CHARACTERIZING EFFECTS OF CHARGED BIOCHAR ON SOIL QUALITY AND PLANT GROWTH IN DEGRADED NORTH CAROLINA HIGH COUNTRY SOILS

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by
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Abstract

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Significant land degradation and topsoil loss has threatened agricultural production, ecosystem function, and soil-based carbon sinks. Climate change threatens all ecosystems and communities on Earth. Reducing carbon emissions is not enough – carbon must be drawn down from the atmosphere and sequestered (Intergovernmental Panel on Climate Change [IPCC], 2018; Woolf et al., 2016). Biochar addresses each of these issues, providing a foundation for healthy, long-term soil regeneration and sustainably sequestering carbon within the soil for millennia. While interest in biochar is rapidly increasing, the actual product itself as well as its effect on various soil types can vary, necessitating local studies on specific feedstocks, pyrolyzation methods, post-production preparation, and soil application. This study investigates biochar made in a TLUD from hardwood chips, which, alongside four organic amendments (compost, vermicompost, aerated compost tea, and anaerobic digester effluent), was applied to a degraded sandy soil in Zionville, North Carolina. A single growth of spinach was used to compare yields from the various applications.

The application of biochar alone increased the yield of spinach by 66% over the control. The organic amendments further increased yields, but with different effects due to the addition of biochar. Compost and vermicompost, both solid amendments, saw reduced yields due to the addition of biochar, while aerated compost tea (ACT) and anaerobic digester effluent (ADE), both liquid amendments, saw increased yields due to biochar.

"The soil is the great connector of lives, the source and destination of all. It is the healer and restorer and resurrector, by which disease passes into health, age into youth, death into life. Without proper care for it we can have no community, because without proper care for it we can have no life."

-Wendell Berry, *The Unsettling of America*, 1977

Acknowledgments

I would like to express my gratitude to the Earth for constantly demonstrating her massive capacity for healing and regeneration – a constant cycle of change, birth and death, decay and regeneration.

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I am thankful for the people healers and the planet healers, those that have supported me and inspired me and for which I would not be in the same position today – Marcus Henderson and Black Star Farmers, Ameya Majmudar, John D. Liu, David Shaw and Santa Cruz Permaculture, the Organic Grower's School, Suzanne Coyle, Ken Crouse, Ahna Robbins and Abby Frye.

Dedication

This thesis is dedicated to the Earth and to a return to balance. I hope in some small way it contributes to greater understanding of and connection with nature, to a shared healing of the soil, the land, and the people, and to a new Earth.

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Introduction

Addressing the Problem

Despite growing levels of urbanization and the loss of direct connection with the Earth for a growing percentage of the global population, humanity cannot escape its dependence on and membership in the global ecosystem. Without a healthy planet, human life is threatened. Soils play an immeasurable role as a foundation for terrestrial life – they are the intermediary between rock and plant, the foundation of terrestrial food chains, and home to much of the network that links an ecosystem together.

The industrial revolution spawned the false promise of industrialized agriculture, suggesting that an immense streamlined food production system could be erected without the need for large amounts of human labor. As farming grew more and more mechanized, people left the fields. But people were not the only life to leave the soil. Decades of poor farming practices, deforestation, and other extractive and exploitative industry have stripped soils of biodiversity, compacted it and allowed for massive amounts of soil loss through erosion (Pimentel, 2005). This not only challenges the stability and biodiversity of ecosystems across the globe with desertification, but also threatens the potential for the Earth to provide food for the growing human population (Pimentel, 2005).

There is hope both for the restoration of Earth's many ecosystems and the security of humanity's future, and a crucial component is regenerative agriculture. Through amending the way food is produced, soil and ecosystem health can be replete and sustainable, resilient food production capabilities can be secured. It all begins with soils: regenerating healthy soils will ensure healthy ecosystems, food security, and resilient landscapes.

Biochar and Planet Health

Due to both land degradation and pre-existing soil characteristics, not all agricultural soils are as productive as they could be. A promising solution to land degradation and agricultural soil quality comes in the form of biochar. Biochar is the product of biomass pyrolysis, in which biomass is heated to high temperatures in the absence of oxygen (Lehmann & Joseph, 2015). The resulting charcoal-like substance can be useful in rehabilitating soil and stimulating long term soil health, benefiting nutrient retention and flow, oxygen and water availability, and allowing for a healthy soil microbiome and a stable concentration of soil nutrients.

The Intergovernmental Panel on Climate Change (IPCC) has set the goal of limiting global warming to a maximum of 1.5°C above pre-industrial levels. In addition to drastically reducing carbon emissions, carbon must also be removed from the atmosphere to reach this goal (IPCC, 2018). Amending soils with biochar is a promising practical climate change mitigation strategy. Biochar is a stable form of concentrated carbon. Creating and applying large amounts of biochar to soils sequesters large amounts of carbon for centuries to come while investing in healthier soils, higher crop yields, and more resilient agriculture. Further carbon sequestration occurs through the growth of the soil microbiome and the increase in plant yields.

While biochar has been shown to have positive effects on soils across the Earth, the product itself, its application to soils, and its effects can vary greatly, sparking the need for studies on specific biochars and their applications in specific soils (Lehmann & Joseph, 2015).

Purpose of Study

This study aims to investigate local biochar production and application techniques for North Carolina's High Country. Focusing on low-budget and low-tech production, charging, and application methods, solutions for small organic farms will be investigated. The aim is to develop a realistic biochar production, charging, and application method that can offer immediate stimulation to plant growth while maintaining practicality and low cost for small farms. The study will focus on degraded soil in order to aid farmers interested in regenerating land and soil for sustainable food production.

A top-lit updraft gasifier (TLUD) was used as the primary means of biochar production. It is easily built at a low cost and is simple to operate. The feedstock was hardwood chips, which are a plentiful waste material in this region. Charging methods included vermicompost, aerated compost tea, and anaerobic digester effluent. Each of these constitutes a realistic charging method for small farms.

Significance of Study

The aim of the study was to provide the North Carolina High Country agricultural community with information about how to make, charge, and apply biochar effectively on a budget as well as how that biochar's application to degraded soil can affect plant growth in the short term. Plant growth, demonstrated through leaf quantity and size during growth and yield after harvest, was measured to determine the differences in immediate effect of the various charged and uncharged biochar applications. While this aims to provide tangible evidence of the effects of the soil amendments, a more in-depth chemical analysis of the soils was performed to illuminate the changes in soil health and composition due to the soil amendments. Additionally, a biochar-specific test was performed to characterize this specific biochar and allow it to be classified and compared to other biochars. This could stimulate more interest in small-scale, low budget biochar production, which could be very beneficial to small organic farms and gardens.

Research Hypothesis and Question

The hypothesis is that biochar charged with each of the four organic amendments will result in greater plant growth than unamended soil. Uncharged biochar will likely result in slightly inhibited plant growth or no change at all, while organic amendments applied without biochar will result in greater growth, but most likely not as great as with biochar. Of the four charges, vermicompost is expected to result in the greatest increase in plant growth, followed by compost, AD effluent and then aerated compost tea. While AD effluent and aerated compost tea are not expected to provide as the positive results expected of vermicompost or compost, they could provide a rapid means of charging biochar compared to charging with a solid amendment. Soil tests are expected to show increases in soil nutrients, primarily the macronutrients P and K, as biochar and organic charges are added. This is expected because of the direct nutrient addition from biochar and charges as well as an increase in nutrient retention as a result of the biochar addition. The research question is as follows:

What methods of organic charging and application of hardwood chip biochar produced in a top-lit updraft gasifier (TLUD) are most immediately effective at enhancing plant growth in degraded North Carolina High Country soil?

Charges include aerated compost tea, vermicompost, compost, and anaerobic digester effluent.

Limitations of Study

Biochar can last in soil for hundreds of years or more (Lehmann & Joseph, 2015). This short-term study is of value because it is important to small farmers that their biochar application results in immediately beneficial effects; however, this study was limited by time. A long-term study would be valuable in charting the effects on soil health and plant growth over multiple growing seasons to truly comment on this specific biochar's efficacy in regenerating degraded High Country soils and enhancing long-term plant growth. In only a few weeks, the full effects of nutrient cycling, decomposition, erosion and leaching cannot be thoroughly evaluated.

The scale of the field experiment did not allow for randomization and replication. For each unique treatment, only one test plot was used.

This short-term study still offers value because it demonstrates the immediate effects of certain applications of biochar on plant growth and soil health. This demonstrates to farmers what to changes to expect in immediate plant growth from applications of biochar and the four organic amendments. While the results of this study are not completely conclusive, trends were identified and a foundation for further exploration has been laid.

Additionally, this study is limited by the amount of charged biochar that can be produced. The amount of vermicompost was limited due to the pace of worm growth and reproduction.

Review of Literature

Soil Health Problems

As the foundation of terrestrial life, soil plays a unique role as the foundation for the food web and the backbone of life on land (Jehne, 2017). Healthy soils host a wealth of microbial and fungal life, from bacteria to nematodes to mycorrhizal fungi, which help complete the cycle of nutrients and life, breaking down minerals and biomaterial to provide nutrients to growing plants. Healthy soil also acts as a sponge, providing water and oxygen to plant roots and microbial life. Without healthy soils, plant growth is threatened, and, in turn, so are the animal kingdom and humankind.

Millenia of agriculture have altered and often impaired soils that once thrived. Modern industrialized agriculture, with powerful machinery and chemicals, has been especially harmful to soils around the world. From recurrent tilling to the use of chemical biocides to fallowing and monocropping, industrial agricultural methods have stripped soils of microbial diversity, limited water infiltration and moisture retention, and caused massive topsoil loss through rampant erosion (Gomiero, 2016; Pimentel, 2006). This not only impacts biodiversity, the global climate, and many different ecosystems, but threatens food security worldwide (Eswaran et al., 2001).

A dramatic shift in the way we grow food is necessary, especially as a growing population requires a growing food production volume. Regenerative agricultural practices can be used to restore healthy topsoil, create a thriving and resilient soil microbiome, rehydrate the land, and ensure a healthy future for both people and the planet. At the same time, regenerative agriculture can sequester massive amounts of carbon in the soil, making them one of the most promising large scale climate change mitigation strategies to date (Jehne, 2017).

Biochar and Soils

Biochar is a pyrogenic carbonaceous material created by heating biomass to temperatures greater than 250°C in an environment with little to no air (Lehmann & Joseph, 2015). Rather than combusting, with little oxygen available the feedstock is pyrolyzed, which results in a structure of fused aromatic rings (Lehmann & Joseph, 2015). Much of biochar's eminence is owed to this structure. Unlike other pyrogenic carbonaceous materials such as charcoal, biochar is generally distinguished by its use as an agricultural amendment (Lehmann & Joseph, 2015). It is noted, however, than there are other applications that do not fall into this category but are still commonly referred to as biochar, such as when biochar is used for air or water filtration, odor reduction, or humidity regulation (Schmidt & Wilson, 2014).

Interest in biochar has grown immensely in recent decades due to its potential to augment soil health in a wide variety of ways. Much of biochar's utility in soil is owed to its highly porous structure. This structure helps greatly with water, nutrient, and oxygen retention and availability. For soils that are sandy and struggle with water and nutrient loss due to leaching, biochar can help retain nutrients and water due to its porosity (Lehmann & Joseph, 2015) as well as its high cation exchange capacity (Liang et al., 2006), which helps it adsorb cations and provide plant-available nutrients (Culman et al., 2019). For soils that have a high clay content and struggle due to low water infiltration and drainage and lack of oxygen, biochar's porosity provides space for water to move and for oxygen to reach plants' root hairs and microbial communities within the soil (Lehmann & Joseph, 2015). Biochar provides habitat for soil microbial life, which is the backbone of health soils, healthy plants, and a healthy planet (Schmidt, 2014). Biochar is also noted for is its ability to act as either a semiconductor or a conductor of electricity. Higher temperature biochar, such as biochar made via gasification, has been shown to act as a conductor of electricity (Joseph et al., n.d.) due to its higher crystallinity (Lehmann & Joseph, 2015). This conductivity can foster more rapid exchange of electrons between microbes, enhancing the microbial network within the soil (Liu, 2019).

Biochar has been recognized as a realistic and promising climate change mitigation strategy (Food and Agriculture Organization of the United Nations, 2020; Hoffman-Krull, 2019; Project Drawdown, n.d.; USDA Agriculture Research Service, 2020). Biochar feedstocks include various types of organic matter, which is high in carbon that was drawn down from the atmosphere by plants through photosynthesis. In the production of biochar, around 50% of the carbon initially present in the feedstock is locked away (Lehmann, 2007) for anywhere between a few decades to over 2000 years (Lehmann & Joseph, 2015). The recalcitrance of biochar makes it especially appealing as a long-term solution to soil health and carbon sequestration (Thomas & Gale, 2015). Further carbon sequestration occurs when biochar is used to augment soil health, resulting in the growth of the soil microbiome and greater plant growth, both of which draw more carbon out of the atmosphere and sequester it in the form of life (Lehmann & Joseph, 2015).

The production of biochar generally involves starting a fire, which releases carbon into the atmosphere. When performed correctly, the production of biochar remains significantly carbon negative for two reasons. Biochar feedstocks are generally waste wood products with no other primary use. Waste wood is commonly either burned as slash or left to decompose. Unlike slash burning, creating biochar in a biochar kiln results in at least 50% of the carbon initially present in the feedstock being locked away in the recalcitrant form of biochar, keeping it out of the atmosphere for centuries to come (Amonette, et al., 2021). Compared to slash burning, which immediately releases almost all of the feedstock's carbon into the atmosphere, using a biochar kiln results in an immediate decrease in carbon emissions. Biochar kilns also generally exhibit greater combustion efficiency than open burn piles, greatly reducing the global warming potential by limiting harmful gases such as carbon dioxide, methane, nitrous oxides, and other volatile organic chemicals (Cornellison et al., 2016). Wood can take years to decompose, significantly elongating the process of breaking down and releasing carbon to the atmosphere. While the majority of carbon present in decaying woody biomass quickly decomposes over a few decades, the remaining minority of carbon can take over a century to fully decompose and leave the soil (Fraver et al., 2013; McFee & Stone, 1966). Although biochar production has a higher initial output of carbon emissions than allowing wood to decompose, it locks away more carbon in the long term than decomposition, making it a more appropriate use of waste wood than slash burning or decomposition in terms of carbon emission and climate change potential.

Biochar Production, Charging, and Application

It is important to note that not all biochar is alike. The growing global understanding of biochar is finding that biochars can vary greatly and have different utilities and effects in soil depending on feedstock, production temperature, pyrolysis residence time and other factors (Lehmann & Joseph, 2015). This creates the possibility of making "designer biochar" with specific characteristics, such as high porosity or high phosphorus (Lehmann & Joseph, 2015). Not every type of biochar can mitigate every soil health issue as well as other types can, which often creates the need for some degree of specialization in biochar production to achieve sufficient results in addressing specific soil deficiencies. Still, according to a meta-analysis performed in 2015, "if random biochars were indiscriminately applied globally," an application rate of 50 t/ha "would generate mean yield increases of 18 per cent" (Lehmann & Joseph, 2015). At times, biochar has been shown to be detrimental to immediate plant growth, especially when applied uncharged (Agegnehu et al., 2016). It has also shown to be quite beneficial to plant growth, at times resulting in yield increases of over 400% (Agegnehu et al.).

The biochar production process begins with a feedstock, which can be virtually any dry biomass, such as wood, grass, manure, or bone. The feedstock undergoes pyrolysis, which involves heating to temperatures over 250 ℃ in the absence of oxygen (Lehmann & Joseph, 2015). Many pyrolyzation methods involve elaborate and expensive systems aimed at continuous production, high levels of homogeneity, or high production volume. Gasification is a similar process to pyrolyzation and also produces biochar, but a small amount of air is permitted (Wang & Wang, 2019). Gasification techniques are often more reasonable with a lower budget, making them more applicable to small farms. The top-lit updraft gasifier, or TLUD (Figure 1), is a widely used small-scale gasification device that can be made from inexpensive and often scrap materials.

A steel drum with holes in the bottom is filled with a feedstock, which is lit at the top of the drum. Without sufficient oxygen to completely burn, the feedstock partially combusts, acting as the heat source for the pyrolyzation of the rest of the biomass. Holes in the bottom of the drum allow air infiltration and upward flow of gases. Atop the main drum sits the top half of another drum with a chimney installed. The chimney pulls an upward draft, sucking air in through the holes in the side of the half drum and allowing secondary combustion to occur, which burns any partially combusted gases and drastically reduces harmful emissions. Rather than a mix of volatile organic chemicals, the two main gaseous byproducts are water vapor and carbon dioxide.

Figure 1

A TLUD made from 55-gallon steel drums and steel duct material

Biochar is highly adsorptive due to its porosity and, with improper use, can be a detriment to soil health and plant growth in the short term because it can adsorb nutrients from the soil, taking them from the plants (Schmidt, 2011). Because of this, it is generally necessary to charge biochar with nutrients to produce immediately beneficial effects on plant growth. Charging is generally performed by mixing biochar with compost and allowing it to sit for anywhere between a few weeks and a year or more (Schmidt, 2011). This allows the nutrients in the compost to be adsorbed and fill the biochar's pores as well as decreases the hydrophobicity of biochar, allowing it to act more efficiently as a sponge for water and dissolved nutrients (Hagemann et al., 2017). When applied to soil, the charged biochar does not adsorb nutrients from the soil, instead providing greater nutrient availability to the soil food web and to the roots of plants. Biochar has also been shown to improve the composting process when added to a compost pile, a method termed "co-composting." When biochar is co-composted, higher temperatures, lower methane emissions, and quicker overall composting result due to heightened microbial activity and greater methanotrophic than methanogenic activity (Sonoki et al., 2012).

After charging, biochar can be added to soils. This is generally measured in metric tonnes per hectare (t/ha). Budget, soil needs, and production capabilities often dictate application rates, which can vary from 1 t/ha (International Biochar Initiative, 2018) to over 150 t/ha (Lehmann & Joseph, 2015). Charged biochar can be added to the surface or mixed into the soil. A no-till approach involves surface application or low-depth mixing with a tool such as a broadfork or power harrow. Vertical mixing within the soil column, permitted by worms, arthropods, and more, allows the biochar to be distributed more evenly within the soil over time (Lehmann & Joseph, 2015).

Research Methodology

This study sought to investigate applications of biochar on small organic farms, using low-tech and low-budget methods and local materials. It investigates the use of hardwood chip biochar produced in a TLUD and mixed with vermicompost, compost, anaerobic digester effluent, and aerated compost tea. Hardwood chips are readily available from many local sources. A TLUD is easily manufacturable with scrap materials on a low budget and is also relatively easy to use and maintain. Compost, vermicompost and aerated compost tea are easy to produce. Anaerobic digesters are an exciting technology with growing interest in the agricultural industry and can provide a method of quickly turning wet waste biomass into useful soil fertilizer. While they require a greater investment and slightly more maintenance than compost, compost tea, or vermicompost, their effluent could provide a highly efficient and effective means to charge biochar and return nutrients to the soil.

A TLUD was built with two 55-gallon drums. Holes were drilled in the bottom of the bottom drum, which is left open at the top (Figure 2). The top half of a second drum was tapered to fit in the top of the bottom drum. It is fitted with a chimney made of metal ducting, which helps create a draft that pulls air upwards through the TLUD. Ports for three thermocouples were installed in the side of the TLUD to allow temperature logging during burns (Figure 3).

Figure 2

Air inlet holes created in the bottom of the TLUD

Figure 3

Tubes welded into the TLUD to adapt three thermocouples

The inlet holes in the bottom of the TLUD initially let in too much air and resulted in temperatures over 1000 ℃. Aiming for a maximum temperature around 700-750 ℃, a few pieces of metal were added to the bottom of the TLUD to throttle some of the incoming air and reduce the temperature (Figure 4). This was successful in reducing average temperatures, but maximum temperatures still fluctuate some due to disparities in feedstock water content, bulk density, and air flow.

Figure 4

Metal welded on the TLUD air inlet holes to reduce incoming air

Wood chips and trimmings were acquired from Blue Ridge Energy from right of way clearings for powerlines. These are likely from primarily hardwood species. The chips were dried on a black plastic mat in the sun to a moisture content of 14-15%.

Biochar was produced in the TLUD and temperature was charted during the process. After the burns were complete, they were quenched with water and then dried until all free water was gone. Table 1 displays the data from the two burns. Despite similar feedstock masses and water contents, there are major differences in maximum temperature, pyrolyzation time, and biochar produced. While the same feedstock was used, it is not uniform in bulk density, allowing significant differences to arise in pyrolyzation and in the amount of biochar produced.

Table 1

Biochar burn data

	Burn 1	**Burn 2**
Feedstock	Wood chips from Blue Ridge Energy right of way clearing	Wood chips from Blue Ridge Energy right of way clearing
Time (mins)	35	50
Feedstock mass (kg)	27.40	29.35
Feedstock water content	13%	12%
Biochar wet mass (kg)	609	440.3
Uncrushed biochar volume (gal)	12	16
Biochar water content	66%	67%
Biochar dry mass estimate (kg)	5.84	5.41
Production efficiency	21%	18%
Maximum temperature (℃)	979	767

The biochar from both burns was mixed and then crushed by hand and sieved to a maximum size of 2mm (Figure 5 and

Figure **6**).

Figure 5

Wood chip biochar

Figure 6

Crushed wood chip biochar

The plant growth study was performed on a 125 x 4 foot strip of degraded soil at Against the Grain Farm in Zionville, N.C. (Figure 7). The strip was once used to grow tobacco, which heavily degraded the soil. Against the Grain Farm has been regenerating the soil with organic and biodynamic methods. Before the strip was cleared for this study, a cover crop of sorghum sudan, crimson clover, millet, and buckwheat was grown.

Figure 7

Test strip at Against the Grain Farm in Zionville, N.C.

The soil in the test plots is classified by the USDA as a Saunook loam (USDA Natural Resources Conservation Service, 2020). Samples of unamended soil were taken from each third of the test strip and mixed into three samples, which were sent to the North

Carolina Department of Agriculture (NCDA) for a soil analysis prior to any amendment or planting (Figure 8).

Figure 8

Unamended degraded soil

The soil in the test plot was analyzed to determine the soil texture, which was classified according to USDA soil texture standards (USDA Natural Resources Conservation Service, n.d.). It is classified as a sand (Figure 9). It is 93.4% sand, 0.66% silt, and 0% clay (Table 2).

Figure 9

Field trial soil texture classification (soil texture denoted by red dot)

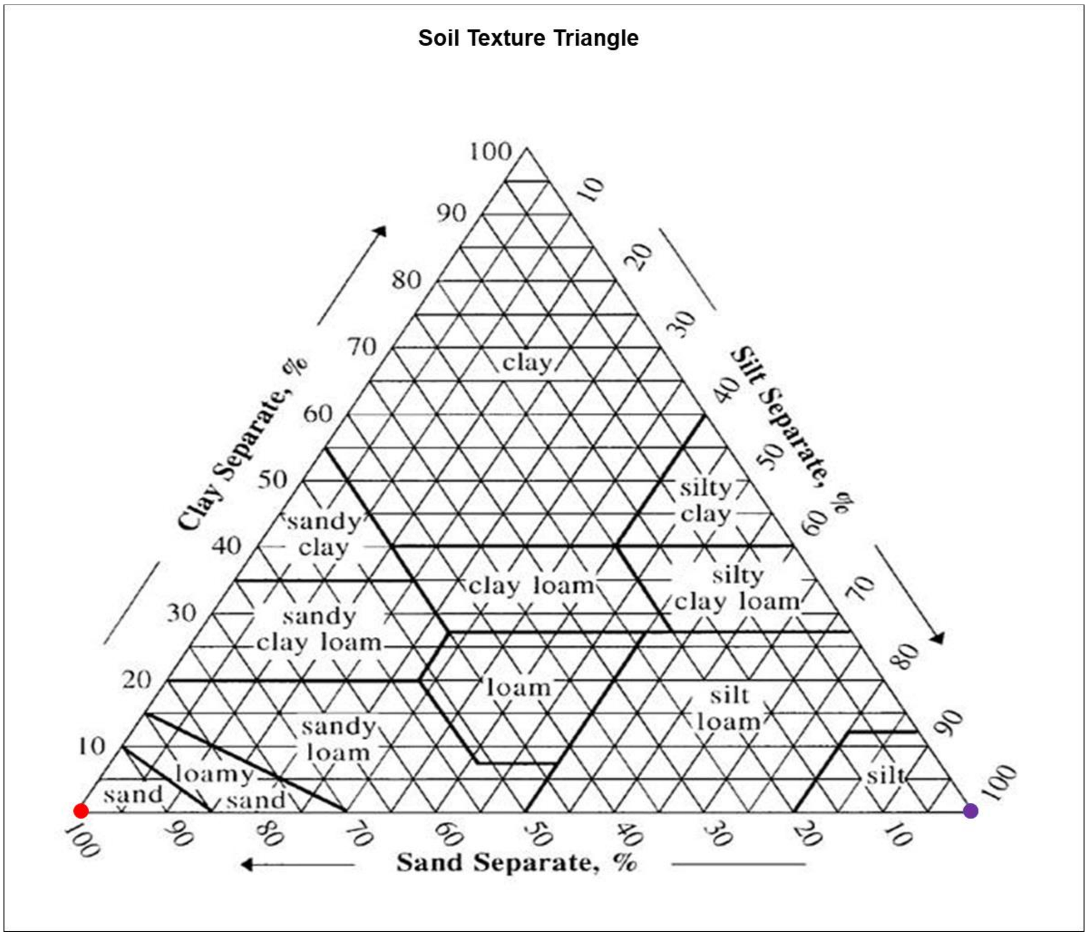


Table 2

USDA soil particle size distribution

USDA particle size	Percent composition
Very coarse sand	15%
Coarse sand	24%
Medium sand	24%
Fine sand	25%
Very fine sand	11%
Silt	1%
Clay	0%

The strip was separated into thirteen plots that were 4 feet wide, each separated by a 4 x 4 foot gap to prevent any cross-contamination. All but two plots were 4 feet long. The remaining two plots, plots 5 and 11, were 3 feet 2 inches and 2 feet 4 inches, respectively. This was done because there was not enough vermicompost to amend these plots at the same biochar per area and vermicompost per area ratios, as is discussed later. Each plot size allowed the same spacing between plants and the same average area per plant.

As Table 3 demonstrates, twelve different amendments were prepared. One included only uncharged biochar. Four amendments included only compost, vermicompost, aerated compost tea (ACT), or anaerobic digester effluent (ADE) without biochar. Another three included compost, ACT, and ADE as well as biochar without any charge time. In these plots, biochar and the other amendment were added to the plot at the same time without having been mixed previously. Last, four plots included biochar charged with vermicompost, compost, ACT, and ADE. This amendment strategy was selected to investigate the differences between each of the four charges, the effect of charging biochar, and the function of biochar itself both alongside and apart from the four organic amendments. All biochar was added at a rate of 1.5 kg (3.3 lbs) per 4 x 4 foot plot, which equates to about 10 metric tons/ha (4.5 tons/acre). This rate was selected because it is common among previous studies, has generally resulted in successful crop yields, and is economically feasible.

Table 3

Test plots and amendments

Plot Number	Amendment	Biochar kg (lb)	Biochar metric tons/ha (tons/acre)	Organic amendment	Solid amendment tonnes/ha (tons/acre)	Liquid amendment L/ha (gal/acre)	Charge Time	Plot size	No. of plants
1	Compost+BC	1.5 (3.3)	10 (4.5)	4.95 kg compost	33.3 (14.9)			4' x 4'	30
2	BC+ACT	1.5 (3.3)	10 (4.5)	3 L ACT		20200 (2160)		4' x 4'	30
3	BC	1.5 (3.3)	10 (4.5)					4' x 4'	30
4	BC+ADE-c	1.5 (3.3)	10 (4.5)	3 L ADE		20200 (2160)	72 hours	4' x 4'	30
5	BC+VC-c	1.2 (2.65)	10 (4.5)	5.9 kg VC	50.1 (22.4)		0-4 months	4' x 3'2"	24
6	ACT			3 L ACT		20200 (2160)		4' x 4'	30
7	Compost+BC-c	1.5 (3.3)	10 (4.5)	4.95 kg compost	33.3 (14.9)		17 days	4' x 4'	30
8	Control							4' x 4'	30
9	BC+ADE	1.5 (3.3)	10 (4.5)	3 L ADE		20200 (2160)		4' x 4'	30
10	ADE			3 L ADE		20200 (2160)		4' x 4'	30
11	VC			4.25 kg VC	50.1 (22.4)			4' x 2'4"	18
12	Compost			4.95 kg compost	33.3 (14.9)			4' x 4'	30
13	BC+ACT-c	1.5 (3.3)	10 (4.5)	3 L ACT		20200 (2160)	2 hours	4' x 4'	30
						BC = biochar			
						VC = vermicompost			
						ACT = aerated compost tea			
						ADE = anaerobic digester effluent			
						-c = charged			

The amendments for plots 1, 7, and 12 were prepared with mature compost, primarily from food scraps, sourced from B.A.D. Composting in Boone, N.C. Plot 12 received only compost. Plot 1 received compost and biochar that were mixed immediately before addition to the soil. The amendment for plot 7 included biochar that had been mixed and allowed to charge with compost for just over two weeks (Figure 10). Biochar is often charged via co-composting, or mixing with compost at the beginning of the composting process, but mature compost for this study was sourced a few weeks before the planting date, so it was not co-composted.

Figure 10

Compost and biochar before mixing and charging

The amendments for plots 5 and 11 were prepared with mature vermicompost that was up to 6 months old (Figure 11). The amendment for plot 11 consisted only of vermicompost. The amendment for plot 5 consisted of biochar that was mixed with vermicompost at a 20% ratio by wet mass and co-composted for up to 4 months. Because the biochar was added incrementally as the vermicompost grew, the residence time ranged from 0-4 months in vermicompost that had matured for up to 6 months. Not enough mature vermicompost was created to amend a full 4 x 4 foot plot with the same biochar ratio as the other plots with biochar. To maintain the same biochar per soil area ratio and vermicompost per soil area ratio, the areas for plots 11 and 5 were made smaller than all other plots.

Figure 11

Vermicompost without biochar (left) and co-composting with biochar (right)

The amendments for plots 2, 6, and 13 were prepared with aerated compost tea. To brew the compost tea, a full 5 gallon bucket of water sat for 24 hours to off gas any chlorine. A 1 gallon paint strainer bag was filled with about 1 L of mature compost, 25 g cold water kelp, and 50 mL black strap molasses (Figure 12**Figure 13**) (Ingham, 2005). The mature compost was sourced from B.A.D. Composting in Boone, N.C. With the paint strainer bag secured in the bucket by a clothespin, the mixture was aerated by an air pump/aerator to ensure it remained aerobic for the duration of the process (Figure 13). The air pump used was a 40 gallon aquarium air pump providing 2.33 psi and 3 liters per minute of air through two air stones. After 72 hours of continuous aerated steeping, the paint strainer bag with compost and the aerator were removed and the ACT was stirred and then separated into three separate containers of three liters each. 1.5 kg of biochar was added to one container for a full two hour charge. After two hours, all three containers of ACT were evenly spread over their respective plots. Plot 6 received ACT alone, which was sprayed on the plot evenly with a small pump sprayer. Plot 2 received biochar first and then was sprayed evenly with ACT. Plot 13 received the biochar that had been charged, which was strained and applied to the plot before the remaining ACT was evenly sprayed on the plot.

Figure 12

Kelp and molasses before addition to ACT

Figure 13

Aerating and steeping ACT

The amendments for plots 4, 9, and 10 were prepared with anaerobic digester effluent. The ADE was sourced from the anaerobic digester at Appalachian State's Nexus Project greenhouse. Plot 10 received ADE alone. Plot 9 received biochar and then was sprayed evenly with ADE. For plot 4, 1.5 kg of biochar was steeped in 12 L effluent for 72 hours (Sekar et al., 2014) and then strained (Figure 14). The biochar was added and the remainder of 3 liters was sprayed evenly on the plot.

Figure 14

Biochar steeping in ADE

Some biochar was left uncharged and was added to plot 3. Plot 8, the control plot, received no amendment.

After any charging, all solid amendments, including charged and uncharged biochar, vermicompost, and compost, were spread on their respective plots. Each plot, including those without solid amendments, was mixed with a power harrow, loosening the soil and mixing in any amendments to a depth of around 10-15 cm (Figure 15). The harrow was raised to ensure no debris was left on it after each plot to prevent any cross-contamination. Liquid amendments, including ACT and ADE, was sprayed evenly with a pump sprayer after the power harrow passed each plot.

Figure 15

Power harrow mixing one of the test plots

After all amendments and mixing were complete, 17-day old organic spinach starts were planted in each plot with 8-9” spacing (Figure 16 and Figure 17). The plots were evenly watered each day for the first three days of growth and then transitioned to weekly watering.

Figure 16

Freshly planted spinach

Beginning two days after planting, the spinach plants were measured and the number of leaves, leaf lengths, and leaf widths were recorded. Each week, measurements alternated from odd to even numbered plants, measuring half of the total plants in each plot each week. Leaf length and width values were used to estimate leaf areas using the formula for the area of an ellipse. Wilted and dead plants were also recorded. Because of dropping temperatures, a mylar row cover was added to the entire row to prevent frost from damaging plants (Figure 17).

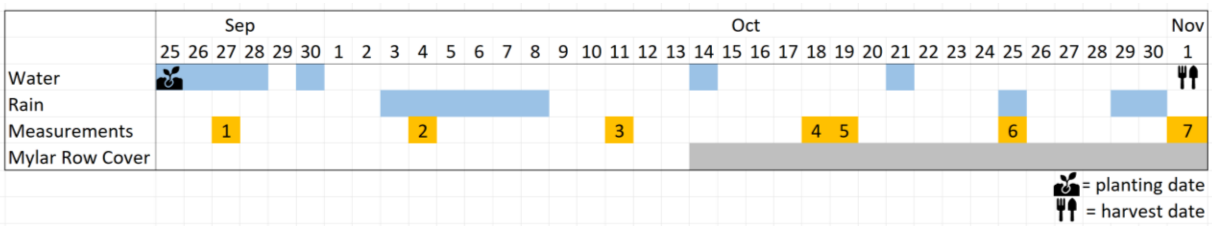
Figure 17

Mylar row cover added to plot to prevent frost damage

After 37 days of growth, some plots were producing marketable spinach plants. Because these plants were ready to harvest and a significant freeze was expected in the coming week, all plants from each plot were harvested. Figure 18 shows the timeline from planting through harvest. Each plant was harvested with a trowel, with care taken to ensure roots were not damaged. They were gently shaken to remove most of the dirt from the roots and placed in separate bags, one bag for each plot.

Figure 18

Plant growth timeline



After harvesting all the plants, each plot's yield was rinsed well to remove any excess dirt or debris. They were spun to remove bulk moisture in a spin dryer (Figure 19) and air dried.

Figure 19

Spin dryer used to remove bulk moisture from harvest

Next, each plot's yield was measured. Marketable plants were counted and then cut to remove the roots from the shoots (Figure 20). Total marketable yields were measured, both with and without roots, for each plant. Marketable yield includes healthy, sizable, non-wilted plants with any wilted or dead leaves removed. Root and shoot lengths were measured with either the root or shoot stretched to its full length. Then each plot's yield was dried for over 24 hours in a drying oven around 60-65 C and measured again to compare dry masses and water contents.

Figure 20

Spinach plant cut to separate root from shoot

After harvesting, soil samples were taken again from each plot and sent to the NCDA for a soil analysis.

A sample of the same biochar used in the field experiment was sent to Control Laboratories in Watsonville, California for a biochar chemical and physical analysis. Additionally, to compare biochar production methods, three additional batches of biochar were made in three different reactors – the TLUD, the open pit, and the closed kiln. To ensure consistency in feedstock, poplar logs were used rather than wood chips. These three samples were also sent to Control Laboratories for a biochar analysis. Data from the two burns that produced the hardwood chip biochar for the field experiment was shown in **Error! Reference source not found.**

Table **4** shows the data from each poplar burn. Control Laboratories is approved by the International Biochar Initiative to test biochar for their IBI Biochar Certification Program (International Biochar Initiative, 2020). The data from the biochar analyses was then used to compare the various biochars using the International Biochar Initiative's online Biochar Classification Tool (International Biochar Initiative, 2018).

Table 4

Poplar burn data comparison

	TLUD	**Open pit**	**Closed kiln**
Feedstock	Poplar logs	Poplar logs	Poplar logs
Time (mins)	30	44	
Feedstock mass (kg)	31	25.5	3.9
Feedstock water content	12%	12%	14%
Biochar wet mass (kg)	9.05	17.6	1.2
Uncrushed biochar volume (gal)	8	15	6
Biochar water content	80%	82%	0%
Biochar dry mass estimate (kg)	1.14	3.14	1.2
Production efficiency	4%	14%	36%
Maximum temperature (°C)	1180	925	-

Results

Field Experiment

Figure 21 displays the percentage of surviving plants from each plot. Figure 22 displays the average yield of surviving plants in each plot. Figure 23 shows the total extrapolated yield of each plot. Since the two plots with vermicompost did not have the same plot size or amount of plants originally planted as the rest of the plots, the total yields of those plots were extrapolated to reflect the same yield in grams per square foot of a full 4x4 plot.

Figure 21

Surviving plants from each plot

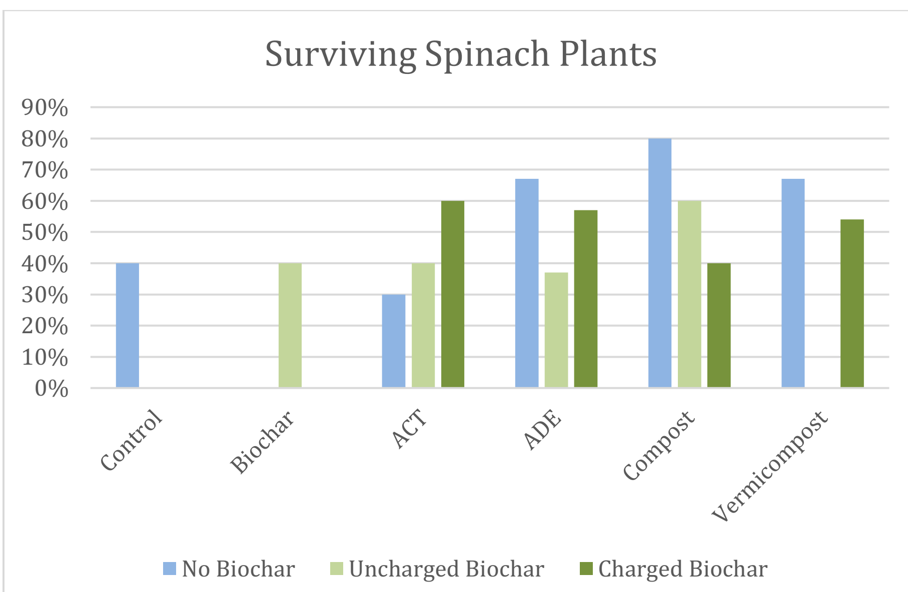


Figure 22

Average yield of surviving plants in each plot

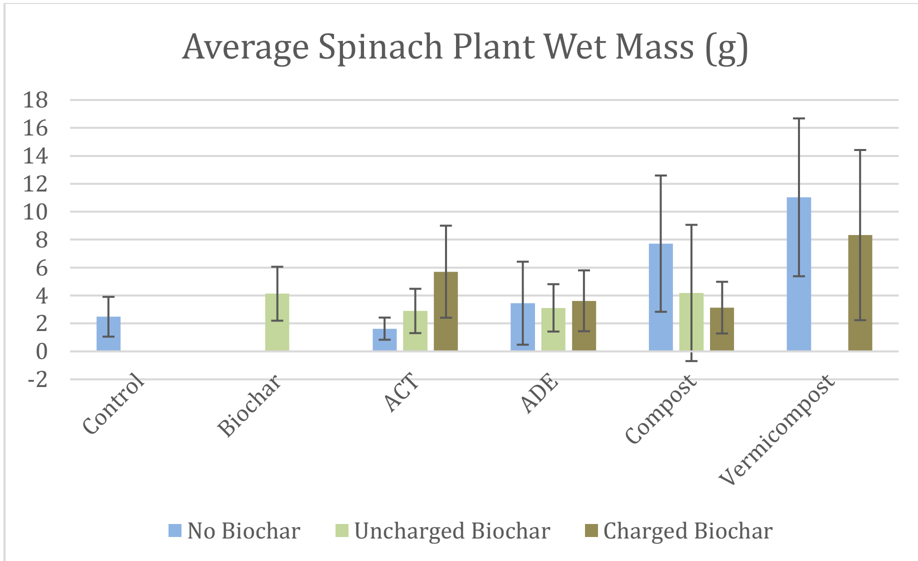


Figure 23

Total extrapolated yield of each plot

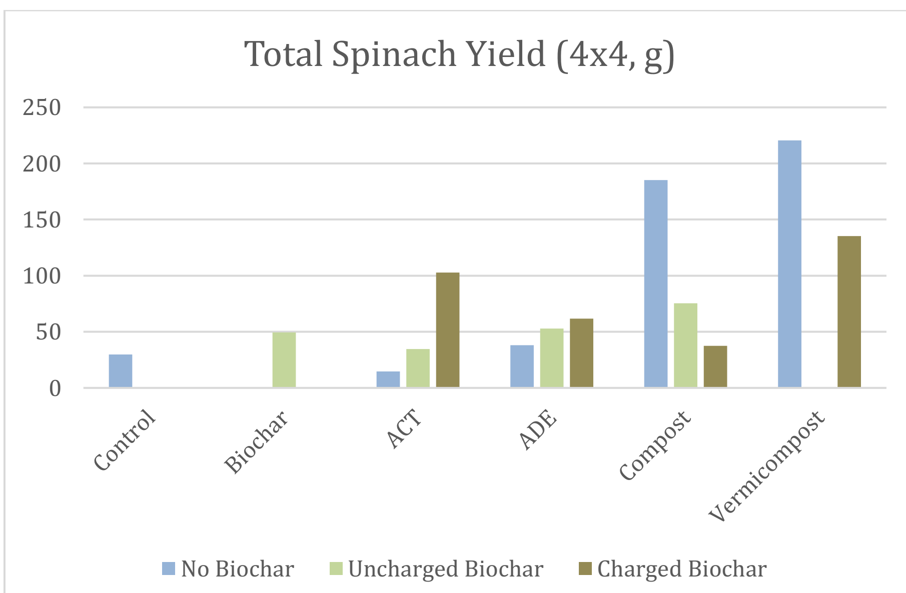


Figure 21 and Figure 22 show similarity in the trends of plant survival and average wet mass of surviving plants, especially within each different treatment's plots.

Effects of Organic Amendments

As expected, vermicompost provided the highest amount of nutrients, followed by compost and then the two liquid amendments, ACT and ADE (Figure 22 and Figure 23). Vermicompost, both with and without charged biochar, resulted in a far higher yield than the control plot or the plot with only biochar.

Effects of Biochar

Figure 22 and Figure 23 also suggest that biochar alone resulted in a higher yield than the control plot.

Biochar seemed to affect the two solid amendments, vermicompost and compost, differently than the two liquid amendments, ADE and ACT. With the solid amendments, the addition of biochar resulted in lower yield, as seen in Figure 22 and Figure 23. While there was no plot with vermicompost and uncharged biochar, it is evident in the compost plots that, compared to the compost alone, adding uncharged biochar resulted in a lower yield. This same trend is evident when analyzing plant survival rates, as demonstrated by Figure 21.

The plots with liquid amendments, ACT and ADE, exhibited different effects. With ACT, adding biochar increased the yield (Figure 22 and Figure 23**Error! Reference source not found.**). Charging the biochar further increased the yield. This trend is similar with plant survival as well (Figure 21). The plots with ADE resulted in the most conflicting results. Total yield increased slightly with uncharged biochar and then a little more with charged biochar (Figure 23). Average wet mass was relatively constant between all three plots with ADE, decreasing slightly with the addition of uncharged biochar but increasing slightly when the biochar was charged (Figure 22). Plant survival in ADE plots decreased slightly when charged biochar was added and decreased significantly when uncharged biochar was added (Figure 21).

Figure 24 and Figure 25 chart the growth of the plots with ACT and ADE over the first three weeks after amending and planting in-ground. In the first week, all plots regardless of biochar, ACT, and ADE grew at a similar rate. After two weeks, the plot with only ACT and no biochar had grown slower than the control. While the plot with ACT and uncharged biochar was not growing much faster, the plot with ACT and charged biochar had grown far more than the control. Similarly, the plot with ADE alone had grown far less than the control at two weeks. The plots with ADE and both charged and uncharged biochar were growing at a similar rate to that of the control.

Figure 24

Effects of biochar and ACT, first three weeks of growth

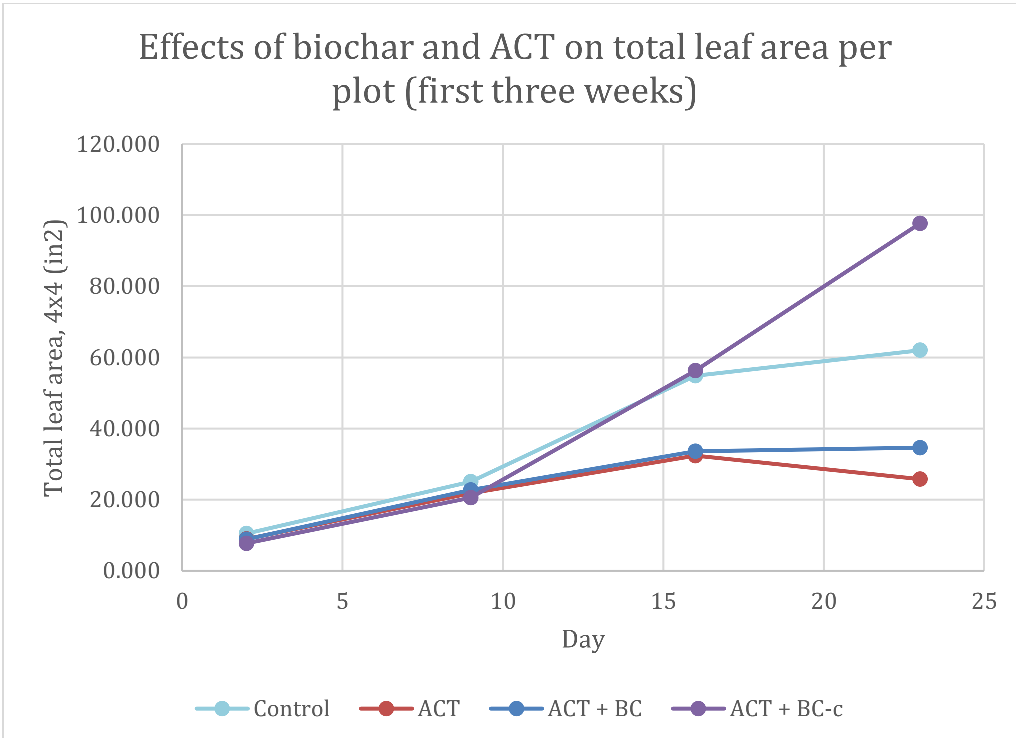
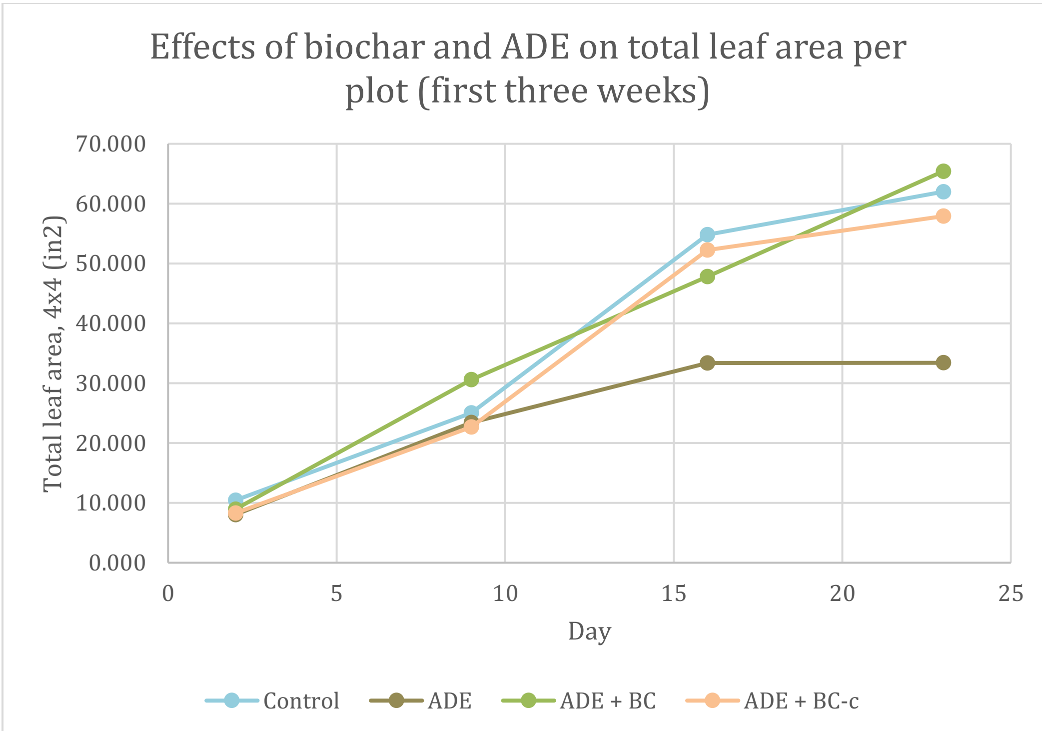


Figure 25

Effects of biochar and ADE, first three weeks of growth



As the plants grew, the plots with biochar charged in ACT and ADE remained the ones with the largest plants; however, the difference between the plot with charged biochar and the control was far more pronounced with ACT than with ADE (Figure 26 and Figure 27). The plot with ACT and uncharged biochar resulted in a similar final leaf area to the control, with the ACT treatment alone performing worse than the control. Compared to the plot with ADE, the addition of uncharged biochar resulted in a similar final leaf area, which was significantly higher than the control.

Figure 26

Effects of biochar and ACT, entire growth

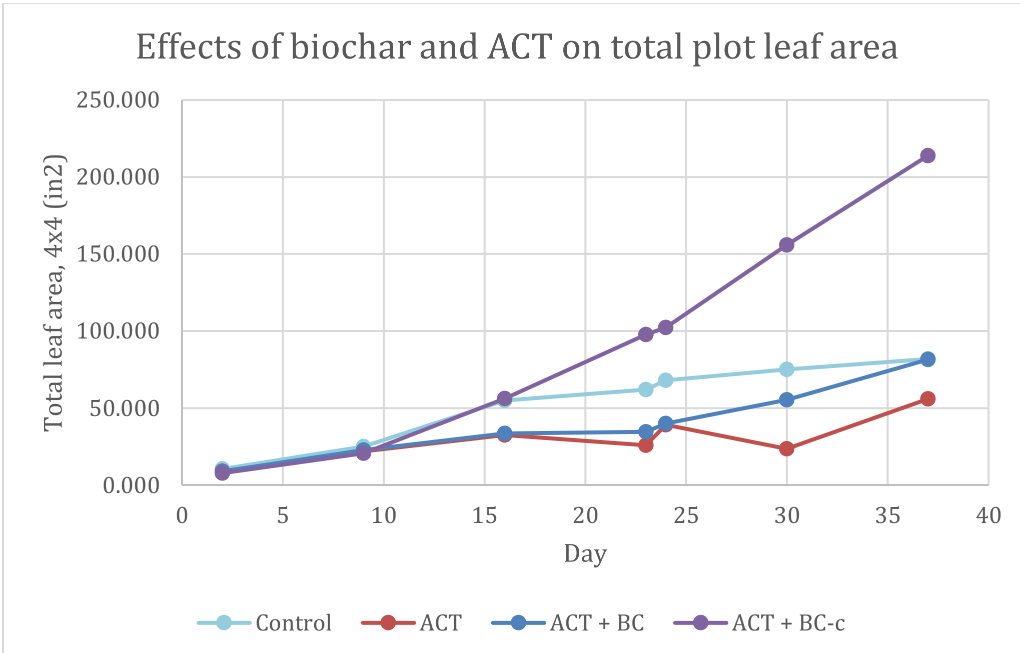
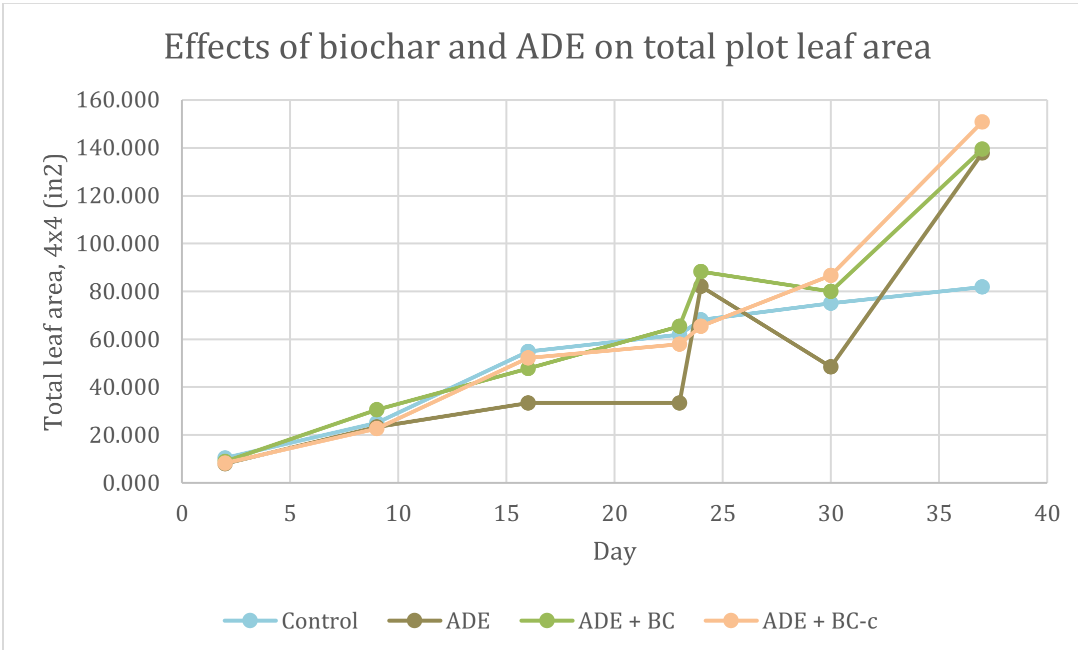


Figure 27

Effects of biochar and ADE, entire growth



A two-tailed Welch's t-test with unequal variances was performed on select pairings of data from each plot (Table 5). All of the harvested spinach shoot wet masses from each plot were compared to evaluate the significance of the findings. Alpha was set at 0.05, aiming for a 95% confidence interval for the findings. It was confirmed that the plot treated with biochar had greater yields than the control. It was also confirmed that adding uncharged or charged biochar to compost reduced yields. The t-test confirmed that adding biochar to ACT increased yields and that yields were further increased by charging the biochar in ACT. When comparing biochar charged with organic amendments and uncharged biochar added without organic amendments, vermicompost was the only organic amendment/charge to present a significant difference in the t-test. The difference between vermicompost alone and with charged biochar was not found to be significant in this test. Neither were the differences in charging or not charging biochar when added to compost, charging or not charging biochar when added to ADE, or adding biochar to ADE. While these results cannot be confirmed with a 95% confidence interval, the sample size in this experiment was low and these trends are still quite possible. It is important to note that this field experiment was performed without replication or randomization, so it is possible that other factors contributed towards these statistically significant differences. While these results reflect trends shown in other studies, more investigation is necessary to confidently confirm them.

Table 5

t-test data for select pairings of spinach shoot wet mass data

Treatment pairs	n	Mean	Variance	2 tail p-value	Reject null hypothesis? (95% confidence interval)
Control	12	2.4809	3.7262	0.0274	yes
BC	12	4.1294	2.0324		
VC+BC-c	13	8.3284	37.1265	0.2615	no
VC	12	11.0327	31.9505		
Com+BC-c	12	3.1340	3.4271	0.2062	no
Com+BC	18	4.1841	6.7119		
Com+BC	18	4.1841	6.7119	0.0045	yes
Com	24	7.7155	23.8027		
Com+BC-c	12	3.1340	3.4271	0.0003	yes
Com	24	7.7155	23.8027		
ACT+BC-c	12	2.8959	2.5178	0.0044	yes
ACT+BC	18	5.7062	10.8613		
ACT+BC	18	2.8959	2.5178	0.0281	yes
ACT	9	1.6268	0.6281		
ADE+BC-c	17	3.6231	4.7457	0.4556	no
ADE+BC	17	3.1171	2.8727		
ADE+BC	17	3.1171	2.8727	0.7400	no
ADE	11	3.4508	8.8353		
BC	12	4.1294	2.0324	0.0323	yes
VC+BC-c	13	8.3284	37.1265		
BC	12	4.1294	2.0324	0.2107	no
Com+BC-c	12	3.1340	3.4271		
BC	12	4.1294	2.0324	0.1102	no
ACT+BC-c	12	2.8959	2.5178		
BC	12	4.1294	2.0324	0.5157	no
ADE+BC-c	17	3.6231	4.7457		

Soil Testing

Three pre-treatment soil samples were taken to gauge the initial soil condition (Table 6). The testing strip was split into thirds and soil from the top four inches at various locations along each third was mixed well and sent to the NCDA for a soil analysis. After the harvest, soil from various locations in each of the thirteen plots was taken from the top four inches and mixed well. This was also sent to the NCDA for a soil analysis (Table 7). The soil test results were presented with spinach selected as the crop, so the nutrient contents are presented as indices, which vary depending on crop need. Due to the high mobility of nitrogen, it is not included in NCDA soil analyses.

Table 6

NCDA soil test results from untreated soil

Test	Treatment	CEC (meq/100cm3	Exchangeable Acidity	pH	P-I	K-I	P2O5 Recommendation (lb/ac)	K2O Recommendation (lb/ac)
Test 1		17.1	0.4	7.3	91	134	40	0
Test 2		16.9	0.5	7.2	79	87	60	40
Test 3		16.2	0.6	7.2	83	67	50	80

Table 7

NCDA soil test results from treated soil post-harvest

Test	Treatment	CEC (meq/100cm3	Exchangeable Acidity	pH	P-I	K-I	P2O5 Recommendation (lb/ac)	K2O Recommendation (lb/ac)
Plot 1	Com + BC	15	0.2	7.3	85	113	50	10
Plot 2	ACT + BC	12.9	0.2	7.4	77	125	60	0
Plot 3	BC	14.5	0.2	7.3	84	130	50	0
Plot 4	ADE + BC-c	14.3	0.2	7.4	76	117	60	10
Plot 5	VC + BC-c	15.9	0.1	7.4	95	183	30	0
Plot 6	ACT	14.6	0.3	7.3	73	103	70	20
Plot 7	Com + BC-c	17	0.1	7.4	88	146	40	0
Plot 8	Control	14.3	0.2	7.3	87	110	40	10
Plot 9	ADE + BC	14.4	0.2	7.4	85	107	50	20
Plot 10	ADE	15	0.3	7.3	76	95	60	30
Plot 11	VC	14.5	0.3	7.3	92	157	40	0
Plot 12	Com	16.8	0.3	7.3	89	135	40	0
Plot 13	ACT + BC-c	13.9	0.5	7.2	82	77	50	60

Some differences between the tests taken prior to amendment and those taken after harvesting are significant. The differences between the three initial soil tests are also substantial. Full soil test results are shown in the Appendix in Table A 1.

The soil was initially lacking in P and K. The pH was slightly alkaline. The cation exchange capacity was low in general, but within the expected range for a dark colored sand (Mengel, n.d.).

Compared to all three of the initial soil tests, little significant change was noted in cation exchange capacity, pH, base saturation, and many micronutrients. Plots treated with vermicompost and compost, however, had higher P and K indices than the average pre-treatment test value.

Biochar Testing

The hardwood chip biochar used in the field experiment was sent to Control Laboratories along with three samples of poplar biochar made with three different production methods for a chemical and physical analysis. The results are presented in Table 8.

Table 8

Biochar analysis results from Control Laboratories

Production method	*TLUD*	TLUD	Open pit	Closed kiln
Feedstock	*Hardwood chips*	Poplar logs	Poplar logs	Poplar logs
Organic C (% dry matter)	*77.9%*	90.3%	88.8%	76.9%
Total N (ppm)	*11100*	8300	6500	3700
NH4-N (ppm)	*59.8*	12.7	4.9	8.0
NO3-N (ppm)	*1.0*	5.8	2.7	1.7
Organic N (ppm)	*11082*	8268	6477	3669
Volatile matter (% dry weight)	*14.8%*	12.2%	14.6%	34.8%
P (ppm)	*1378*	104	74.3	33.5
K (ppm)	*3562*	2171	658	565
Fe (ppm)	*12011*	898	91	57.9
Mn (ppm)	*420*	22.9	16.6	14.6
Zn (ppm)	*162*	2.5	2.3	-
Cu (ppm)	*35.4*	4.8	3.7	4.5
B (ppm)	*22.3*	6.3	5.5	ND
As (ppm)	*3.1*	-	-	-
Cd (ppm)	*3.6*	-	-	-
Cr (ppm)	*3.5*	0.25	-	0.5
Co (ppm)	*0.94*	-	-	-
Pb (ppm)	*9.2*	0.15	0.24	-
Mo (ppm)	*0.46*	-	-	-
Hg (ppm)	-	-	-	-
Ni (ppm)	*2.4*	0.94	-	-
Se (ppm)	-	-	-	-
Cl (ppm)	*53.7*	68.8	44.6	20.6

EC (mS/cm)	*0.124*	0.088	0.056	0.018
pH	*7.63*	9.17	8.35	4.81
Liming value (% CaCO3)	*10.4%*	4.5%	6.3%	4.3%
Carbonates (%CaCO3)	*1.10%*	1.40%	1.50%	0.00%
Butane activity (g/100g dry)	*2.7*	4.1	4.9	1.3
Surface area correlation (m2/g dry)	*218*	264	290	173
H:C molar ratio	*0.62*	0.39	0.50	0.87
Total ash (% dry mass)	*10.2%*	2.0%	1.2%	0.6%
Bulk density	*11.5*	6.56	5.8	7.6

Data from the biochar analysis results were used to classify the four different biochars using the International Biochar Initiative's online Biochar Classification Tool (International Biochar Initiative, 2018). Table 9 displays the results. Carbon storage class ranks carbon storage from 0 (no C storage value) to 5 (high C storage value) and ranks liming class from 0 (no liming value) to 3 (high liming value). BC100 estimates the amount of C initially present in the biochar that will persist after 100 years. The hardwood chip biochar used in the field experiment had a relatively low carbon storage value with only 390 g/kg persisting after 100 years. It does have liming value. The poplar biochar produced in the TLUD resulted in a very high carbon storage value, with most of the carbon persisting for over 100 years, but a lower liming value. The open pit had a medium carbon storage value and a low liming value and the closed kiln had no carbon storage value and low liming value.

Table 9

IBI Classification

Production method	Feedstock	Carbon storage class (0-5)	BC100 (g/kg)	Liming class (0-3)
TLUD	Hardwood chips	2	390	2
TLUD	Poplar logs	5	632	3
Open pit	Poplar logs	3	444	1
Closed kiln	Poplar logs	0	*No value*	1

Discussion

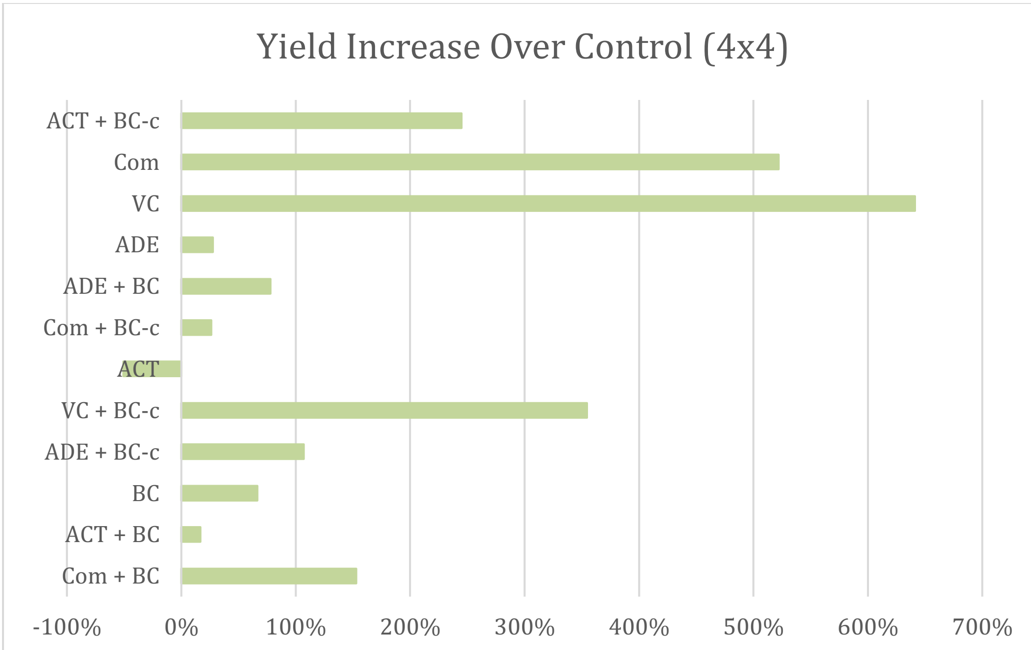
Field Experiment

Effects of Organic Amendments

As expected, vermicompost was the most nutrient dense amendment. Vermicompost is also expensive and somewhat more complicated to produce than ordinary compost, making it somewhat less applicable to widespread production and application. Compost performed well, resulting in a 522% yield increase over the control compared to the 641% yield increase over the control in the vermicompost plot (Figure 28). ADE and ACT resulted in significantly lower yield increases, which is expected because they are more dilute in nutrient content and more easily leached away than solid amendments.

Figure 28

Yield increase over control for each plot



Effects of Biochar

Application of uncharged biochar alone is not generally recommended, especially for soils that are degraded and lack nutrients. Still, the plot with uncharged biochar resulted in a higher yield than the control (Figure 28). This could be a culmination of factors. Biochar could have provided some fertilizing value to the degraded soil. While biochar from woody feedstocks generally does not offer the nutrient value, especially in N, P, and K, that biochar from other feedstocks like peanut shells, corn, or manure, it does offer a good balance of these nutrients (Lehmann & Joseph, 2015). Higher temperature biochars, such as the biochar used in this experiment, are known to generally exhibit a higher concentration of nutrients (Lehmann & Joseph, 2015). While the plants were regularly watered and received some rain, keeping the roots from drying out completely, the biochar is likely to have also helped keep the soil more moist, supplying plants with more water than in plots without biochar and helping them maintain more constant growth.

Because biochar acts as a battery, adsorbing and storing nutrients, it can make nutrients less immediately available to plants. In the plots with vermicompost, the addition of charged biochar reduced the yield (Figure 22 and Figure 23) and slightly reduced the survival rate (Figure 21). This is most likely because the biochar had adsorbed much of the nutrients from the vermicompost, making them less immediately plant available. The same trend is visible in the plots with compost. A downward trend in yield and survival rate arises as uncharged and then charged biochar is added (Figure 21, Figure 22, and Figure 23). The plot with uncharged biochar and compost is likely to have performed better than the plot with charged biochar because, without the charging period, less nutrients had been adsorbed by the biochar. This made them more immediately available to the plants. With subsequent grows on the same plots and no further amendments, it is likely that this trend will reverse. As nutrients are leached away from the plots without biochar, the plots with biochar are likely to retain their fertility. The biochar that was initially uncharged will begin to adsorb nutrients, but not as effectively as the biochar that was charged prior to application.

These results highlight biochar as a long-term solution for soil-building. Immediate results, as with the compost and vermicompost plots, could be somewhat negative. In the long run, however, a foundation for soil regeneration has been laid with the addition of biochar, both charged and uncharged. The sandy soil will better retain water and nutrients and will provide better habitat for a healthy soil microbiome.

Biochar had the opposite effect on the liquid amendments. With both ACT and ADE, adding uncharged and then charged biochar resulted in higher overall yields (Figure 23). As Figure 21 and Figure 22 show, average plant yield and plant survival rate increase with the addition of biochar in the ACT plots. In the plots with ADE, the effect of biochar on the average yield of surviving plants and the plant survival rate was less conclusive. Uncharged biochar decreased the average plant yield and the survival rate, but the addition of charged biochar resulted in a similar yield and survival rate to the plot with ADE alone.

Without a solid substrate to anchor them in the soil, liquid amendments leach away quickly. Figure 24 and Figure 25 show this effect. During the first two weeks, the plants treated with ACT and ADE alone grew at around the same rate as the control plot, but as their growth progressed, the plots with ACT or ADE and no biochar showed comparatively lower and lower growth rates. On the opposite end of the spectrum, the plots with biochar charged with ACT and ADE began to show greater growth than the other ACT or ADE plots and the control. The effects of leaching are clear. The daily watering in the first few days followed by the daily rain during the second week of in-ground growth (Figure 18) are likely to have carried away much of the nutrients offered by the ACT or ADE. In the plots without biochar to hold nutrients in, much of the fertilizing value initially added was lost.

This experiment suggests a few things about soil regeneration. First, biochar alone can be beneficial, but is augmented by the addition of nutrients and organic matter, especially from a solid amendment like compost or vermicompost. With solid amendments, increases in yield should not be expected to be immediately high, but it is likely that less fertilizing or amendment will be needed in subsequent seasons and any fertilizing value added will go further. Liquid amendments like ADE and ACT help improve the soil and grow larger plants, but are far more valuable amendments when biochar is incorporated to help retain them.

Soil Testing

Limited changes were observed in the soil test results. Biochar is noted for its high cation exchange capacity and is often used to raise the CEC of certain soils. In this short term study, the plots with biochar did not have a significantly higher cation exchange capacity than the soil samples taken pre-treatment or the soil samples from plots without biochar. The pH was initially slightly alkaline and did not change significantly with the addition of biochar or any of the organic amendments.

The most significant differences seen in the soil test results were in phosphorus and potassium levels. Most of the plots with compost or vermicompost had higher potassium and phosphorus indices than the control or the pre-trial test plots. Both compost and vermicompost have high fertilizer value and are expected to increase potassium and phosphorus.

Biochar Testing

The results of the biochar chemical and physical analysis suggest that the hardwood chip used in the field experiment was a good general purpose biochar. The pH was only slightly alkaline at 7.63, which is much more neutral than many biochars, including the poplar biochar produced in the TLUD and the open pit. It also had relatively high values of C, N, P, and K. This could explain why the plot with uncharged biochar alone resulted in higher yields than the control plot. The biochar offered some fertilizing value, providing N, P, and K to the spinach plants that were not receiving enough nutrition from the degraded soil. The relatively neutral pH of the biochar ensured that it did not alter the pH of the soil, which was already slightly alkaline.

The results from the three analyses on poplar log biochar demonstrate how different biochar can be when produced with different pyrolyzation methods. Overall, the TLUD biochar seemed to be the highest quality. It had significantly higher amounts of most of the nutrients that were tested for, including organic N, NH4, and NO3, P, K, Fe, Mn, Zn, Cu, B, and Cl. It also had a higher electrical conductivity. While the temperatures from the closed kiln were not recorded, the maximum temperature of the TLUD was almost 100 C higher than that of the open pit. Biochar made at higher temperature generally tends to have higher electrical conductivity (Joseph et al., n.d.). The TLUD and open pit both produced alkaline biochar, which was expected because of the ash content created by some of the feedstock burning completely. The higher alkalinity from the TLUD biochar than the open pit biochar could be because of higher ash content as well as the increased temperature, which has been shown to increase pH (Rajkovich et al., 2012). If the TLUD had been quenched earlier, it would have likely resulted in more biochar produced and less ash, which would have also lowered the pH.

The surface areas of the open pit and TLUD biochars were significantly higher than the closed kiln biochar. Higher temperature biochar, such as biochar from the TLUD or open pit, tends to have greater surface area (Rajkovich et al., 2012).

The molar ratio of H:C was lowest in the TLUD biochar. H:C ratios are used as an indicator of persistence in soil because they help approximate fused aromatic carbon rings, which are highly recalcitrant (Agegnehu et al., 2016; International Biochar Initiative, 2018).

The TLUD biochar had an extremely low H:C ratio, suggesting a very high level of soil persistence (Joseph et al., n.d.).

The closed kiln produced significantly less useful biochar. Compared to the TLUD and the open pit, pyrolyzation in the closed kiln happens quite differently. The feedstock is not the primary energy source, as the retort inside the kiln is externally heated by a fire. It is also enclosed. There is a tube at the bottom of the retort to vent the escaping gases, but it is significantly harder for gases to escape, which leads to some of the gases recondensing onto the biochar. Biochar from the closed kiln has a strong smell, caused by the high amount of condensed volatile matter, which the chemical analysis shows is much higher than in biochar made in either the TLUD or the open pit. These condensed gases can clog pores, which partially explains the significantly lower surface area in the closed kiln biochar.

The closed kiln biochar had significantly lower nutrient values than either of the other biochars. The most striking result from the closed kiln biochar was the pH, which was 4.81. This is significantly low for biochar. Is it likely that the pH was so low because the internal temperature was low. While the temperature was not measured for pyrolyzation in the closed kiln, low pH, electrical conductivity, surface area, C, and K, as well as high volatile matter are characteristic of biochar made at lower temperatures (Rajkovich et al., 2012; Lehmann & Joseph, 2015). Despite being a less useful biochar, the biochar from the closed kiln could be of greater value in highly alkaline soil, where it could help balance the pH.

While they were both produced in the TLUD, biochars from the poplar logs and hardwood chips were significantly different. Although the hardwood chips and the poplar logs had similar initial water contents, the chips throttled airflow more than the logs, which is likely the main reason for the higher maximum temperature in the log burn. Higher temperature generally reduces C and increases N in biochar (Lehmann & Joseph , 2015) , which could partially explain these differences in the two biochars. The poplar logs produced lower values in almost every nutrient, which suggests poplar is not a good feedstock for biochar with high fertilizer or mineral value. Interestingly, the electrical conductivity was significantly higher in the hardwood chip biochar than the poplar log biochar, which is generally not the case in biochar produced at lower temperature (Rajkovich et al., 2012). Softwoods generally have much lower electrical conductivities than hardwoods (Joseph et al., n.d.; Rajkovich et al., 2012). While poplar is not a softwood, it could exhibit similar properties because of its low density, which is more akin to a softwood than other hardwoods.

The pH of the hardwood chip biochar was much more neutral than the poplar biochar, which is partially due to the lower temperature (Rajkovich et al.). The surface area was similar but slightly lower than the poplar biochar. The ash content was significantly higher, which could be due to the fact that greater surface area is exposed on the wood chips than the poplar logs, allowing greater combustion. The H:C molar ratio was also much higher in the hardwood chip biochar, which significantly decreases its soil persistence.

The results from the IBI Classification demonstrated that the closed kiln does not produce biochar with a high carbon storage or high liming value. The TLUD and open pit showed a wide range, but had medium to high carbon storage value and anywhere from low to high liming value. If liming value is a goal, allowing the burn to run longer than usual will create more ash and a higher liming value.

These tests demonstrate that, while they are far cheaper and less complex than some industrial biochar production processes, the TLUD and open pit both make high quality biochar.

Lessons Learned in Biochar Broduction

This section focuses on my experience producing and using biochar.

Feedstock Procurement and Preparation

Virtually any dry biomass can be converted into biochar. My experience is limited to a few feedstocks, including wood chips, wood logs, and tall grasses.

There are many easily accessible sources of waste biomass. Especially in a heavily wooded area, wood waste is common. Right of way clearings for powerlines, slash piles from land clearing, waste from sawmills, and yard trimmings are all plentiful and can often be acquired for free. Farm waste, such as corn stover, rice husks, or hemp waste, is also commonly used in biochar production. Tall grasses are often grown as energy crops because of their high rate of growth. *Miscanthus*, *Arundo donax*, and bamboo are examples of fast-growing grasses that are commonly used in biochar production.

One consideration when sourcing waste material is the potential for contamination with heavy metals. Heavy metals can accumulate along roadsides, bioaccumulating in plants growing in these areas (Altaf et al., 2021). These areas are often regularly maintained, creating regular biomass waste, so care should be taken not to use contaminated feedstock. Feedstocks and biochar can both be tested for heavy metals and other contaminants. There are simple field tests, such as the germination test or the worm avoidance test, to determine if feedstocks or biochar are safe (Major, 2009).

Feedstocks must be adequately dry to burn and char properly. A moisture content of 15% or lower is ideal. If they are too wet, they will have trouble getting hot enough to fully pyrolyze. Moisture contents above 20% generally will not burn enough to pyrolyze at all. Wet feedstock can also cause significantly higher emissions because high temperature is needed to thoroughly burn all volatile gases (Cornellison et al., 2016; Hoffman-Krull, n.d., 9). Feedstocks with a high surface area to volume ratio can be dried relatively quickly in the sun. Wood chips can take as little as a few weeks in direct sun without rain to dry. Grasses can also dry quickly either standing or in laying the sun. Fresh logs generally take a year to dry enough to burn well.

Passive solar driers can be built to quickly dry feedstock. Low tunnels are commonly used. Greenhouses, often vacant during summer months, can also provide the heat and airflow needed to dry feedstock.

Top-Lit Updraft Gasifier (TLUD)

My experience in biochar production has centered around four main production methods, including the TLUD, a modified TLUD with a retort inside, a retort-style kiln, and an open pit/kon-tiki kiln.

As described in the Review of Literature, the TLUD (Figure 1) relies on gasification to pyrolyze feedstock. The feedstock is ignited and partially burns. Without enough oxygen to fully burn and turn to ash, much of the feedstock is pyrolyzed and turns into biochar. At the end of the process, it must be quenched to prevent the feedstock from fully burning or resulting in a high ash content. The balance between an incomplete pyrolyzation, in which some of the feedstock is still not pyrolyzed, and an over-burn, in which some biochar is lost and more ash is created, can take some trial and error to get acquainted with.

Wood chips generally take between 30 and 50 minutes to fully pyrolyze in the TLUD depending on the initial water content and packing density. Hardwood logs generally take around an hour to an hour and 20 minutes, although less dense species like poplar take considerably less time. In my experience, grasses will not pyrolyze well alone in the TLUD. Because of their low density, tall grasses like *Miscanthus* or *Arundo donax* ignite quickly and fully burn in under 5 minutes, leaving virtually no char or ash, making the TLUD a poor choice for grass biochar production.

When using wood chips in the TLUD, it is important that the chips are large enough to allow for airflow. As a pile of wood chips ages, the average particle size shrinks. When loaded into the TLUD, older wood chips pack tightly and don't allow good airflow. Sometimes adding branches, small planks of wood, or even logs can open up space for air to flow better.

A good method to determine if the TLUD is ready to quench is to look at the bottom. It should be sitting on bricks, allowing you to see through the air inlet holes. Once the feedstock at the bottom has been glowing red for 5-10 minutes, it is generally ready to be quenched. I have found water to be the best way to quench a TLUD. I generally prepare 4 or 5 full 5-gallon buckets of water and pour them all into the TLUD after removing the lid. This seems to work better than using a hose because quenching it with a large volume of water ensures the water reaches the bottom of the TLUD, putting out any pockets of fire. Sometimes, even during a good burn, there are small pockets of feedstock that aren't fully pyrolyzed. In regions with limited water access, clay could also be used around the bottom rim and the edge of the top to seal the TLUD.

Of the four methods I've experimented with, I like the TLUD best. It is simple. The feedstock is loaded, the top is installed, the feedstock is lit, and eventually it is quenched. While the production efficiency is lower than that of a retort-style reactor, it requires no firewood or external heat source. Because of its open design, there is likely very little recondensation of organic molecules on TLUD biochar, resulting in greater porosity than biochar from a retort-style reactor. It is also relatively low-emissions because of the secondary combustion and, as the biochar analyses showed, makes high quality biochar.

TLUD with Retort

The TLUD can be modified to include a retort (Figure 29). A retort is an enclosed vented chamber that is externally heated. Within the TLUD, a 35-gallon drum with slits or holes in the bottom is placed. This drum, which acts as the retort, is filled with feedstock. In the space between the inner and outer drums as well as on top of the inner drum, small pieces of wood are placed and packed as tightly as possible. These are lit and the top is installed. The wood burns, creating the heat to pyrolyze the feedstock within the inner drum. The escaping syngas flows out of the bottom of the 35-gallon drum and burns.

Figure 29

TLUD with retort, top removed

The advantage of adding the retort is that, of the feedstock, a higher production efficiency can be achieved. The feedstock does not burn and is all converted into biochar. It can also be lit and left, as it does not require quenching. Adding the retort also allows use of a wider variety of feedstocks. Grasses, which ordinarily do not pyrolyze well in a TLUD, can be easily pyrolyzed in a retort.

Much of the offgassing hydrocarbons recondense onto the biochar. While this could add organic material and potentially offer nutrients to the soil, it reduces the immediate porosity of the biochar, decreasing adsorption of water and nutrients.

Cutting small strips of wood and placing them around the retort is time consuming, so it takes longer to set up than an ordinary TLUD burn. It can be left to burn without quenching. It is important to make sure the firewood used is very dry and is a high energy wood such as locust or oak. Using less energy dense wood, such as pine pallets, could work but might not fully pyrolyze the feedstock in the retort.

Closed Kiln

The retort-style kiln, or closed kiln (Figure 30 and Figure 31), consists of a closed and well insulated kiln with a 35-gallon drum suspended above a grate. The feedstock is loaded into the drum, which is sealed. A fire is built below on the grate and the kiln is sealed. The heat from the fire pyrolyzes the feedstock in the drum. The drum is either fitted with holes or a tube on the bottom to allow syngas, the volatile gases being off-gassed from the heated feedstock, to escape and burn. No quenching is required and the process is completed when the fire goes out.

Figure 30

Closed kiln

Figure 31

Interior of closed kiln

The closed kiln can be used for any feedstock that fits in the 35 gallon drum. Grasses or low-density wood logs such as pine or poplar work well because they require less heat. Wood chips can be pyrolyzed in the closed kiln as well. The kiln should not be loaded more than a third to half full to ensure everything inside fully pyrolyzes.

The main benefit of the closed kiln is that its heat can be used to heat a greenhouse. Many farms already use wood stoves to heat greenhouses. The closed kiln uses some of the heat to create biochar, adding value to the process. The entire system is not cheap, with this specific system costing around $9,000 in materials alone, but it can help reduce electricity or propane costs while heating a greenhouse in the winter.

For biochar production alone, the closed kiln is not an efficient or effective method. The drum cannot take much feedstock and often requires multiple burns, especially with wood chips. While the production efficiency of the feedstock itself is quite high, it requires a much higher firewood mass than feedstock mass, reducing its overall efficiency. It also requires occasional maintenance, especially in ensuring a good seal to retain heat.

One advantage of the closed kiln is that, once lit and closed, it can be left and does not require quenching. Because of the low-oxygen environment inside the kiln and the lack of secondary combustion, the closed kiln has quite high emissions. It could potentially be fitted with a catalytic converter to reduce the emissions.

Open Pit

The open pit, flame cap kiln, or kon-tiki kiln is one of the most primitive means of biochar production. An open pit can either consist of a hole dug in the ground or a steel container (Figure 32). The feedstock is loaded and lit. As the fire spreads and heat builds, more feedstock can be added on top, which is reduced into a much smaller volume of biochar. More feedstock is added until the kiln fills, at which point it can be quenched. Water is generally used to quench the burn, especially with metal open pit kilns.

With an open pit dug into the ground, soil or sand can be used to kill the fire. In forestry applications or other situations with limited access to water, some water can be used to reduce the burn's heat and a metal lid can be placed over the fire, which can be sealed with soil (Hoffman-Krull, 2019).

Figure 32

Open pit made of steel

Compared to an open fire, the open pit is able to make much more biochar because of its walls. The walls prevent full combustion by limiting the air that reaches down into the pit, resulting in 50% or more of the carbon initially present in the feedstock becoming biochar as compared to 1% or less in an open fire (Amonette et al., 2021).

The open pit is an appealing method for large amounts of feedstock. The other three methods of biochar production evaluated here are true batch systems – the feedstock is loaded, pyrolysis occurs, and biochar is removed. The open pit is somewhat closer to a continuous system. Pyrolyzing feedstock is reduced in volume, creating space for more and more to be added. The open pit can be used on various feedstocks, including wood logs and grasses. Wood chips do not seem to get enough airflow to ignite well in an open pit, although coarse and very dry chips can work. Wood chips can be mixed with branches or logs to allow better airflow and combustion.

The open pit is not very efficient, resulting in significantly lower biochar production efficiency than the TLUD. Because of the high heat, volatile gases are generally well burned, reducing in limited harmful emissions in the open pit, potentially even compared with the TLUD (Cornellison et al., 2016). The main advantage of the open pit is its ability to convert large volumes of feedstock. One rendition of the open pit, the Oregon Kiln, is popular in forestry for its ability to quickly convert large amounts of brush or slash into biochar (Robillard, 2019),. This is especially appealing in dry forests, such as in much of California. Dry brush, which creates a major risk for forest fires, can be converted in situ into biochar, which can be applied in the same forest to help build soil and retain water.

Crushing

Depending on the feedstock, biochar particles can be relatively large, which limits its usefulness in soil because of the limited surface area. For homogeneity and effectiveness, many studies crush and sieve biochar to a maximum size of 2mm. Particle size can be leveraged to modify soil. For example, large particle sizes can help increase water and air infiltration, which is especially useful in soils with high clay content (Amonette et al., 2021).

While biochar is relatively easy to crush by hand, bulk crushing can be quite difficult, especially if it there are pieces of unpyrolyzed feedstock mixed in. While it crushes more easily when dry, it also releases large amounts of dust, which are not pleasant to inhale.

Many simple methods of biochar crushing have been used. Biochar can be put in a bag and stepped on, crushed with a piece of wood, or driven over. A roto-tiller can crush biochar while mixing it with compost, manure, or soil. Simple technology such as hammer mills, coffee grinders, garbage dispose-alls, leaf vacuums, and more have been used successfully.

Charging

Charging biochar is an important step in ensuring initial yields are not limited. It can be done using many different methods geared towards different timelines, soil needs, and organic amendments available. Co-composting is one of the more common methods and is especially useful because of the synergies between biochar and compost. Biochar can help compost get hotter, decompose quicker, and release less harmful emissions (Sonoki et al., 2012). While co-composting can take months, charging biochar with mature compost can be done in two weeks. This process is simple - biochar and compost should be well mixed and allowed to sit.

Other solid amendments like manure can also be used to charge biochar. A similar process would be necessary, involving mixing biochar with the manure and allowing it to charge and decompose.

Liquid amendments like ACT and ADE can drastically reduce the charge time of biochar. Rather than two weeks or more, a full charge can take place within three days depending on the amendment. Details on charging biochar with ADE or ACT are provided in the Research Methodology section above. While charging with ADE or ACT is far quicker than with a solid amendment like compost, liquid amendments are much more dilute than solid amendments, so they don't provide the same fertilizing value.

Application

After being crushed and charged, biochar is ready to be integrated into the soil. This can be done a multitude of ways. Biochar is either applied to the surface of the soil or mixed into the top few inches of the soil column. In nature, biochar from wildfires is left on the surface of the soil. As organic material and sediment is deposited, animals disturb the soil and earthworms consume the biochar, resulting in a gradual fragmentation and intermixing with the topsoil (Ponge et al., 2005). Within the agricultural context, it is useful to incorporate the biochar within the soil. This distributes the biochar better and also helps protect it from being blown away by the wind. Biochar can be mixed with hand tools such as a broadfork or power tools such as a power harrow.

A wide variety of application rates has been used, from 1 tonne/ha to over 50 tonnes/ha. 20 tonnes/ha was selected for this study because it is a common, economically feasible application rate that generally produces positive results. Biochar's effects vary on different soils and it occasionally has negative effects on crop growth. Because of this, it is probably best to apply a low rate, such as 5-10 tonnes/ha, and gauge the results with soil tests and observations.

Future Directions

Many sites around the world, from the Brazilian Amazon to the sandy soils of the Netherlands and parts of the Yangtze River in China, demonstrate the lasting effects of biochar on soil health centuries and even millennia after application (Lehmann & Joseph, 2015). Recent long-term study of biochar's effect on soil health, nutrient cycling, and plant growth are limited. The global biochar community has made clear the need for long-term study on biochar, especially in cultivated soils (Agegnehu et al., 2017; Amonette et al., 2021). This study was limited to a single field experiment consisting of a single application of organic amendments and biochar. Further trials in the same plots would illuminate biochar's full effect in soil regeneration and nutrient retention.

Further experimentation with various feedstocks and methods is also needed. Hardwood chips were selected for this research because of their wide regional availability. The TLUD was selected because of its low cost compared to the quality of biochar it produces. Biochar is not all the same and can be designed to improve specific deficiencies in soil, from lack of drainage to low nutrient values. While wood biochar produced at high temperatures, such as in the TLUD, seems to be a good general-purpose biochar, others could target specific issues more effectively. Even when limited to a single feedstock, production methods can be tailored to a specific soil's needs. As Amonette et al. notes, ash content, particle size, level of oxidation, and charging can be adjusted to meet various needs (2021).

Conclusion

This study has illuminated biochar as a useful soil amendment in degraded sandy soils. It demonstrated that uncharged biochar alone could potentially increase crop growth. When incorporated with compost and vermicompost, immediate plant yields seemed to be reduced compared to the yields of compost or vermicompost alone. This result, given more time, is likely to reverse, as plots with biochar are better equipped to retain nutrients and organic matter. When incorporated with ACT, biochar seemed to increase plant yield, especially when properly charged. When incorporated with ADE, fully charged biochar seemed to increase plant yield.

This study has also demonstrated that simple, low cost biochar production and charging techniques can produce high quality, highly effective soil amendments. This suggests that farmers can find success in making their own biochar on a budget.

Further exploration of these findings is necessary to definitively comment on how biochar is interacting with the soil and plants. Replication and randomization would help counteract any potential variability in soil conditions, watering, sunlight, or other conditions. Longer growth trials are also needed to investigate the impact of biochar-based soil amendments on soil and plant growth over time.

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Appendix

Test	Treatment	Bulk Density (g/cm3)	HM %	CEC (meq/10 0cm3	BS%	Exchang eable Acidity	pH	P-I	K-I	Ca% (% of CEC)	Mg % (% of CEC)	S-I	Mn-I	Zn-I	Cu-I	Na	ESP (exchang eable sodium percent)
Untreated ATG TB strip test 1		0.87	0.41	17.1	98	0.4	7.3	91	134	83	11	64	661	147	162	0.2	1
Untreated ATG TB strip test 2		0.83	0.46	16.9	97	0.5	7.2	79	87	84	11	57	759	200	225	0.2	1
Untreated ATG TB strip test 3		0.85	0.51	16.2	96	0.6	7.2	83	67	83	11	62	544	150	173	0.2	1
After grow: plot 1	Com + BC	0.84	0.27	15	99	0.2	7.3	85	113	83	11	49	511	129	156	0.2	1
After grow: plot 2	ACT + BC	0.85	0.27	12.9	99	0.2	7.4	77	125	82	12	51	523	125	144	0.1	1
After grow: plot 3	BC	0.85	0.27	14.5	98	0.2	7.3	84	130	81	12	50	576	163	163	0.2	1
After grow: plot 4	ADE + BC-c	0.87	0.22	14.3	99	0.2	7.4	76	117	83	12	46	626	178	183	0.2	1
After grow: plot 5	VC + BC-c	0.82	0.27	15.9	99	0.1	7.4	95	183	81	12	55	639	194	198	0.2	1
After grow: plot 6	ACT	0.89	0.22	14.6	98	0.3	7.3	73	103	83	12	58	646	165	186	0.2	1
After grow: plot 7	Com + BC-c	0.83	0.46	17	100	0.1	7.4	88	146	83	12	65	645	167	180	0.2	1
After grow: plot 8	Control	0.88	0.32	14.3	98	0.2	7.3	87	110	83	11	66	679	223	220	0.2	1
After grow: plot 9	ADE + BC	0.85	0.32	14.4	99	0.2	7.4	85	107	84	11	59	642	211	214	0.2	1
After grow: plot 10	ADE	0.9	0.32	15	98	0.3	7.3	76	95	83	12	57	598	202	214	0.2	1
After grow: plot 11	VC	0.9	0.27	14.5	98	0.3	7.3	92	157	79	13	75	520	206	202	0.3	2
After grow: plot 12	Com	0.89	0.41	16.8	98	0.3	7.3	89	135	82	12	72	516	204	211	0.3	2
After grow: plot 13	ACT + BC-c	0.87	0.36	13.9	97	0.5	7.2	82	77	82	12	48	457	164	157	0.2	1

Table A 1: Full soil test results from NCDA

Vita

Alex Gray was born in Atlanta, Georgia on June 9, 1996. He attended St. Pius X high school and graduated in 2014. The following August he entered the Georgia Institute of Technology and graduated in 2019 with a Bachelor of Science in Mechanical Engineering. He entered Appalachian State University in August of 2020 and received a Master of Science in Technology in 2022. In the summer of 2021, he received his Permaculture Design Certificate from Santa Cruz Permaculture in Santa Cruz, California.