Biochar Enhances First Year Survival in Hardwood Plantings

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Contents

Abstract

After the passage of the Surface Mining Control and Reclamation Act in 1977, surface mining reclamation practices have often resulted in grass-dominated systems that are overtaken by invasive and/or non-native species, rather than the restoration of native forest ecosystems. In turn, the Appalachian Regional Reforestation Initiative developed the Forestry Reclamation Approach to enhance forest establishment on mined lands. First-year survival of bareroot seedlings (scarlet oak, white oak, and black locust) across three microsites (flat, slope, bottomland) was studied to evaluate the effectiveness of biochar, a wood-derived soil amendment, at a reclaimed gravel mine in Erie County, Pennsylvania. Seedlings were planted with and without biochar, with treated seedlings receiving biochar at a 12% backfill rate, and survival was assessed after one growing season. Overall, biochar increased survival from 89.7% to 93.7%, with the largest gains observed on slope microsites (+7.6%) and scarlet oak (+7.7%). Logistic regression confirmed a significant treatment × microsite interaction, highlighting context-dependent benefits. Beyond improving survival, biochar supports long-term soil carbon storage and can create markets for underutilized forest products, enhancing both ecological and economic outcomes in reforestation efforts. These findings support targeted biochar application as a practical strategy to increase reforestation success on reclaimed lands.

1. Introduction

Since the early 20th century, millions of acres of land in the United States have been surface mined, creating a substantial need for effective reclamation strategies. (Skousen, J., & Zipper, C. E., 2014). Following the passage of the Surface Mining Control and Reclamation Act (SMCRA) in 1977, early reclamation practices emphasized rapid stabilization and compliance, resulting in the widespread conversion of mined lands to grass-dominated systems rather than the restoration of native forest ecosystems. In response, the Appalachian Regional Reforestation Initiative (ARRI) developed the Forestry Reclamation Approach (FRA) to restore productive native forests on mined lands in Appalachia (and similar regions) by providing science-based best management practices that replace traditional grass-dominated reclamation with high-survival tree planting and ecosystem recovery under SMCRA (USFS, 2017). This field study builds on the FRA framework by testing amendments and evaluating growth/survival to provide empirical evidence to improve forest restoration outcomes on reclaimed mine sites.

Bareroot seedling survival is often difficult during the first growing season after planting due to stressors such as drought, deer browse, transplant shock, competing vegetation, pests/disease, and poor planting stock. Biochar derived from wood waste was utilized as a bareroot planting amendment to investigate survival and long-term growth (Figure 1). Biochar is an economically viable soil amendment that increases water-holding capacity and improves soil structure while providing long-term carbon storage. The goal of this study was to determine appropriate application rates and locations where biochar amendments can provide a meaningful increase in survival to facilitate biochar amendments at scale for large reforestation projects.

Figure 1. Planted White Oak Seedling (Biochar Applied)

2. Methods

2.1 Site Layout

The study was conducted at a reclaimed gravel mine in Erie County, Pennsylvania (Figure 2). Site preparation occurred approximately six months prior to the planting date, consisting of invasive species control and deep soil ripping on an 8 ft x 8 ft grid. Historical aerial imagery was reviewed prior to field layout to ensure the study captured areas most impacted from past mining activity. The project was then laid out in the field using a stratified randomized design. Planting sites were stratified by microsite type (flat, slope, bottomland) to account for variation in soil moisture, competing vegetation, and other environmental factors. Within each microsite stratum, planting holes were monumented with an aluminum numeric tag and randomly assigned to treatment (biochar) or control plots. This design allowed for the evaluation of treatment effectiveness while controlling for site heterogeneity.

2.2 Microsite Description

The flat microsite consisted of an open field with minimal relief. It was dominated by herbaceous vegetation, including orchard grass (*Dactylis glomerata*), timothy (*Phleum pratense*), Queen Anne's lace (*Daucus carota*), and birdsfoot trefoil (*Lotus corniculatus*). Soil consisted of a silt loam matrix with a high gravel content. Cross-ripping was conducted before planting to disrupt existing sod and reduce compaction. Across the microsite, suppression from the existing sod thatch was low, with localized exceptions. A representative photograph of the flat microsite is shown in Figure 3(a).

The slope microsite abutted the flat microsite and exhibited a moderate gradient with slopes ranging from approximately 10%–25% (ft/ft). Vegetation was dense and dominated by forbs, primarily mugwort (*Artemisia vulgaris*) and goldenrod (*Solidago* spp.), with scattered woody shrubs including multiflora rose (*Rosa multiflora*) and bush honeysuckle (*Lonicera* spp.). Soil conditions throughout this microsite differed from those observed in the flat and bottomland microsites. They were primarily characterized by unconsolidated material (likely imported from offsite) with intermixed concrete and other debris. Cross-ripping was conducted before planting to reduce compaction and disrupt established vegetation. Residual suppression from existing vegetation was moderate to high, largely due to dense mugwort cover. A representative photograph of the slope microsite is shown in Figure 3(b).

The bottomland microsite abutted the slope microsite and was characterized by minimal topographic relief, poor drainage, and persistently moist soils. Soil color and texture were similar to those observed in the flat microsite. Vegetation was dominated by grasses and forbs, including orchard grass (*Dactylis glomerata*), reed canary grass (*Phalaris arundinacea*), white clover (*Trifolium repens*), and buttercups (*Ranunculus* spp). Cross-ripping was conducted before planting to reduce compaction and disrupt established vegetation. Residual suppression from existing vegetation was generally low, with localized exceptions. A representative photograph of the bottomland microsite is shown in Figure 3(c).

2.3 Biochar Application

Immediately before planting, biochar was incorporated into the planting hole using a shovel at a 12% backfill mix, assuming total planting hole dimensions of 5" diameter x 12" deep (*i.e.,* 16 fl oz biochar mixed in). The biochar used in this study was derived from a softwood feedstock and had a high fixed carbon content (64.5% on a dry basis) with low volatile matter and minimal nitrogen and sulfur concentrations. These properties are consistent with a stable, porous amendment that may improve soil moisture retention and nutrient availability in coarse, low organic mine soils during early seedling establishment (Antonangelo, Sun, & Eufrade-Junior, 2025).

2.4 Year One Monitoring

Bareroot woody seedlings were planted on May 13, 2025, by professional tree planters at a density of 680 stems per acre, consisting of scarlet oak, white oak, and black locust. The seedlings were evaluated in October of 2026 to determine survival, growth, and observed stressors. At each monumented planting location, stems were classified as alive, dead, or missing, and data including species, initial stem diameter, bareroot seedling height, year one height, drought stress rating, suppression rating, and other relevant observations were recorded. Treatment assignment was verified during monitoring by confirming the presence or absence of biochar in the planting substrate to ensure consistency with the field layout.

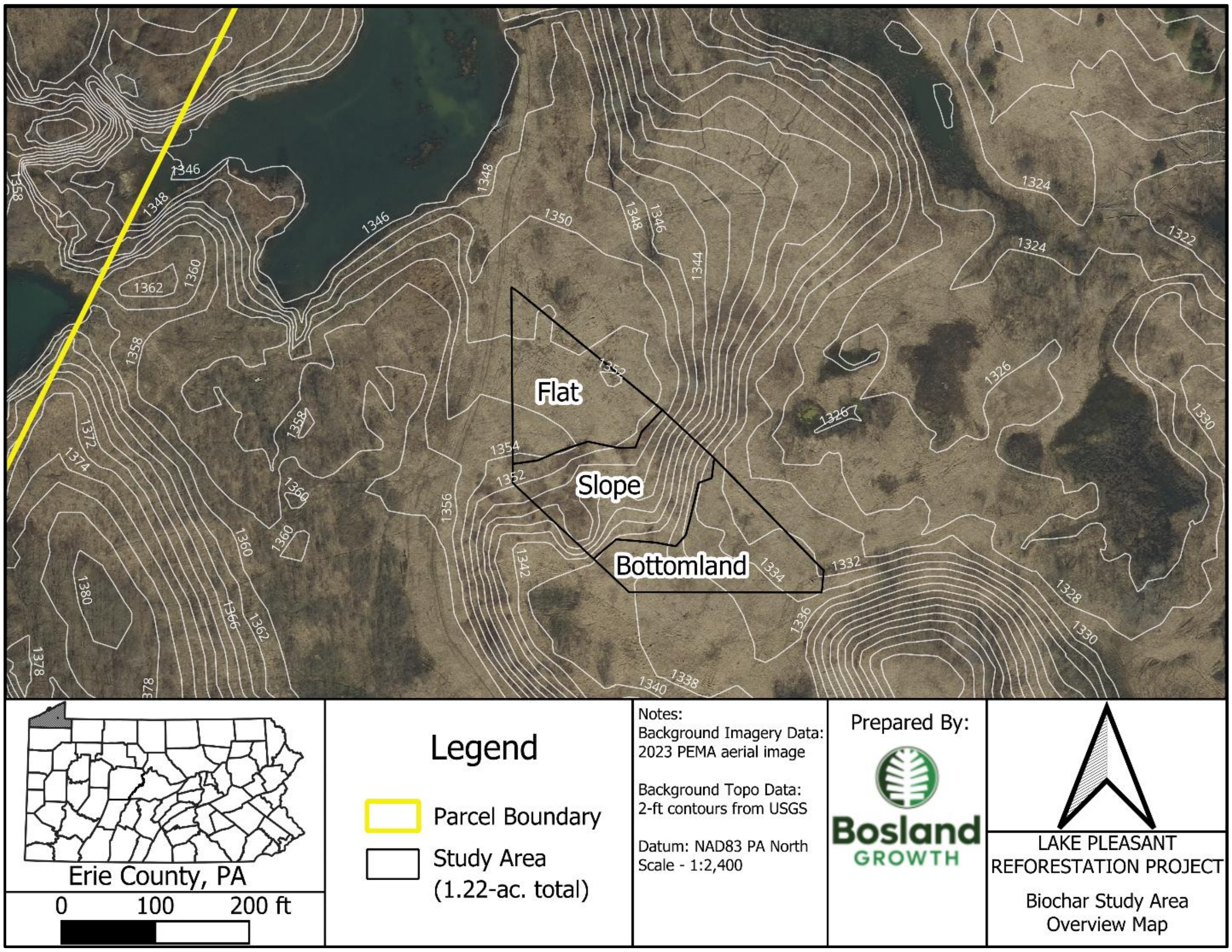

Figure 2. Biochar Study Area Overview Map

Figure 3(a). Flat

Figure 3(b). Slope

Figure 3(c). Bottomland

Figure 3. Representative Photos of Microsites

3. **Results**

3.1 First Year Survival by Treatment, Microsite, and Species

Three species were studied to analyze survival, growth rate, and stress response, as well as determine the applicability and utility of amending bareroot seedlings with biochar during reforestation planting (Table 1).

Table 1. First-year Seedling Survival (%) by Treatment, Microsite, and Species

Table 1a. Overall Survival

Treatment	Seedlings Living	Seedlings Dead	Survival %
Biochar	388	26	93.72%
Control	373	43	89.66%
Total	761	69	91.69%

Table 1b. Survival by Microsite

Microsite	Biochar		Control		Difference (Survival %)
	Sample Size	Survival %	Sample Size	Survival %	
Flat	139	92.81%	139	91.37%	1.44%
Slope	145	95.17%	145	87.59%	7.58%
Bottomland	130	93.08%	132	90.30%	2.78%

Table 1c. Survival by Species

Species	Biochar		Control		Difference (Survival %)
	Sample Size	Survival %	Sample Size	Survival %	
black locust	151	97.35%	169	97.63%	-0.28%
white oak	119	94.96%	108	91.67%	3.29%
scarlet oak	142	90.14%	131	82.44%	7.70%

Biochar application increased first-year seedling survival, with the strongest effects occurring under stressful microsites and in more drought-sensitive species. The results revealed high survival across the study (Biochar = 93.7%, Control = 89.7%). An evaluation of survival by microsite showed the largest gains occurred on slopes, where survival increased from 87.6% in controls to 95.2% with biochar (+7.6%), whereas bottom and flat microsites showed smaller differences (bottom: 90.3% → 93.1%; flat: 91.4% → 92.8%). Species-level responses were also consistent with differences in early establishment stress tolerance: scarlet oak benefited most (82.4% → 90.1%, +7.7%), white oak showed moderate gains (91.7% → 95.0%), and black locust, a nitrogen-fixing pioneer species, exhibited little change (97.6% → 97.4%).

3.2 Logistic Regression Analysis of Seedling Survival

To analyze treatment effects while accounting for species, microsite, and suppression, logistic regression was utilized with first-year survival as the response variable. The model included interactions between treatment and both species and microsite to capture context-dependent effects. In the model, black locust under control treatment in the bottomland microsite with the lowest suppression rating served as the reference category, so all other coefficients represent differences relative to this baseline. The data summary output from R statistical software (v4.5.2) is shown in Table 2.

Table 2. Logistic Regression Coefficients for Seedling Survival

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Call:
glm(formula = Survival ~ Treatment * Species + Treatment * Microsite +
    Suppression, family = binomial, data = data)

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)               4.1825     0.6154   6.797 1.07e-11 ***
TreatmentB               -0.7341     0.8398  -0.874   0.3821
Speciesso                -2.1944     0.5581  -3.932 8.42e-05 ***
Specieswo                -1.4137     0.6209  -2.277   0.0228 *
MicrositeFlat            -0.1595     0.5021  -0.318   0.7507
MicrositeSlope           -0.1195     0.6029  -0.198   0.8428
Suppression2             -0.7675     0.4911  -1.563   0.1180
TreatmentB:Speciesso      0.7702     0.8065   0.955   0.3396
TreatmentB:Specieswo      0.8191     0.9071   0.903   0.3665
TreatmentB:MicrositeFlat  0.1930     0.7079   0.273   0.7852
TreatmentB:MicrositeSlope 1.4052     0.7172   1.959   0.0501 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 429.29  on 819  degrees of freedom
Residual deviance: 390.25  on 809  degrees of freedom
AIC: 412.25

Number of Fisher Scoring iterations: 6

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The interaction between biochar and slope microsites was significant (log-odds = 1.41, $p \approx 0.05$), confirming that biochar improved survival most strongly under water-limited, stressful conditions.

Interactions between biochar and species were positive for scarlet oak and white oak, indicating higher responsiveness, although these were not statistically significant due to high baseline survival in black locust.

4. Discussion/Practical Implementation

4.1 Survival Responses to Biochar Across Microsites and Species

This field trial provides a cost-effective framework for targeting soil amendments during bare-root tree planting showing that biochar is most beneficial under baseline stress conditions associated with low soil moisture availability. Overall, the results indicate that biochar's benefits are context-dependent, emerging primarily in stressful microsites and in species with higher moisture sensitivity. At the same time, survival is already high in resilient species or favorable microsites. Logistic regression results showed no overall main effect of biochar on survival, but a significant treatment × microsite interaction, with the strongest positive response occurring on slope microsites, where water limitation is greatest. These findings suggest that biochar does not uniformly increase survival across all planting environments but instead offers its greatest benefit in stressful microsites where moisture and resource limitation constrain establishment.

Species responses were also context-dependent. The largest treatment-associated increase in survival relative to other species was exhibited by scarlet oak, which is consistent with both the descriptive survival data and the treatment × species interaction patterns observed in the model. Bare-root morphology variations may partially explain this response: scarlet oak seedlings typically exhibited a pronounced central taproot and relatively limited lateral root development compared with white oak, which may increase early sensitivity to soil moisture deficits. Enhanced water retention associated with biochar amendments may therefore have preferentially improved the establishment of scarlet oak seedlings under water-limited conditions. Microsite and species selection should be analyzed when using biochar amendments to maximize survival gains.

This report summarizes results from Bosland's initial field trial and represents a subset of a broader long-term research effort. While early findings suggest that biochar may improve seedling survival, overall mortality is expected to decline in subsequent years, as the highest losses typically occur during the first year after planting. Continued monitoring will be necessary to evaluate long-term survival, growth, and site productivity. Improvements in soil structure, soil nutrient availability, and woody biomass resulting from biochar application may take multiple years to manifest, and longer observation periods will be required to assess these outcomes.

4.2 Cost-Benefit Considerations

Investing in a biochar amendment during bare root planting offers both short-term operational cost savings and potential long-term carbon benefits. Planting at a density of 680 trees per acre and 12% backfill mix resulted in a biochar material cost of $101.23 per acre. Although this adds to upfront material and labor costs compared to untreated plantings, higher first-year survival reduces early losses and helps maintain stem density, supporting faster progress toward long-term FRA stocking targets. In the short-term, a 4% increase in first-year survival equates to approximately $33 per acre in avoided replanting costs, partially offsetting the upfront biochar material cost. However, these upfront costs may be offset even further given that increased early survival improves the probability of maintaining higher stand density, which can translate into greater cumulative biomass. If a higher stocking density persists through stand development, there is the potential to yield four to six extra metric tons CO_2e per acre across a 60-year crediting period, assuming an overall four percent increase in survival and equal growth rate among surviving stems. While long-term outcomes depend on stand development, the modest cost associated with using a biochar amendment during planting is likely to be partially offset in the short term via avoided replanting costs and further mitigated over the long term, as improved early establishment creates the conditions for higher biomass and carbon accrual.

4.3 Practical Implementation

Based on the results of this field trial, Bosland intends to utilize biochar at future sites on landforms similar to the slope microsite, where competing vegetation is dense and water holding capacity is sub-optimal. Additional applications are also proposed at a recently reclaimed coal refuse site, where biochar may be used for its filtration capacity. In these areas, biochar would be incorporated into drainage swales perpendicular to surface flow and keyed into the substrate to function as low-profile check dams. These features would slow runoff and promote filtration of remnant metals and other pollutants mobilized from refuse materials before reaching newly planted seedlings and the West Branch of the Susquehanna River immediately downslope.

Producing biochar from underutilized wood, such as pulpwood, offers both economic and environmental benefits beyond improving reforestation outcomes. Biochar production can generate revenue from low-grade wood that is often left onsite during selective harvests by creating a market for materials that currently have limited value. This economic incentive may support more sustainable forest management practices by encouraging the productive use of low-grade forest products that would otherwise remain unused and contribute to long-term declines in forest health. Biochar also locks carbon in a stable form that can persist in the soil for thousands of years, thus serving as a pathway for long-term carbon sequestration (Kuzyakov et al., 2014). This characteristic aligns reclamation practices with climate goals and enhances the environmental value of restored sites.

5.0 References

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