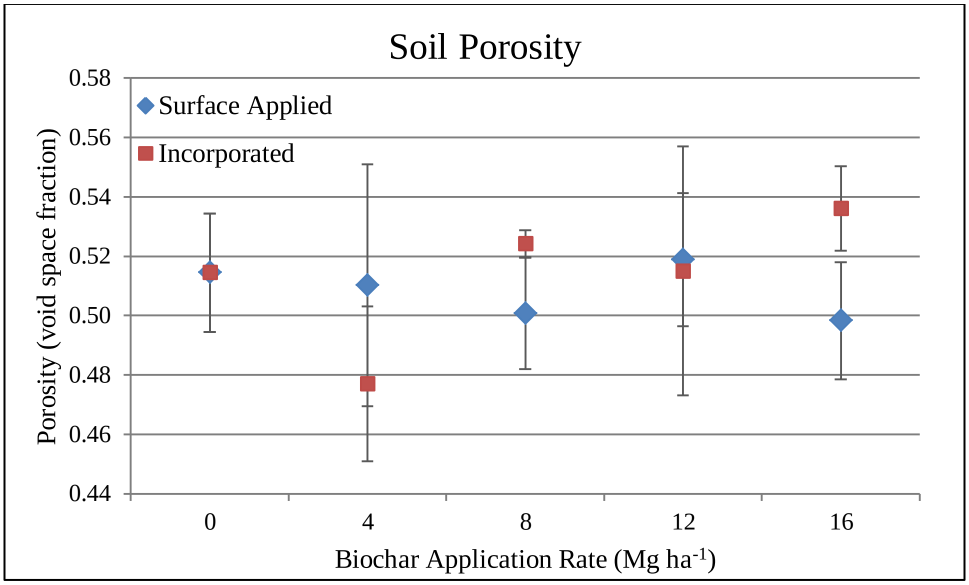

Figure 3.12. Soil porosity response to biochar application rate and method. Vertical lines indicate standard error (*n*=3).

Porosity values are calculated with both bulk density and particle density results. In a study involving biochar application to a clay soil, macroporosity increased with increasing biochar application rate (Castellini, Giglio, et al., 2015). This increase was observed in a clay soil, which has smaller pore sizes than sandy or loamy soils, so the aggregation of particles is more beneficial to macroporosity and water flow in the soil than they would be in a sandy soil. In sandy soils, however, there was also seen an increase the porosity of sandy soils (46% to 57%), however, this occurred underneath charcoal production sites that were exposed to multiple charcoal introductions to the soil over 2 to 14 month period (Oguntunde, Abiodun, et al., 2008). This loading rate of biochar to soil is far greater than that seen in this field study and therefore logical that the one time application of biochar used in this study did not produce similar results to a clay soil or the sandy soil. Similarly, a study using 1, 2.5, 5% by weight also saw an increase in porosity (and decrease in bulk density), however, the lowest rate of this study was equal to the highest rate used in our study indicating that our rates were likely too low to see a similar effect (Abel, 2013).

Measurement of soil water holding capacity, which is intrinsically related to both bulk density and porosity, adds to the growing body of evidence compiled in this paper that did not reveal significant effects of biochar application on the physical soil parameters. Of the four matric water potentials tested (-10, -33, -100, -300 kPa), there was only a significant effect for the lowest potential (-300 kPa, p=0.0290; rate*method p=0.0381) (Figure 3.13). Only the highest rate of incorporated biochar treatment (16 Mg ha^{-1}) produced a significant treatment effect at -300 kPa (p=0.0381). Water potentials above -300 kPa did not produce significant rate or method effects. A similar result was found in a study previously referenced, where both the application of 10 and 50 Mg ha^{-1} of biochar did not produce significant effect on water holding capacity either >-70 and < -70 kPa (Jeffery, Meinders, et al., 2015).

However, other studies did find increases in water holding capacity. One study conducted on Clarion loam soil that was severely compacted before biochar application and benefitted from the mechanical disturbance of tillage as well as biochar itself (Laird, Fleming, et al., 2010). Another study observed increases in plant available soil water at biochar application rate of 1, 2.5, and 5% by weight (Abel, Peters, et al., 2013). Clearly, there is no consistent trend in water holding capacity as it relates to biochar application due to initial variation of soil water holding capacity and the amount and type of biochar added.

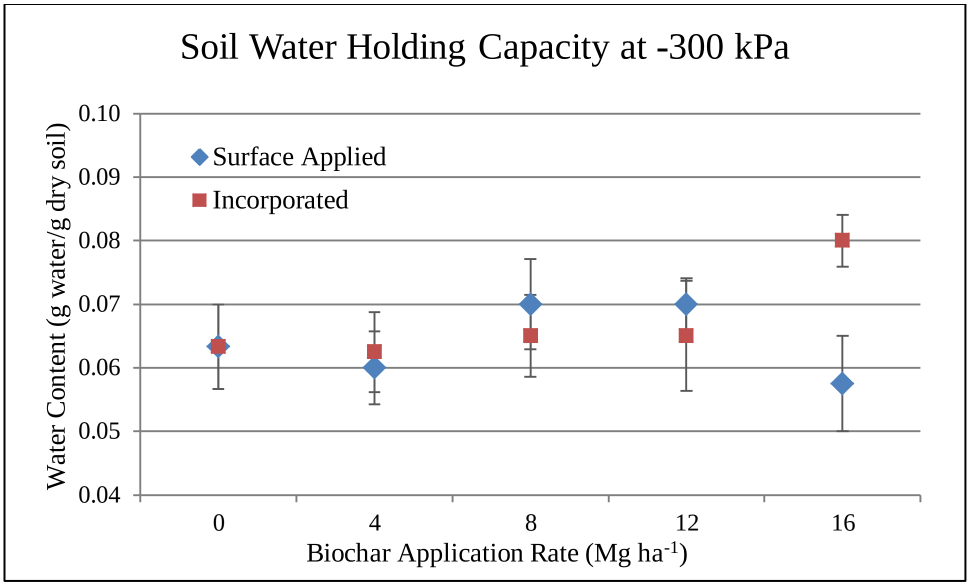

Figure 3.13. Soil water holding capacity (-300 kPa) of soil with surface applied or incorporated biochar. Vertical lines indicate standard error of means (*n*=4).

It is not unexpected that the surface applied treatments of biochar would not significantly affect the physical properties of bulk density, porosity, and water holding capacity, since the surface of each soil sample column was removed to eliminate the effect of substances external to and above the soil itself (vegetation and surface applied biochar). It is possible that rates of biochar application used in this study were too low to overcome natural variation of soil physical properties introduced by vegetation and other biological activities (Hardie, Clothier, et al., 2014, Jeffery, Meinders, et al., 2015). Properties such as bulk density will be affected after a certain point due to dilution of soil minerals by low-density biochar. However, high application rates of biochar may be impractical or even impossible if the stability and productivity of the soil are to be maintained. In addition, there may be negative environmental and agronomic impacts due to excessive biochar application rates.

3.4.2 Soil Nutrient Analysis

Results from the soil nutrient analysis, both 6 months after biochar application (2/14/14) and 22 months after application (6/4/15) were transformed when necessary using the square root function to satisfy normality requirements. Results showed a significant linear trend in both soil test K levels and pH for both sampling dates.

The six-month sample revealed a significant increase in soil extractable potassium, regardless of application method ($p<0.0001$, $p=0.0008$, respectively). Soil extractable K increased with increasing biochar application rates for surface applied and incorporated biochar, which were pooled by application rate for analysis due to a lack of method effect (Figure 3.14).

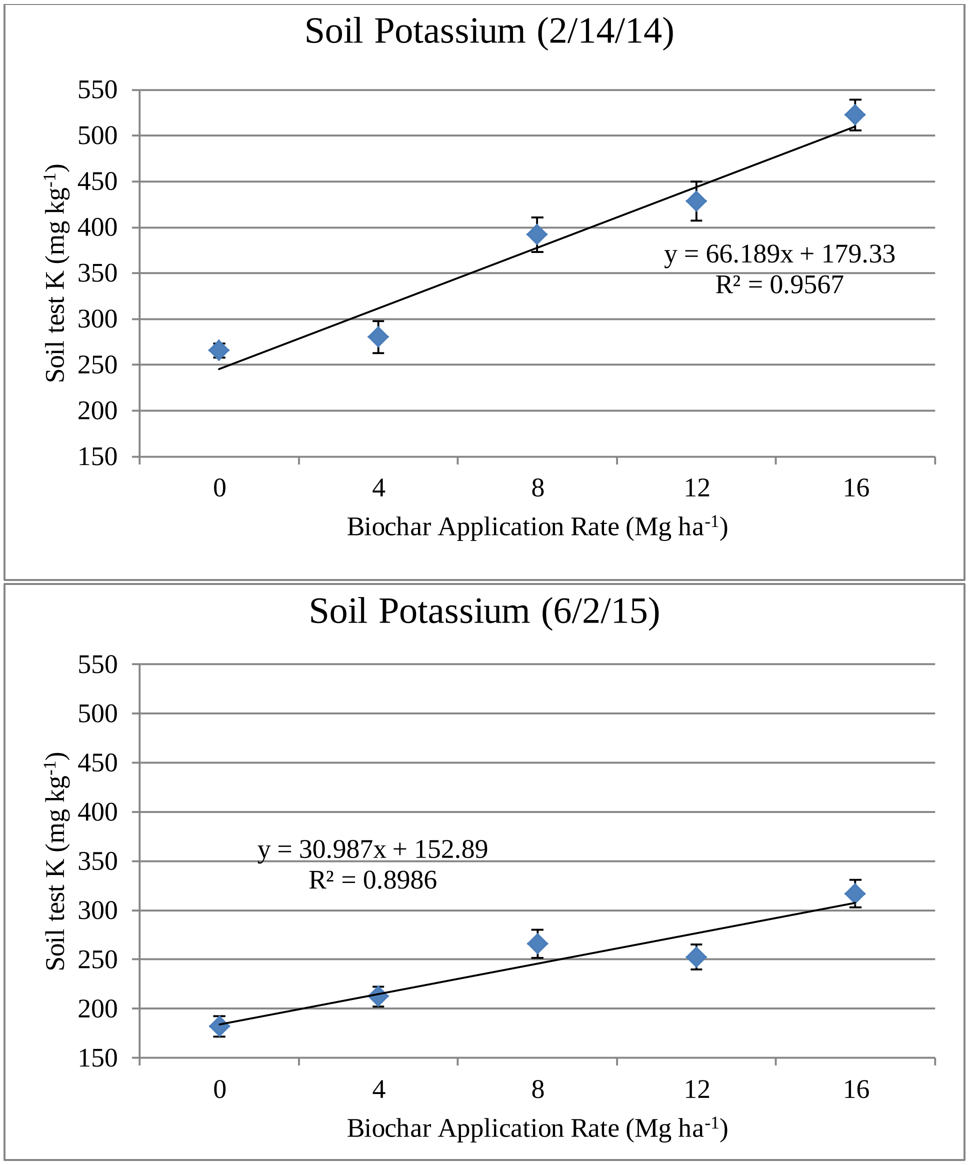

Figure 3.14. Soil test potassium (K) for soil receiving surface applied or incorporated biochar at increasing rates at 6 months after application (2/14/14) and 22 months after application (6/2/15). Vertical bars indicate standard error (n=4 (control), *n*=8 (other rates)).

Moreover, a linear relationship ($p<0.0001$, $R^2>0.9567$) was observed between biochar application rate (regardless of method, rates pooled) and soil test K for the 2/14/14 soil analysis. A significant linear relationship ($p<0.0001$, $R^2>0.8986$) was also observed for biochar application rate and soil test K for both application methods in the final soil analysis. Mean soil extractable K levels increased from 265.8 mg kg^{-1} in control soil to 522.7 mg kg^{-1} with 16 Mg ha^{-1} of biochar in the sixth month analysis. In the 22 month sample, biochar addition increased soil test K from 182.2 mg kg^{-1} to 316.9 mg kg^{-1}, indicating an overall decrease over time, yet still a significant K contribution from biochar. Dramatic increase in soil K levels was not unexpected considering 850 kg ha^{-1} K was applied with 16 Mg ha^{-1} biochar. There may also have been release of K from clay minerals (*e.g.* feldspar, mica) or clay (*e.g.* montmorillonite), but it is unlikely in such a short time after biochar application and with such a high background concentration. The critical level of extractable potassium in Texas that must be present in a soil or loss of yield may occur is 165 mg kg^{-1}. Even in the control (unamended) soils in the field, this requirement was met and crop yield was not likely affected by the addition of biochar. In a recent study done using Switchgrass biochar, a 10% (by weight) addition to soil also significantly increased soil test K in two different clay soils, from 599.3 mg kg^{-1} to 1499 mg kg^{-1} for a Colorado clay soil and 235.3 to 749.7 mg kg^{-1} for a Virginia clay (Kelly, Calderon, et al., 2015). In another study, initial soil test did not show significant nutrient loading from biochar, however at the end of the first growing season the soil K was twice as high as the control (van de Voorde, Bezemer, et al., 2014). This provides further evidence that biochar when applied to soils serves as a reservoir of exchangeable potassium. In our field study, this potassium reservoir was evidenced by the fact that both the 6 month and 22 month samples showed a strong linear relationship between increased biochar application rate and soil test K (Figure 3.14).

For the six month soil analysis, nitrate-N concentrations increased for surface applied biochar treatments but not for incorporated treatments (model $p=0.0144$, rate*method $p=0.0459$); there was no significant effect for the 22 month analysis ($p>0.05$). Six month soil analysis (2/14/14, left) showed a significant increase in nitrate-N for the highest three rates of surface applied biochar treatment (8, 12, 16 Mg ha^{-1}, $p=0.0459$) (Figure 3.15). However, soil concentration of nitrate-N increased from only 1 mg kg^{-1} to 2.5 mg kg^{-1}. The relatively small increase in soil nitrate-N is not expected to affect plant growth (additional fertilizer addition would still be required for crop bermudagrass growth). Soil sampled 22 months after application (6/4/15) revealed a lack of significant differences with biochar application on soil nitrate-N concentration. Plant uptake, leaching and runoff, as well as other potential N losses would easily eliminate the effect of such small changes in soil nitrate-N. Biochar application rates of 16 Mg ha^{-1} supplied in excess of 200 kg ha^{-1} total N, yet soil nitrate-N concentrations were largely unaffected. More importantly, the lack of response of soil nitrate-N levels following biochar application suggests that very small fractions of biochar N are in soluble or readily mineralized forms. Biochar made from grasses pyrolyzed at lower temperatures (250 to 400 °C) has been shown to increase C mineralization in a soil, and when C min increases, N mineralization should also increase if there are residual nitrogen compounds in or around the biochar (Zimmerman, Gao, et al., 2011). In this field study, the only increase seen in soil nitrogen was under surface applied treatments, which could imply that carbon mineralization changes were not significant enough in incorporated treatments to increase nitrogen mineralization.

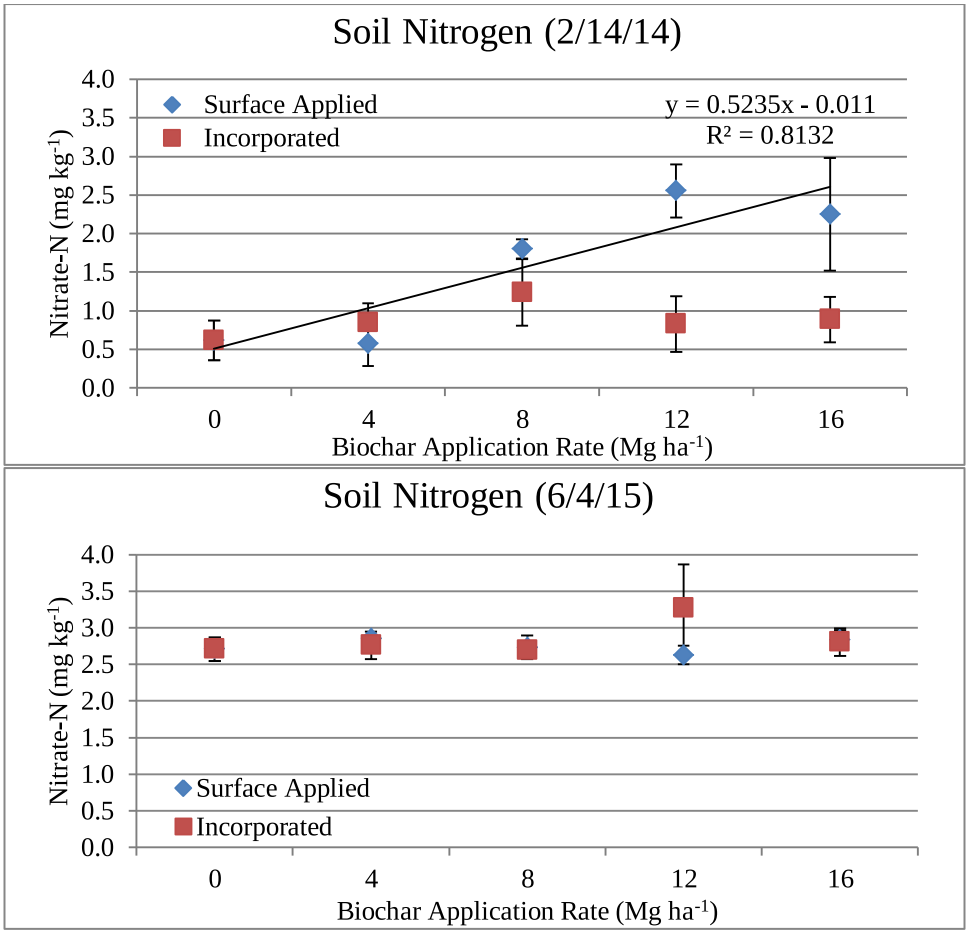

Figure 3.15. Six month and 18 month soil sample analysis for nitrate-nitrogen with respect to biochar application rate and method in the runoff plots. Vertical lines indicate standard error (*n*=4).

There was a significant increase in pH in the initial soil sample (2/14/14) with respect to biochar application rate ($p=0.0119$), regardless of the method of application (Figure 3.16). Unamended soils were acidic ($pH=6.3$) while 16 Mg ha^{-1} biochar addition increased pH by 0.4 to 6.7. The pH measured at the second soil sampling date did not show a significant treatment effect from the addition of biochar, in fact the trend that was present in the first soil sample was reversed in the (6/4/15) sample ($p=0.0257$, $R^2=0.6537$). Many studies have identified biochar as having significant liming potential, due to the high proportion of basic cations typically present in biochar (Jeffery, Verheijen, et al., 2011, Laird, Fleming, et al., 2010, van de Voorde, Bezemer, et al., 2014). Bermudagrass was reestablished after the first winter due to a cold snap in late spring. To re-establish this bermudagrass, the plots were irrigated using tap water which contains a significant concentration of sodium and bicarbonate. Basic cation addition through irrigation may have caused the increases in pH seen in the control plots during the second sampling date relative to the first. In that case, biochar would appear to have had a buffering effect, and the higher cation exchange capacity reported in similar studies could have held some of the cations so that they did not contribute to increased pH seen in the control plot (Chen, Du, et al., 2011, Liang, Lehmann, et al., 2006). This would be consistent with the linear decrease observed in pH for increasing surface applied biochar.

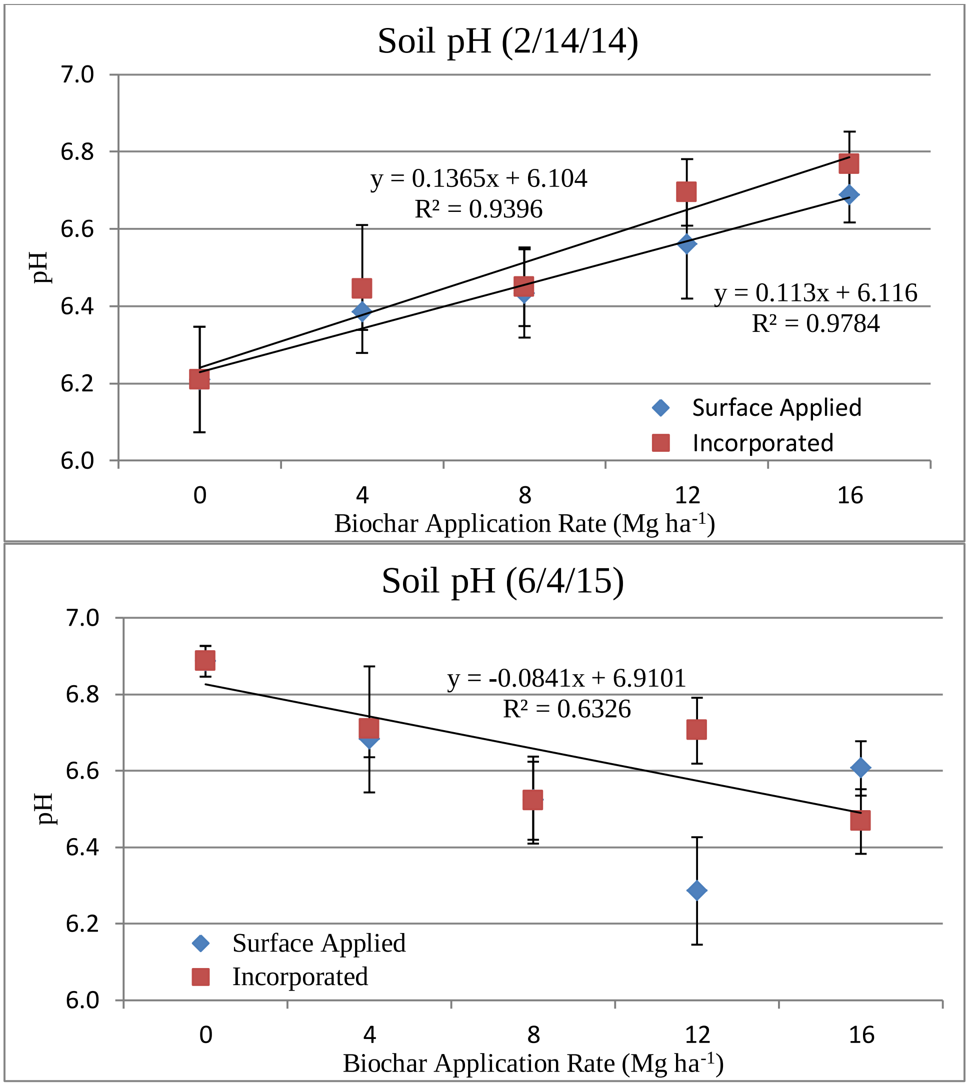

Figure 3.16. Soil pH response to biochar application rate. Vertical lines indicate standard error (*n*=4).

Soil nutrient analysis revealed a significant relationship between increasing biochar application and several soil test parameters. Increases in soil extractable potassium concentration and pH were proportional to the increase in biochar application.

Yet, there was no effect of increasing biochar application on soil physical properties. These results suggest that biochar applied to soil will provide some fertilizer and liming effects that could affect plant growth. Using biochar addition to improve soil physical properties as a method to improve crop growth may be unlikely at rates evaluated in the current study.

Routine soil nutrient was conducted (pH, electrical conductivity, Nitrate-N, P, K, Ca, Mg, S, Na) and there was no significant soil nutrient response in P, EC, Ca, Mg, S, or Na for either the six month sample ($p>0.1225$) or the 22 month sample ($p>0.0537$). The mean values for biochar application treatments for both sampling dates are listed in the table below (Table 3.7 and 3.8).

Table 3.7. Six month mean soil concentration of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH.

2/14/14	Biochar Application Rate (Mg ha^{-1})							
		Surface Applied				**Incorporated**		
Nutrient	0	4	8	12	16	4	8	12	16
pH	6.21	6.39	6.43	6.56	6.69	6.45	6.45	6.70	6.77
					μmhos cm^{-1}				
EC	223.5	202.8	221.3	228.3	236.8	208.0	216.8	222.8	238.5
					mg kg^{-1}				
NO_3-N	0.62	0.58	1.80	2.55	2.25	0.85	1.24	0.83	0.89
P	293.6	343.3	325.2	354.7	303.5	278.3	293.9	338.4	324.4
K	318.7	269.6	372.9	461.7	486.4	345.2	344.5	449.9	475.4
Ca	1214.2	1133.6	1157.6	1688.8	1120.3	1542.1	1140.5	1679.2	1302.4
Mg	127.3	109.0	114.1	111.2	120.9	104.3	122.2	125.7	115.2
S	32.1	18.6	21.6	18.1	18.3	15.7	16.8	20.2	19.0
Na	107.9	90.5	72.6	59.9	67.1	60.3	73.5	80.1	58.1

Table 3.8. Twenty two month mean soil concentration of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH.

6/2/15	Biochar Application Rate (Mg ha^{-1})								
	Surface Applied					**Incorporated**			
Nutrient	0	4	8	12	16	4	8	12	16
pH	7.04	6.75	6.70	6.46	6.63	6.73	6.53	6.73	6.49
					µmhos cm^{-1}				
EC	162.0	144.0	160.1	159.3	156.5	149.8	149.8	156.5	162.0
					mg kg^{-1}				
NO_3-N	2.71	2.85	2.73	2.63	2.83	2.76	2.69	3.27	2.81
P	268.1	327.2	317.8	352.2	279.7	312.5	301.5	327.1	344.4
K	182.0	208.73	271.47	248.9	318.9	215.8	259.9	255.9	314.9
Ca	1231.5	1080.7	1194.6	1591.1	1049.5	1621.2	1145.4	1724.3	1352.4
Mg	124.1	113.6	128.7	113.5	125.8	119.4	127.2	127.2	126.5
S	9.96	8.36	9.41	10.46	8.59	9.52	9.35	9.96	9.99
Na	24.3	15.8	16.5	10.6	15.3	11.9	14.9	14.8	9.9

3.4.3 Biomass Yield

Over the course of this study, there were seven independent bermudagrass harvests. The first harvest occurred in the fall of 2013, the next five occurred during the 2014 growing season, and the last occurred in the summer 2015 growing season. Mean biomass yields for soil with increasing application rate of biochar ranged from 2.33 to 6.47 Mg ha^{-1} on individual harvest dates, with the exception of the first clipping of the 2014 growing season which had lower biomass due to a late season freeze (0.72 to 1.20 Mg ha^{-1}). Biomass yield did not differ ($p>0.2079$) for soil with biochar applied at increasing rates, surface applied or incorporated, on any harvest date. Similarly, cumulative biomass yield did not show a significant ($p=0.8206$) treatment effect with respect to biochar application rate or method of application. Mean cumulative biomass yields over a two-year period (seven cuttings) ranged from 2.23 to 2.86 Mg ha^{-1} (Figure 3.20).

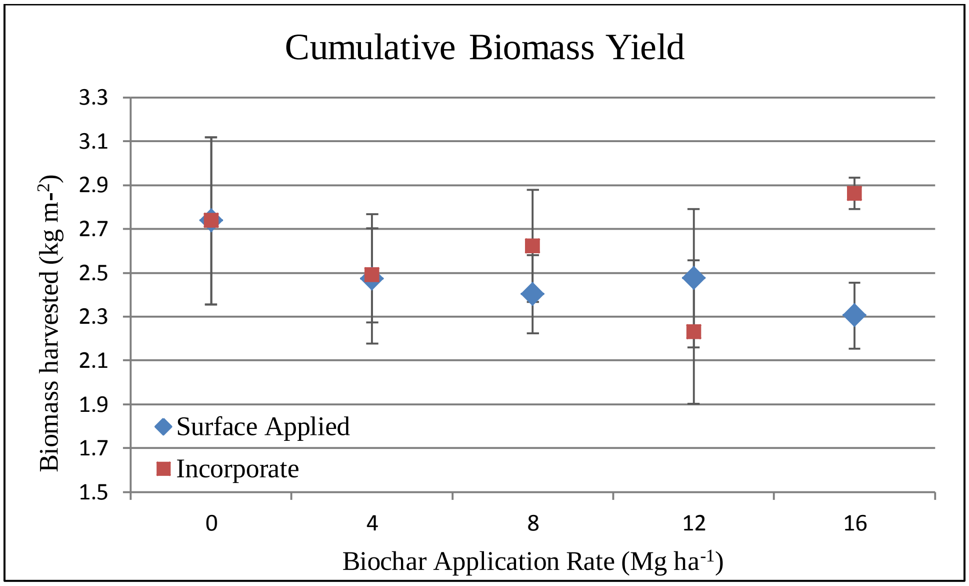

Figure 3.17. Cumulative biomass yield for soil with increasing biochar application rates, surface applied or incorporated. Vertical lines indicate standard error of means (*n*=4).

Physical properties that enable the soil to retain and supply moisture to plants are of particular interest production systems utilizing biochar. Yet, the lack of significant biomass response to biochar application in this field study may have been due in part to the lack of significant changes in soil physical properties. Other studies have found a plethora of responses to biochar application in terms of biomass production, though most of the current body of evidence is based on short term (one growing season) studies

(Jeffery, Verheijen, et al., 2011). In a study involving the addition of 0, 10, 15, and 20 Mg ha^{-1} cow manure biochar to sandy soil, the corresponding rates of biomass production increased with increasing biochar application, reaching a maximum yield increase at 15 Mg ha^{-1}. For the highest rate of biochar application (20 Mg ha^{-1}), the yield was less than that of 15 Mg ha^{-1}, indicating that continued biochar application is not beneficial to crop yield and may at some point even decrease yield (Uzoma, Inoue, et al., 2011). In a study that compared maize biochar, hydrochar, and wood biochar application to maize yield, there was a lack of significant increase in any crop yield parameter without the addition of fertilizer (Reibe, Ross, et al., 2015). In a recent study, three separate crops were unaffected by biochar application (0, 20, 50 Mg ha^{-1}) to sandy clay loam in terms of crop yield and emergence (Jay, Fitzgerald, et al., 2015). This is corroborated by other recent studies, including the application of 10 Mg ha^{-1} to restoration sites, there was no significant effect on biomass yield (van de Voorde, Bezemer, et al., 2014). It is clear that the results of this study were not atypical, and the benefits of biochar application as it relates to biomass yield are not ubiquitous. When soils are capable of providing sufficient moisture and nutrients to crops, biochar is likely to have little appreciable effect on crop yield (Jay, Fitzgerald, et al., 2015).

While soil physical properties do not necessarily translate directly to water availability to plants, they are an indication of potential plant available water. The fact that most of the physical soil parameters showed a lack of observable response to biochar application supports is supported by the lack of significant change in biomass values. Aside from soil physical parameters, biomass harvests were not affected by soil nutrient and pH increases associated with biochar application. There are at least two possible explanations: the background levels of soil nutrients were high enough that the native soil provided all the nutrients that were necessary for plant growth.

The prior land use for the area in this study was included dairy production and improved pasture. As such, the nutrient levels, particularly for P and K were inherently very high. The unamended soil had high concentrations of P (260 mg kg^{-1}) and K (280 mg kg^{-1}), but required N (0.6 mg kg^{-1} in control soil) addition, which was not supplied significantly supplied by biochar. According to the fertilizer recommendation provided by Texas A&M AgriLife, at concentrations above 50 mg kg^{-1} P and 220 mg kg^{-1} K there is 0 recommended addition of the respective fertilizer. Thus, background concentrations of P and K were sufficiently high in this soil so as to nullify any fertilizing potential of biochar for these nutrients. The secondary nutrients, Ca, Mg, and S were also at levels high enough to not require the addition of additional nutrients.

3.4.4 Runoff and Sediment

Results from the collection and analysis of runoff and sediment reflect the overall trend observed for soil physical and chemical properties. The cumulative runoff depth (mm) produced by the field plots was not significantly affected by the application of biochar (p=0.7683). Plots 147 (incorporated 8 Mg ha^{-1}), 152 (surface applied 4 Mg ha^{-1}), and 168 (incorporated 12 Mg ha^{-1}) were not included in the GLM procedure because of a shallow clay subsoil (observed to be within 15 cm of the surface during soil sampling) that consistently produced disproportionally large volumes of runoff in these 3 plots which were adjacent to one another and thus not likely to be a treatment effect. Mean cumulative runoff depths ranged from 47.5 mm and 76.4 mm depth (Figure 3.21). A similar study also did not show significant changes in runoff volumes in response to the addition of 1.5 and 3 Mg ha^{-1} of biochar (Schnell, Vietor, et al., 2012).

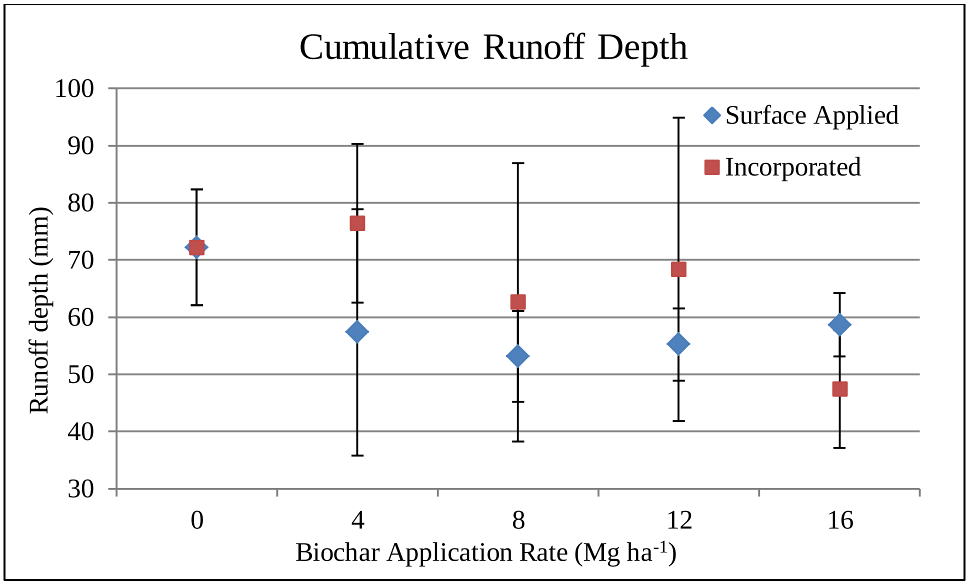

Figure 3.18. Mean cumulative runoff depth with respect to biochar application rate and method. Vertical lines indicate standard error (*n*=4).

Similar to the results for runoff, the cumulative sediment (g m^{-2}) with respect to biochar application rate or application method over 27 recorded rainfall events was not significant (p=0.4825). Cumulative average sediment loss ranged from 14.05 to 34.03 g m^{-2} (Figure 3.22). Because sediment loss is facilitated and necessarily linked to runoff volume, it is logical that the cumulative average sediment loss was also not significant with regard to biochar application rates.

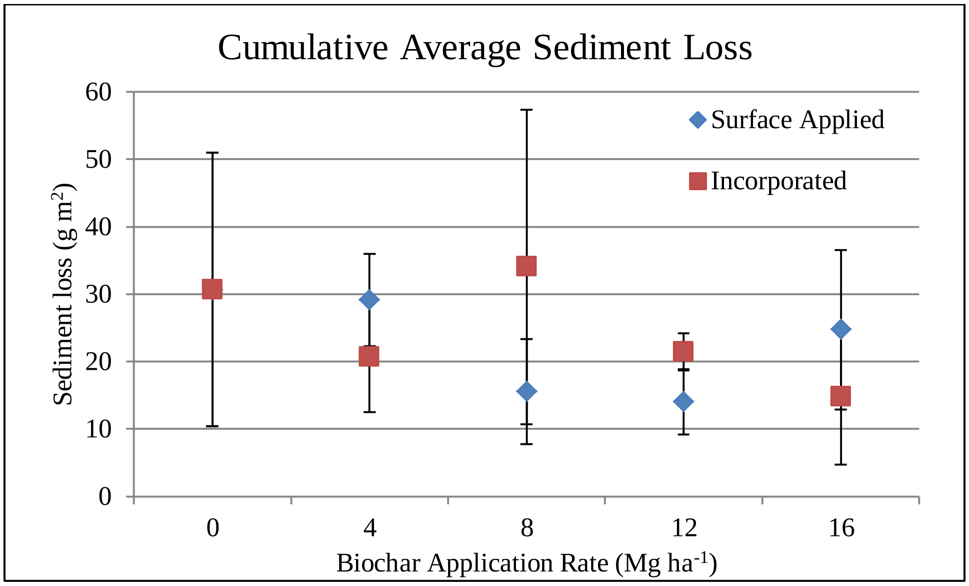

Figure 3.19. Cumulative sediment loss with respect to biochar application rate and method (collected 1/9/14 - 3/31/15). Vertical lines indicate standard error (*n*=4).

Biochar application did not affect soil physical properties or bermudagrass yield, and similarly, did not affect runoff or sediment loss. The major factors that influence the production of runoff are the rainfall and the runoff curve number, according to the SCS Runoff Equation (USDA-SCS, 1985):

$$Q=\frac{[P\text{-}0.2\left(\frac{1000}{CN}\text{-}10\right)]^2}{P+0.8(\frac{1000}{CN}\text{-}10)}$$

Where:

Q= runoff (in)

P= rainfall (in)

CN = runoff curve number

The CN value is determined using the hydrologic soil group, which is determined by the native properties of the soil, and by the type and condition of the vegetation presentation at the site. As the hydrologic group progresses (based on subsoil) from low infiltration (group D) to high infiltration (group A), the curve numbers decrease, indicating that there is a lower potential for runoff. Similarly, as the health of the vegetation (soil surface coverage) increases from poor to good, the CN decreases and the potential for runoff is lower.

In the context of this study, the factors affecting runoff differences between plots and treatments are those that affect CNs (since rainfall was constant throughout the plot area) are: the vegetation quality and the hydrologic soil class. Since there were not significant biochar related changes in physical properties (saturated hydraulic conductivity in surface and subsoil did not change) and in bermudagrass growth and yield across treatments, the lack of significant runoff differences is logical and expected. Sediment loss is intrinsically related to runoff volume. Although there were many measurable runoff events, and sediment loss was observed, a lack of significant treatment effect with respect to biochar application was observed.

Linear regression did provide some insight to explain variation of runoff across the plot area. Porosity values were significantly correlated with water holding capacity values ($p<0.0010$, $R^2=0.3082$), indicating that there were indeed differences in the physical parameters in the soil, though not necessarily induced by the addition of biochar. Additionally, this supports the fact that biochar application rates may have been too low to overcome natural levels of variation in soil physical properties present at the study site.

3.5 Conclusions

Biochar application to Booneville fine sandy loam soil at the rates used in this project affected some chemical properties (potassium and pH) but did not significantly influence the physical structure or hydrologic function of the soil. As a result, bermudagrass yield was not affected by the addition of biochar, and thus neither was runoff or sediment loss from the research plots. Even though there were significant increases in soil test K, the background level of nutrients at this site likely overshadowed and masked the fertilization effect of biochar application. This was especially true for extractible P and Ca, which had very high levels in the control soil. Background levels of nutrients at the study site would not be typical of marginal soils.

The proposed system of biochar application to increase productivity of marginal soils is uncertain. Large or repeat applications of biochar may be necessary to actually improve soil physical properties and affect plant growth and productivity. Although nutrient levels were not typical of marginal soils at this site, soil physical properties were. Increasing biochar application rate or frequency to affect soil physical properties would also have affect soil chemical properties. It is likely that excessive nutrient loading may occur if biochar is continually applied to soils. The solubility and fate of these applied nutrients are uncertain. In a previous studies, toxic levels of PAHs where found in soils underlying charcoal production sites where wood tar was discharged onto soils for extended periods of time (Edenborn and Severson, 2007, Erstfeld and Snow-Ashbrook, 1999). While chemical properties of sorghum biochar used in the current study differ from other biochar sources, long term loading of nutrients and organic compounds should be evaluated in future studies.

4. GREENHOUSE STUDY

4.1 Objectives

The first objective was to measure the effects of biochar application rate and application method on soil nutrient content, bermudagrass emergence rates, evapotranspiration dynamics, and biomass production for three contrasting soil types. The second objective was to relate variation of soil nutrient content, biomass production and nutrient uptake to application rate of biochar for each soil type.

4.2 Materials and Methods

Similar to the field study, biochar application rates of 0, 4, 8, 12, 16 Mg ha^{-1} were surface applied or incorporated into three contrasting soils (Rader fine sandy loam, Burleson clay, Ships clay). A total of 30 treatments were installed into column lysimeters and replicated 4 times. Columns were arranged in a randomized complete block design and managed under greenhouse conditions for 3 months. Columns were constructed out of 14.9 cm diameter opaque polyvinylchloride pipe cut into sections 66 cm in length (Figure 4.1). To provide support for the soil on the bottom of the column and also provide drainage, black permeable landscaping fabric was glued to 20 cm round perforated drain caps (NDS, Inc., Woodland Hills, CA) and secured inside the bottom of the pipe using adhesive and screws. At the top of each column, holes were drilled in the columns opposite one another and nylon rope was tied so that each column could be lifted from above.

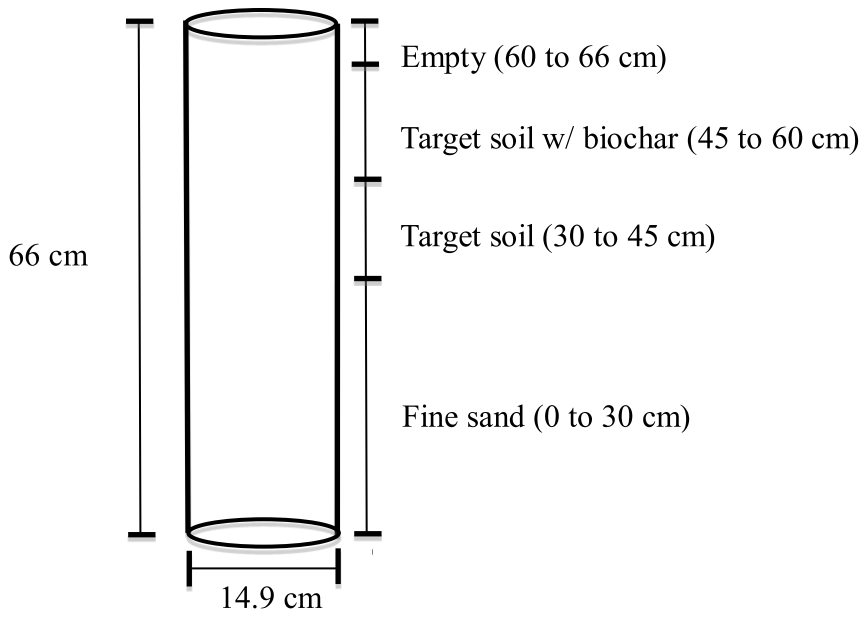

Figure 4.1. Dimensions of columns and depth soil layers added to each column for three soil types with and without surface applied or incorporated biochar.

Soil was passed through 2 mm sieve prior to being added to each column in 5 cm increments. The soil was allowed to settle in the columns during the saturation process to reach the target bulk density (Table 4.1).

Table 4.1. Bulk density for each soil type used in the greenhouse study; planned density and observed at the end of study (mean values for 0 to 15 cm depth).

Bulk density (g cm^{-3})	Rader fine sandy loam	Burleson clay	Ships clay
Planned	1.70	1.40	1.50
Observed (mean of control (0 to 15 cm))	1.59	1.32	1.39

The 30 to 60 cm depth was filled with fine sand to provide adequate tension for water drainage. The 15 to 30 cm depth was filled with pure target soil (Rader fine sandy loam, Burleson clay, Ships clay). The surface layer, 0 to 15 cm depth, was filled with target soil or soil/biochar mixture. For surface applied biochar, biochar was added after addition of the surface 15 cm of target soil and seeding of bermudagrass (*cynodon dactylon*). Column height extended 5 cm above the soil surface to allow for watering.

Biochar was incorporated with target soil by mixing for 1 minute in a 0.05 m^3 capacity electric cement mixer (30 rpm) prior to addition to the soil columns. For incorporated treatments, the weight of soil (adjusted for moisture) plus biochar needed to pack all replications for each treatment was added to the cement mixer. Target soils with surface applied treatments were also mixed in the cement mixer even though there was no biochar in the mixer to ensure that there was no variation in the data due to mixing. Soil columns were placed in Rubbermaid bins and saturated from the bottom up in reverse osmosis water for 10 days. Columns were allowed to drain for 1 week to reach field capacity. Bermudagrass was seeded at a rate of 5 g m^{-2} (approximately 320 seeds per column) prior to the addition of surface applied biochar and gently pressed into the soil surface. Thus, the bermudagrass seed was covered with the biochar in the surface applied treatments but not in incorporated biochar treatments.

4.2.1 Seedling Emergence and Surface Temperature Measurement

After the completion of the biochar application and bermudagrass seeding, the number of actively growing seedlings per column was counted daily. In addition, soil surface temperature was taken every day in between 2 PM and 3 PM using a handheld infrared thermometer. Seedling counts were taken immediately after surface temperature readings each day from 1 to 31 days after planting. Seedlings were counted by hand for the entire area of each column. Germination index was developed using these daily counts:

$$\text{Germination Index (GI)} = \sum_{0}^{i} \frac{\text{seedling count on day i after planting}}{\text{day i after planting}}$$

Where:

i = number of days after planting

4.2.2 Soils

Three soil types were used to evaluate the effects of biochar on bermudagrass production. Soils included Rader fine sandy loam, Burleson clay, and Ships clay. Soils were chosen to represent of soils that are prevalent in the south central United States. Soil chemical properties (pH, conductivity, extractable nutrients) were analyzed for each soil type before treatments were imposed (Table 4.2).

Table 4.2. Soil nutrient analyses of three soil types used in the greenhouse, no biochar added. Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

Parameter	Rader fine sandy loam	Burleson clay	Ships clay
pH	6.86	6.75	7.91
		μmhos cm^{-1}	
EC	231.0	837.0	576.5
		mg kg^{-1}	
NO_3-N	17.58	70.78	4.42
P	28.7	96.6	49.0
K	116.0	308.9	604.4
Ca	415.9	4689.3	11440.3
Mg	48.1	426.2	432.0
S	14.60	31.86	15.01
Na	204.9	295.0	72.1

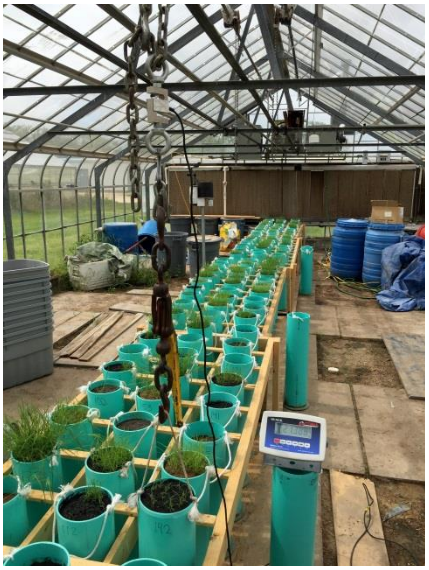

Figure 4.2. Greenhouse weighing apparatus. Consisted of a hanging load cell (1 g resolution) attached to a lockable lever load binder which allowed the researched to lift the column just enough to weigh it.

Control soil treatments as well as biochar application rates of 8 and 16 Mg ha^{-1} for both surface applied and incorporated treatments for each soil type were weighed to determine weight of column and soil at field capacity (2 weeks after saturation). Routine weighing of columns was used to estimate ET and determine the amount of water to add to the columns to return soil to field capacity. Weights were taken every 3 to 4 days and the water was added back to the columns in two equal amounts on successive days, to reduce flooding stress on seedlings. Columns were weighed using a hanging load cell with a resolution of 1 g attached to a lockable lever load binder so that the columns could be lifted slightly off the ground in place (Figure 4.2). The amount of water added to the intermediate treatments (4 and 12 Mg ha^{-1}) was determined by averaging the amount of water lost in 0 and 8 Mg ha^{-1} and 8 and 16 Mg ha^{-1} treatments.

4.2.3 Biomass Harvest and Tissue Sampling

Biomass yield was measured 48, 71, and 86 days after planting. Biomass was clipped using hand scissors to 5 cm above the soil surface and removed. Biomass was bagged and weighed to obtain a fresh weight and dried for 72 hours at 65°C. Dry weights of biomass were then taken and used to calculate biomass dry matter yield. After the second clipping, no additional water was applied to columns to evaluate treatment effects on bermudagrass growth under increasing moisture-stress. Biomass tissue samples were tested for nutrients (Nitrogen + Minerals (P, K, Ca, Mg, Na, S, Fe Cu, Mn and B) at the Texas A&M AgriLife Extension Soil, Water, Forage Testing Laboratory at Texas A&M University (http://soiltesting.tamu.edu/). Nitrogen was determined by high temperature combustion (Sweeney, 1989). Minerals were determined by ICP analysis of a nitric acid digest (Kachurina, Krenzer, et al., 2000). Mass of nutrients taken up and removed by biomass tissue were calculated by multiplying concentration by mass and compared to amounts found within soil treatments. Cumulative nutrient recovery efficiency (RE) was calculated after the final biomass harvest. Recovery efficiency is measurement of the increase in crop uptake of a nutrient into the aboveground portion of the plant (Snyder and Bruulsema, 2007). It is calculated using the weight of biomass harvests multiplied by the corresponding concentrations of nutrients measured in the tissue to find the mass of nutrient taken up by the plant, correcting for plant uptake in control soils.

$$\mathrm{RE}= \frac{(\mathrm{U}\text{-}\mathrm{U_o})}{\mathrm{F}}$$

Where:

RE = Recovery efficiency (g nutrient harvested/g nutrient applied)

U = cumulative nutrient uptake in aboveground crop biomass with biochar (g per pot)

U_o= cumulative nutrient uptake in aboveground crop biomass with no biochar (control) (g per pot)

F = amount of nutrient applied in biochar (g per pot)

4.2.4 Soil Sampling

As the columns were packed with soil, soil samples were taken for nutrient analysis for each layer of soil added, and each biochar treatment rate. Samples were taken by treatment for the top 15 cm of soil (0 to 15 cm), soil beneath the top 15 cm (15 to 30 cm), and the fine sand at the bottom (30 to 60 cm). After the final clipping was completed, another set of soil samples were taken from the same discrete depths in each column.

Destructive soil sampling of each column was completed immediately after the final clipping (5/22/15). Columns were sectioned using a Milwaukee Sawzall and intact core samples were collected for 0 to 15 cm and 15 to 30 cm. The 30 to 60 cm soil samples consisted of fine sand was placed in a clean bucket and homogenized, then a sub-sample was collected. The intact cores were measured for length and diameter, then placed in a drying over at 45 °C for 72 hours and weighed to find bulk density. They were then pulverized and mixed, then submitted for routine nutrient sampling (pH, NO3-N, EC and Mehlich III P, K, Ca, Mg, Na, and S, http://soiltesting.tamu.edu/). Electrical conductivity and pH were determined using a 1:2 soil: de-ionized water ratio, left to equilibrate for 30 minutes, and measured with a conductivity or hydrogen sensitivity probe, respectively (Rhoades, 1982, Schofield 1955). Mehlich-III solution was used to extract P, K, Ca, Mg, Na and S from soil samples and analyzed using ICP (Mehlich, 1978, Mehlich, 1984). The NO_3–N in KCl extracts of soil was analyzed through cadmium reduction (Kachurina, Krenzer, et al., 2000, Keeney, 1982).

4.3 Statistical Analysis

Mean daily surface temperatures, germination index, soil nutrient concentrations, biomass harvests, and nutrient recovery efficiency were analyzed for normality and homogeneity of variance (Levene's HOV test treatment vs affected parameter e.g. soil surface temperature) before being using PROC ANOVA at a significant level of $p=0.05$ to separate treatment effects (SAS). When normality was violated, data was transformed using either a square root function or natural log. This was necessary for germination index and biomass harvest data (square root). Data for each soil type was analyzed independently from one another. When significant treatment effects were observed, treatment means were separated using the least squared means (LSMEANS) function of SAS with the Tukey adjustment. Mean nutrient uptake with respect to nutrient application was tested for linear and quadratic relationships using the PROC GLM function in SAS.

4.4 Results and Discussion

4.4.1 Surface Temperature and Bermudagrass Establishment

Considering mean daily surface temperature (2PM) over the 31 day establishment period, it was observed that surface applied biochar addition significantly increased surface temperature for all three soil types (Figure 4.3). There was a significant difference in surface temperature due to biochar application method and rate for all three soil types ($p<0.0001$, $p<0.0055$, respectively). Surface applied biochar increased surface temperatures with increasing application rate. For Rader soil, surface applied BC treatments increase temperatures 2.8 to 8.6 °C relative to the control and followed a quadratic relationship, with a peak existing near 12 Mg ha^{-1} ($p<0.0109$, $R^2=0.9714$) and (Figure 4.3). Similarly, surface applied biochar increased soil surface temperature 3.6 to 5.7 °C in the Burleson soil ($p=0.0055$) and followed a quadratic relationship ($p=0.0214$, $R^2=0.9605$). Biochar application to Ships clay soils significantly increased surface temperatures 1.8 to 6.4 °C on compared to control treatments ($p<0.0001$) and followed a linear relationship ($p=0.0150$, $R^2=0.9804$). This finding is support by previous reports that have demonstrated reductions in soil albedo and increases in soil temperature in response to biochar application (Genesio, Miglietta, et al., 2012, Meyer, Bright, et al., 2012).

While soil temperatures were generally near optimum condition for bermudagrass establishment under greenhouse conditions, higher soil temperatures under field conditions with early planting (cooler air and soil temperatures) could be beneficial. However, increased soil temperatures could result in negative impacts as well, including higher evaporative losses of water and increased decomposition rates of soil organic matter (Genesio, Miglietta, et al., 2012). Increased soil temperatures could mitigate reported benefits of biochar applications to reductions in greenhouse gas emissions by decreasing the amount of carbon stored in soil organic matter (Meyer, Bright, et al., 2012). Temperatures recorded at 2 PM via weather station are displayed in the figure below (Figure 4.4). The weather station used was a Campbell scientific (Logan, UT) weather station with temperature and relative humidity attachments.

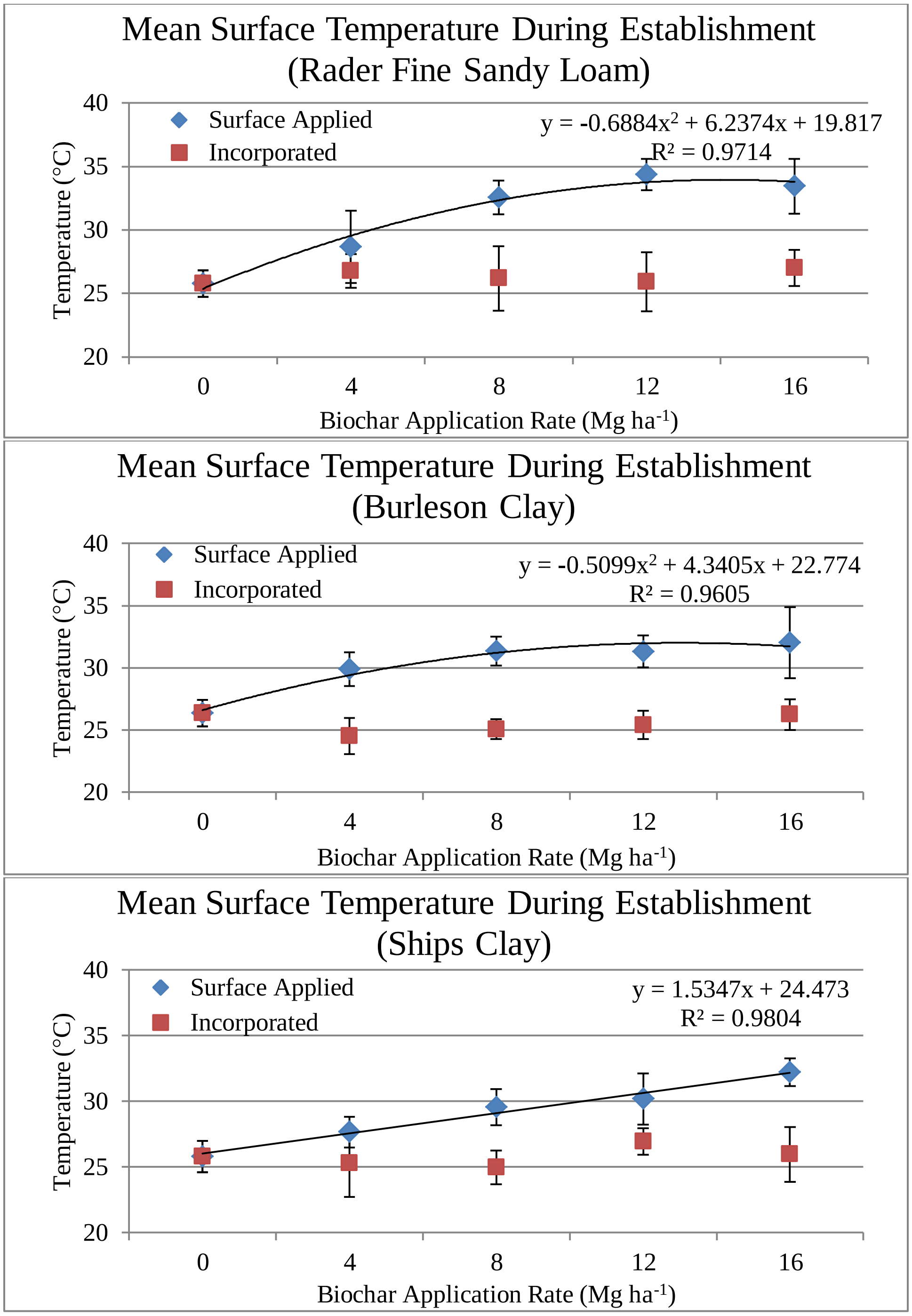

Figure 4.3. Mean surface temperature (2/25/15 to 3/28/15) by biochar application rate and method for Rader, Burleson, and Ships clay. Vertical lines indicate standard error (*n*=4).

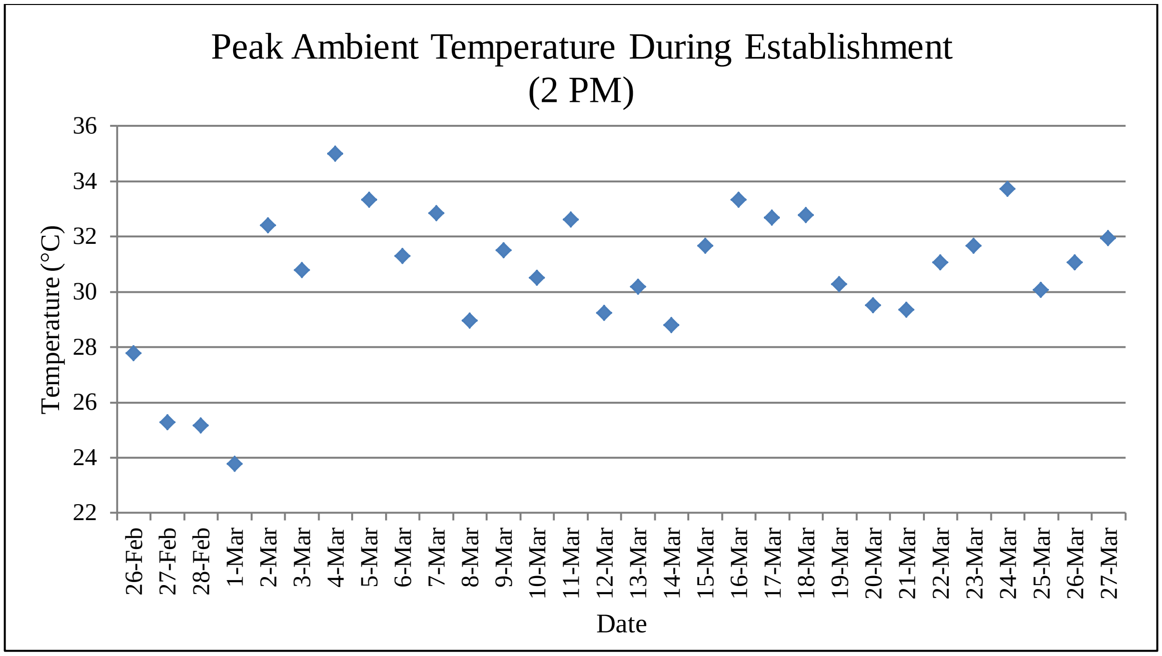

Figure 4.4. Peak daily ambient temperature during establishment measured by a weather station inside the greenhouse (2 PM temperatures displayed).

As previously mentioned, the incorporated biochar treatments had minimal impacts on soil surface temperature as measured by infrared thermometer. Yet, surface applied biochar increased the surface temperature by as much as 25 °C above the ambient temperature at maximum daytime temperature. For example, on 03/29/2015, ambient air temperature was 25.4° C in the greenhouse while mean surface temperature of 16 Mg ha^{-1} surface applied treatment to Rader soil was 54.7°C.

Daily seedling counts were used to calculate germination index (GI) by taking the sum of daily seedling counts divided it by the amount of days from planting in order to assess the seed vigor in response to biochar addition (Gupta, 1993) (Figure 4.5).

Bermudagrass grown in Rader soils showed no significant change in germination index as a result of biochar application ($p=0.29$). In Burleson clay, there was a significant change in both surface applied and incorporated treatments for GI for biochar application rate and method ($p=0.006$, $p<0.0001$, respectively). Surface applied biochar treatments followed a quadratic relationship with respect to rate, where GI was maximized near 8 Mg ha^{-1} and the lowest GI was observed at 16 Mg ha^{-1} ($p=0.0001$, $R^2=0.88$). The incorporated treatments followed a quadratic relationship with the peak GI values in between 8 and 12 Mg ha^{-1} ($p<0.0001$, $R^2=0.82$). In Ships clay columns, both the surface applied treatments ($p=0.025$, $R^2=0.89$) and the incorporated treatments ($p=0.014$, R2=0.90) followed quadratic relationships, with the highest GI values found for 8 Mg ha^{-1} in surface applied treatments and 4 Mg ha^{-1} for incorporated treatments.

It is unclear why intermediate biochar application rates produced higher germination index numbers which indicate a faster emergence and/or higher number of live seedlings and why that effect diminishes with increasing biochar application. As previously seen, surface temperatures increased with increasing surface applied biochar application and the GI results reflect a general decrease of seedling vigor with increasing biochar application rate after 8 Mg ha^{-1}. There could have been an impediment of seedling establishment due to high temperatures caused by biochar application. Soil surface temperatures have been shown to be significantly increased at a depth of 5 cm due to the application of biochar (Genesio, Miglietta, et al., 2012). In addition, as seen in this field study, biochar releases salts into the soil to which it is applied.

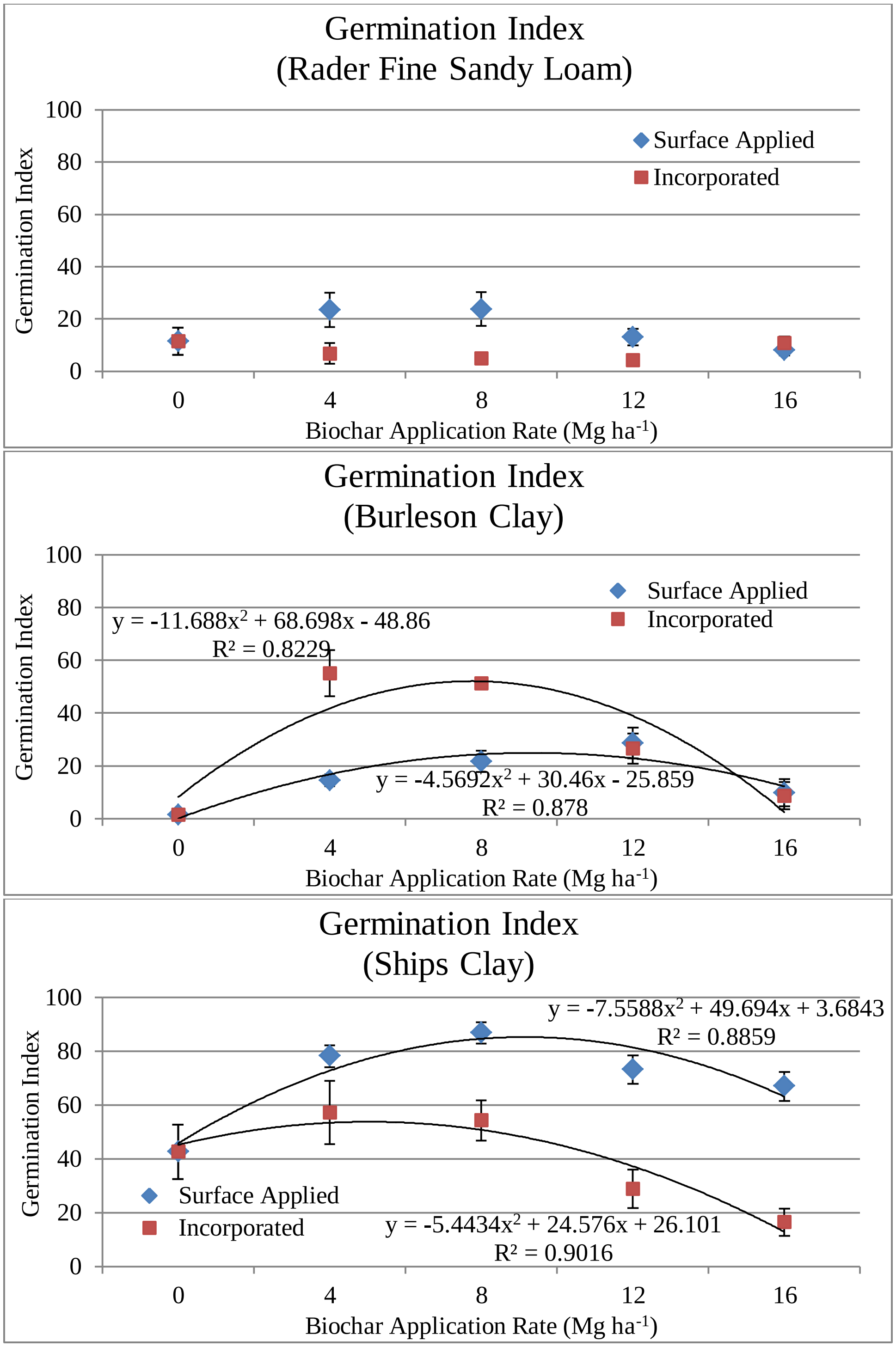

Figure 4.5. Germination index with response to biochar application rate and method. Vertical lines indicate standard error (*n*=4).

4.4.2 Crop ET

The results of evapotranspiration measurements (actual evapotranspiration in millimeters per day) for each growing cycle where watering took place (2/25/15 to 4/14/15) and (4/15/15 to 5/7/15) are shown in the table below (Table 4.3).

Table 4.3. Evapotranspiration for three soil types with increasing rates of surface applied or incorporated biochar for the first (2/25/15 – 4/14/15) and second (4/15/15 – 5/7/15) growth cycle.

		Biochar Application Rate (Mg ha^{-1})				
		Control	Surface Applied		Incorporated	
		0	8	16	8	16
ET$_{first}$ (mm day^{-1})	Rader	4.30	4.84	4.18	4.13	4.25
	Burleson	4.59	7.32	5.46	4.71	4.29
	Ships	5.12	4.72	3.95	6.24	5.08
ET$_{second}$ (mm day^{-1})	Rader	5.57	5.82	5.34	5.18	5.52
	Burleson	7.60	9.63	9.48	8.98	6.48
	Ships	5.03	6.76	6.78	5.88	5.71

ET was not significantly different with respect to biochar application (rate or application method) for Rader fine sandy loam soil for either the first or second growing cycles ($p>0.0866$) (Figure 4.6). In the first growth cycle, there was a significant increase in soil ET with incorporated BC in Burleson soils ($p=0.0065$), but not in the second growth cycle ($p=0.0668$). In Ships clay, as well, there was a significant increase in ET for incorporated BC applications compared to surface applied BC for the first growing cycle (p=0.0045) but not the second (p=0.2159).

Although the low albedo of surface applied biochar absorbs more solar radiation and produces higher temperatures on the surface of the soil, this effect is likely diminished after bermudagrass established and shaded the surface. The most likely explanation for the water loss patterns were related to biomass production and surface applied biochar promotion of establishment. The incorporated biochar had 123% greater GI at 8 Mg ha^{-1} (51.3) than surface applied BC at 8 Mg ha^{-1} (21.7) and was 3000% higher than the control soil (1.6), thus resulting in greater biomass production and transpiration contributing to greater net loss of water. Transpiration in the greenhouse pots likely dominated ET, not evaporation, and thus biochar had a greater effect through plant promotion of biomass rather than surface heating.

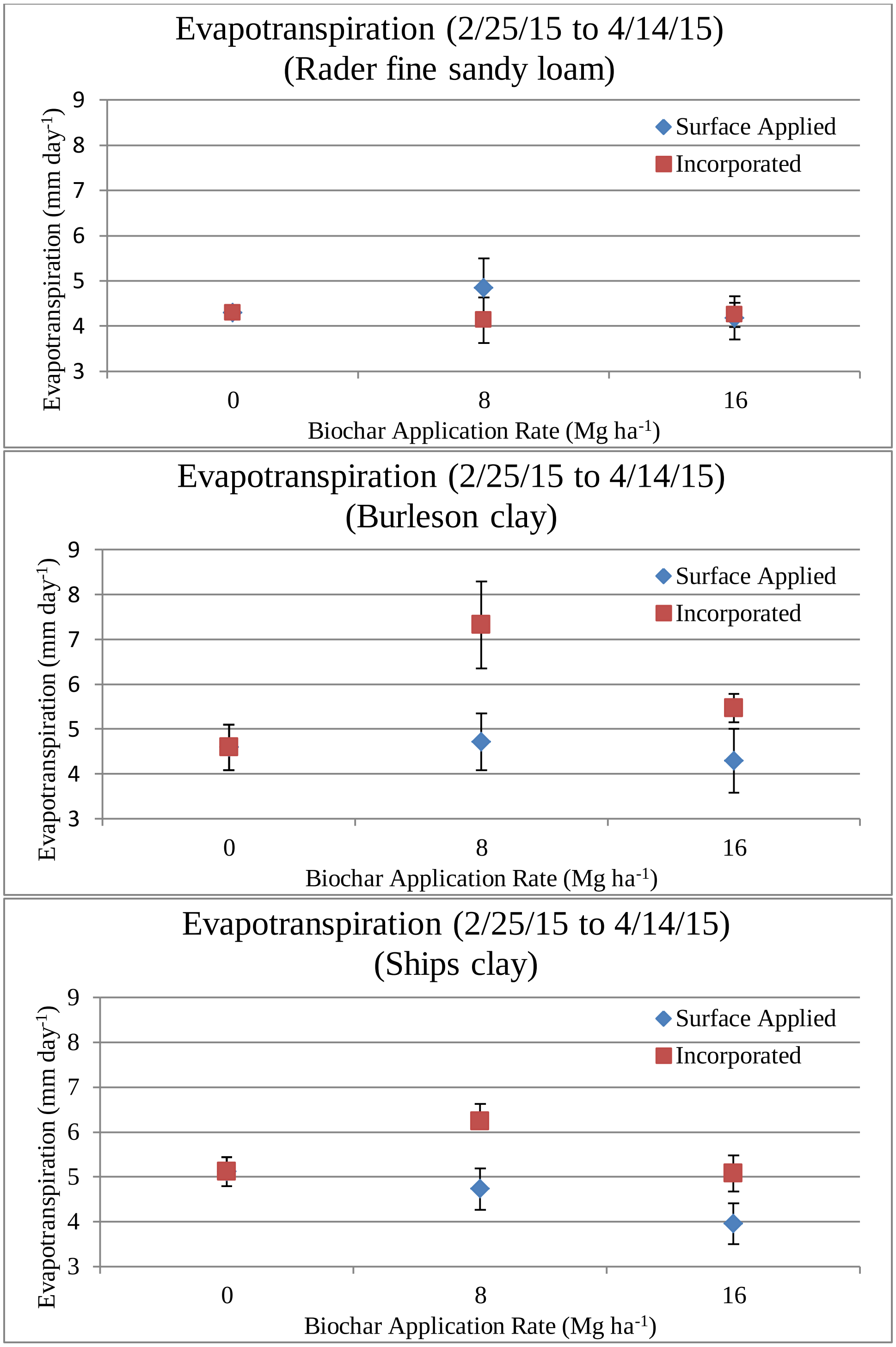

Figure 4.6. Evapotranspiration with regard to biochar application for Rader, Burleson, and Ships clay for the first clipping cycle. Vertical lines indicate standard error (*n*=4).

4.4.3 Biomass Yield

In addition to the impact of biochar on bermudagrass establishment, biochar application rate and method affected biomass yield collected throughout the growing season. However, biochar application rate or method did not produce a consistent effect in bermudagrass yield across multiple soils types.

Rader fine sandy loam soils were much less productive than the other two soils, in terms of both seedling coverage and biomass yield. Maximum biomass yields were observed during the second harvest ranging from 1.0 – 2.1 Mg ha^{-1}. Rader soil had a modest concentration of NO_3-N (18 mg kg^{-1}). There was a statistically significant decreasing trend in biomass yield with increasing SA biochar application rate for the second ($p=0.0071$, $R^2=0.9092$) and third harvest ($p=0.0001$, $R^2=0.8550$). In Rader soils, there was no significant effect ($p>0.2155$) due to biochar application rate for INC treatments (Figure 4.7). It is unclear why there was poor establishment and growth in Rader soils, as previously stated biochar releases salts into the soil which could have impeded establishment and thus biomass yield. Surface applied biochar reduced growth of bermudagrass in Rader fine sandy loam for both the second and third harvest, and thus there may have been a temperature-related yield decrease that was especially pronounced after multiple growth and harvest cycles.

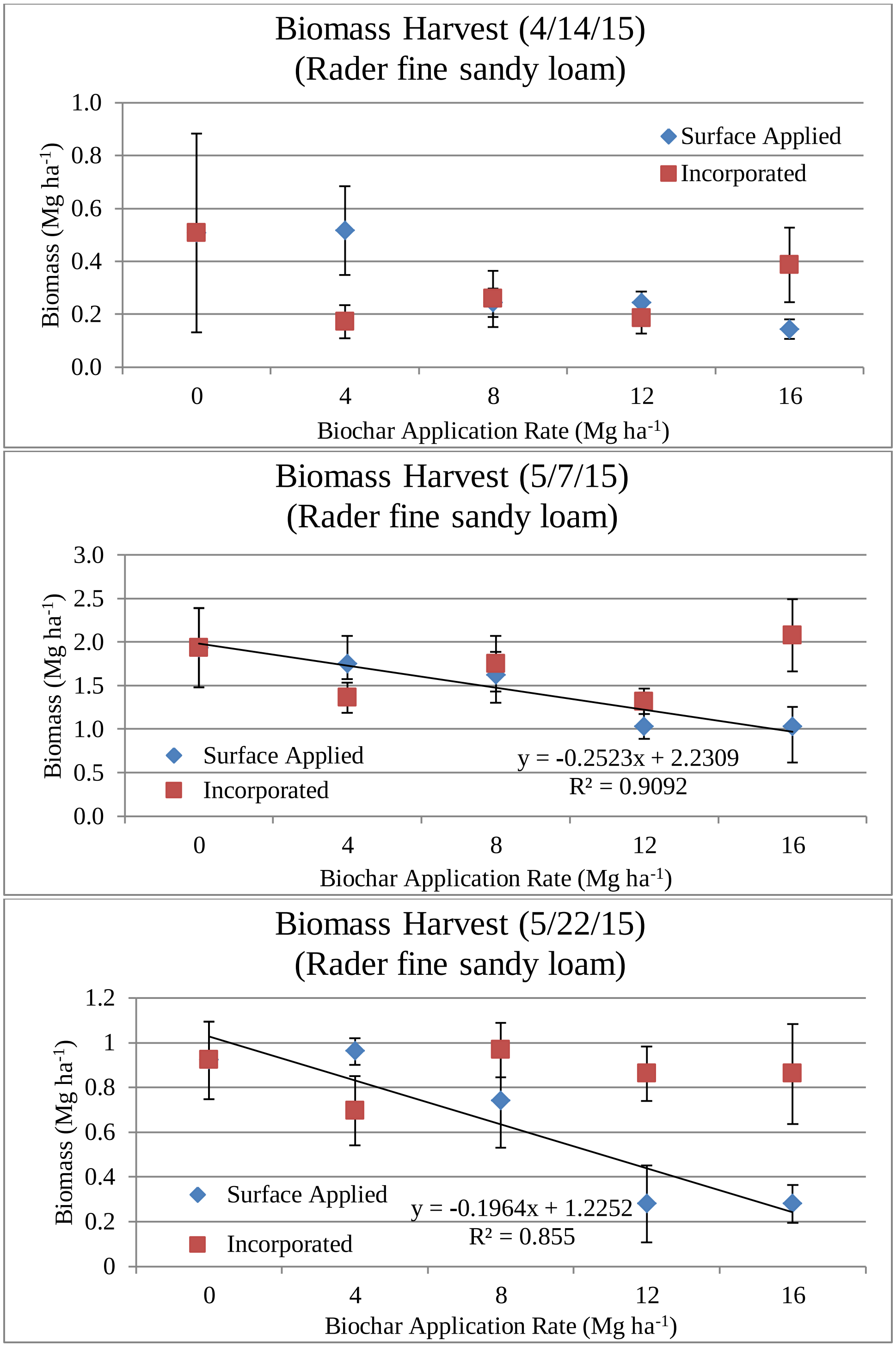

Figure 4.7. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Rader fine sandy loam soil. Vertical lines indicate standard error (*n*=4).

Burleson clay soil produced the greatest biomass yields of all soil types tested, yet it had very low initial biomass yields for control soils. This may have been due to compaction caused by the planting and the pressing of seeds into the soil surface (which could also explain low control and surface applied values for germination index in Burleson clay soil). The fact that control soils and surface applied plots produces less initially supports this. Biomass yield ranged from 5.9 to 13.5 Mg ha^{-1} during the second harvest. The Burleson soil had the greatest residual NO_3-N concentration of all soils (71 mg kg^{-1}). In the first harvest (4/14/15) there was a significant biochar application method and rate effect ($p<0.0001$, $p=0.0383$, respectively). A significant quadratic response was observed for surface applied ($p=0.003$, $R^2=0.755$) and incorporated ($p<0.0001$, $R^2=0.9611$) biochar (Figure 4.8). The inflection of the quadratic response was much greater for incorporated biochar, with the optimum rate near 8 Mg ha^{-1}. The response for incorporated biochar was much less pronounced, with the optimum application rate between 8 and 12 Mg ha^{-1}. As mentioned in a previous section, Uzoma 2011 applied 0, 10, 15, 20 Mg ha^{-1} cow manure biochar and showed a maximum maize yield increase at 15 Mg ha^{-1} and a diminished effect at the highest rate 20 Mg ha^{-1}. This indicated that continued biochar application may not be beneficial to crop yield and could potentially decrease yield at high application rates. Nitrogen immobilization in soil is possible with addition of carbon sources in the form of biochar. Lehmann 2003 found diminished yields due to biochar application and wide C:N ratios at high biochar application rates due to the addition of large amounts of carbon. This is a possible explanation for the diminished yields in the quadratic relationship observed, since no additional nitrogen was added to soils in this study.

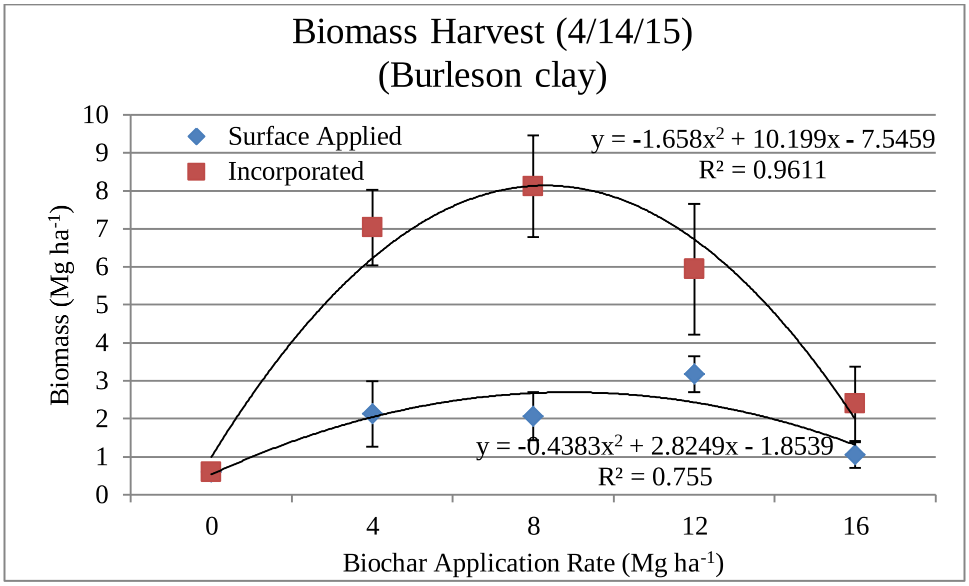

Figure 4.8. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Burleson clay (4/14/14). Vertical lines indicate standard error (*n*=4).

The second biomass harvest was also significant with respect to biochar application method (p<0.0001). In this harvest, however, the surface applied biochar treatments produced significantly higher biomass yields (p<0.0001) than the incorporated biochar treatments (Figure 4.9). This is in contrast to the first biomass harvest. However, biomass yields were similar for incorporated treatments produced by the first and second harvest (*e.g.* 4 Mg BC ha^{-1}: 7 Mg ha^{-1} (4/14/15) and 6 Mg ha^{-1}

(5/7/15)). The surface applied treatments produced as much as 6-fold greater biomass in the second harvest. This suggests that effects of surface applied biochar may not be immediate as observed with incorporated BC, or were due to initial compaction issue which incorporated biochar mitigated. Soluble nutrients in surface applied BC must be leached into the rooting zone to benefit crop growth. Moreover, irrigation water was applied to replace ET, limiting the potential leaching of nutrients.

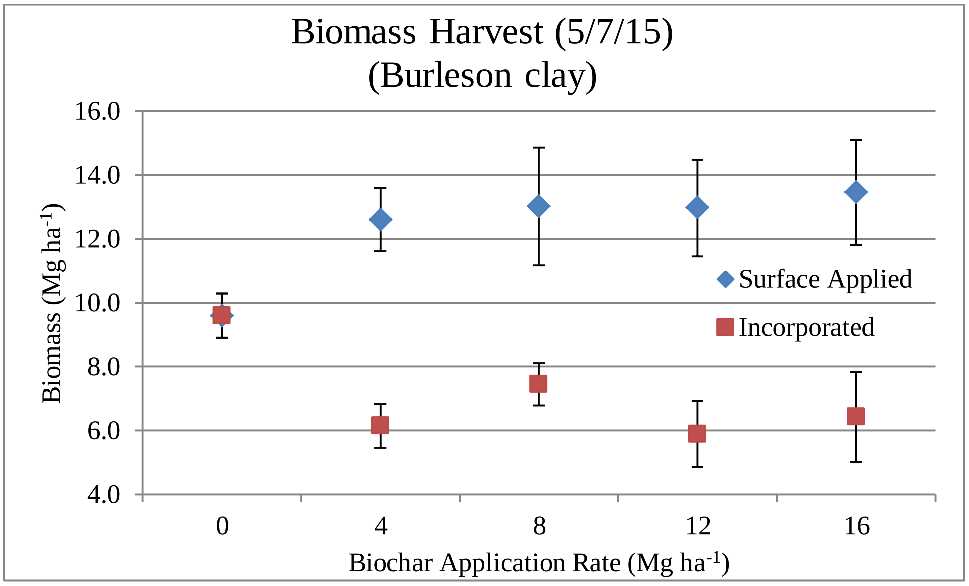

Figure 4.9. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Burleson clay (5/7/15). Vertical lines indicate standard error (*n*=4).

For the third biomass harvest, a significant quadratic response to biochar application rates was observed for surface applied (p=0.0235, R^2=0.90) and incorporated biochar ($p=0.0049$, $R^2=0.996$). Similar to the first biomass harvest, biomass yields declined with larger application rates, particularly rates above 12 Mg ha^{-1}. Soil reserves of NO_3-N were likely depleted during the first two harvests, and lack of nitrogen mineralized from biochar sources reduced yield during the third harvest (Figure 4.10). Yet, responses to biochar sources of nutrients were still observed. Collectively, it provides strong evidence that high application rates (>12 Mg ha^{-1}) of biochar were reducing biomass production in the Burleson soil.

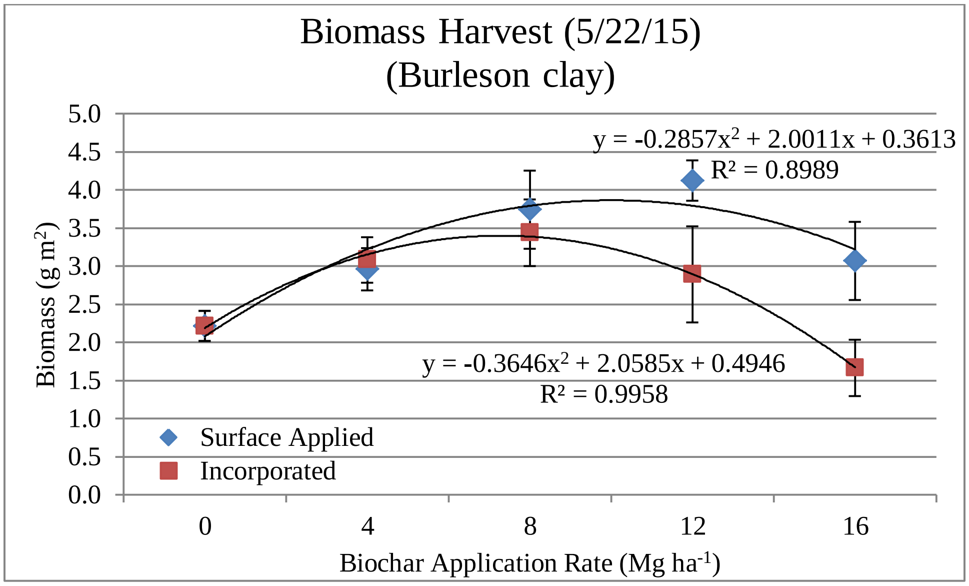

Figure 4.10. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Burleson clay (5/22/15). Vertical lines indicate standard error (*n*=4).

The first biomass harvest (4/14/14) for Ships clay showed no significant effect due to biochar application rate or method (p=0.3291, p=0.1460, respectively). Like the initial biomass harvest for Burleson clay, control columns showed the lowest yield, possibly due to poor establishment due to similar surface compaction. Yields associated with increasing surface applied rates (Figure 4.11) appeared to follow a similar trend as was observed for GI, though the biomass values were more variable and a statistical effect was not present (Figure 4.5). This suggests that plant stand (population) may have influenced biomass yields. Moreover, Ships soil had the lowest concentration of NO_3-N of all soils tested.

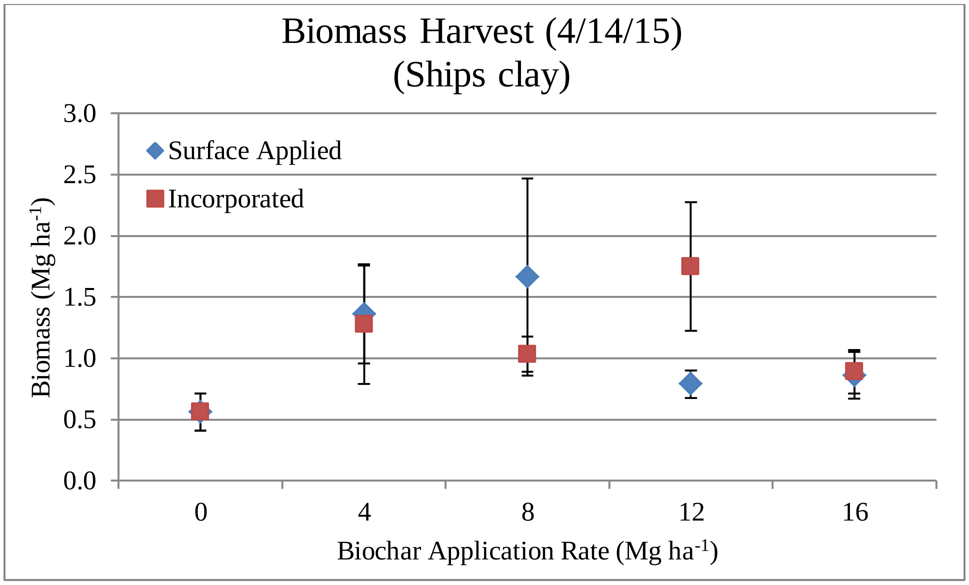

Figure 4.11. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Ships clay (4/14/15). Vertical lines indicate standard error (*n*=4).

In the second biomass harvest, there was a significant linear relationship ($p=0.015$, $R^2=0.88$) between increasing incorporated biochar application rate and bermudagrass yield (Figure 4.12). Similar to initial harvests for Burleson clay soils, incorporated treatments produced a higher biomass yield in earlier harvests for Ships clay as well, with surface applied biochar producing higher values in later harvests. This may be an indication of slower release and/or delayed exposure to biochar nutrients when biochar is surface applied. As nutrients were removed from soil during the first harvest, nutrients associated with biochar application may have played a larger role in observed biomass yields. Biomass harvest ranged from 1.8 to 2.9 Mg ha^{-1}.

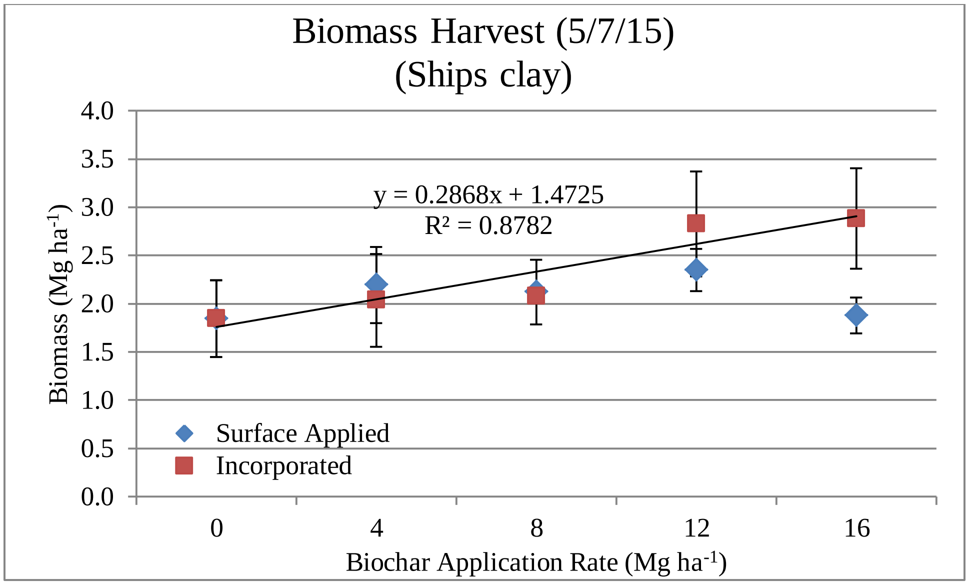

Figure 4.12. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Ships clay (5/7/15). Vertical lines indicate standard error (*n*=4).

In the third harvest (5/22/15), however, Ships clay soil produced increased biomass with respect to biochar application method (p=0.0026) (Figure 4.13). Surface applied biochar resulted in higher biomass yields, and showed a significant linear relationship with biochar application rate (p=0.047, R^2=0.59) compared to incorporated treatments. Incorporated treatments were not significantly different from the control (p=0.616). For both Burleson and Ships clays, surface applied biochar led to higher biomass yields in later harvests, whereas incorporated treatments were more immediately productive. This could have been a delayed nutrient release in surface applied biochar, or an effect of incorporated biochar preventing surface compaction of clay soils at planting. Again, low concentration of residual N and limited mineralization of biochar N likely limited biomass production.

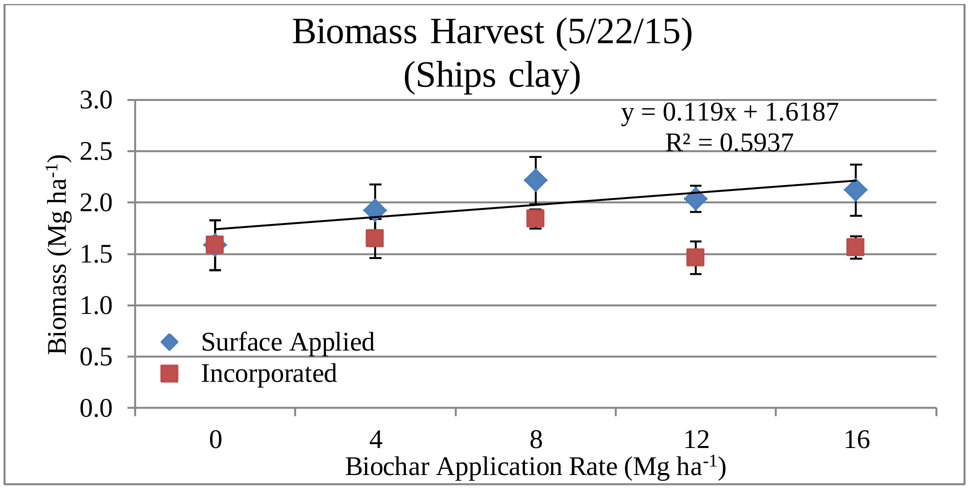

Figure 4.13. Biomass (bermudagrass) yield with response to biochar application rate and method grown in Ships clay (5/22/15). Vertical lines indicate standard error (*n*=4).

4.4.4 Nutrient Application vs. Uptake

Mean nutrient uptake for each nutrient and soil was plotted against the amount of the corresponding nutrient added via biochar. For all of the nutrients tested, only 3 (Ca, Na, and B) showed a statistically significant relationship (Figure 4.14). For each of these three statistically significant cases, which were for secondary (Ca), micro- (B) or nonessential nutrients (Na). Calcium showed a linear decrease ($p=0.0320$, $R^2=0.8694$), while Boron ($p=0.0183$, $R^2=0.9994$) and sodium ($p=0.0059$, $R^2=1$) both showed a quadratic relationship with maximum applied to uptake ratio for the equivalent of 8 Mg ha^{-1} biochar addition. This indicates that there was not a significant relationship between the amount of nutrients added with biochar and the amount taken up in the bermudagrass tissue and that the nutrients added to the soil in the form of biochar were largely unavailable to plants.

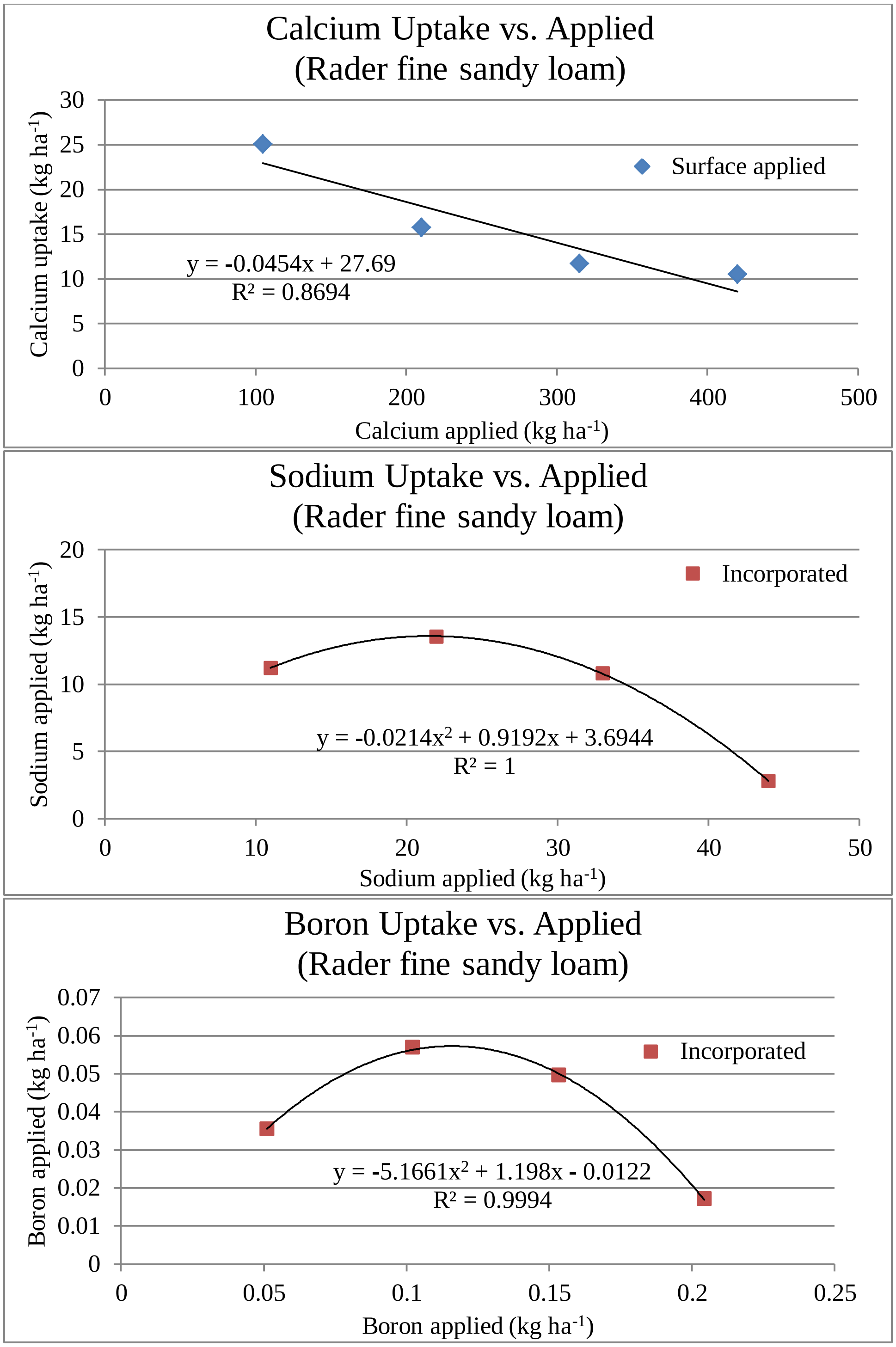

Figure 4.14. Nutrient uptake with respect to nutrient applied via biochar application.

In these several instances where there was a statistically significant effect, incorporated treatments in the fine sandy loam soil showed a maximum level of nutrient uptake for intermediate rates, indicated, as seen in the biomass yield results, that increasing application of biochar does not indefinitely increase plant nutrient uptake and yield, that biochar is most effective in encouraging crop growth at the intermediate rates used in this study.

4.4.5 Nutrient Recovery Efficiency

Using the nutrient recovery efficiency calculation, the amount of biochar-nutrient taken up in the tissue of the bermudagrass harvested in this study was quantified for each nutrient and soil (Tables 4.12 through 4.20). A portion of the recovery efficiencies obtained for the nutrients tested in this greenhouse study were negative, and many of them were below 1, indicating biochar sources of nutrients were largely unavailable or that antecedent soil nutrients exceed crop requirements. An RE value well below 1 can reflect an inefficient cropping system, indicating that the native soil can supply the nutrients necessary for crop growth (Snyder and Bruulsema, 2007). Generally, recovery efficiencies for N are generally at or less than 50%, less than 10% for P, and 40 % for K (Baligar 2001). The values in this study varied widely, though are generally higher than the average for P and below average for K. RE values were not significant at $\alpha=0.05$.

In Rader soils, higher levels of surface applied biochar resulted in low recovery of applied nutrients (Table 4.15 and 4.16). In the latter two biomass harvests in Rader soils, there was observed a linear decrease in biomass as a result of increasing rates of surface applied biochar application which corresponded with decreased nutrient uptake. Limited nitrogen availability and subsequent reduction in biomass production may have reduced the potential for recovery of biochar nutrients. Incorporated treatments had higher biomass harvest values in the final two clippings for Rader, as well, which could correspond with positive RE values for INC treatments.

Table 4.4. Mean recovery efficiency (percent) in bermudagrass grown in a Rader fine sandy loam soil for nutrients applied to soil via biochar.

Recovery Efficiency (Percent)						
			Biochar Application Rate (Mg ha^{-1})			
Nutrient	SA	INC	4	8	12	16
N	-21	57	57	28	9	-22
P	0	24	27	14	12	-6
K	-5	12	9	5	5	-5
Ca	-6	-1	-1	-2	-6	-4
Mg	-6	3	0	0	-1	-4
Na	-27	9	-7	-5	-8	-15
Zn	-2	2	1	1	0	-1
Fe	0	1	1	0	0	0
Cu	-5	4	1	0	2	-4
Mn	-15	60	74	30	6	-18
S	-38	39	16	11	2	-27
B	-48	-33	-74	-33	-26	-29

Table 4.5. Recovery efficiency (percent) in bermudagrass grown in a Rader fine sandy loam soil for nutrients applied to soil via biochar.

	Recovery Efficiency (Percent)							
	Surface Applied				Incorporated			
Nutrient	4	8	12	16	4	8	12	16
N	20	-31	-43	-28	95	88	60	-16
P	22	-8	-8	-7	32	35	32	-5
K	3	-10	-8	-5	14	20	17	-5
Ca	-5	-7	-6	-5	3	4	-5	-4
Mg	-4	-9	-6	-5	4	8	4	-4
Na	-37	-31	-22	-16	22	22	6	-14
Zn	0	-3	-2	-2	1	4	3	-1
Fe	0	-1	0	0	1	1	1	0
Cu	-1	-7	-5	-4	4	8	10	-4
Mn	10	-19	-30	-21	138	78	41	-15
S	-13	-57	-47	-33	45	80	52	-21
B	-75	-50	-36	-31	-73	-15	-15	-27

In Burleson soil, positive RE values indicate that biochar sources of nutrient were likely available for plant uptake, except for a the lowest rate of biochar application in both surface applied and incorporated biochar (most notably N, which both had negative RE values close to -0.5). With sufficient residual N in soil, biochar nutrients enhance biomass production and nutrient recovery from biochar. For every nutrient applied to Burleson soils through biochar, the highest value for RE was found for the 8 Mg ha^{-1} biochar application rate, for both surface applied and incorporated (Table 4.17 and 4.18). This is similar to the results observed for biomass harvest values observed in the first and third harvest for Burleson clay. This could support the conclusion that high applications rates of biochar can reduce biomass production, reducing nutrient recovery, though values were not significant at α=0.05.

Table 4.6. Mean recovery efficiency (percent) in bermudagrass grown in a Burleson clay soil for nutrients applied to soil via biochar.

Recovery Efficiency (Percent)						
			Biochar Application Rate (Mg ha^{-1})			
	SA	INC	4	8	12	16
N	76	30	-55	132	68	68
P	29	30	1	55	33	30
K	23	18	1	38	23	20
Ca	10	3	-1	19	1	7
Mg	9	5	-2	15	8	7
Na	9	-2	-14	15	6	8
Zn	3	3	1	5	3	3
Fe	1	1	1	2	1	1
Cu	9	12	4	18	10	10
Mn	13	15	-4	29	16	14
S	90	96	51	162	93	66
B	7	4	-1	13	6	4

Table 4.7. Recovery efficiency (percent) in bermudagrass grown in a Burleson clay soil for nutrients applied to soil via biochar.

	Recovery Efficiency (Percent)							
	Surface Applied				Incorporated			
Nutrient	4	8	12	16	4	8	12	16
N	-48	176	67	110	-63	87	68	26
P	-6	57	26	40	8	53	39	20
K	1	41	23	27	1	35	24	13
Ca	0	19	10	11	-1	19	-9	4
Mg	-1	18	8	10	-3	12	8	3
Na	-5	23	6	12	-22	7	5	3
Zn	0	5	3	4	2	5	3	1
Fe	0	2	1	1	1	2	1	1
Cu	2	16	7	12	6	20	14	7
Mn	-6	27	13	19	-1	31	20	8
S	27	159	82	90	75	164	104	41
B	2	15	7	6	-4	10	5	2

Nutrient recovery efficiency results from Ships clay soils revealed that biochar applied to the surface of the soil may have contributed to nutrient uptake into bermudagrass more so than incorporated biochar treatments (Table 4.19 and 4.20). When rates were pooled, only at the highest two rates of biochar application were there a significant portion of RE values that were positive. Clearly, nutrient recovery efficiency was not consistently influenced by biochar addition. When considering this and the results from comparing nutrients applied to nutrient uptake, it appears that much of the nutrient added with biochar was not available to the bermudagrass grown in the columns.

Table 4.8. Mean recovery efficiency (percent) in bermudagrass grown in a Ships clay soil for nutrients applied to soil via biochar.

Recovery Efficiency (Percent)						
			Biochar Application Rate (Mg ha^{-1})			
	SA	INC	4	8	12	16
N	12	-34	-39	-24	21	0
P	8	-6	-11	-3	15	2
K	4	-5	-10	-4	9	1
Ca	2	-9	-6	-1	-5	0
Mg	2	-3	-4	-1	3	0
Na	0	-2	-2	-2	1	-1
Zn	1	0	0	0	1	0
Fe	0	-1	-1	-1	0	0
Cu	1	-5	-9	-4	4	0
Mn	13	-11	-9	-1	10	3
S	16	-22	-36	-9	26	6
B	0	-8	-19	-3	0	6

Table 4.9. Recovery efficiency (percent) in bermudagrass grown in a Ships clay soil for nutrients applied to soil via biochar.

Recovery Efficiency (Percent)								
	Surface Applied				Incorporated			
Nutrient	4	8	12	16	4	8	12	16
N	44	12	-13	6	-123	-60	55	-6
P	18	12	-3	4	-39	-18	32	0
K	9	5	-3	2	-29	-12	21	-1
Ca	3	6	-2	1	-16	-8	-9	-1
Mg	5	4	-1	1	-13	-6	7	-1
Na	2	1	-1	0	-6	-4	3	-1
Zn	3	1	-1	1	-4	-1	4	0
Fe	1	0	0	0	-2	-1	1	0
Cu	3	2	-3	1	-21	-10	11	-1
Mn	18	19	5	9	-36	-21	15	-2
S	40	23	-13	13	-112	-41	65	0
B	-11	9	-10	11	-28	-15	10	1

4.4.6 Soil Nutrients

The results from the soil analysis of the 120 soil columns at three different sampling depths (0 to 15 cm, 15 to 30 cm, and 30 to 60 cm) are displayed in the tables below, separated by soil type and sampling depth (Table 4.21 to 4.29). Although the soil in the 30 to 60 cm depth of the columns was identical, it is listed separately because of the potential for nutrient leaching from the layers of soil and/or biochar above. The values listed are the means of the four repetitions. Results for control soil in the top 15 cm generally showed high levels of Ca, K, and pH, indicating that there may have been nutrients added with irrigation water, even though a reverse osmosis filter was used. Soil analysis results had erratic distributions and could not be reliably analyzed with ANOVA. The mean values of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH for each soil and depth are listed in the tables below (Table 4.21 to 4.29).

Table 4.10. Soil nutrient analysis for Rader fine sandy loam (0 to 15 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	8.13	8.01	7.89	8.21	8.16	7.90	7.72	8.06	7.81
					μmhos cm^{-1}				
EC	294.4	477.0	297.8	401.8	399.5	467.5	388.8	393.3	479.5
					mg kg^{-1}				
NO_3-N	7.19	21.44	7.58	6.45	6.64	7.06	8.36	4.40	8.21
P	41.4	50.9	35.4	46.9	37.8	66.0	72.7	43.0	66.6
K	307.4	483.8	388.3	461.1	510.0	345.4	366.1	401.4	329.7
Ca	2864.9	8392.5	4779.3	8571.9	7353.1	5741.5	5414.8	6052.5	5669.1
Mg	178.0	383.1	207.8	386.1	300.8	366.9	365.1	295.7	375.5
S	19.68	26.45	14.07	14.14	19.17	19.65	13.80	23.28	20.97
Na	172.2	187.9	102.9	88.7	82.4	300.3	261.2	136.0	311.7

Table 4.11. Soil nutrient analysis for Burleson clay (0 to 15 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	8.21	7.61	8.09	8.16	7.66	7.89	8.19	8.01	7.84
					μmhos cm^{-1}				
EC	414.4	274.3	366.3	435.8	293.5	424.3	344.5	368.5	235.5
					mg kg^{-1}				
NO_3-N	6.78	8.41	4.71	8.76	5.76	9.28	7.57	5.17	9.69
P	52.3	54.6	45.6	58.9	43.4	55.5	46.2	44.9	28.8
K	496.1	251.3	376.1	462.2	282.0	284.5	353.1	342.0	267.4
Ca	6611.0	2377.7	5848.3	7099.0	3731.1	4743.6	3877.9	6240.9	454.0
Mg	336.3	215.5	286.0	392.4	213.0	296.6	220.8	303.2	54.1
S	19.33	16.22	16.18	20.29	17.65	24.98	20.57	14.03	34.99
Na	185.0	151.1	210.1	171.3	178.9	307.9	224.6	183.7	206.6

Table 4.12. Soil nutrient analysis for Ships clay (0 to 15 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})							
	Control	Surface Applied				Incorporated		
Parameter	0	4	8	12	16	4	8	12	16
pH	7.78	8.00	7.98	7.68	7.68	7.93	7.96	8.13	8.24
					µmhos cm^{-1}				
EC	252.8	387.5	329.0	358.5	397.8	247.3	317.5	301.3	487.5
					mg kg^{-1}				
NO_3-N	10.01	5.51	6.37	5.26	9.60	3.49	6.79	2.80	8.01
P	44.8	46.0	53.7	56.7	57.7	28.5	34.3	42.3	48.2
K	288.3	420.1	260.5	362.5	409.5	262.8	419.4	308.9	519.5
Ca	1555.4	5925.6	2393.4	4804.2	4848.4	2647.8	5233.1	1422.2	8607.2
Mg	136.6	282.9	217.9	291.6	301.9	131.1	219.7	134.4	389.6
S	21.80	18.31	23.04	14.82	16.84	19.99	13.74	37.28	15.72
Na	188.2	163.4	333.9	237.0	167.5	158.9	101.4	279.1	131.6

Table 4.13. Soil nutrient analysis for Rader fine sandy loam (15 to 30 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})							
	Control	Surface Applied				Incorporated		
Parameter	0	4	8	12	16	4	8	12	16
pH	7.34	7.53	7.20	7.54	7.73	7.30	7.68	7.56	7.60
					µmhos cm^{-1}				
EC	188.5	184.8	169.0	187.8	187.5	179.5	218.0	171.8	187.0
					mg kg^{-1}				
NO_3-N	3.86	6.28	4.63	3.78	4.74	2.68	1.96	4.10	1.81
P	28.7	29.9	27.8	30.9	30.5	30.1	31.8	31.1	31.3
K	98.5	121.4	131.4	158.5	158.4	111.6	201.6	146.4	177.7
Ca	426.0	799.6	451.0	472.7	831.1	475.1	2557.2	551.6	454.1
Mg	42.6	47.4	40.3	43.5	47.1	43.7	129.1	47.3	47.5
S	20.53	23.96	19.19	31.62	26.68	15.41	12.29	19.24	22.90
Na	151.1	145.8	109.7	133.1	123.2	134.0	89.2	133.9	142.1

Table 4.14. Soil nutrient analysis for Burleson clay (15 to 30 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	7.55	7.61	7.60	7.62	7.57	7.50	7.48	7.50	7.44
					μmhos cm^{-1}				
EC	467.6	406.8	393.8	385.3	438.8	398.3	381.3	405.3	502.3
					mg kg^{-1}				
NO_3-N	24.47	6.99	5.13	8.05	14.15	9.02	11.77	2.53	21.79
P	85.9	81.8	82.0	81.5	79.8	78.7	76.0	80.4	90.0
K	253.2	246.4	252.1	239.9	250.9	262.7	253.0	266.2	296.1
Ca	4555.1	4420.7	4546.0	4400.0	4468.7	5037.0	4267.2	4643.2	4717.5
Mg	365.2	360.0	357.7	358.1	359.1	367.9	355.0	363.4	372.7
S	15.09	12.85	15.34	11.34	12.71	13.29	12.58	17.47	17.63
Na	105.3	110.2	110.1	104.2	111.5	44.4	53.7	70.4	73.6

Table 4.15. Soil nutrient analysis for Ships clay (15 to 30 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	8.33	8.31	8.28	8.17	8.27	8.35	8.23	8.31	8.32
					μmhos cm^{-1}				
EC	420.5	425.8	426.0	1324.5	426.3	436.3	459.5	422.8	447.0
					mg kg^{-1}				
NO_3-N	3.00	2.35	1.97	3.12	0.65	3.27	1.68	2.06	3.75
P	30.9	34.5	32.2	31.9	31.0	33.6	47.5	35.5	37.0
K	475.9	490.3	463.7	371.3	487.8	488.3	526.6	491.8	512.0
Ca	9378.1	9302.1	9065.1	6932.5	9278.8	9519.9	9800.8	9886.3	10060
Mg	395.5	397.8	394.3	297.4	394.0	394.0	423.3	411.7	408.1
S	15.94	16.06	16.84	15.16	17.82	18.87	18.15	16.55	16.84
Na	55.2	59.6	54.0	70.1	61.3	59.6	67.1	61.3	61.5

Table 4.16. Soil nutrient analysis for sand below Rader fine sandy loam (30 to 60 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})							
	Control	Surface Applied				Incorporated		
Parameter	0	4	8	12	16	4	8	12	16
pH	8.01	7.96	7.83	7.78	8.00	7.87	7.90	8.16	8.02
					µmhos cm^{-1}				
EC	159.0	133.5	178.3	153.0	194.8	184.0	171.3	168.5	159.8
					mg kg^{-1}				
NO_3-N	7.28	5.93	7.70	7.67	7.72	5.79	7.24	6.74	8.00
P	148.2	156.4	165.9	169.5	172.2	164.6	155.8	133.9	150.6
K	11.0	9.6	11.6	9.0	14.7	11.2	11.3	9.1	15.5
Ca	795.2	814.4	715.8	734.1	804.8	681.6	738.9	730.7	814.9
Mg	33.9	34.1	33.4	31.6	34.0	31.7	32.6	30.9	36.7
S	43.46	36.53	44.74	45.94	63.97	50.35	47.18	34.30	50.30
Na	48.2	21.8	52.4	14.5	66.6	40.7	43.0	33.8	33.9

Table 4.17. Soil nutrient analysis for sand below Burleson clay (30 to 60 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	7.93	7.88	7.75	7.67	7.86	7.70	7.93	8.08	7.78
					µmhos cm^{-1}				
EC	135.1	144.5	145.5	149.0	156.3	173.5	137.8	129.3	159.0
					mg kg^{-1}				
NO_3-N	7.12	5.97	6.19	6.16	7.72	6.72	5.26	4.49	9.00
P	147.9	151.1	156.8	169.8	160.0	171.4	145.4	149.6	164.7
K	7.8	5.9	8.7	8.0	8.2	9.0	6.6	5.9	9.9
Ca	801.6	782.0	751.4	776.1	729.9	738.4	720.2	757.3	932.8
Mg	33.0	31.2	31.1	31.4	31.4	32.2	29.8	30.0	36.1
S	42.95	44.57	42.02	43.80	51.95	59.29	33.12	30.06	50.70
Na	3.7	3.7	9.8	6.4	7.3	7.6	7.5	6.9	8.9

Table 4.18. Soil nutrient analysis for sand below Ships clay (30 to 60 cm). Displayed are the results of Mehlich III extractable P, K, Ca, Mg, S and Na, KCl extractable NO_3-N, electrical conductivity (EC) and pH analysis.

	Biochar Application Rate (Mg ha^{-1})								
	Control	Surface Applied				Incorporated			
Parameter	0	4	8	12	16	4	8	12	16
pH	7.84	7.76	7.82	7.82	7.91	7.81	7.86	7.84	7.88
					μmhos cm^{-1}				
EC	138.3	155.8	165.3	146.5	141.5	156.5	146.5	153.8	148.5
					mg kg^{-1}				
NO_3-N	6.50	6.04	7.95	8.14	8.47	7.50	7.18	6.54	6.15
P	162.6	157.3	149.5	145.8	154.7	161.5	172.2	165.4	166.9
K	9.2	7.4	7.5	6.6	7.7	9.0	8.1	7.9	7.6
Ca	808.2	770.9	756.4	701.6	761.5	860.6	850.4	846.2	844.2
Mg	32.4	32.4	31.2	28.5	31.9	33.8	33.7	33.6	34.1
S	43.60	46.09	45.62	28.62	40.58	54.89	45.19	48.85	45.90
Na	4.8	4.7	5.3	4.2	5.1	6.7	8.8	5.0	5.6

4.4.7 Bulk Density

Bulk density results from the greenhouse agree with bulk density results obtained from field studies, in that there was no significant change in bulk density due to biochar application rate or method for any of the soils tested, both for the top 15 cm ($p=0.2570$) where biochar was applied directly, or for 15 to 30 cm ($p>0.0772$) (Figures 4.30, 4.31, and 4.32). Just as with the field study, the volumetric rate of biochar application was at most one percent, which is not a high enough application rate to directly affect the bulk density physically. In the field study, it was observed that there was a lack of significant porosity increase associated with biochar application, and it is likely that the same was true with the greenhouse columns, though porosity was not directly assessed.

Table 4.19. Bulk density measured in Rader fine sandy loam at two depths (0 to 15, 15 to 30 cm).

	Biochar Application Rate (Mg ha^{-1})							
	Surface Applied				**Incorporated**			
Bulk density (g cm^{-3})	0	4	8	12	16	4	8	12	16
0 to 15	1.59	1.56	1.51	1.63	1.58	1.60	1.51	1.58	1.56
15 to 30	1.70	1.32	1.72	1.61	1.66	1.66	1.57	1.68	1.67

Table 4.20. Bulk density measured in Burleson clay at two depths (0 to 15, 15 to 30 cm).

	Biochar Application Rate (Mg ha^{-1})								
	Surface Applied					**Incorporated**			
Bulk density (g cm^{-3})	0	4	8	12	16	4	8	12	16
0 to 15	1.32	1.35	1.34	1.33	1.33	1.38	1.37	1.41	1.34
15 to 30	1.25	1.27	1.30	1.36	1.39	1.29	1.33	1.32	1.18

Table 4.21. Bulk density measured in Ships clay at two depths (0 to 15, 15 to 30 cm).

	Biochar Application Rate (Mg ha^{-1})								
	Surface Applied					**Incorporated**			
Bulk density (g cm^{-3})	0	4	8	12	16	4	8	12	16
0 to 15	1.39	1.37	1.40	1.43	1.41	1.36	1.37	1.31	1.34
15 to 30	1.24	1.37	1.31	1.32	1.38	1.36	1.39	1.38	1.34

4.5 Conclusions

In terms of soil surface temperature, the dark color of the biochar and thus its low albedo have a greater influence when they are on the surface of the soil and are directly exposed to solar radiation. When incorporated, the biochar was less influential in terms of both surface temperature and in the case of Ships clay, moisture retention.

Biochar addition significantly affected the yield of biomass from the columns under certain situations and for Burleson soils the biomass was increased by biochar addition in a quadratic relationship for the first and third event. That is, the yield for biomass, in 4 separate instances in Burleson clay which produced the most significant amount of biomass, produced the largest biomass in between 8 Mg ha^{-1} and 12 Mg ha^{-1} (Figure 4.8 and 4.10). This increased effectiveness at moisture and nutrients stressed conditions could lend support to the original focus of this project, which is to evaluate biochar as method for improving the productivity of marginal farmland. However, data collected in terms of nutrient uptake and use efficiency did not reveal any trend and nutrients added to the soil by biochar were not consistently available to bermudagrass.

Important to the effectiveness of biochar, then, is the specific reason why soils would be considered marginal cropland. If they are deemed not suitable for cultivation due to compaction (low infiltration rates, higher bulk density) or other physical soil properties, then the addition of biochar may not be as effective as other methods. However, if there is a nutrient deficit in soils that might also be low in carbon, the addition of biochar may be beneficial to soil health and vegetation growth if the nutrients in biochar can be delivered to plants.

5. GENERAL CONCLUSIONS

Biochar application to soils tended to have significant effects on soil nutrient levels; however, it did not produce significant effects on the physical properties tested in this study. Since the scope and mission of this project involve the reclamation of marginal cropland into productive bioenergy cropland, it is important to consider the practicality, longevity, and actual influence of biochar addition on vegetation growth and the factors associated with it.

When biochar is applied to a soil with high levels of nutrients, the fertilization capacity of the biochar may be limited, as evidenced by lack of effects on field biomass in this study. However, the effects of biochar nutrient additions will likely be more pronounced in soils with lower background levels, when the deficit in nutrients is greater between crop requirements and biochar nutrient content. Biochar application may have the most beneficial use in soils with low pH (due to its liming effect due to the addition of basic cations through biochar application) and low nutrients. Biochar application rates of most benefit tended to be the intermediate rates in this study, between 8 and 12 Mg ha^{-1}, beyond which increased application led to decreased yields. Biomass harvested in Burleson clay soil columns in the greenhouse for 8 and 12 Mg ha^{-1} was higher than that of other rates in the first and third harvest and germination index values were highest in between 8 and 12 Mg ha^{-1} rates, all of which occurred regardless of whether or not biochar was surface applied or incorporated. In terms of biochar application method, significant soil nutrient responses to biochar were generally present regardless of method because the solubility of the nutrients in biochar allow for mobility through the soil. Biochar addition to the surface may help encourage early planting emergence through warming of the surface and enhanced moisture retention, though increasing biochar rates past a certain point may raise the temperature too much to be beneficial. This provides further evidence that applying biochar to soils in indefinitely increasing rates is not likely beneficial. Additionally, when biochar is applied to the surface of the soil, keeping the biochar on the site to which it was applied can be difficult due especially to wind erosion.

Biochar application to soils is still a viable option, however, for disposing of the byproduct of pyrolysis used to generate plant-based biofuel. It may be well suited to land applications in reclamation situations, where soil nutrients have been leached out due to soil disturbances or in acidic sites that need both the addition of basic cations. More research is yet needed to understand the complex interaction that biochar has with soil chemically and physically across multiple types of both biochar and soil.

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