Pine sawdust biochar as a potential amendment for establishing trees in Appalachian mine spoils

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ARTICLE INFO

Citation:
Fields-Johnson WC, Fike HJ, Galbraith MJ, Maguire OR, Day DS, Zedaker MS, Mathis JE (2018) Pine sawdust biochar as a potential amendment for establishing trees in Appalachian mine spoils. Reforesta 6: 1-14.
DOI: https://dx.doi.org/10.21750/REFOR.6.01.54.

Editor: Vladan Ivetić, Serbia
Received: 2018-08-01
Accepted: 2018-11-14
Published: 2018-12-28

Abstract

Early growth and survival of tree seedlings is often poor on reclaimed coal surface mines in Appalachia. Biochar produced in bioenergy generation has potential for use as an amendment to improve seedling performance. Mine soil was collected from a recently reclaimed coal surface mine in Wise County, Virginia and mixed with loblolly pine (*Pinus taeda* L.) sawdust biochar, simulating application rates of 2.3, 11.2 and 22.5 Mg ha^{-1}. Unplanted leaching columns and 4 L tree planting pots were filled with these biochar-soil mixtures, plus controls of pure mine soil and pure biochar. For the tree planting pots, additional pots were created where the biochar was applied as a topdressing at the same application rates as in the mixtures. One-year-old seedlings of both American sycamore (*Platanus occidentalis* L.) and black locust (*Robinia pseudoacacia* L.) were planted. Unplanted leaching columns were leached with collected rainwater for six months to simulate weathering. Trees were grown for one growing season. Black locust had higher average above-ground dry woody biomass (24.4 g) than American sycamore (17.0 g), and also higher below-ground biomass (61.0 g compared to 30.2 g). The pure biochar produced greater average below-ground biomass (99.9 g) than the pure mine soil (46.9 g). All of the biochar treatments produced greater average above-ground woody biomass (19.1 g – 33.4 g) than the pure mine soil (10.9 g). After weathering, biochar provided less available soil phosphorus, calcium and iron than the mine soil itself while increasing soil carbon and organic matter. High (22.5 Mg ha^{-1}) biochar applications increased soil volumetric water holding capacity to 18.6% compared to 13.4% for pure mine soil. Naturally-occurring herbaceous biomass in the pots was negatively correlated with above-ground woody biomass at $r = -0.483$. Topdressing and full incorporation of biochar were not significantly different in their effects on biomass. Results suggest that pine biochar either broadcast at 2.3 - 22.5 Mg ha^{-1}, or mixed in planting holes with backfill soil, will promote faster above-ground growth and larger root systems in seedlings in mine soils. Further studies should test these methods in the field over multiple years and further refine recommendations of the rate of biochar to use and how best to apply it. New systems are being developed in Appalachia to produce biofuels and biochar from local biomass and to recycle biochar into the land base to enhance future biomass productivity. Applying 4 L of biochar mixed with the backfill of newly-planted trees is the top recommended practice for tree performance.

Keywords

Pyrolysis; Reclamation; Reforestation; Biomass; Bioenergy

Contents

1 Introduction

The Appalachian Region in the eastern United States is in a period of transition in energy, employment and land usage. Over 1.2 x 10^6 ha have been permitted for surface mining of coal (Pizarchik 2012; Demchak et al. 2004) in Appalachia, leaving behind land in various conditions of abandonment or reclamation. This land base ideally will continue to provide energy, employment, recreation, building materials, food, water and other ecosystem services to the peoples of Appalachia. The Appalachian Regional Reforestation Initiative (ARRI) (Angel et al. 2005) was begun in recent years to achieve these ends using the Forestry Reclamation Approach (FRA) (Burger et al. 2005), a reforestation technique focused on soil improvements. Biochar offers an avenue to link soil improvement technology for reforestation with the energy economy in Appalachia. Additionally, a comprehensive Bioregional Economic Development model is presently being deployed to identify synergistic linkages between the FRA and economic transition strategies emerging across the Great Appalachian Valley region (Mathis and Jenkins 2016).

New technologies, such as pyrolysis, hold the potential to solve transition challenges for Appalachia by producing electrical energy, liquid fuels and charcoal from biomass materials. Fast pyrolysis is the rapid heating of biological materials in a low oxygen environment (Ji-lu 2007) which yields charcoal at a rate of about 15% to 19% of the original dry biomass of the feedstock while generating surplus energy and products such as bio-oils, syngas and other chemicals (Mullen et al. 2010; Bridgewater 2012). This charcoal is called “biochar” when it is used as a soil amendment for agronomic purposes. Biochar is a stable organic material, but is also comparable to clay minerals in its function and form in the soil (Laird 2009). At higher pyrolysis processing temperatures, the resulting biochar contains greater proportions of graphene, a form of polyaromatic carbon. Graphene consists of a one-atom thick planar sheet that resembles a honeycomb (Antal and Gronli 2003), and stacked sheets of graphene form graphite. Xylem and other plant vessels and structures are left intact during pyrolysis, providing porosity, and are partly comprised of this graphitic material following pyrolysis, which provides long-term chemical stability.

Historically, biochar was added to soils in the Amazon rainforest by indigenous peoples (Lehmann et al. 2003). With biochar addition, these *Terra preta* (“dark earth”) soils had greatly enhanced fertility and carbon levels in comparison to neighboring natural soils. These properties have lasted for over 500 years to the present day, indicating that biochar is a long-term soil amendment and carbon sink (Lehmann et al. 2003; Wolf et al. 2010). Dark earth sites from primitive agriculture also exist in tropical Africa (Woods et al. 2009). Biochar has also been found in prairie soils, the grasslands of the central region of the United States having been burned regularly (Skjemstad et al. 1996) and this region has among the most fertile and highest-carbon soils in the world. The consensus of many studies is that biochar applied in a wide range of rates generally improves the aboveground productivity of plants, especially in acid, low-fertility soils, even though below-ground effects on productivity and soil properties are often variable (Biederman and Harpole 2013). Biochar is particularly effective at controlling many types of pollution on mined lands and can help these lands be successfully re-vegetated (Anawar et al. 2015). Biochar may be found to facilitate the reclamation and reforestation of low fertility, acidic mined land by improving the performance of planted trees, which is the subject of this study. Productive forests have potential to provide an array of economic opportunities and ecosystem services including, but not limited to, feedstock for biofuels (Mathis 2016a, 2016b).

Biochar enhancement of soil fertility is undergoing increasing study (Lehmann et al. 2009). As a fertilizer, biochar directly provides nutrient cations, available phosphorus (P) and some labile organic matter for consumption by soil microbes. As a fertilizer enhancer, biochar provides increased cation exchange capacity and pH on acid soils such as Ultisols and Oxisols (Lehmann et al. 2009). Biochar potentially also can moderate alkalinity and salinity of other soil types that might be found on mined lands (Liu and Zhang 2012). Biochar properties depend on processing temperature during pyrolysis (Mukherjee et al. 2011), and beneficial changes to biochar accrue over time and are enhanced through interactions with natural soil (Mukherjee et al. 2014). These changes increase the cation exchange capacity and water holding capacity of soils lacking the clay minerals or organic materials to provide such functions, as is typical for most mine soils following reclamation.

Tree growth and health can benefit from the addition of biochar to soils (Scharenbroch 2009). Among biochars, wood made into charcoal through traditional methods, such as in kilns, earthen mounds or pits, provides the most consistently high increases in productivity, perhaps because of its greater porosity due to the presence of intact water-conducting vascular tissues (Spokas et al. 2011). Biochar generally enhances the activity and increases the biomass of beneficial soil microorganisms (Lehman et al. 2011) and can induce systemic resistance to fungal disease through indirect effects on the soil environment and microbial community (Elad et al. 2010). This helps in the survival and development of young trees which face a number of pest and disease issues in stressful environments. Thus, biochar is a promising soil amendment with the potential to help solve many of the key issues on reclaimed mined lands for the long-term.

Building from biochar research, the Institute for Regenerative Design & Innovation (IRDI), in collaboration with Home Grown Energy (HGE), is presently identifying integrative synergies between traditional and emerging energy resources through the strategic deployment of Integrated Energy Parks. HGE and IRDI are assessing the integration of its Living-Lab Platform model into two proposed Integrated Energy Parks in hopes of accelerating Central Appalachia’s energy transition (Mathis 2016b; ARC 2013). HGE’s new Cellulose to Hydrogen Power (CHyP) System produces biochar along with biodiesel by heating woody biomass under low oxygen conditions in a controlled environment. The biodiesel can be managed and marketed in the same way as petroleum diesel. Both of the Integrated Energy Parks in Beverly, West Virginia, USA and Ironton, Ohio, USA are designed to produce 24,000 Mg of biochar per year at each location. Locally-harvested biomass could thus be recycled back into the local environment in the added-value form of biochar.

The CHyP System utilized by HGE is designed to produce diesel fuel meeting the standards for ASTM D-975 No. 2-D S15. In addition, the CHyP System will produce 15% by weight biochar per Mg of biomass. The system is designed as a continuous-flow process. The process begins with the receipt of biomass feedstock, which is chipped on location in the surrounding forest and transported to the feedstock management area of the plant site. These chips will go through a secondary grinding step using a PPI manufactured Crumbler under license from Forest Concepts in Auburn, Washington. The maximum size of the feedstock that can be delivered to the CHyP System is 13 mm. The Crumbler's secondary grind provides a chip that is approximately 0.25 inches in diameter with aspect ratios from 1-2. The secondary grinding is followed by a screening step using a 12-mesh screen to remove the fines from the chips. From the screening operation, the crumbled chips are conveyed into the dryer. The prepared biomass is then processed through the CHyP Unit.

IRDI is also deploying three Living-Lab Platforms throughout North Carolina in partnership with Bio-Regen Coop and SYNC Bio-Resources with a specific focus on oil seed crops including industrial hemp. The modularity of the platform design affords this economic development strategy with a "plug-and-play" capability regarding the two Integrated Energy Parks. HGE and IRDI are outlining next steps to ensure optimal replication throughout the region with a specific focus on both utilizing the projected 48,000 Mg of projected biochar production for regenerating mine sites across the central Appalachian region as well as assessing use of oil seed crops in general with a specific focus on industrial hemp.

The goal of this study, using laboratory and greenhouse techniques, was to determine beneficial application rates and methods for biochar use to help establish trees on mine soils. The first objective was to evaluate the effects of biochar application rates on mine spoil properties using soil weathering columns. The second objective was to determine the best biochar application rate and method to use for enhancing the growth of plantings of two native woody plant species, black locust (*Robinia pseudoacacia* L.) and American sycamore (*Platanus occidentalis* L.), growing in an Appalachian coal mine soil.

2 Materials and methods

2.1 Mine soil and biochar mixing

Mine soil material for this study was collected from an active mine site in Wise County, Virginia, and baseline properties were determined (Fields-Johnson 2011) (Table 1). Only the fine fraction (less than 2 mm diameter) was used for the weathering column experiment in order to remove the random effects of highly variable coarse material. The whole soil, including coarse rock fragments, was used for the tree growth experiment to better simulate soil conditions on mined lands. These materials were combined with pine (*Pinus taeda* L.) based biochar synthesized by heating sawdust at 452 °C in a fixed bed, fast pyrolysis reactor. This type of biochar was chosen because it contains low levels of nutrients and salts. The biochar and its sawdust feedstock were observed with light and electron microscope imagery to ascertain visually observable physical structures, such as particle sizes and pore spaces. Biochar was applied at rates equivalent to 2.3, 11.2 and 22.5 Mg ha^{-1} based on the top surface area of the pots. Additional treatments included controls of pure mine spoil and pure biochar. Pure biochar was used as a medium to determine its suitability (or toxicity) to the trees.

2.2 Weathering columns

Polyvinyl chloride (PVC) pipes (2.5 cm diameter x 30 cm length) fitted with fiberglass screens across the bottom were used in the weathering study. These columns were filled with their respective treatment combinations in three replications and soil samples were collected immediately from the reserve mix for testing. The columns were leached with rainwater (15 ml) which was added weekly for six months to simulate initial weathering conditions. Following this preliminary weathering period, soil saturated hydraulic conductivity was measured for each column. Conductivity was measured by maintaining a constant head of water in the column (30 cm from the top of the head of water to the bottom of the soil column), and then measuring the rate at which the water was released from the bottom of the column. Following conductivity testing, a second set of soil samples was taken from the columns for analysis.

2.3 Tree plantings

For the tree growth experiment, 4 L plastic pots (16 cm diameter x 20 cm height) were used to grow black locust and American sycamore trees. These species were chosen because historically they have been used in the reforestation of mined lands due to their fast growth and high tolerance to a wide range of soil conditions. Biochar was applied at 2.3, 11.2 and 22.5 Mg ha^{-1} by both top-dressing or by incorporation into the soil by hand mixing. The two tree species were planted in each biochar level × incorporation method treatment for a total of 12 normal treatments in three replications each. Each tree species also was grown in control treatments of pure mine soil and pure biochar. There were three replications of each treatment for a total of 42 pots.

Trees for the study were obtained as one-year-old bare root seedlings from the Virginia Department of Forestry's Augusta Forestry Center (Augusta County, VA). Once planted on 24 February, 2011, the trees were arranged in the greenhouse in a random layout, measured for biomass index ((root collar diameter)^2 X height) and grown at 21 – 24^{o}C. Water was applied as 15 min of mist nightly plus a weekly soaking to bring soils up to field capacity. Volunteer herbaceous vegetation in the pots was not controlled. 20 ml of liquid fertilizer was applied to each pot on 3 March, 11 April, and 7 July, which contained an average nutrient content of 169 mg l^{-1} orthophosphate, 23 mg l^{-1} nitrate and 621 mg l^{-1} ammonium.

2.4 Biomass harvesting

The trees and any herbaceous biomass growing in the pots were harvested and measured for biomass index and oven dry (105˚C for 12 hours) matter biomass on 2 November, 2011. Pots were then brought to field capacity and weighed, allowed to dry in the greenhouse until all remaining vegetation had fully wilted (20 January, 2012) and then weighed again to determine plant available water holding capacity. Roots were then washed of soil and rocks, visually assessed, photographed, oven dried and weighed to determine root biomass. In cases where rocks and soil could not be washed out of matted roots, the roots were weighed with the rocks, burned with open combustion and then just the rocks were weighed to determine the weight of the roots by difference.

2.5 Soil sampling

Soil samples from each column were dry sieved (#10, 2-mm screen) and analysis was conducted by the Virginia Tech Soil Testing Laboratory for properties including: organic matter percentage by loss on ignition, soil solution pH, plant (Mehlich-3) extractable Ca, P and K, and soluble salts by electrical conductance (Maguire and Heckendorn 2011). Sub-samples were further processed in a ball mill and then total soil C and N were determined by dry combustion with an Elementar varioMAX CNS macro element analyzer (Elementar, Hanau, Germany). Photographs of washed roots and light microscope and scanning electron microscope images were taken of biochar materials used in the experiment.

Table 1. Properties of mine spoil material from Wise County, Virginia used in materials for soil columns and planting pots for biochar trials on soil properties and tree growth effects.

Mine Spoil Property	Value
Coarse fragments (> 2 mm)	64%
Brown sandstone	53%
Gray sandstone	44%
Siltstone	1%
Shale	0%
Coal	3%
Fine fraction (< 2 mm)	36%
Sand	45%
Silt	28%
Clay	27%
pH (1:1 Soil:Water)	5.62
Soluble salts (1:2 Soil:Water)	120 mg kg^{-1}
CEC	5.0 $cmol_{q+}$ kg^{-1}
Base saturation	100%

2.6 Experimental design

The experiment had a 2 x 2 x 3 + 4 (species x application method x biochar level + pure biochar and pure mine soil controls for each tree species) factorial structure and was conducted and analyzed as a completely randomized design with three replications per treatment using JMP software (SAS Institute, Cary NC) and Tukey HSD mean separations at the alpha = 0.05 level following ANOVA.

3 Results

Pine sawdust underwent some shrinkage and fracturing during the fast pyrolysis process, but remained nearly the same size and shape as is evident from light microscope imagery (Figures 1 and 2). Scanning electron microscope imagery (Figure 3) confirmed that wood tracheids remained intact with typical tracheid diameters on the order of 5 µm. Reference data before and after weathering are shown in Table 2. Increasing biochar application increased organic matter content and total carbon, but decreased the extractable P, Ca and Fe (Table 3).

Figure 1. Light microscope image of loblolly pine (*Pinus taeda*) sawdust used for biochar feedstock (1 mm scale shown).

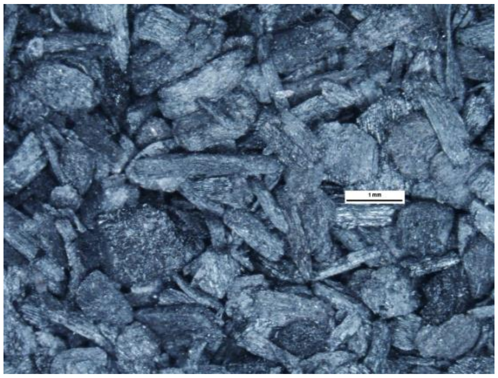

Figure 2. Light microscope image of loblolly pine (*Pinus taeda*) sawdust biochar from fast pyrolysis (1 mm scale shown).

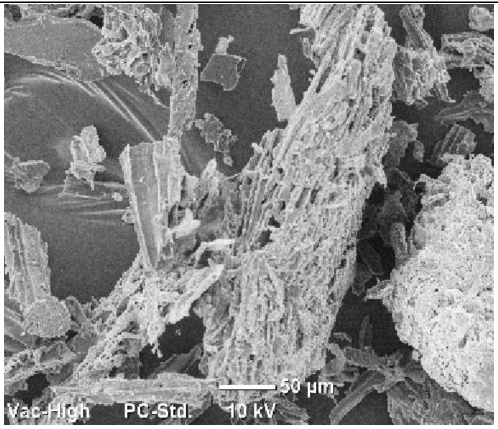

Figure 3. Scanning electron microscope image of loblolly pine (*Pinus taeda*) sawdust fast pyrolysis biochar (50 um scale shown).

Table 2. Mine soil and pine sawdust biochar properties (SS = Soluble Salts, SHC = Saturated Hydraulic Conductivity) by application rate (Mg ha^{-1}) before (pre) and after (post) six months of weathering with rain water (n = 3).

Biochar Rate Mg ha^{-1}	Pre / Post	**pH**	**Tot N mg kg^{-1}**	**P mg kg^{-1}**	**K mg kg^{-1}**	**Ca mg kg^{-1}**	**Base Sat. %**	**Org. Mat. g kg^{-1}**	**Total C g kg^{-1}**	**SS mg kg^{-1}**	**SHC cm min^{-1}**
0	Pre	5.35	1.0	34	59	648	76	17	24.0	124	--
0	Post	5.68	0.9	32	82	676	85	16	23.2	107	0.12
2.3	Pre	5.17	1.0	32	59	625	77	18	23.5	115	--
2.3	Post	5.53	0.9	32	80	658	85	17	24.5	98	0.00
11.2	Pre	5.17	1.0	32	60	634	77	19	26.4	124	--
11.2	Post	5.50	0.9	31	79	623	85	20	26.6	107	0.00
22.5	Pre	5.19	0.9	31	60	661	76	23	27.6	137	--
22.5	Post	5.63	0.9	29	74	604	85	22	28.3	73	0.00
100%	Pre	6.63	1.1	16	38	81	78	962	317.2	73	--
100%	Post	7.55	1.0	10	56	87	100	982	300.1	42	7.33

Table 3. Soil properties in response to biochar level following six months of weathering in soil columns. Treatments within rows having different letters differ at α = 0.05 based on Tukey's HSD (n = 3).

	Biochar amendment rate, Mg ha^{-1}			
Property	0	2.3	11.2	22.5
P mg kg^{-1}	32.3 a	32.0 a	31.0 ab	29.3 b
Ca mg kg^{-1}	676.3 a	657.7 ab	622.7 bc	603.7 c
Fe mg kg^{-1}	55.9 a	53.1 a	51.7 a	47.0 b
OM g kg^{-1}	16 c	17 c	20 b	22 a
Total C g kg^{-1}	23 c	25 bc	27 ab	28 a

No interaction effects among tree species and other treatment factors were identified at the α = 0.05 level, and all main effects were evaluated across all levels of the other factors, rather than evaluating and reporting each individual treatment combination effect. Trees grown in 100% biochar had greater root biomass compared with tree roots from the un-amended mine soil (Table 4). All levels of biochar application increased aboveground biomass growth compared to the un-amended mine soil. Black locust had greater root biomass and a greater above-ground woody biomass than American sycamore. The 100% biochar treatment also had the greatest volumetric water holding capacity (VWHC), and that variable increased significantly with increasing levels of biochar application (Table 5).

Trees grown in pure spoils tended to have a weakly developed root structure (Figures 4 and 5) that followed gaps between coarse fragments and along the pot wall. Pure biochar produced the fullest root structures for both black locust (Figure 6) and American sycamore (Figure 7). These roots grew well without competing herbaceous vegetation (due to the absence of herbaceous plants from seeds and scions in the new biochar material). Herbaceous biomass and above-ground woody biomass were negatively correlated (r = -0.483, p = 0.000).

Table 4. Average biomass of two tree species grown in mine spoils amended with five levels of pine sawdust biochar. Significant differences (indicated by different letters next to values in columns, mean separation by Tukey HSD, α = 0.05) are shown by biochar level, application method and tree species for each spoil type following one growing season. Root biomass and woody biomass were transformed by Log_{10} for mean separations due to high standard errors. Standard errors of means are in parentheses.

	Root Biomass (g)	**Above-ground Wood Biomass (g)**	**Herbaceous Biomass (g)**
Biochar Rate			
100%	99.9 (27.5) a	33.4 (6.8) a	0.2 (0.2) a
22.5 Mg ha^{-1}	37.7 (8.5) ab	19.1 (2.3) a	5.2 (1.5) a
11.2 Mg ha^{-1}	40.6 (6.8) ab	20.7 (2.5) a	4.0 (1.2) a
2.3 Mg ha^{-1}	30.0 (3.3) ab	25.7 (4.0) a	2.6 (2.0) a
0.0 Mg ha^{-1}	46.9 (23.6) b	10.9 (2.6) b	6.7 (1.6) a
Application Method			
Top Dressing	40.2 (3.8) a	24.1 (2.7) a	2.4 (0.8) a
Mixed	32.0 (6.4) a	19.6 (2.2) a	5.4 (1.6) a
Species			
Black Locust	61.0 (12.7) a	24.4 (2.9) a	4.4 (1.0) a
American Sycamore	30.2 (3.5) b	17.0 (1.6) b	3.8 (1.1) a

Table 5. Volumetric water holding capacity results from applications of five levels of pine sawdust biochar to two tree species growing in mine soils showing significant differences (indicated by different letters next to values in columns, mean separation by Tukey HSD, α = 0.05) by biochar level and application method following one growing season. Standard errors of means are in parentheses.

		Volumetric Water Holding Capacity (%)
Biochar Rate	100%	49.8 (2.0) a
	22.5 Mg ha^{-1}	18.6 (0.6) b
	11.2 Mg ha^{-1}	16.3 (0.5) bc
	2.3 Mg ha^{-1}	14.9 (0.4) cd
	0.0 Mg ha^{-1}	13.4 (0.5) d
Method	Top Dressing	16.8 (0.5) a
	Mixed	16.5 (0.6) a

Figure 4 and 5. Black locust roots (left) and American sycamore and grass roots (right) growing in pure mine soil with no biochar additions following one growing season.

Figure 6 and 7. Black locust root (left) and American sycamore roots (right) growing in pure pine sawdust biochar following one growing season.

4 Discussion

Applications to mine soils by either topdressing or mixing of 2.3 - 22.5 Mg ha^{-1} of pine sawdust biochar produced through fast pyrolysis had significant positive effects on above-ground tree growth over a single season. Pure biochar also produced more root biomass than the pure mine soil and is a potential medium for the early propagation and growth of tree seedlings. There was a clear advantage in terms of increased woody biomass growth of trees grown in pure biochar in these experiments. This was likely due to the faster root growth, higher water holding capacity and the lack of competing herbaceous vegetation in the pure biochar. Studies on use of biochar to remediate coal fly ash storage sites have shown that it improves chemical properties for plant establishment (Belyaeva and Haynes 2011). However, it was found to not have enough N and labile C to improve plant growth in those studies, indicating the need for supplemental use of fertilizer or compost. It is also clear that black locust has higher early growth rates than American sycamore, both above and below-ground. This is consistent with its being a fast-growing, early-successional legume tree species.

Biochar could be priced on its energy value at the time of this experiment, which is comparable to that of metallurgical coke (Moss 2010). Coke prices have varied widely based on demand trends in recent years (www.steelonthenet.com/files/blast-furnace-coke.html) costing between 167 US Dollars (USD) Mg^{-1} and 400 USD Mg^{-1}. To purchase low-cost (200 USD Mg^{-1}) biochar and apply at the high rates trialed here (22.5 Mg ha^{-1}) across the landscape would require 1,000 USD ha^{-1} invested (before considering the cost of application). Under current conditions, and with no value for carbon sequestration, it is unlikely that this would be an economical way to grow trees on mined lands for use as a profitable bioenergy crop. Baker (2008) found reclamation costs to total 4,284 ha^{-1} in 2018 USD (http://www.usinflationcalculator.com/), so the cost of biochar materials at the high rate would increase reclamation costs by at least 23%. However, if added directly into the planting holes of the bare root seedlings planted on mined sites at a volume comparable to the volumes of pots used in this study (4 L), then young trees could be expected to have improved early survival and growth and thus better establishment. This would cost 341 USD ha^{-1} in biochar material for 2,500 trees planted ha^{-1} (assuming a biochar bulk density of 0.13 g cm^{-3}) and would be expected to produce an initial effect comparable to spreading the biochar across the entire site at the experimental rate. This treatment is economically feasible and would benefit seedling performance. However, this effect would be limited to the period of establishment before the tree roots grew out of the planting hole. As a growth media, biochar has proven suitable for use in plant containers for nurseries (Dumroese et al. 2011), as a substitute for vermiculite in potting mixes (Headlee et al. 2014), and as a superior material for hydroponic production (Nichols et al. 2010). It also can reduce rainwater runoff and nutrient discharge in green roof applications (Beck et al. 2011).

The superior ability of biochar to retain water as compared to sandy soils (Zhang et al. 2016) could also be beneficial for mine land reclamation sites that have high levels of sandstone or other coarse materials. They reported that increasing biochar application amounts reduced saturated hydraulic conductivity in sandy soil. Their results contrasted with the high saturated hydraulic conductivity of pure biochar used in this experiment. These differences may be due either to the greater porosity of the biochar in this experiment compared to theirs or because of the very low saturated hydraulic conductivity of the unamended mine soil material used in this experiment.

Biochar made from poultry litter increased water-holding capacity in pot experiments, contributing to increased lettuce seed germination (Revell et al. 2012a), increased available P in proportion to its application rates, contributing to faster maturation of tall fescue on a field site (Revell et al. 2012b) and increased soil cation exchange capacity at high rates, but the salt content was toxic to plants at application rates greater than 2.5% by weight (Revell et al. 2012a). Care must be taken in choosing the type of biochar used, based on its feedstock, especially in high-rate applications, as there are clear differences between wood-based and manure or litter-based biochars.

Container size may also have limited our ability to fully measure treatment effects. Tree roots in char-amended soils often were pot-bound when measured at the end of the growing season. These trees may have reached a growth plateau prematurely in the season, lessening the degree to which treatment effects could be expressed and observed. Herbaceous above-ground biomass was negatively correlated with woody above-ground biomass and may have also been a contributing factor, negatively affecting woody growth due to competition for water and other resources.

Future field studies will incorporate treatments which include use of biochars derived from woody biomass as well as assess integration of regional municipal biosolids as sources of nutrients and labile carbon. These biochars will be tested as amendments applied either as a broadcast treatment across a site or directly as backfill to tree planting holes as well as other potential agricultural crops including industrial hemp. Improved growth would be expected compared to un-amended mine soil. A field study carried until harvest would better inform logistical and economic questions about using pyrolysis technology or HGE’s Renewable Diesel technology to enhance reclamation efforts in Appalachia.

Using HGE as a benchmark as well as IRDI’s proven Living-Lab Platform, when the two facilities in Central Appalachia are established in the region, the biochar produced can then be added to the mine soils by incorporation into the soils adjacent to trees in plantations in order to realize the goal of carbon-negative, soil-regenerative bio-energy project designed to accelerate the transition of the Central Appalachian coalfields. As a captive resource (i.e. not having to be bought off the market at the coke price), biochar might be more financially feasible for application in large amounts with dedicated energy systems, although this will depend on several factors, including potential credits for sequestered carbon and the value of other products leaving the facility.

5 Conclusions

The pure biochar treatment produced greater root biomass than the pure mine soil. All of the biochar treatments produced greater average above-ground woody biomass than the pure mine soil, although no differences were detected between application rates. High biochar applications increased soil volumetric water holding capacity compared to pure mine soil. Topdressing and full incorporation of biochar were not significantly different in their effects on biomass. Pine biochar should help young seedlings grow faster above-ground in mine soil when either broadcast or concentrated in planting holes. Root growth would also be enhanced by concentrating this biochar in planting holes. Due to the economics of topdressing biochar versus mixing it into planting holes, we recommend mixing 4 l of pine biochar into the backfill of each planted tree as the optimal application method.

6 Acknowledgments

Many thanks to those who made this research possible including: J. Eric Mathis with the Institute for Regenerative Design and Innovation (formerly The JOBS Project), Keith Pauley with the Mid-Atlantic Technology, Research and Innovation Center for providing funding, and Ken Moss with Piedmont Bioproducts for providing biochar material.

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