Ongoing Biochar Research:

Into Ecological and Economically Sustainable Applications in Small and Mid-size Managed Ecosystems

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Flower crop (VA) Credit: Stonecrop Farm

Executive Summary

A collaboration between Dovetail Partners, Virginia Tech, and the University of Minnesota was awarded a Biomass Research and Development Initiative (BRDI) grant in 2018. The project, titled *Life-Cycle Assessment of Biochar in Agricultural and Forest Ecosystems: Effects on Production, Soil Fertility, and Economic Impact* was developed to explore "real world" applied research into how biochars produced locally would affect soils and ultimately their crops. The study sought to determine the impact of biochar amendments on soil carbon and nutrient retention on working lands across a variety of soil types, cropping systems, and climates in the United States.

The motivation for this project arose from the perspective that little specific information has been available historically to landowners and managers about effective rates of biochar application, application methods, and anticipated benefits to crop yield, soil fertility, or carbon sequestration. Standards for testing biochar have been proposed but are not consistently used and the necessity to match biochar characteristics to soils is an added variable (as compared to chemical inputs which are fairly homogenous, with known outcomes in a given application).

While carbon credit schemes are developing, their criteria are variable from program to program and cost prohibitive for most biochar users at this time.

The BRDI project found biochar amendments increased soil carbon in the three geographic locations' field trials and increased soil nitrogen availability in two of the three. In this study, the pyrolysis conditions appeared to be as important as local soils and climate's influences on the efficacy of biochar treatments, which is notable because the chars for this project were intentionally locally produced and non-commercial. The field experiments experienced a cross section of the issues typically facing farmers: weather extremes, planting and input challenges, and crop failures; however, even these gave insight to the effects biochar had on the agricultural pursuits the project sought to investigate, finding that local-scale biochar production and use can create meaningful increases in soil carbon.

The project included a Life Cycle Analysis[1] for the "common garden" experimental plot where more extensive research was done than at the growers' sites. The LCA highlighted the importance of the biochar's feedstocks, its proximity, and their pyrolysis conditions. It also showed biochar applications are a safe bet for improving soil organic matter, but if a producer/user is interested in biochar for selling carbon offset credits they need to consider the real energy cost of producing and potentially transporting the feedstock, because even though the biochars for this project were locally produced, their production and transportation still had a significant impact on the carbon neutrality of its application.

As an outcome of the BRDI project, the research into "real world" biochar use in agriculture and forestry will continue with an expanded BRDI team by way of a project titled: **Assessing the influence of biochar preparation methods on soil health in diverse managed ecosystems.** This project will explore the changes in soil microstructure and how it may promote soil health by increasing carbon sequestered in soil aggregates by increasing the connectivity of microbial communities among soil microsites. The research will examine the interactive effects of biochar and soil composition on multiple metrics of soil health, including: soil carbon content and mineralization, soil micro-structural and aggregation, bioavailable nitrogen, and microbial activity and diversity.

[1]LCA provides a mechanism for systematically evaluating the environmental impacts linked to a product or process and in guiding process or product improvement efforts. For more information about LCA, see: https://dovetailinc.org/portfoliodetail.php?id=5e8f46902fea8

Introduction

A collaboration between Dovetail Partners, Virginia Tech, and the University of Minnesota was awarded a Biomass Research and Development Initiative (BRDI) grant in 2018. BRDI is a joint project of the US Department of Agriculture and the Department of Energy which coordinates research and development (R&D) activities concerning bio-based fuels, products, and power across federal agencies.[2] The project, titled **Life-Cycle Assessment of Biochar in Agricultural and Forest Ecosystems: Effects on Production, Soil Fertility, and Economic Impact** was developed to explore "real world" applied research into how locally produced biochars would affect soils and ultimately their crops.[3]

The overarching objective of the project was to test the general effectiveness of biochar in enhancing soil fertility, agricultural productivity, and soil carbon sequestration in diverse managed ecosystems, e. g., pasture, vegetable gardens, orchards, and forests. The project included field research at multiple sites in three US states: New Mexico, Virginia, and Minnesota. Agricultural sites were installed in NM, VA and MN while forestry sites were all in MN because of longstanding previous research which dovetailed with this project.

Due to the COVID pandemic, the three-year project took five years to complete, including data collection and analysis for three growing seasons. The study sought to determine the impact of biochar amendments on soil carbon and nutrient retention on working lands across a variety of soil types, cropping systems, and climates in the United States. To no surprise, and in line with both research and commercial field experience, the effect of biochar as a soil amendment depended on the soil's characteristics and the properties of the biochar applied. This project found biochar amendments increased soil carbon in the three geographic locations' field trials and increased soil nitrogen availability in two of the three. In this study the pyrolysis conditions appeared to be as important as local soils and climate's influences on the efficacy of biochar treatments which is notable because the chars for this project were locally produced and non- commercial.

The results of the research provided a cross section of the issues typically facing farmers: weather extremes, planting and input challenges, and crop failures; however, even these gave insight to the effects biochar had on the agricultural pursuits the project sought to investigate, finding that local-scale biochar production and use can create meaningful increases in soil carbon and overall carbon.

As with much research, more questions arose from the BRDI project about specific aspects of the use of biochar in ag systems. One issue with biochar—which is often a slow-to-start soil amendment but whose effects can last for decades to centuries—is the need for longer term research. The BRDI project team has been fortunate to be awarded funding to continue the research with a follow-up AFRI[4] project which is discussed in a later section of this report.

Organic Corn Plots (MN) Credit: K Fernholz

[2]BR&D Initiative | Biomass Research & Development (biomassboard.gov)

[3]Biochar is a term for charcoal which is used for biological ends, as opposed to heat. It is most commonly used as a soil amendment, but it has significant potential as a way to sequester carbon long-term and may be a lower-cost alternative to activated carbon. For additional background on biochar, see: Biochar 101, available at: https://dovetailinc.org/portfoliodetail.php?id=5e28c20e735a8.

[4]Agriculture and Food Research Initiative (AFRI) | National Institute of Food and Agriculture (usda.gov)

Background

Biochar has attracted the interest of farmers in recent years but enthusiasm for its claimed benefit as a soil amendment has outpaced scientific understanding of how and under what climate, soil, and management circumstances its benefits can best be achieved. While most studies have demonstrated generally positive effects of biochar in temperate soils, production responses vary over a wide range, and mechanisms underlying changes in soil organic matter dynamics and nutrient cycling are poorly understood (e.g. Jeffrey et al. 2011, Pluchon et al. 2016).

The point of the BRDI project was *to study approaches to biochar application that are both ecologically and economically sustainable in small and mid-size managed ecosystems.* To achieve that, there was a need to examine the efficacy of biochar across a diversity of managed ecosystems and to understand the mechanisms by which biochar enhances soil fertility. Eleven growers in three regions of the US were recruited to receive biochar from a local source and use it in an agricultural application. The sites, crops, and biochar feedstocks for the participants are shown in Table 1 and the protocol for the plots is attached in Appendix C. Biochar analysis data can be found in Appendix B.

Table 1. BRDI Field Test Plots[5]

Farm or Site	Crop/Land Use	Biochar Feedstock[6]
New Mexico (NM)	Misc garden vegetable	Pecan Hulls
Minnesota (MN)	Organic Corn (commercial)	Softwood
	Superior National Forest (Jack Pine primarily)	Softwood
Virginia (VA)	Pasture	Hardwood
	Vineyard	Hard and softwood mix
	Market Flowers	Hard and Softwood mix
	Pasture-based "Common Garden*"	Hardwood, Softwood, and Switchgrass

*This site was a larger scale randomized installation with more detailed analysis for both the soil-biochar interactions and for the LCA. It is also the site for the follow-up AFRI project.

[5]All test plots followed the same design with variation only in the number of repetitions: control, high-rate biochar only, low-rate biochar only, "charged" biochar at both high and low rates.

[6]The source of the hardwood and softwood feedstocks were from harvest slash and sawmill wastes. The switchgrass was sourced from a field harvested for hay.

Little specific information has been available historically to landowners and managers about effective rates of biochar application, application methods, and anticipated benefits to crop yield, soil fertility, or carbon sequestration. Standards for testing biochar have been proposed but are not consistently used and the necessity to match biochar characteristics to soils is an added variable (as compared to chemical inputs which are fairly homogenous, with known outcomes to a given application).

The rural development aspect of increasing the resilience and profitability of agricultural production continues to be a struggle because creating wealth by producing food and fiber on smaller tracts is challenging. However, the demand for organic and locally-produced food and fiber continues to grow, which could make locally produced biochar used to improve soils and crop yields more appealing. Yet recognition among producers that biochar is an economically and ecologically viable soil amendment is not widespread[7] due in no small part to the "unknowns" highlighted above.

The effectiveness of biochar in forests is even less definitive and far less researched than for agricultural applications. There are conflicting research results regarding the impacts of biochar on forest soil properties and subsequent growth, yield, and resilience of tree growth. In a recent meta-analysis of the limited literature, Thomas and Gale (2015[8]) observed an increase of 41% in growth of woody species biomass. However our project, which includes forest research in Northern MN spanning over 10 years, saw little to no difference in survivability and growth compared to the control.[9]

The majority of forest owners manage forests for multiple goals. These goals include enhancing wildlife habitat, promoting forest health, recreation, and timber production. An important component for all of them is a healthy forest system. During periods of drought, maintaining healthy forest systems is difficult, especially ensuring the success of planted regeneration. For example, in northern Minnesota on the Superior National Forest, certain jack pine (*Pinus banksiana*) stands have been replanted in three successive years (2015, 2016, and 2017) due to unacceptable levels of mortality because of drought.[10] Since biochar has been found to increase water holding capacity in most soils, it should be a valuable forest management tool by promoting mechanisms for increasing survival and productivity in forest systems, which inspired the inclusion of forests in the BRDI portfolio.

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[7]Survey and Analysis of the US Biochar Industry, 2018. Dovetail Partners. Available at: https://dovetailinc.org/portfoliodetail.php?id=5e2605ebbc039

[8]Thomas, S.C., Gale, N. Biochar and forest restoration: a review and meta-analysis of tree growth responses. New Forests **46**, 931–946 (2015). https://doi.org/10.1007/s11056-015-9491-7

[9]**Effect of Biochar and Manual Vegetation Control on Early Growth and Survival of Planted Jack Pine (Pinus banksiana Lamb.) Seedlings in Northern Minnesota;** Robert A. Slesak, Sara G. Kelso, and Marcella A. Windmuller- Campione; Forest Science, 2022, 68, 104–112; https://doi.org/10.1093/forsci/fxab053

[10]personal communication with R. Seybold, silviculturist on the Superior National Forest

Superior National Forest plot applications, MN Credit: University of MN

What was learned?

There were several insights gained from the project that relate to the effectiveness of biochar as a soil amendment for working lands:

Matching Biochar to Soils

The project reinforced the understanding that matching soil characteristics to the char's characteristics is critical to a successful application. The "charging" or inoculation of the biochar prior to incorporation in the soil is also important, however a simple additive (like the high nitrogen bloodmeal used in the BRDI study) may have only short-lived effects as opposed to more complex additives like compost or more balanced NPK supplements.[11]

Life Cycle Analysis

The LCA (Life Cycle Analysis)[12] of the common garden installation highlighted the importance of the biochar's feedstocks and their pyrolysis conditions from the perspectives of both the biochar's effectiveness in the field and its holistic effectiveness for the soil, crop, and any climate effects. The choice of feedstock material, the pyrolysis conditions, and the pyrolysis equipment are all important considerations in the overall product and its effect on the climate. Each of those choices affect the characteristics of the biochar which, in turn, affect the optimization of the soil-biochar match.

Biochar for Climate Benefit

Biochar applications are a safe bet for improving soil organic matter, but if a producer/user is interested in biochar for selling carbon offset credits they need to consider real energy cost of producing and potentially transporting the feedstock. For instance, the switchgrass biochar used in this project had the greatest gross increase in soil carbon storage but when the carbon costs of producing and transporting the hay are considered, it is actually a neutral to slightly negative transaction. That is a particularly notable observation because the biochars were locally produced, but their production and transportation still had a significant impact on the carbon neutrality of its application.

As with the biochar's physical characteristics, the production technology used and its operating parameters affect the carbon footprint of a given biochar. In this project, "local" biochars were used to minimize transportation, and the material used in each state was from a different producer—none of them commercial producers. In that sense they were "custom" and had different characteristics[13].

"Common Garden" installation:

- Warm season grass pasture at Virginia Tech's Catawba Sustainability Center
- 40 plots in a randomized block design, established Fall 2019
- Locally sourced hay, hardwood, and softwood biochar

Spreading biochar in the Catawba common garden Swtichgrass pasture prior to incorporation. (VA) Credit: Jeb Barrett

[11]In soil amendments (i.e., fertilizers) N-P-K is the ratio of the three main macronutrients that all plants need to grow: Nitrogen (N), Phosphorus (P), and Potassium (K).

[12]LCA provides a mechanism for systematically evaluating the environmental impacts linked to a product or process and in guiding process or product improvement efforts. For more information about LCA, see: https://dovetailinc.org/portfoliodetail.php?id=5e8f46902fea8

[13]See Appendix B for Biochar analyses.

Importance of Biochar Charging

The final significant take away from the BRDI project is that the media used to "charge" or inoculate the biochar prior to application is also an important factor affecting the performance of the soil-crop system. For the sake of minimizing variables, this study used a simple high- nitrogen product[14] with minimal other chemical characteristics which had only a short-term effect. Typically, a more complex method is used to fill biochar's porous microstructure with water containing elemental chemicals and/or microflora. This process allows the biochar to have an immediate positive effect as opposed to the raw biochar uptaking those constituents from the soil into which it's been introduced, possibly suppressing crop growth.

A deeper dive into the details of what was learned is provided in Appendix A.

What's Next: Follow-on Research

The research into "real world" biochar use in agriculture will continue with an expanded BRDI team by way of a project titled: **Assessing the influence of biochar preparation methods on soil health in diverse managed ecosystems.** This project will explore the changes in soil microstructure resulting from application of biochar and how it may promote soil health by increasing carbon sequestered in soil aggregates which we expect increases the connectivity of microbial communities among soil microsites. The research will examine the interactive effects of biochar and soil composition on multiple metrics of soil health, including: soil carbon content and mineralization, soil micro-structural and aggregation, bioavailable nitrogen, and microbial activity and diversity.

The AFRI project will use imaging technologies to provide a window into the microscopic world of soil. Techniques such as computed micro-tomography (micro-CT) and focused ion beam scanning electron microscopy (FIB-SEM) will be used to obtain a three-dimensional (3D) digital representation of actual soil microstructure.

Processes that occur at the microscopic scale determines the water retention properties for soil and are of direct importance to microbial communities and the biogeochemical processes they regulate. Microscopic imaging thereby provides a quantitative basis to understand how biochar application alters soil structure and what this means for microbes.

The objective of the team's research is to evaluate methods for producing and activating biochar as a soil amendment for improving soil health in diverse managed ecosystems. The team suspects changes in soil microstructure promote soil health by increasing carbon sequestration in the soil's constituent aggregates resulting in retention of water and nutrients among soil microsites. Using a combination of field experiments, advanced imaging techniques, and modeling the mechanisms by which biochar influences soil structural and hydraulic properties will be examined to determine the mobility of nutrients, carbon, and microbial communities. That research will be done in controlled field studies across a range of managed agricultural systems (pasture, row-crop, forest) and soil types (6 orders of fine and coarse texture soils). This research will include new and existing biochar experiments to encompass a range of temporal perspectives on the benefits of biochar to growers and the long-term implications for how biochar potentially influences multiple indicators of soil health[16].

The USDA Natural Resources Conservation Service recommends several crucial indicators[17] to evaluate soil health including: soil carbon content and mineralization potential, soil structural stability, bioavailable nitrogen, and microbial activity and diversity. Biochar applications have been demonstrated to enhance all of these indicators in a variety of soil ecosystems, primarily through modification of the soil microstructure in ways that enhance soil aggregation and hydraulic properties.

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[14]Mason City By-Products, Inc.; 775 15th NW, Mason City, IA; Porcine Dried Bloodmeal, Guaranteed Analysis (12-0- 0)

[15] AFRI is the Agriculture and Food Research Initiative of the USDA's National Institute of Food and Agriculture. Agriculture and Food Research Initiative (AFRI) | National Institute of Food and Agriculture (usda.gov)

[16]**Soil health** is the sustained capacity of soil to function as a vital living ecosystem to support plants, animals, and humans.

[17]Soil Assessment | NRCS (usda.gov)

The tests will explore whether:

- In fine texture soils will biochar improve drainage/ permeability because increased biochar enhances porosity, decreases tortuosity, and increases velocity of water moving through the soil-biochar matrix?
- In coarse texture soils will biochar enhance water holding capacity because biochar increases micro-pore space and slows water velocity through the soil-biochar matrix?
- Biochar amendments will increase microbial activity and biogeochemical cycling due to greater porosity and less tortuous streamlines which will enhance connectivity among biofilms and resource rich microsites in the soil-biochar matrix?
- The effect of biochar on soil fertility depends on the interactions of biochar with the availability of nutrients in the native soil because the availability of inorganic nutrients is an outcome of the stoichiometric balance between the elemental chemistry of microbial biomass and nutrients present in the bulk organic matter?

Bottom Line

The BRDI sponsored project reinforced the body of knowledge that biochar has benefits in agricultural applications but must be a tailored amendment as opposed to a one-size-fits-all option. A key outcome is the follow-up research project which will look at the mechanisms by which biochar IS effective in soils and how to maximize its potential. The need to expand the body of knowledge about biochar—as one of the most accessible Carbon Drawdown and Removal technologies[17] currently—is of growing importance as the climate change clock ticks away.

The AFRI project will utilize state-of-the-art imaging capabilities of the Virginia Tech NanoEarth Facility and the U.S. DOE's National Energy Technology Laboratory (NETL) in Morgantown WV to characterize the surface properties of biochar using SEM, FIB-SEM, and micro-CT imaging.

The microscopic structure of biochar is heterogeneous, with very high surface area. As microbes colonize the surface, effective properties of the material will be altered. Microscopic imaging will therefore provide a basis to understand how biochar microstructure influences microbial colonization and related influences on effective properties, in particular the surface wetting energy. The surfaces for biochar may not be water-wet prior to microbial colonization, so the influence of microbial colonies on surface wetting energy is likely to be an important factor for understanding water retention properties. Assessments of the surface wetting behavior will be an input for the successive simulation modeling.

Spreading biochar on Pasture Plots prior to incorporation (VA) Credit: H Groot

[17]Biochar is one of seven carbon capture and storage technologies named by the Intergovernmental Panel on Climate Change (IPCC), see: Biochar's Role in Climate Mitigation, 2020, Dovetail Partners. Available at: https://dovetailinc.org/portfoliodetail.php?id=5f3c24debc853

Appendix A: A Deeper Dive[18] into "What was Learned"

The goal of this study was to examine the effect of realistic application rates of locally-sourced biochar on working farm soils in New Mexico, Minnesota, and Virginia, representing a range of soil types and cropping systems. Specifically, four indicators of soil health in agricultural systems: soil organic carbon, total soil nitrogen, soil pH, and soil electrical conductivity. The effect of the biochar amendment depended on initial soil characteristics and the properties of the biochar applied. The Virginia site saw the best outcomes, with increased soil carbon and nitrogen and marginally higher soil pH with a biochar application rate of 2.5 kg/m2 (11.15 tons/acre). Minnesota also saw an increase in soil carbon, but the under-pyrolyzed biochar applied there was acidic, and drove down soil pH. New Mexico, which had the lowest baseline soil carbon and nitrogen levels and highest initial pH and electrical conductivity values, showed little response to biochar application beyond a slight increase in soil carbon. Taken together, these results emphasize the importance of understanding baseline soil and biochar characteristics, as well as the desired outcome, before biochar application to agricultural soils. Biochar generally had neutral-to-positive effects across the three sites studied.

Impact of Feedstock Choice on Carbon Balance

In our analysis, softwood and hardwood outperformed hay in carbon sequestration over the life cycle of biochar feedstocks and their application to soils. The wood feedstocks' density and higher lignin content made for an efficient conversion to biochar (Groot et al. 2020, Lehmann et al. 2006), producing more biochar per unit feedstock and requiring fewer pyrolysis runs than the hay to create the same mass of biochar. The scrap wood and lumber also had the benefit of being waste materials left over from lumber processing and up-cycled, rather than produced to purpose, i.e., the energy associated with felling, cutting, and milling wood feedstock is not accounted for here in contrast to warm season grass hay which is often produced intentionally for bioenergy. Several LCAs have concluded that waste product feedstocks are best for creating net negative emissions in biochar systems, while biochar systems that use feedstocks, particularly grasses, grown specifically for pyrolysis tend to result in neutral-to-positive emissions (Ibarrola et al. 2012, Hammond et al. 2011, Roberts et al. 2010). The most appropriate feedstock for a biochar system in a given area will vary depending on what is locally available and what the alternative uses of the biomass would be. Cost of feedstocks and shipping can also be a limiting factor, yet another reason why it is best to use waste products sourced as close as possible to the pyrolysis and application sites.

Pyrolysis Technology and Carbon Balance

The majority of emissions associated with each biochar came from the pyrolysis process itself. This aligns with the results from many other LCAs conducted on biochar systems (see Matuštík et al. 2020). Given the outsized impact of pyrolysis emissions on the overall carbon balance, making adjustments to maximize biochar production and limit greenhouse gas emissions during pyrolysis would be a key way to improve the carbon storage of the system as a whole. Pyrolysis temperature and timing are major drivers of biochar mass yield; slow heating rate, long residence time, and high temperatures (~500-100°C) tend to produce the most biochar per unit of feedstock while also creating a product with desirable physical and chemical characteristics (Joseph et al. 2021, Weber and Quicker 2018, Lehmann et al. 2006).

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[18]The Effects of Biochar and Reactive Iron Additions on Soil Carbon and Nitrogen Retention by Jared P. Conner and Biochar Amendment as A Tool For Improving Soil Health And Carbon Sequestration in Agro-Ecosystems by Sophia E. Drew; Thesis submitted for degree of Master of Science in Biological Sciences

Many life cycle assessments performed for biochar systems have focused on larger-scale pyrolysis plants where co-production of energy (and therefore avoided emissions from fossil fuels) contribute to overall carbon sequestration (Azzi et al. 2019, Homagain et al. 2015, Hammond et al. 2011). The analysis for this project focused solely on the carbon sequestration potential of biochar applied to soil. smaller-scale biochar producers typically do not have the technology to capture and use co-products for energy, so there must accessing carbon offset benefits are challenging in the current market framework. This project, however, saw net carbon storage driven by increases to soil carbon alone with the hardwood and softwood biochars in most scenarios, which is supported by results from other LCAs where soil carbon storage is the primary contribution to overall carbon sequestration (Matuštík et al. 2020). These results demonstrate that local-level biochar production can play a part in carbon sequestration efforts even when advanced pyrolysis technology is not available or practical due to cost or scale.

Soil Carbon Dynamics

While all three types of biochar (hardwood, softwood, and switchgrass derived) drove increases in soil carbon, the switchgrass char was notable in that the soil carbon increase was larger than the amount of biochar added (increase of 12.02 kg carbon per plot after 10 kg of biochar was applied). That could mean the Switchgrass biochar may have induced a negative priming effect, possibly by slowing the mineralization and/or increased stabilization of plant- and microbially-derived soil organic matter. A study by Zimmerman et al. (2011) that compared the priming effects of oak, pine, and grass biochar produced at a range of pyrolysis temperatures over 500+ days post-application showed that biochar made from grass suppressed soil organic carbon mineralization across the board. For their hardwood and softwood biochars, the pyrolysis temperature influenced whether soil carbon mineralization was elevated or suppressed, with a correlation between pyrolysis temperature and suppression of mineralization (Zimmerman et al. 2011). Most biochars demonstrated some level of suppression on soil carbon mineralization later in the incubation, suggesting that biochar's negative priming capacity increases over time (Zimmerman et al. 2011). Blanco-Canqui et al (2019) also found evidence of negative priming in a long-term field experiment, where plots amended with wood biochar exhibited an increase in soil carbon that was almost double the biochar carbon added six years earlier.

Accurately estimating soil carbon residence over the long term (in this study, 100 years) is critical to predicting the net carbon balance of biochar systems. Due to the range of feedstocks and pyrolysis methods included under the umbrella term of "biochar", coupled with the difficulty of estimating how biochar will behave over hundreds to thousands of years. In general, biochars produced at higher pyrolysis temperatures are expected to mineralize more slowly over time (Joseph et al. 2021, Fang et al. 2014).

The size fraction where each biochar contributed the most carbon could provide additional insight into the longevity of the additional soil carbon observed after biochar application. Several studies have demonstrated increased soil aggregation following biochar application, as well as preferential incorporation of biochar carbon in microaggregates and the organo-mineral fraction, generally defined as <250µm in size (Yoo et al. 2017, Weng et al. 2017). Organic matter protected within aggregates or stabilized on clay particles in these size fractions is generally believed to be well-protected from microbial access and mineralization, and therefore represent long-term pools of soil carbon (Six et al. 2002). In our soil samples collected one year after biochar application, the soil carbon gains in the <250µm fractions represented 23% (hay), 17% (softwood) and 15% (hardwood) of total increases in soil carbon. These percentages may be expected to increase as physical and biological processes break down the larger pieces of biochar. More long-term biochar field studies are needed to examine how biochar is incorporated into and/or accelerates the formation of soil aggregates over decades to centuries.

Conclusions From Drew's Thesis

This life cycle assessment of biochar made from up-cycled softwood and hardwood waste, and purpose-grown hay applied to Southwest Virginia pasture soils demonstrated that local-scale biochar production and use can create meaningful increases in soil carbon and overall carbon sequestration. The differences in carbon balance and global warming potential over the full life cycles of the three feedstocks made clear that not all biochar is equal with regard to its carbon storage capacity. The switchgrass biochar, which contributed the most to soil carbon, was also the most carbon-intensive to harvest and transport. In contrast, the softwood and hardwood feedstocks contributed somewhat less to increases in soil carbon storage, but achieved negative carbon balances over their life cycles (-4.58 kg and -3.94 kg, respectively), due primarily to the lower emissions associated with their harvest, pyrolysis, and transportation.

The carbon balance of upcycled-wood pyrolysis remained negative in all but a few sensitivity analysis scenarios that assumed 50% carbon loss and higher transportation distance and pyrolysis gas yields. These results suggest that producers can maximize the carbon storage capacity of biochar systems by using agricultural or timber processing waste products as feedstocks, investing in appropriately-scaled technologies to decrease or capture energy produced during pyrolysis, and minimizing transportation distances for feedstocks and biochar.

Study Site and Field Experiment

A primary focus of the project was a tightly controlled research installation—in contrast to the "random" farmer's plots; referred to as the common garden. This part of the experiment was established in an n-factorial, randomized block design in order to assess differences among the eight treatment combinations and minimize variance due to spatial heterogeneity. As shown in Figure 2.1, the experimental design consisted of eight different treatment combinations of the two factors: biochar and activation with blood meal. Either a control treatment with no biochar (C), hardwood biochar (HW), C4-grass hay biochar (H), or softwood biochar (SW) were applied with or without blood meal to "activate" the raw biochar. In order to achieve a random configuration of treatments in this common garden experiment, five replicate blocks of nine, 2m x 2m treatment plots each were delineated in July 2019 and isolated from grazers by erecting a temporary electric fence around the perimeter of the column of blocks. Two meters space was left between plots within a block to ensure discrete treatment application, with ~ 3m of buffer between each block.

The biochar and blood meal were spread on the field plots in September 2019. Ten kg of biochar was applied to each 2m x 2m plot to achieve an application rate of 2.5 kg/m2 (11.15 tons biochar/acre). Similarly, 400 g of dried, homogenized blood meal powder was applied to each 2m x 2m plot to achieve an application rate of 0.1 kg/m2 (0.446 tons/acre). These amendments were then incorporated into the top 10 cm of soil using several passes of a tractor with a discing attachment.

After 11 months, there was a 6.5-13.5% increase in soil pH relative to control due to amendment with biochar

At 11 months, amendment with biochar drove a 32-48% decrease in the electrical conductivity of the soils in this experiment ($p < 0.01$; Fig. 2.3b), which indicates a higher affinity of the biochar-amended soil for free ions such as inorganic nitrogen species for example.

Biochar application increased bulk soil organic C by 48-78% ($p < 0.0001$) in both the 1 and 11 month samples (Fig 2.4).

Effects of Biochar Properties on Soil Chemistry

All of the biochar types (hardwood, softwood, and switchgrass feedstocks) used in this study increased soil C, decreased available (inorganic) N, and increased pH after 11 months. Because biochar's effect on soil chemistry has been widely studied (Novak et al., 2009) (Jien and Wang, 2013) these findings were anticipated – and reinforce the potential for biochar to increase soil organic matter, reduce the leaching of N, and alter the soil environment.

Notably, the influence of blood meal on N availability was transient and not detectable after 11 months. This indicates that co-applying blood meal with biochar is primarily useful for offsetting potential biochar-induced decreases in available nitrogen in the short term, a finding that could inform land managers' decisions of when and how to apply biochar. In other words, co- application of blood meal with biochar reduced the potential for biochar to immobilize nitrogen, but this effect was not detectable after 11 months, when all biochar treated plots had lower extractable N relative to control plots.

These findings also suggest that application of an organic fertilizer between 1 and 11 months after biochar application might be effective in offsetting reductions in available nitrogen.

However, recent studies on the plant availability of inorganic nitrogen captured by biochar in soil actually suggest that this might not be necessary, and there is an emergent understanding that biochar slowly releases inorganic N (Hagemann et al., 2017) (Haider et al., 2020). As Lee et al., 2018 pointed out, a biochar-induced reduction in the immediate supply of inorganic N could actually be considered beneficial due to the lowered potential for N leaching from soils, especially as nitrate, the most mobile form of available N. This increased N retention via temporary immobilization or adsorption to biochar is reminiscent of the increased N retention realized by farmers who grow cover-crops during the winter, and the combination of cover cropping with the use of biochar could be a potentially effective strategy for minimizing N export from agroecosystems (Dabney et al., 2001) (Zhou et al., 2020).

Forestry Aspect of the Project[19]

Survival of planted seedlings following a regeneration harvest can be challenging and early interventions through silvicultural treatments may be required for successful stand establishment. This aspect of the project tested the influence of soil amendment (biochar plus compost, compost-only, or control) and vegetation control (VC; applied either initially or annually for five years using brush saws) on the growth and survival of jack pine at three sites in northern Minnesota. Application of the biochar plus compost soil amendment increased seedling survival by 30% relative to the control in the first year, but there was no significant difference in survival among soil amendment treatments after five years. Both soil amendments increased diameter growth relative to the control (14% increase with biochar plus compost, 10% increase with compost only), with most of the biochar plus compost effect attributed to the compost. Annual VC increased diameter growth by 17% relative to initial VC, but overall effects on survival and growth were generally small relative to reported effects of VC via herbicide. The limited short-term influence of biochar and manual VC on growth and survival of jack pine indicates that these practices are likely not an effective means to increase jack pine establishment, but other benefits (e.g., increased carbon storage) may become apparent with time.

Study Implications: Emerging changes to forest conditions and climate are likely to create challenges for successful regeneration in even-aged silvicultural systems. Early interventions such as application of soil amendments and vegetation control may be required to increase seedling survival. However, our findings indicate that biochar application and manual vegetation control were not very effective at increasing survival and growth of planted jack pine seedlings across a range of site conditions in northern Minnesota. Further study is warranted to determine whether other biochar application rates and techniques or other forms of vegetation control are more effective for successful jack pine establishment.

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[19]Effect of Biochar and Manual Vegetation Control on Early Growth and Survival of Planted Jack Pine (Pinus banksiana Lamb.) Seedlings in Northern Minnesota; Robert A. Slesak, , Sara G. Kelso, , and Marcella A. Windmuller-Campione; Forest Science, 2022, 68, 104–112; https://doi.org/10.1093/forsci/fxab053

Appendix B: Figures and References

Figure 2.1 Experimental design and layout of biochar work at Catawba

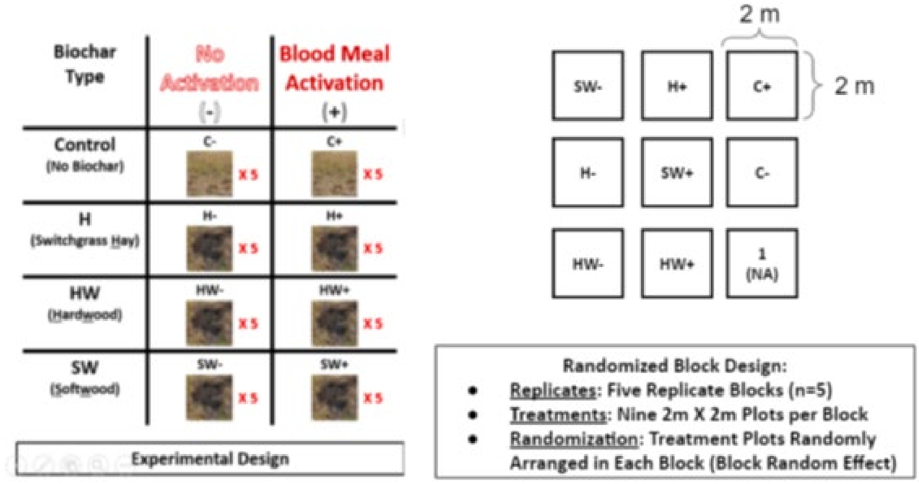


Figure 2.3 Electrical conductivity at 1 month (Fig. 2.3a) and 11 months (Fig. 2.3b) after amendment with biochar.

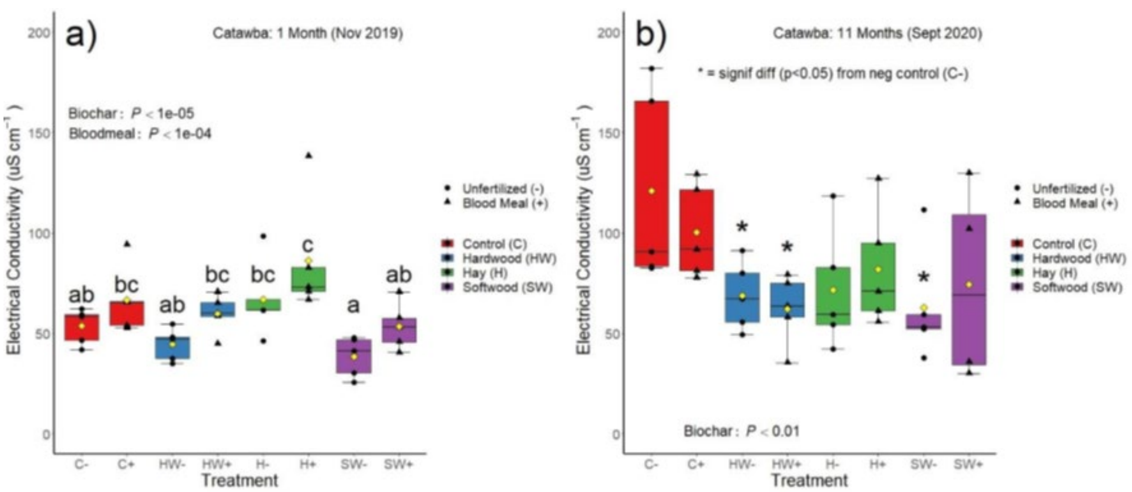
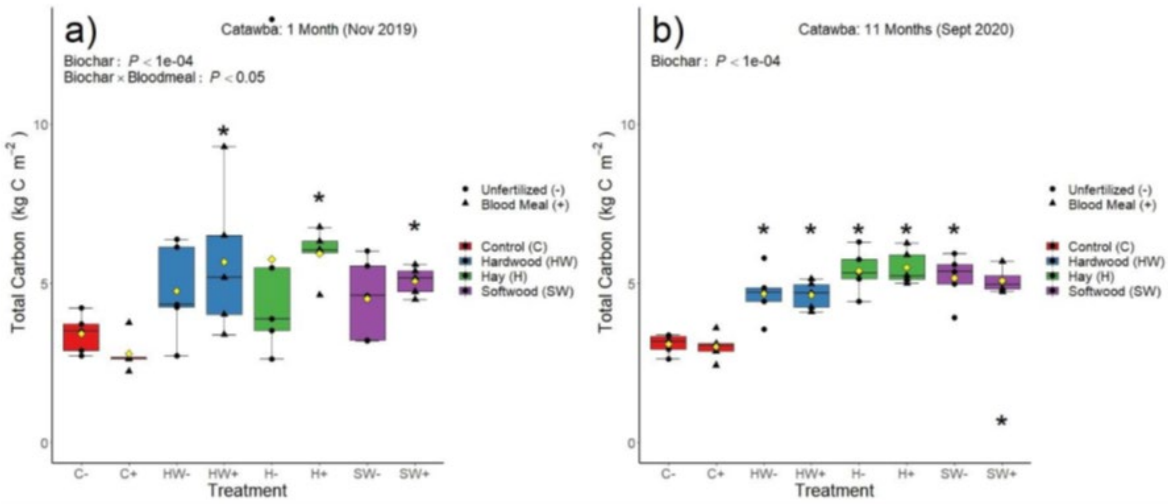


Figure 2.4 Total C of the bulk soil at 1 month (Fig. 2.4a) and 11 months (Fig. 2.4b) after amendment with biochar.



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Appendix C: Biochar Analyses

Feedstock	Bulk Density (lb/cu ft)	Organic Carbon as % of total dry mass	Hydrogen/Carbon (H:C)	Total Ash % of total dry mass	Total Nitrogen	pH	Electrical Conductivity	Liming (neut. Value as-CaCO3)	Carbonates (as-CaCO3)	Butane Act.	Surface Area (m2/g dry)
Switchgrass	8.4	66.6	0.53	20.6	1.75	9.78	4.88	7.4	1.4	0.9	161
Hardwood	18.4	84.5	0.39	5	0.66	8.8	0.225	7.2	1.8	1.7	188
Softwood	11.9	90.8	0.38	1.3	0.17	6.75	0.069	3.9	0.9	2.9	226
Pecan Hulls	21.5	84.5	0.38	4.2	0.89	8.52	0.144	5.1	1.1	1.8	192
Mixed wood	16.8	52.5	1.29	2.2	0.47	3.48	0.075	1.3	0	0.2	140
Mixed wood	22.2	57.3	1.12	2.2	0.47	5.81	0.063	4.5	0	0.3	142
Mixed wood	22.3	53.7	1.26	3.2	0.49	5.36	0.062	4.3	0	0.4	147
Mixed wood	22.9	58.3	1.06	2.4	0.45	4.9	0.048	4.3	0	0.4	146
Mixed wood	16.2	50.9	1.43	2.2	0.44	5.85	0.068	4.1	0.1	4.8	285
Mixed wood	20.3	66.8	0.32	26.4	0.56	7.82	0.124	14	7.1	10.2	458

	Particle Size Distribution (%)					
	< 0.5mm	0.5-1mm	1-2mm	2-4mm	4-8mm	8-16mm
Switchgrass	30.1	30.5	24.3	13	2.1	0
Hardwood	24.8	12.6	15	25.4	18.4	3.8
Softwood	16.4	8.9	14.6	30.7	25.2	4.2
Pecan Hulls	8.9	10.2	23	29.6	27.6	0.7
Mixed wood	0.2	0	0.3	7.3	49.6	42.5
Mixed wood	26.5	11.8	14.3	22.8	18.1	6.6
Mixed wood	20.9	11.7	11.8	18.1	28.5	9
Mixed wood	26.7	15.5	17	20.4	16.2	4.1
Mixed wood	0.5	0	0	2.4	34.3	62.7
Mixed wood	49.4	22.9	15.2	11.1	1.4	0

	Basic Soil Enhancement Properties					
Feedstock	Total (K) mg/kg	Total (P) mg/kg	Ammonia (NH4-N) mg/kg	Nitrate (NO3-N) mg/kg	Organic (Org-N) mg/kg	Volatile Matter (% Dry Matter)
Switchgrass	42603	3565	7.3	1.9	17511	28
Hardwood	2510	209	5.3	0.7	6559	26.1
Softwood	605	67	4.6	0.8	1670	24
Pecan Hulls	4273	599	2.3	1	8925	25.1
Mixed wood	1492	158	3.6	1.9	4658	78.9
Mixed wood	1646	134	0	2.3	4683	71.2
Mixed wood	1323	149	2.4	0	4851	77.3
Mixed wood	1789	98	0.2	0.4	4545	64.8
Mixed wood	1719	120	0	0.2	4377	79.8
Mixed wood	579	3117	3.3	0.5	5551	18

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