2022

EVALUATING RESTORATION OUTCOMES: RED SPRUCE REFORESTATION IN THE WEST VIRGINIA HIGHLANDS

Benjamin Rhodes
University of Kentucky, bmrhodes07@gmail.com

Digital Object Identifier: https://doi.org/10.13023/etd.2022.84

Recommended Citation

Rhodes, Benjamin, "EVALUATING RESTORATION OUTCOMES: RED SPRUCE REFORESTATION IN THE WEST VIRGINIA HIGHLANDS" (2022). *Theses and Dissertations--Forestry and Natural Resources*. 63.
https://uknowledge.uky.edu/forestry_etds/63

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student’s advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student’s thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Benjamin Rhodes, Student

Dr. Christopher Barton, Major Professor

Dr. Steven Price, Director of Graduate Studies

EVALUATING RESTORATION OUTCOMES: RED SPRUCE REFORESTATION IN THE WEST VIRGINIA HIGHLANDS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Forest and Natural Resource Sciences in the
College of Agriculture, Food and Environment
at the University of Kentucky

By

Benjamin Rhodes

Lexington, Kentucky

Director: Dr. Christopher Barton, Professor of Forest Hydrology and Watershed Management

Lexington, Kentucky

2022

ABSTRACT OF THESIS

EVALUATING RESTORATION OUTCOMES: RED SPRUCE REFORESTATION IN THE WEST VIRGINIA HIGHLANDS

Red spruce (*Picea rubens*) is the keystone species of the red spruce-northern hardwood forest, a unique high-elevation plant community that supports hundreds of animal species in the Central Appalachians. These forests were devastated by the Industrial Logging Era of the late 1800s and early 1900s, and they remain in a degraded and fragmented state. Current restoration efforts include red spruce plantings on old field sites and reclaimed coal mines. This project seeks to aid those efforts by evaluating restoration outcomes for vegetation and soils along a ten-year chronosequence. Specifically, the study aims to determine whether restoration site soils and vegetation are trending towards reference conditions, and how those trends vary between old field and reclaimed mine planting sites. Analysis revealed several promising trends in vegetation and soils. Additionally, red spruce planted on mined lands perform as well or better than those planted on old fields, owing in part to greater availability of soil nutrients on reclaimed surface mines.

KEYWORDS: Ecological Restoration, Forestry Reclamation Approach, Legacy Mined Land, Old Field, Reforestation, Red Spruce.

Benjamin Rhodes

04/27/2022

Date

EVALUATING RESTORATION OUTCOMES:
RED SPRUCE REFORESTATION
IN THE WEST VIRGINIA HIGHLANDS

By

Benjamin Rhodes

Christopher Barton

Director of Thesis

Steven Price

Director of Graduate Studies

04/28/2022

Date

ACKNOWLEDGMENTS

Thank you to the following individuals and organizations, who helped make this project possible. Dr. Chris Barton, my advisor and committee chair, provided consistent, timely guidance throughout the project. My advisory committee, Dr. John Lhotka, Dr. Jacob Muller, and Dr. Kenton Sena, asked thought-provoking questions and provided valuable feedback. My fellow graduate students, particularly Sarah Tomke and my FOR 601 classmates, have given me input and support at many points during the project. My field assistant, Jacob Jones, was invaluable during data collection. Many CASRI experts, including Dave Saville, Doug Manning, Mike Elza, and Amy Lovell, lent me their time and expertise. Several organizations collaborated with me for experimental planning and site access, including The Nature Conservancy in West Virginia, the Monongahela National Forest, Canaan Valley State Park, and Canaan Valley National Wildlife Refuge. The University of Kentucky Appalachian Center provided valuable funding through the Eller and Billings Student Research Award. Lastly, many thanks to Briana Snyder for all of her technical and moral support over the past two years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Red spruce (Picea rubens) is a keystone species of high-elevation Central Appalachian forests. It is the linchpin of a unique plant community that supports hundreds of animal species, including many rare, threatened, and endangered species. Red spruce ecosystems in the Central Appalachians were devastated by the Industrial Logging Era of the late 1800s and early 1900s, and they remain in a degraded and fragmented state throughout most of their former range (Byers et al. 2010). This reduction in range and connectivity greatly impacts the long-term sustainability of Central Appalachian spruce-hardwood forests, especially in light of predicted climate-driven range shifts (Beane and Rentch 2015).

A partnership of over eighteen state, federal, and private organizations known as the Central Appalachians Spruce Restoration Initiative (CASRI; restoreredspruce.org) works to restore resilience and connectivity to these forests. CASRI's restoration projects include red spruce plantings on legacy mined lands and old-field sites, involving hundreds of personnel and hundreds of thousands of trees per year. These large-scale projects depend on timely acquisition of reliable, quantitative data on planting efficacy.

The partnership has implemented short-term (1-2 year) efficacy monitoring on many of its restoration sites, but there is little information on the mid-term (5-10 year) results of these tree plantings. This project seeks to fill this knowledge gap. CASRI scientists and practitioners provided input on research needs and study design, helping to ensure that this study provides useful and timely information for ongoing restoration projects.

This study aims to determine the mid-term impacts of red spruce restoration plantings on the vegetation and soils of reforestation sites in the highlands of east-central West Virginia. Specifically, the study aims to answer three questions:

1. How does restoration planting efficacy vary between restored mined lands and restored old-field sites? Discovering the nature and causality of this variation will greatly enhance land managers' ability to choose ideal sites for red spruce restoration plantings. Common knowledge suggests that old-field plantings should perform better, as mined sites have been subjected to extensive environmental degradation and are generally considered to be poor-quality planting sites.
2. Are restoration sites on a trajectory towards the target ecosystem's vegetation composition? Knowing whether sites are trending towards their target forest composition, and the drivers of variability in these trends, will help to determine whether any planting prescriptions require modification to produce the desired forest type.
3. Are restoration sites on a trajectory towards the target ecosystem's soil characteristics? Understanding the restoration sites' soil characteristics will provide insight on red spruce growth and vegetation composition in the mined and old field sites. Soils information may also be used to determine limitations in these disturbed landscapes that could influence the efficacy of the restoration activities.

The rationale for these research questions and objectives will be explored in greater detail in the literature review below.

CHAPTER 2. LITERATURE REVIEW

Red spruce restoration is vital for the long-term health of Central Appalachian forests. Red spruce is the keystone species of the red spruce – northern hardwood ("spruce-hardwood") forest type, which was once the dominant high-elevation forest type in the Central Appalachians and still serves as the primary habitat for hundreds of animal species (Byers et al. 2010). However, red spruce was virtually extirpated from the Central Appalachians during the Industrial Logging Era of the late 1800s and early 1900s. Without red spruce, the spruce-hardwood forest did not recover from the landscape-scale clearcuts and raging wildfires of the Industrial Logging Era (Korstian 1937). The demise of the spruce-hardwood forest, in turn, imperiled many of the animal species that rely on it for habitat. Today, West Virginia's spruce-hardwood forest has naturally regenerated on only about 50,000 acres, or 10% of its pre-logging range, and these second-growth forests are scattered across numerous isolated and fragmented patches (Byers et al. 2010). These trends of deforestation and recovery are typical of Central Appalachian spruce-hardwood forests. This unique forest type has lost much of its original resilience, connectivity, and ecological value. Additionally, climate change poses a severe threat to red spruce ecosystems in the Central Appalachians, with an 85% reduction in spruce-suitable habitat predicted for West Virginia by the year 2080 under conservative climate models (Beane and Rentch 2015). This prediction essentially sets a time limit for the reestablishment of large, healthy, climate-resilient spruce-hardwood forests.

With many spruce-dependent wildlife species in serious decline, and with rising extinction pressure from climate change, active restoration of the spruce-hardwood forest is imperative to ensure the long-term health of Central Appalachian forests. Studies have shown that active restoration is a critical supplement to passive protection (Thomas-Van Gundy and Sturtevant 2014), and large coalitions of conservation organizations have implemented active restoration across broad swaths of the Central and Southern Appalachians (CASRI 2010; SASRI 2014). However, little quantitative research has been performed to evaluate the efficacy of these active restoration projects.

Active restoration of red spruce is particularly critical in open, non-forested areas. Red spruce has a low rate of natural recruitment in open areas such as old fields (Cavallin and Vasseur 2008) and, likely, abandoned mined lands. This is due in part to its extremely specific light requirements; it is dependent on advance reproduction, germinating in the low-light conditions of a mature forest understory and only responding to increased light levels after several years of understory growth (Burns and Honkala 1990). Germination and emergent seedling survival are negatively affected by full sunlight (Westveld 1931). Additionally, red spruce seedlings have a strong preference for podzol soils, which form under conifer forests over hundreds of years (Stickel 1928) but degrade rapidly following deforestation (Barrett and Schaetzl 1998). These light and soil issues are compounded by the lack of mature, seed-producing red spruce trees throughout most of the species' former range. Therefore, many deforested open areas lack the light requirements, soil requirements, and seed source necessary for natural recolonization by red spruce. Natural recolonization of red spruce in these areas tends to produce small dense clumps with low interconnectivity, limiting its usefulness as habitat as well as its potential for seed dispersal (Fortney and Rentch 2003). Therefore, deforested open areas such as old fields and abandoned mined lands are crucial focal areas for active restoration of red spruce.

Both old field and abandoned mined lands pose unique challenges for restoration. The term “old field” refers to abandoned farmland, either pasture or row crops, which develops a unique vegetative community through secondary succession (Odum 1960). For the first several years following cessation of agriculture, this community is dominated by graminoids, which are then succeeded by forbs, which may then reach a steady state or follow a variety of successional pathways. Despite the vegetative changes, short-term site productivity typically stays stagnant and, in some cases, declines relative to crop production (Odum 1960). Additionally, old fields are prone to nutrient depletion, raising the potential for sub-optimal long-term plant growth (Stinner et al. 1984; Richter et al. 1994). However, despite these potential limitations on productivity, old fields generally have soil and vegetative conditions conducive to a wide variety of planting projects and are therefore a major focus of reforestation projects.

For decades, old fields have been the primary focus of large-scale reforestation efforts in the eastern United States. They offer near-ideal conditions for a variety of reforestation techniques with minimal site preparation and few requirements for specialized personnel, leading to generally high efficacy at very low cost per acre (Schweitzer et al. 1997). Old field reforestation techniques generally focus on the establishment of one to three major overstory species and rely on natural colonization of other native species to complete the target plant community (Allen 2008). While this natural colonization does not always occur, sometimes leading to long-term issues with community composition, old field reforestation is nevertheless considered to be a highly efficient and effective method of reestablishing native forests at the landscape scale (Schweitzer et al. 1997; Allen 2008).

Abandoned surface mines, on the other hand, have a long history of environmental degradation and costly, often ineffective, reclamation. In 1977, the federal Surface Mining Control and Reclamation Act (SMCRA) was passed, enacting a broad suite of reforms targeted at rectifying the widespread environmental issues caused by surface mining earlier in the twentieth century (Menzel 1981). Between 1977 and 2015, 2.4 million acres of mined lands in Appalachia were reclaimed using SMCRA practices (Barton et al. 2017a). Erosion, flooding, and subsequent pollution were several of the most extreme issues associated with early surface mines. Therefore, SMCRA reclamation involved several erosion control practices such as recontouring mined lands with compacted mined spoil and revegetating the site with fast-growing ground cover (Menzel 1981; Adams 2017). Due to this highly competitive, often non-native, early-successional vegetation, coupled with the compacted, rocky, organic-matter-poor soil, these sites often enter a state of arrested succession, in which successional pathways are blocked by poor growing conditions and the sites remain as low-productivity grasslands rather than succeeding towards shrubland and forest (Groninger 2017). Tree plantings on these sites often have extremely high mortality and stunted growth, and thus forest restoration is typically not incorporated into SMCRA reclamation (Barton et al. 2017b).

While this grassland reclamation is still the federal standard for surface mine reclamation, increased interest in reestablishing forests on legacy surface mines has led to the development of the Forestry Reclamation Approach (FRA) (Burger et al. 2017). This set of practices includes extensive site preparation, including soil decompaction and removal of non-native vegetation, to facilitate tree planting and to promote the survival and growth of planted seedlings. FRA practices have been adopted in many parts of the Central

Appalachians, including the high elevations of West Virginia, to restore native forests on SMCRA-reclaimed legacy mine lands.

In summary, while there are barriers to productivity and tree growth on both old fields and legacy mined lands, those barriers are much greater on mined sites than on old fields. Old fields have a well-documented history of low cost, high efficacy planting projects across a variety of forest types, whereas reforestation projects on mined sites face many physical, chemical, and biological challenges and can be costly. The FRA offers a novel approach that has proven generally successful in increasing the efficacy rates of legacy mined land reforestation projects, but its efficacy in restoring high-elevation conifer forests, as well as its efficacy relative to old field planting projects, have not yet been the subject of rigorous study. The spruce-hardwood forest type is unique in Central Appalachia, and the high elevations of Appalachia have a unique environmental history including extensive exposure to acid rain (McLaughlin and Tjoelker 1992). The relative success rates of old field and mined site FRA reforestation, particularly in this unique Central Appalachian ecosystem, represent a knowledge gap that this study aims to fill.

Data collection focused on meaningful metrics that can be quantitatively compared to the restoration projects' target reference conditions, namely the conditions of the red spruce-yellow birch forest type described by Byers et al. (2010). One such metric is ground cover vegetation. The spruce-birch forest type is typified by a unique distribution of ground cover categories: 8% cover in the short shrub stratum, 6% cover in the herbaceous stratum, and 53% cover in the non-vascular stratum (Byers et al. 2010). Reclaimed mined lands and old fields, on the other hand, will have much more herbaceous cover and much less non-vascular cover (Pickett 1982; Groninger et al. 2017). Therefore, broadly speaking, a successful red spruce restoration project on a field or mined site will see a gradual decrease in herbaceous cover and an increase in non-vascular cover as it approaches reference conditions.

Similarly, the podzol soils associated with mature red spruce forests are typified by unique conditions. Their organic horizons are known as folistic epipedons, meaning the organic layer is at least 15 cm in depth, and their mineral layers tend to have high cation exchange capacity, low pH, low base saturation, and low nutrient content compared to other West Virginia soils (Byers et al. 2010). Notably, nitrogen is the one major nutrient that has an above-average concentration in spruce-influenced soils relative to other forest soils of West Virginia (Byers et al. 2010). Moreover, they are characterized by eluviation of clay, metals, and organic material from their uppermost mineral horizons, leading to distinct patterns of stratification (Barrett and Schaetzl 1998). Soil characteristics at old-field sites vary based on past land use, and soil characteristics at former mined sites vary based on the reclamation approach used (Zipper et al. 2013; Sena et al. 2018). However, both site types will undoubtedly have soil chemistry and organic horizon depths that are markedly different from spruce-influenced reference conditions. While it can take centuries for spruce-associated soils to fully form, soil conditions on mined lands can improve rapidly after implementation of the Forestry Reclamation Approach (Miller et al. 2012; Sena et al. 2018; Littlefield et al 2013). Therefore, changes in soil should be observable over the course of these chronosequences, particularly for mined sites, and these changes can be compared against reference values for spruce-associated podzol soils to determine whether sites are trending towards reference soil conditions.

The literature outlined above is a critical component of this study. In combination with data gathered from REF, it provides the reference values against which sites' vegetation and soils will be compared, and it provides crucial context for evaluation of the relative performance of mined and old field sites.

CHAPTER 3. MATERIALS AND METHODS

3.1 Study sites

This study's project area is divided into three parts: three former mined sites, three old field sites, and one reference site. All seven sites are located in the highlands of eastern West Virginia. See Appendix A for site maps. The single reference site was supplemented by well-documented reference conditions in the literature: vegetation surveys from Byers et al. (2010) and Westveld (1931), and soil data from Byers et al. (2010) and SoilWeb (University of California and USDA NRCS 2019). Paired chronosequences were established by selecting one mined site and one old field site from each of the following ages: one, seven, and ten full growing seasons post-planting. The plantings for these age classes occurred in the spring seasons of 2020, 2014, and 2011, respectively, with the exception of the ten-year old field planting, which occurred in the fall of 2010. This difference in planting season would have negatively impacted the seedlings' initial (2010-2011) survival, as fall plantings are more vulnerable to first-winter mortality relative to spring plantings (David Saville, CASRI, per communication). This in turn would affect the present-day density (trees/acre) of the planted trees. It is not expected to directly affect any other experimental variables, although density changes could have secondary effects on spruce seedling performance.

The mined chronosequence sites will be referred to as M1, M7, and M10 for years one, seven, and ten, respectively. The old field chronosequence sites will be referred to as F1, F7, and F10 for years one, seven, and ten, respectively. The reference site will be referred to as REF.

The mined sites are located within the Monongahela National Forest (MNF) at a location known as the Mower Tract, a 40,000-acre parcel situated on top of Cheat Mountain at an elevation of 3,000-4,000 feet. The Mower Tract was historically dominated by red spruce-northern hardwood forests, which were completely clearcut during the Industrial Logging Era of the late 1800s to early 1900s. It was logged again in the mid-1900s, and then approximately 2,500 acres of the Mower Tract were strip mined in the 1980s. After mining operations ceased, the area was reclaimed by compacting the remaining soil, which mostly consisted of fragmented shale, and planting grasses and tree species, many of which were non-native. As of 2010, the mined lands on Mower Tract were in a state of arrested succession, dominated by poor-quality grasslands and patchy low-richness stands of stunted non-native conifers. To remediate these poor site conditions, the MNF partnered with the non-profit organization Green Forests Work (GFW) and other CASRI partners to restore the former mined lands. Large-scale restoration began in 2010 and has continued to the present day. This project’s mined land study sites are located in the recently-restored areas. All soils on the mined study sites are classified as Udorthents, mudstone and shale, low base.

F1 and F10 are located on conservation lands in Canaan Valley, West Virginia. Like the Mower Tract, Canaan Valley sits above 3,000 feet in elevation, was once dominated by red spruce-northern hardwood forests, and has a history of extensive logging.

After the Industrial Logging Era, many of the former forests were converted to pasturelands. Then, in 1971, Canaan Valley Resort State Park (CVSP) was established, beginning a trend of conserving former pastureland for conservation and recreation. CVSP, Canaan Valley National Wildlife Refuge (CVNWR), and other CASRI partners have conserved a large block of Canaan Valley, and beginning in the early 2000s those partners began restoring old fields to red spruce-northern hardwood forests. F1 and F10 are located on CVSP lands. The study sites' soils are Andisols, with the dominant Belmont series (Typic Hapludalfs) grading to the Calvin series (Aquic Fragiudalfs) in wet areas.

Due to a lack of Canaan Valley planting areas with appropriate site histories, F7 was located on private conservation land on Pharis Knob, West Virginia. This site's elevation (3500-3700 ft.) and latitude are intermediate between the Mower Tract and Canaan Valley. Like Canaan Valley, Pharis Knob was fully deforested during the Industrial Logging Era, and then the mountain's slopes were converted to pastureland. Low-intensity cattle grazing continued on the site until roughly 2012, when fences were built to keep cattle out of restoration areas. Like the Canaan Valley study sites, the Pharis Knob study sites' soils belong predominantly to the Belmont series, grading to the Calvin series (Inceptisol; Typic Dystrochrepts) on higher, steeper slopes. Overall, F7 is very similar to F1 and F10 in terms of climate and soil series, making it an appropriate addition to the old field chronosequence.

REF is located at an elevation of 4100 feet in a roughly 100-year-old red spruce stand near Gaudineer Knob, one of the peaks within the broader Cheat Mountain landscape. This site is not an old-growth stand; it was clearcut during the Industrial Logging Era and allowed to regenerate naturally. This is representative of the red spruce-yellow birch forest described by Byers et al. (2010), which is the standard restoration target for CASRI spruce plantings. The soils of this site belong primarily to the Gauley series of Spodosols.

These sites are comparable in terms of macroclimate and spruce suitability. All of them were historically dominated by red spruce forests, all are well within the interior of red spruce's current range (Byers et al. 2010), and all fall on or near the border of USDA plant hardiness zones 5a and 5b. The only exception is the seven-year-old field site on Pharis Knob, which lies fully within plant hardiness zone 5a. Its position relatively low on the mountain slope does, however, place it in the warmer area of zone 5a, making its climate fairly comparable to conditions at the other six sites (https://planthardiness.ars.usda.gov/).

3.2 Survey Methodology

At each of the six planting sites, eight survey transects were laid out, arranged in two groups of four. At the reference site, only one group of four transects was used, as the majority of reference information is drawn from vegetation and soil data provided by Byers et al. (2010), Westveld (1931), and SoilWeb (University of California and USDA NRCS 2019). To determine the locations of each transect group, each site was subdivided into small areas (5-10 acres) based on topography and other natural boundaries, and then two subdivisions were randomly selected as locations for the transect groups. Transects were arranged in groups due to the constraints of site geometry, not for the purposes of experimental blocking.

For each transect group, the origin of the first transect was located at a randomly-selected spruce seedling within the pre-selected subdivision. From the origin, the first transect was laid out along a random azimuth. The length of the transect depended on the density of the restoration planting being surveyed; it extended until it captured ten red spruce seedlings. These seedlings, and all other seedlings measured, fell within one meter on either side of the transect's center line, making the transect a total of two meters in width. The second, third, and fourth transects were laid out at right angles to the first transect, starting at the origin, midpoint, and endpoint, respectively, forming an "E" shape. These transects also captured ten spruce seedlings each. In the rare instances when transects were unable to capture ten spruce seedlings before leaving the planting area, additional seedlings were measured at random from the non-surveyed zones between transects. In the equally rare instances when transects ran through extremely dense areas of planted spruce, they were extended to a minimum of 20 meters, regardless of how many spruce were captured.

Along each transect, data collection included: species of each planted tree, distance between planted trees, 2020 growth (first internode length) of each red spruce, vigor of each red spruce (see below), and height of each planted tree. Additionally, within a 2x2m plot at the midpoint of each transect, category-based groundcover diversity was recorded. At the center point of each of these plots, soil samples were collected at depths 0-10 and 10-25 cm. Soils were analyzed for pH, P, K, Ca, Mg, Zn, total C and N, soluble salts, cation exchange capacity (CEC), base saturation, and texture. Soil pH was measured in a 1:1 soil:water paste, and soluble salts (soil electrical conductivity) was measured in a 1:3 soil:water solution with a conductivity bridge (Soil and Plant Analysis Council, 2000). Concentrations of P, K, Ca, Mg, and Zn were measured by Mehlich III extraction and analysis by ICP-MS (Inductively coupled plasma mass spectrometry) (Soil and Plant Analysis Council, 2000). Total C and N were quantified using a CHN

(Carbon/Hydrogen/Nitrogen) Analyzer (LECO Corporation, St. Joseph, MI, USA) (Nelson and Sommers, 1982). Particle size distribution was evaluated by the micropipette method (Miller and Miller, 1987). Cation exchange capacity and base saturation were assessed using the ammonium acetate method at pH 3 (Soil and Plant Analysis Council, 2000). See Appendix B for a sample data sheet. See Appendix C for soil data tables.

Vigor was assigned on a 0-5 scale, based on four common health indicators for red spruce seedlings: chlorosis, needle loss, branch loss, and malformation. Each seedling started with a score of 5, which was reduced by 1 for each health indicator observed. If the seedling was completely dead, it was assigned a score of 0.

Growth rate was measured separately and thus was not considered when assigning a vigor score. This growth rate measurement was taken by using 2020 annual growth as a proxy. 2020 annual growth was determined by measuring the first internode length of each red spruce seedling.

3.3 Data Analysis

Transects were the experimental unit for the overwhelming majority of analysis. The only exceptions were the two statistical indices described below for Question 2, which used site as their experimental unit.

Analysis of relative performance of mined versus old field sites (Question 1) was broken into three general steps. First, identify instances of significant variation in red spruce height, growth, and vigor between mined and old field sites at each year on the chronosequence. Second, determine the overall drivers of variability in red spruce height, growth, and vigor at each year on the chronosequence. Third, from within those overall drivers, identify the drivers that contributed most significantly to the instances of variation identified in the first step.

To identify instances of significant differences in red spruce height, growth, and vigor between mined and old field sites at each year on the chronosequence, nine one-way analyses of variance (ANOVAs) were performed: one for each of the three spruce variables at each of the three chronosequence time points. For each ANOVA, site type was the independent variable, and spruce height, growth, or vigor was the dependent variable. Each ANOVA was followed with a Tukey's Honest Significant Difference (HSD) test.

To determine the overall drivers of transect-level variability in red spruce height, growth, and vigor at each year on the chronosequence, a principal component analysis (PCA) was used to evaluate drivers of full-dataset (all site, soil, and vegetation variables) variability. These PCA results were used to determine the initial input variables for nine generalized linear models (GLMs): one for each spruce variable at each time point. These GLMs were then refined using stepwise regression. The resulting regression equations revealed the most influential variables driving overall variation in seedling height, growth, and vigor.

To then identify which of these overall drivers contributed most significantly to the instances of variation identified in the first step, another round of one-way ANOVA + HSD analyses was performed. For each ANOVA, site type was the independent variable, and one of the overall drivers was the dependent variable. Overall drivers that varied significantly with site type were identified as the primary drivers behind differences in red spruce seedling performance between mined and old field sites.

All of the above analysis was performed using R version 4.1.2 (R Core Team 2021), "agricolae" package (de Mendiburu and Yaseen 2020).

To evaluate whether restoration sites' vegetation is on a trajectory towards reference conditions (Question 2), Jaccard's Similarity Coefficient (JSC) was used to compare tree species composition of: (1) field to mined sites at each time point, (2) study reference site to literature reference conditions as described in Byers et al. (2010), and (3) each site to literature reference conditions. JSC is a simple index of similarity between two groups: in this case, groups of tree species (Jaccard 1912). Additionally, the Shannon – Weiner Diversity Index (SWDI) of each site's tree and shrub species compositions, including literature reference conditions, was computed (Spellerberg and Fedor 2003). Additionally for Question 2, target values for red spruce height, growth, vigor, and density were determined using reference information from REF and from literature sources. Simple comparisons were used to determine whether mined and old field study sites are meeting these target values.

To evaluate whether restoration sites' soils are on a trajectory towards reference conditions (Question 3), focal variables were selected based on known indicators of podzolization (Stickel 1928; Barrett and Schaetzl 1998) and availability of literature reference data (Byers et al. 2010; University of California and USDA NRCS 2019). These focal variables are pH, percent carbon content, percent nitrogen content, and percent clay. Analysis in R began with two-way ANOVAs evaluating effects of treatment (site type and age), depth (0-10 or 10-25 cm sample), and the interaction of treatment and depth on each of the focal variables. The next analysis step depended on whether significant effects were found for treatment, depth, treatment*depth interaction, or some combination thereof.

Where only treatment was significant, chronosequence progression towards reference conditions was evaluated for the average focal variable value across both sampling depths. This progression was evaluated using a one-way ANOVA (focal variable average ~ treatment) and a Tukey's HSD test.

Where depth was significant, chronosequence progression towards reference was evaluated for each sampling depth individually as well as for stratification (Depth 1 minus Depth 2). This was carried out using three one-way ANOVAs + HSD tests per focal variable, using Depth 1 value, Depth 2 value, and stratification as the dependent variables for these three analyses.

No significant effects were found for treatment*depth interaction, or for any other combinations of treatment, depth, and treatment*depth interaction, and so no analysis methods were prepared for those situations.

CHAPTER 4. RESULTS

4.1 Question 1: Mined vs. Old Field Performance

When evaluating spruce seedling height, growth, and vigor at mined versus old field reforestation sites, significant differences were observed ($\alpha = 0.05$) in seedling height at all time points and in seedling vigor at Year 1. No significant differences were noted for vigor at Year 7 or Year 10, or for growth rate at any time point.

For height (Figure 1), a small but significant difference was observed at Year 1, with the old field site slightly outperforming the mined site, with mean height 0.39 vs. 0.36 m. Then, at Year 7 and Year 10, mined sites outperformed old field sites by a significant and clearly observable margin, with mean height 1.58 m vs. 1.37 m at year 7, and 2.01 m vs. 1.47 m at year 10. Based on GLM analysis (Table 1), the greater average height at the

Year 1 old field site was driven primarily by significantly lower soil pH relative to the Year 1 mined site. Meanwhile, greater average heights at the Year 7 and Year 10 mined sites were driven by shallower slope at Year 7 greater soil magnesium concentration at Year 10, relative to their old field counterparts. Other variables that significantly contributed to the height GLMs did not vary significantly between treatments. These variables were aspect at Year 1 and soil phosphorus concentration at Year 7, with cooler aspect and greater phosphorus correlating to greater seedling height.

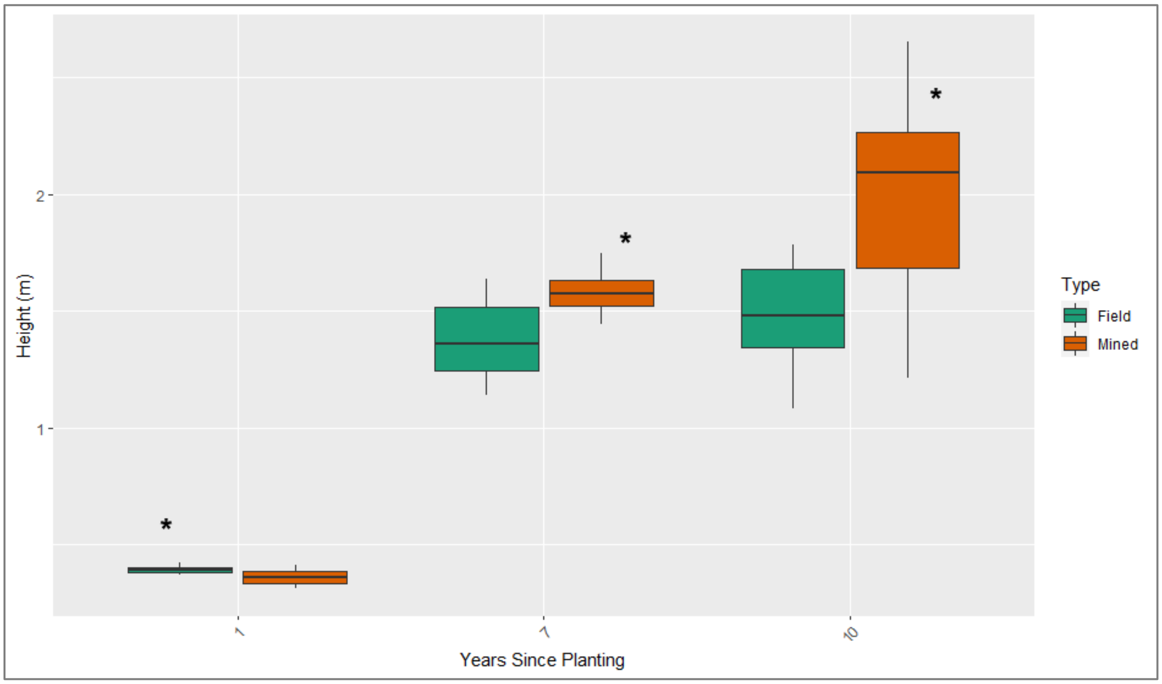


Figure 1. Comparison of seedling heights between mined and old field transects at years 1, 7, and 10. Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers. Asterisks indicate the significantly greater site type at years when significant height differences were observed.

For growth rate (Figure 2), no significant differences were found between mined and old field sites. At each year on the chronosequence, variation between transects was observed, but this variation was not driven by treatment. GLM results (Table 2) suggest several other drivers for growth rate differences between transects. These drivers included pH and slope, with lower pH and shallower slopes contributing significantly to greater growth rate at Years 1 and 10, respectively. Additionally, shrub cover significantly influenced seedling growth, but with a less straightforward relationship: at young ages, seedling growth was negatively influenced by shrub cover, whereas at Year 10 seedling growth was positively influenced by shrub cover.

Table 1. Generalized linear models based on stepwise regression of seedling height (H) response to environmental variables. Column "p (treatment)" displays ANOVA p-value determining whether regression variables varied significantly with treatment.

Year 1	**H = 0.70 - 0.055 pH + 0.014 Asp - 1.13 SolSalts - 1.02x10^{-4} Mg**		**R^2 = 0.69**
Variable (unit)	*t value*	*p > |t|*	*p (treatment)*
pH *	-2.25	0.046	0.021
Aspect (1-5, warmer-cooler) **	-2.27	0.044	0.27
Soluble salts (mmhos/cm) ***	-1.64	0.13	2.58x10^{-6}
[Mg] (mg/kg) ***	-1.24	0.24	0.00036
Year 7	**H = 1.47 + 0.42 P – 0.024 Slope + 0.0034 Graminoid**		**R^2 = 0.65**
Variable (unit)	*t value*	*p > |t|*	*p (treatment)*
[P] (mg/kg) **	4.07	0.0016	0.092
Slope (%) *	-3.18	0.0080	0.024
Graminoid (% cover)	1.77	0.10	0.202
Year 10	**H = 4.53 + 0.0036 Mg – 0.69 pH + 0.016 Shrub**		**R^2 = 0.42**
Variable (unit)	*t value*	*p > |t|*	*p (treatment)*
[Mg] (mg/kg) *	3.60	0.0036	0.00020
pH	-1.74	0.11	0.62
Shrub (% cover)	1.45	0.17	0.42

* Variable contributes significantly to GLM and varies significantly with treatment
** Variable contributes significantly to GLM but does not vary significantly with treatment
*** Variable varies significantly with treatment but does not contribute significantly to GLM

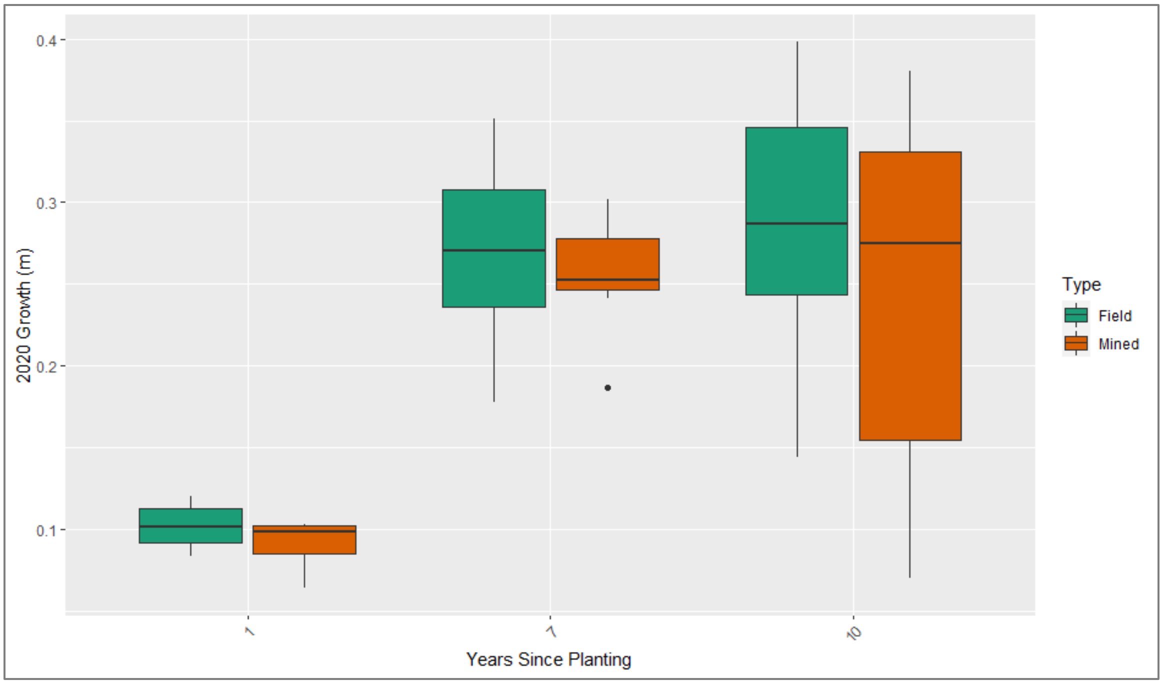


Figure 2. Comparison of seedling growth between mined and old field transects at years 1, 7, and 10. Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

Table 2. Generalized linear models based on stepwise regression of seedling growth (G) response to environmental variables. Column "p (treatment)" displays ANOVA p-value determining whether regression variables varied significantly with treatment.

Year 1 **G = 0.20 - 0.020 pH**			$\mathbf{R^2 = 0.37}$
Variable (unit)	*t value*	$p > \lvert t \rvert$	*p (treatment)*
pH *	-3.13	0.0074	0.021
Year 7 **G = 0.10 + 0.013 CEC - 0.0020 Shrub + 0.00037 K**			$\mathbf{R^2 = 0.39}$
Variable (unit)	*t value*	$p > \lvert t \rvert$	*p (treatment)*
CEC (meq/100g) *	3.25	0.0070	0.014
Shrub (% cover) **	-2.96	0.012	0.37
[K] (mg/kg) ***	1.44	0.18	0.0045
Year 10 **G = 0.26 + 0.0063 Shrub - 0.0057 Slope**			$\mathbf{R^2 = 0.42}$
Variable (unit)	*t value*	$p > \lvert t \rvert$	*p (treatment)*
Shrub (% cover) **	2.47	0.028	0.42
Slope (%)	-1.43	0.18	0.929

* Variable contributes significantly to GLM and varies significantly with treatment
** Variable contributes significantly to GLM but does not vary significantly with treatment
*** Variable varies significantly with treatment but does not contribute significantly to GLM

For seedling vigor (Figure 3), the Year 1 mined site dramatically outperformed the Year 1 old field site (average vigor 3.94 vs. 2.79). GLM regression (Table 3) shows that this difference is driven mainly by significant differences in soluble salts between treatments. At Year 7 and Year 10 sites, average vigor was similar between mined and old field seedlings. There was significant variation between transects, but this variation was not driven by treatment. GLM results suggest other drivers for this inter-transect variation. Increasing vigor was associated with lower soil pH and higher calcium concentrations at Year 7, and with shallower slopes and increasing shrub cover at Year 10.

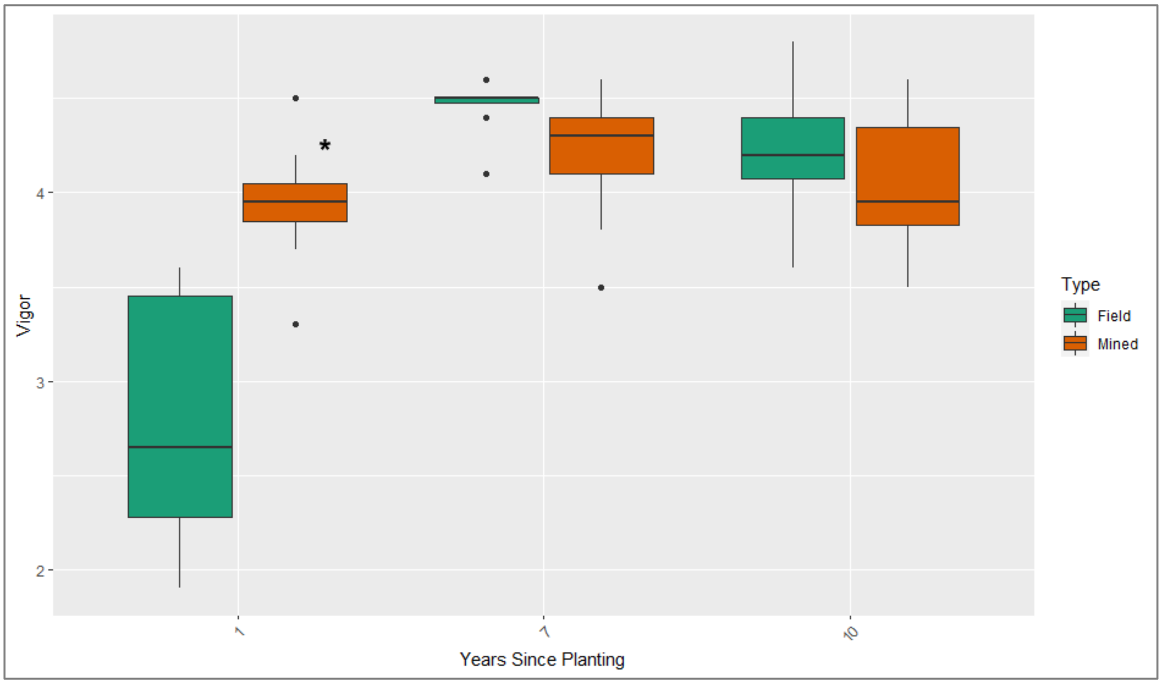


Figure 3. Comparison of seedling vigor between mined and old field transects at years 1, 7, and 10. Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers. Asterisks indicate the significantly greater site type at years when significant vigor differences were observed.

Table 3. Generalized linear models based on stepwise regression of seedling vigor (V) response to environmental variables. Column “p (treatment)” displays ANOVA p-value determining whether regression variables varied significantly with treatment.

Year 1	**V = 0.69 + 0.0098 Slope - 6.43 SolSalts + 0.068 Shrub + $8.35x10^{-5}$ Ca**		**R^2 = 0.82**
Variable (unit)	*t value*	*$p > \lvert t \rvert$*	*p (treatment)*
Slope (%) ***	1.49	0.16	0.0045
Soluble Salts (mmhos/cm) *	-3.68	0.0036	$2.58x10^{-6}$
Shrub (% cover) **	3.18	0.0087	0.75
[Ca] (mg/kg)	2.00	0.070	0.24
Year 7	**V = 1.79 – 0.24 pH + 0.00023 Ca**		**R^2 = 0.68**
Variable (unit)	*t value*	*$p > \lvert t \rvert$*	*p (treatment)*
pH *	-4.63	0.00047	0.011
[Ca] (mg/kg) ***	1.66	0.12	0.010
Year 10	**V = 0.60 + 0.012 Shrub – 0.0091 Slope**		**R^2 = 0.60**
Variable (unit)	*t value*	*$p > \lvert t \rvert$*	*p (treatment)*
Shrub (% cover) **	3.55	0.0035	0.42
Slope (%)	-1.75	0.10	0.929

* Variable contributes significantly to GLM and varies significantly with treatment
** Variable contributes significantly to GLM but does not vary significantly with treatment
*** Variable varies significantly with treatment but does not contribute significantly to GLM

4.2 Question 2: Vegetation Trends

A trend towards reference conditions would be represented by an increase in JSC over time. Neither old field nor mined sites displayed any such trend (Table 4). Old field sites displayed the opposite trend, with JSC decreasing over time, whereas for mined sites JSC remained consistently low.

A trend towards reference conditions could also be represented by sites’ SWDI approaching, over time, that of the literature reference system. Again, no such trend was observed in old field or mined sites (Table 5). Each chronosequence’s SWDI approximates a parabolic curve, with its highest point at Year 7, lowest point at Year 10, and an intermediate diversity value at Year 1.

Aside from JSC and SWDI, which are indices of the study sites’ overall tree and shrub communities, trends in planted seedling height, growth, and density could indicate a trend towards reference conditions for the red spruce portion of the target spruce-hardwood community. Height and growth are displayed above in Figure 1 and Figure 2, respectively, and density is displayed below in Figure 4. At M10 and F10, average heights were 1.68 m and 1.47 m, respectively. At the same sites, average growth rates were 25 cm and 29 cm for M10 and F10, respectively. Density varied widely between sites: M1, M7, and M10 contained an average of 93, 125, and 210 spruce seedlings per acre, respectively, while F1, F7, and F10 contained an average of 554, 158, and 577 spruce seedlings per acre, respectively. This was compared against the density of mature red spruce at REF within the forest's oldest age class, i.e., the first wave of succession after the forest was logged roughly 100 years ago. This REF density was 178 first generation spruce per acre, which aligns closely with the literature reference of approximately 185 first generation spruce per acre (Pauley 1988; Byers et al. 2010).

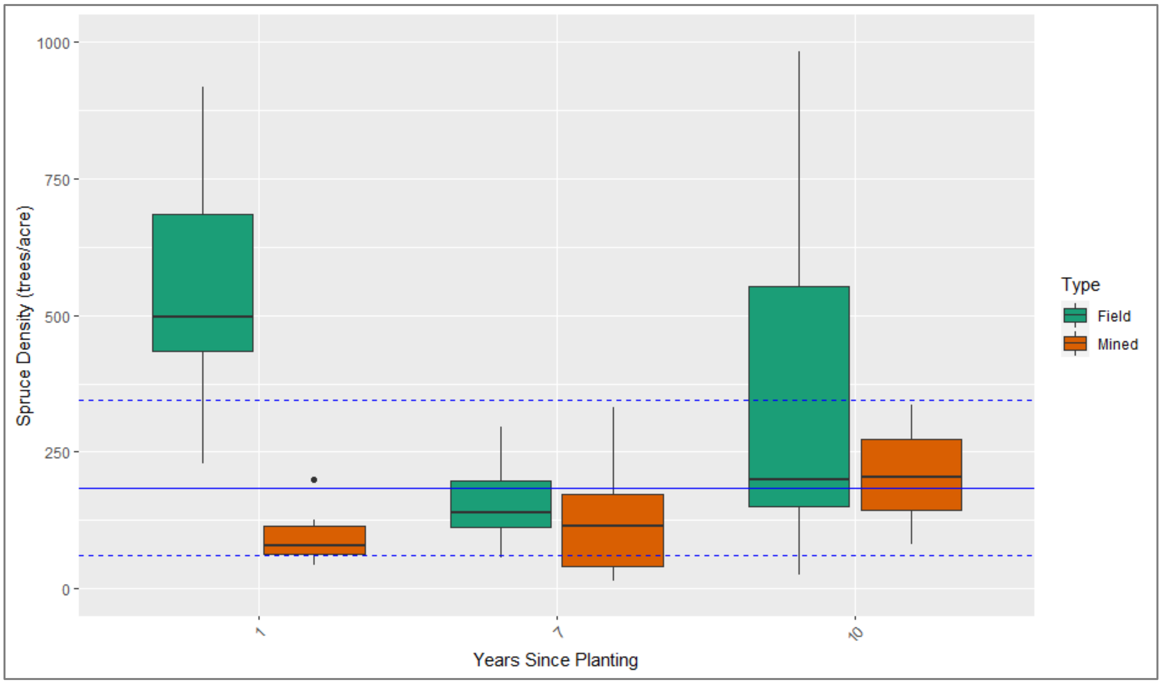


Figure 4. Comparison of red spruce seedling density between mined and old field transects at years 1, 7, and 10. Solid blue line represents literature average (185 trees/acre); dotted blue lines represent reference site density range (62-346 trees/acre). Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

Table 4. Jaccard’s Similarity Coefficient (JSC) for site pairs’ tree and shrub species compositions.

Site 1	**Site 2**	**Jaccard’s Similarity Coefficient**
M1	F1	0.5
M7	F7	0.5
M10	F10	0.33
REF	Literature Reference	0.57
M1	Literature Reference	0.27
M7	Literature Reference	0.19
M10	Literature Reference	0.27
F1	Literature Reference	0.42
F7	Literature Reference	0.32
F10	Literature Reference	0.25

Table 5. Shannon-Weiner Diversity Index (SWDI) for sites’ tree and shrub species compositions.

Site	**Shannon-Weiner Diversity Index**
M1	1.24
M7	1.67
M10	0.93
F1	0.87
F7	1.69
F10	0.73
REF	0.53
Literature Reference	0.86

4.3 Question 3: Soil Trends

Soil pH (Figure 5) varied significantly with treatment (site type + year). It did not vary significantly with either sample depth or the interaction of treatment and depth. Based on ANOVA + Tukey's HSD, only F7's soil pH was similar to that of the reference site. However, the mined chronosequence shows a trend towards reference conditions, with a significant drop in pH between M7 and M10.

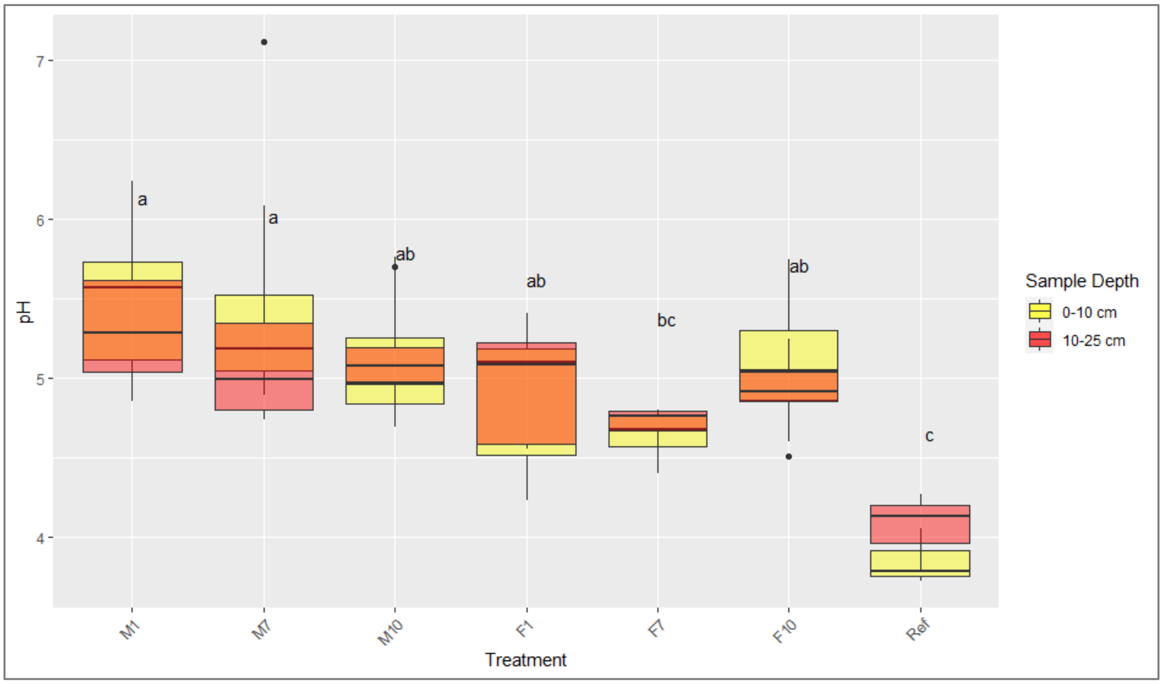


Figure 5. Transect soil pH by sample depth and site. Letters indicate Tukey's HSD groupings for soil pH, averaged across both depths. Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

Percent soil nitrogen content (N; Figure 6) varied significantly with treatment and depth, but not with the interaction of treatment and depth. Based on ANOVA + Tukey's HSD, at Depth 1 (0-10 cm), F1, F7, F10, and M10 had N% similar to reference conditions. At Depth 2 (10-25 cm), all study sites had N similar to reference conditions. N stratification (Depth 1 – Depth 2) showed clear progression over time towards reference conditions on mined sites, whereas stratification on field sites was similar to reference conditions throughout the chronosequence.

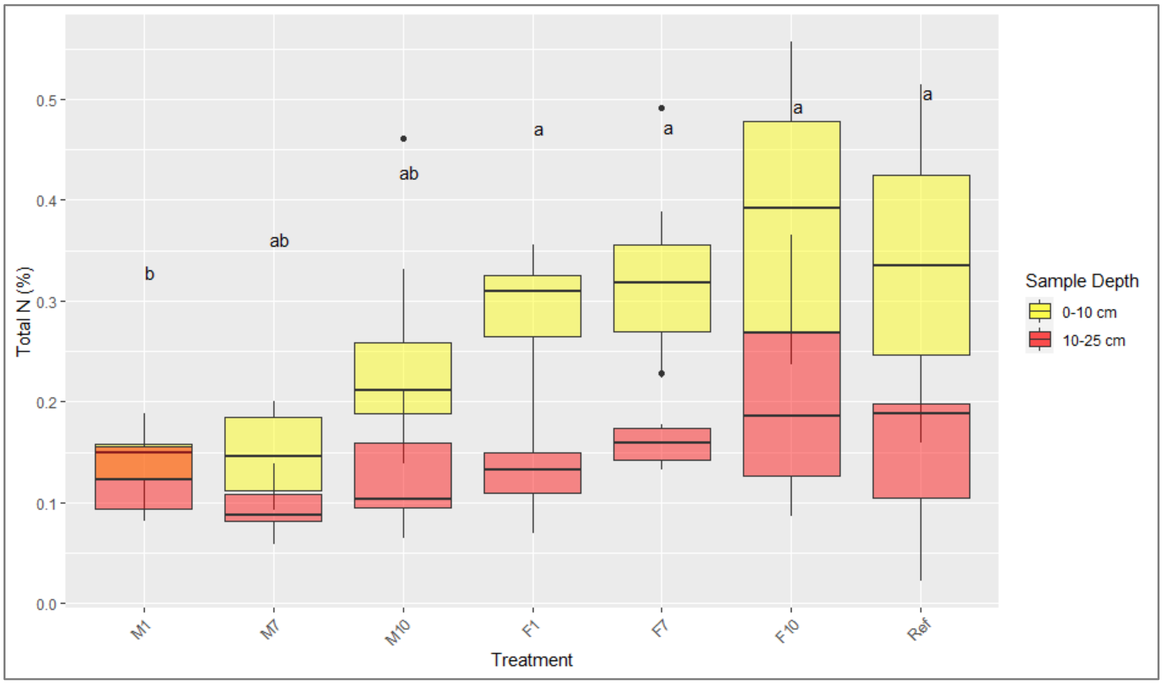


Figure 6. Transect soil nitrogen by sample depth and site. Letters indicate Tukey's HSD groupings for nitrogen content stratification (Depth 1 minus Depth 2). Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

Percent soil carbon content (C; Figure 7) varied significantly with treatment and depth, but not with the interaction of treatment and depth. Based on ANOVA + Tukey's HSD, at Depth 1 (0-10 cm), F10 had C similar to reference conditions, and all study sites had C similar to one another. At Depth 2 (10-25 cm), all study sites had C similar to reference conditions. C stratification (Depth 1 – Depth 2) showed no progression over time for either field or mined chronosequence. C stratification overall was greatest at the reference site, followed by field sites, followed by mined sites.

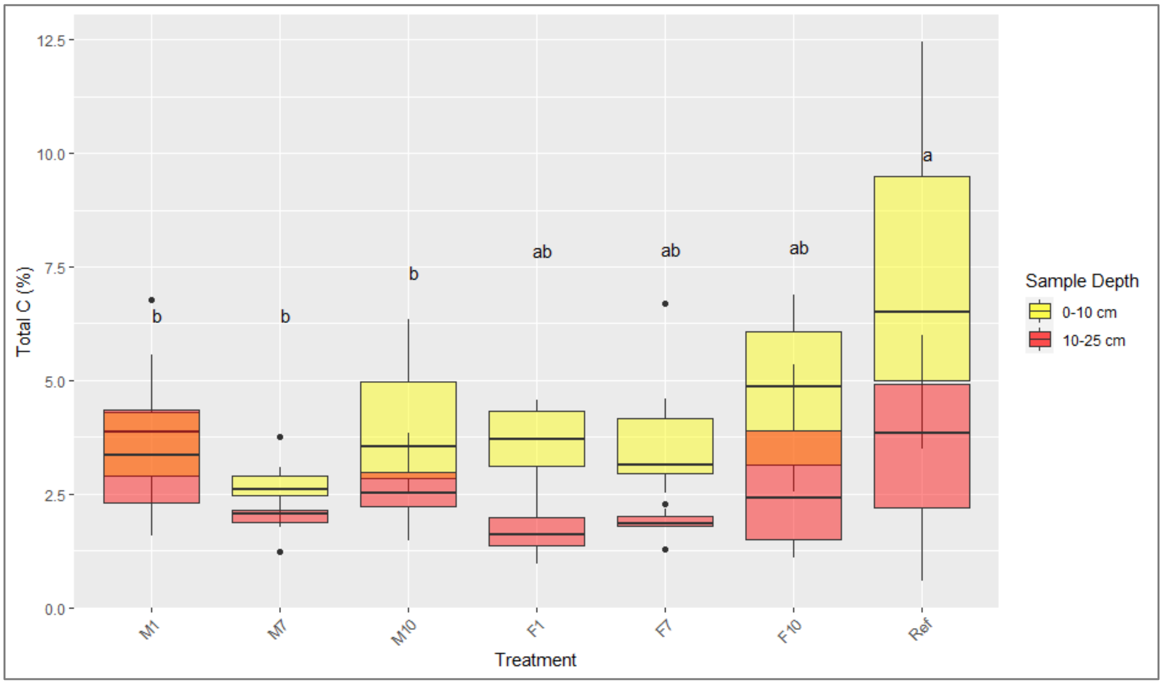


Figure 7. Transect soil carbon by sample depth and site. Letters indicate Tukey's HSD groupings for carbon content stratification (Depth 1 minus Depth 2). Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

Percent soil clay content (clay; Figure 8) varied significantly with treatment and depth, but not with the interaction of treatment and depth. Based on ANOVA + Tukey's HSD, at Depth 1 (0-10 cm), all study sites had clay similar to reference conditions and to one another. At Depth 2 (10-25 cm), no study sites had clay similar to reference conditions. Clay stratification (Depth 1 – Depth 2) was similar across all study sites, which were all highly dissimilar from reference conditions. Clay stratification overall was greatest at the reference site, and only at the reference site was clay higher at Depth 1 than at Depth 2.

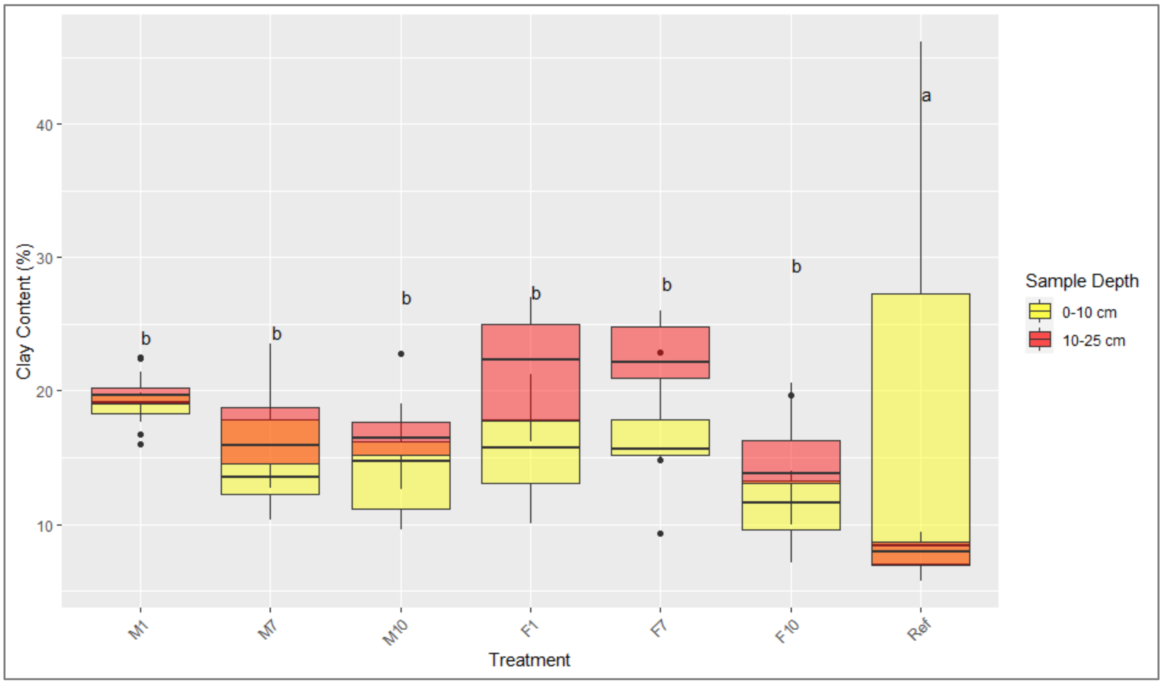


Figure 8. Transect soil clay content by sample depth and site. Letters indicate Tukey's HSD groupings for clay content stratification (Depth 1 minus Depth 2). Boxes represent medians and interquartile ranges, whiskers represent non-outlier minimums and maximums, and dots represent outliers.

CHAPTER 5. DISCUSSION

5.1 Question 1: Field vs. Mined Performance

The differences observed between old field and mined sites did not align with initial expectations. Although trees planted on SMCRA-reclaimed surface mines typically have poor growth and development (Burger et al. 2017), this study suggests that, with FRA reclamation techniques, they are largely equivalent or superior to old field sites for red spruce restoration. Where red spruce planted on mined sites showed superior performance relative to those on old fields, the difference was explained partially by site characteristics such as slope, and partially by increased availability of magnesium in the soil. Other soil nutrients – phosphorus, potassium, and calcium – appeared prominently in GLMs as overall drivers of spruce seedling performance. This is puzzling at first glance, as the study's mined sites, prior to restoration, had soils with very low productivity and little to no pedogenesis. The old field sites, on the other hand, have generally well-formed soils that are at least productive enough to support healthy grass and shrub communities. Thus, given that soil nutrient availability is a major driver of red spruce seedling performance, it seems intuitive that the better-developed, higher-productivity soils of old field sites would yield larger, healthier spruce.

However, despite the apparent productivity of old fields relative to mined sites, studies of nutrient dynamics in old fields have discovered common trends that could be deleterious to the growth of red spruce. Stinner et al. (1984) discovered net losses of P, Ca, and Mg in old fields, due primarily to soil leaching. Similarly, Richter et al. (1994) discovered net losses of Ca and Mg in old fields, due to leaching and uptake by vegetation during succession from field to shrubland to woodland. Because reclaimed mines often languish in a state of arrested succession (Adams 2017), vegetative uptake is likely a less significant driver of nutrient depletion on mined sites relative to old fields. Additionally, and perhaps more importantly, the study area's long-term exposure to acid rain not only drives patterns of nutrient leaching but can also either exacerbate negative effects of soil nutrient deficiencies or amplify positive effects of soil nutrient abundance on red spruce growth (McLaughlin and Tjoelker 1992).

Since the 1950s, the eastern United States, particularly the Appalachians, have been subjected to acid rain resulting from atmospheric pollution (Cogbill and Likens 1974). This trend of acid deposition peaked in the late 1970s and early 1980s, then declined through the 1990s and 2000s (Lynch et al. 2000). This history of acid deposition, alongside the lower-intensity acid rain of today, has numerous effects on soil chemistry and plant growth. Firstly, acid rain increases the rate of cation leaching, which typically lowers nutrient availability. Additionally, when soil nutrients are scarce, acid rain can cause secondary reactions that inhibit nutrient uptake by plants, including red spruce (McLaughlin and Tjoelker 1992). Given patterns of nutrient depletion in old fields (Stinner et al. 1994; Richter et al. 1984), these inhibitory secondary reactions may have occurred on this study's old field sites. However, on reclaimed mine lands with large quantities of unweathered rock in the upper soil strata, acid rain can actually increase nutrient availability through increased weathering of these rocks (Gentry et al. 1991). In cases such as this, where soil nutrients are abundant, acid rain has been shown to induce secondary reactions that increase the net photosynthesis of red spruce (McLaughlin and Tjoelker 1992). Thus, acid rain may have a twofold beneficial effect on red spruce seedlings planted on reclaimed mine lands: an overall increase in nutrient availability, and an increase in net photosynthesis. These effects may explain the seemingly counterintuitive trends observed in the relative performance of red spruce seedlings on mined and old field sites.

It is also possible that soil compaction played a role in the relative height of mined and old field seedlings at Year 7 and Year 10. While the mined sites were mechanically decompacted prior to planting, the old field sites did not receive comparable site preparation. All old field sites are abandoned pastureland, and under high-intensity grazing pastureland can suffer from soil compaction, which can have a negative impact on vegetation growth (Vanderburg et al. 2020). Due to the low intensity of past grazing on this study's old field sites, as well as the duration of abandonment, soil compaction may not have played a significant role in the height differences observed; however, quantitative data on soil compaction were not collected.

The only area in which old field spruce plantings significantly outperformed the mined sites was in Year 1 seedling height. At the same time, the mined treatment dramatically outperformed the old field in average seedling vigor at Year 1. While GLM analysis showed that these differences were driven by variation in pH and soluble salts, respectively, the statistics do not capture human error in the form of poor planting practices implemented at the field site. Due to labor shortages driven by the COVID-19 pandemic, the Year 1 field site was planted very late in the season, by which time many seedlings were in extremely poor health due to extended storage in their shipping boxes (pers com, Mike Powell, The Nature Conservancy in West Virginia, May 2021). This almost certainly explains the difference in vigor, and it casts doubt on the GLM explanation for height variation.

An alternative explanation is that the difference in height was driven by significantly greater overall ground cover, particularly graminoid cover, on old fields. This is consistent with existing literature on red spruce life history. Spruce seedlings are adapted to germinate in the low-light understory of a mature forest and spend several years establishing themselves there (Burns and Honkala 1990). When established in open conditions with minimal ground cover, red spruce seedlings are prone to poor health and desiccation (Westveld 1931). Thus, the higher-cover conditions of old field sites are more conducive to this early-life phase than the low-cover conditions of mined sites. However, seedlings that successfully establish themselves in low-cover conditions and survive 2-3 years benefit from reduced competition for light and resources relative to their high-cover counterparts, leading to increased long-term performance (Westveld 1931). On mined sites, this improved performance is further enhanced by greater nutrient availability, leading to significant long-term benefits relative to field sites.

Several inverse relationships were observed between slope steepness and seedling performance, as well as positive relationships between cooler aspect and seedling performance. As with the trends described above, these observations align with existing literature, which identifies cool, wet areas with gentle slopes as the most suitable locations for red spruce forests (Beane et al. 2013; Byers et al. 2010).

5.2 Question 2: Vegetation Trends

Three trends were observed that could constitute evidence of progress towards reference conditions in the study sites' plant communities: an increase in absolute vegetation cover on mined sites, patterns of spruce seedling performance study-wide, and patterns of spruce seedling density. The second trend is particularly strong, as most treatments are meeting or exceeding reference values for natural red spruce height, growth, and vigor.

In a large-scale study of red spruce's natural regeneration after clearcuts, Westveld (1931) measured height and growth rate for seedlings up to 11 years old. This is equivalent to this study's year 10 seedlings, as seedlings are one year old when planted. At 11 years of age, Westveld's seedlings averaged 1.68 m tall with 20 cm of annual growth. Seedlings at M10 averaged 2.01 m tall with 25 cm of annual growth, and seedlings at F10 averaged 1.47 m tall with 29 cm of annual growth. Additionally, seedlings at REF had an average vigor score of 3.63, while M10 and F10 scored an average of 4.04 and 4.19, respectively. Thus, based on reference values for height and growth described by Westveld and for vigor measured at REF, M10 exceeds all reference values for spruce seedling performance, and F10 seedlings are slightly below reference height but are above reference values for growth and vigor.

Trends in density of planted spruce are somewhat more varied, although most planting sites meet or exceed reference values (Pauley 1988; Byers et al. 2010) for red spruce density (Figure 4). F1 and F10 have average densities more than double the reference average and density ranges almost entirely outside the range determined by REF. This increased density was not found to have a significant effect on seedling height, growth rate, or vigor. M1 and M7 have average densities below the reference average, but their density ranges fall largely within the range determined by REF.

The high densities of F1 and F10 mean that those sites could undergo significant levels of seedling mortality while still remaining at or above reference density. On the other hand, mortality over time at M1 and M7 could drive them below the reference density range. Even so, these two sites are currently within the reference density range, and the other four sites are well within or above that range. Assuming these densities remain relatively constant until canopy closure, all study sites are on track towards reference values for red spruce density.

The trends above are strong indications that the red spruce component of the target spruce-hardwood forest is progressing towards reference conditions. However, this alone is insufficient evidence to support the claim that study sites are trending towards reference conditions. To support that claim, the study sites' hardwood communities would also need to show trends towards reference conditions, and neither JSC nor SWDI provided evidence of such trends.

Pickett (1982) found that, in old field succession from a plowed state – which might be considered intermediary between this study's old field and mined sites – Shannon-Weiner diversity and woody plant cover increased non-linearly, annual and biennial herbaceous cover decreased non-linearly, and perennial herbaceous cover and absolute cover followed roughly parabolic curves. Moreover, there was extreme inter-annual variability in all of these variables. This study's design, with only three time points on its chronosequence, did not capture enough data points to correct for interannual and inter-site variability to accurately describe these non-linear trends. Thus, while the spruce components of this study's sites are trending strongly towards the reference spruce-hardwood forest conditions, the hardwood component, and therefore the overall stand composition, remains uncertain.

5.3 Question 3: Soil Trends

Overall, several trends were observed that support the assertion that study sites' soils are trending towards reference conditions. Mined sites' soil pH is decreasing, and the Year 7 field site's pH is already similar to reference conditions. Similarly, soil nitrogen stratification is increasing over time on mined sites, approaching reference values, and all old field sites have nitrogen stratification similar to reference values. No clear trends over time, either towards or away from reference conditions, were observed in carbon content or clay content.

Because the old field sites, at the time of planting, had already undergone extensive pedogenesis, the changes observed in their soils since planting are likely due almost entirely to changes in vegetation, including the growth of planted red spruce. Mined sites, on the other hand, started with no identifiable soil profile and essentially began the process of pedogenesis at the time of planting. Therefore, changes in their soils are likely due to a combination of several soil forming factors, particularly climate and vegetation. Thus, while changes in mined soils have been more pronounced, it is more difficult to isolate the effects of planted red spruce within those changes.

Overall, the soil trends described above provide some support, albeit inconclusive, for the assertion that study site soils are trending towards reference conditions.

CHAPTER 6. CONCLUSION

This study's results corroborate and connect several trends that have been observed in prior literature. These trends, combined with this study's quantitative data on red spruce seedling performance, fill the knowledge gap on the absolute and relative efficacies of red spruce reforestation projects on legacy mined lands and old field sites in the Central Appalachians.

Old field sites offer abundant herbaceous cover that supports the early development of red spruce seedlings, but the combination of acid rain and nutrient depletion has led to sub-optimal long-term seedling performance. Still, old field sites are overall performing within reference parameters and offer the benefit of relatively low planting costs, meaning that they continue to be a strong option for large-scale plantings.

Mined sites, on the other hand, require extensive and costly site preparation for FRA forest restoration, but this increased cost produces significantly improved results. Red spruce seedlings planted on mined lands show long-term growth that is markedly superior to that of old field plantings and that of reference conditions. These trends suggest that FRA red spruce reforestation on mined lands, though relatively costly, will produce a functional red spruce forest more quickly than old field plantings.

The threat from climate change imposes a severe time restriction on red spruce reforestation (Beane and Rentch 2015), and the scope of reforestation required remains massive (Thomas-Van Gundy and Sturtevant 2014). The scope of legacy mined lands is also massive: roughly 1.5 million acres in Appalachia (Zipper et al. 2011), at least 25,000 acres of which fall within the high elevations of West Virginia (Branduzzi 2020). Given the rapid rate of red spruce growth on mined lands, these 25,000 acres represent a key area which, alongside old field restoration, will be critical to the timely landscape-scale restoration of red spruce – northern hardwood forests.

APPENDICES

Appendix A: Site Maps

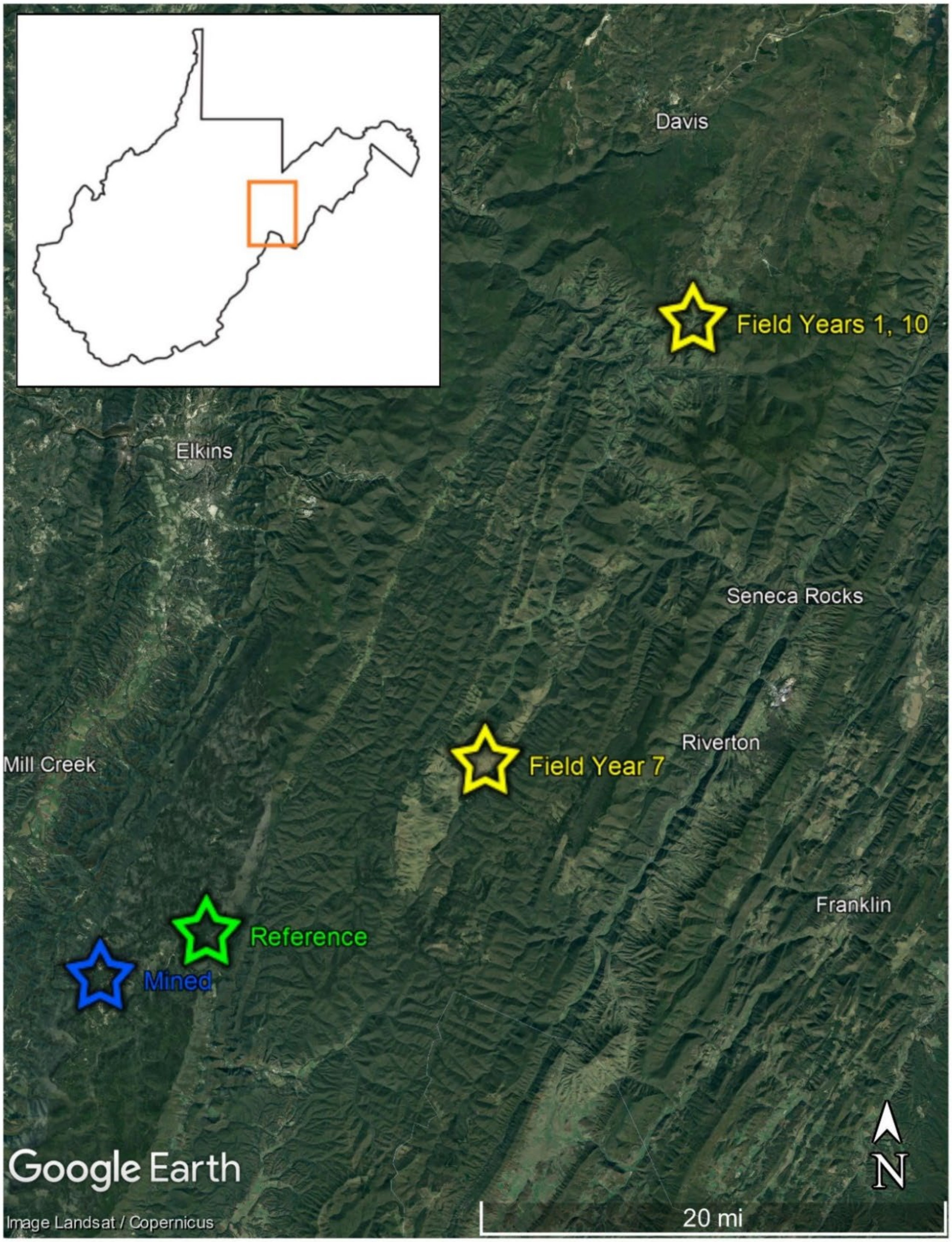


Figure A1. General site locations.

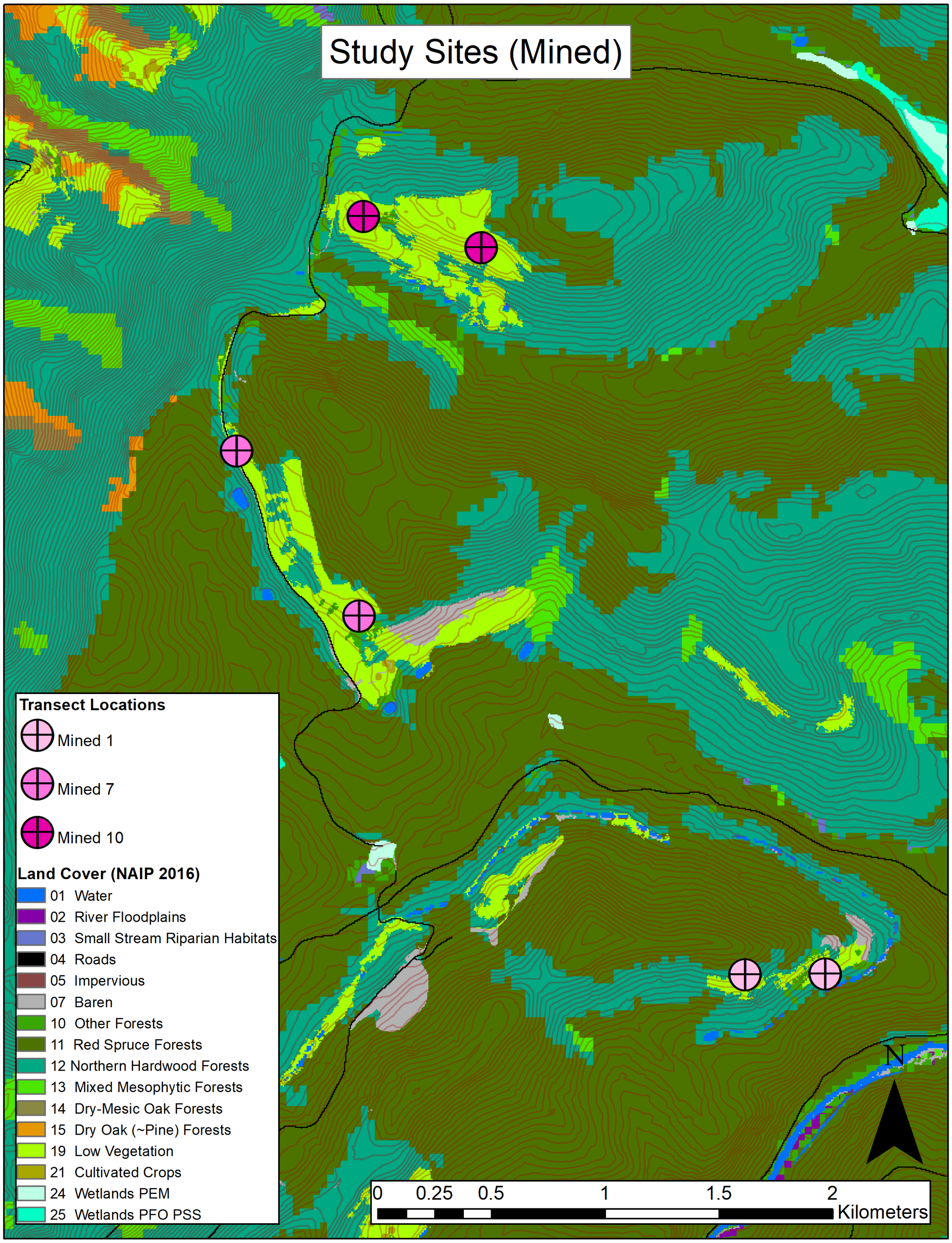


Figure A2. Mined site locations with 2016 land cover and 20 ft. contours. Map layers provided by West Virginia GIS Technical Center (https://wvgis.wvu.edu/data/data.php).

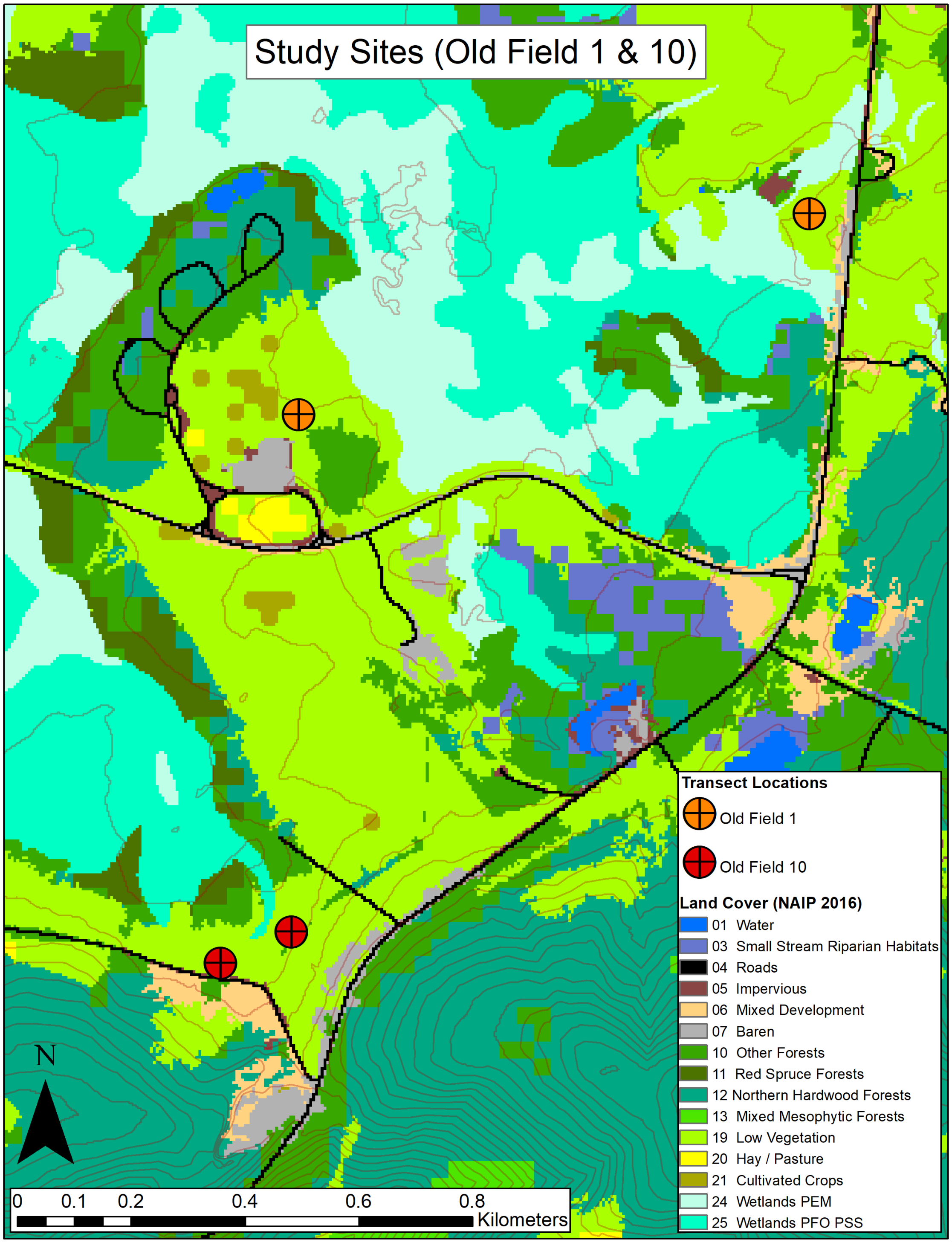


Figure A3. F1 and F10 locations with 2016 land cover and 20 ft. contours. Map layers provided by West Virginia GIS Technical Center (https://wvgis.wvu.edu/data/data.php).

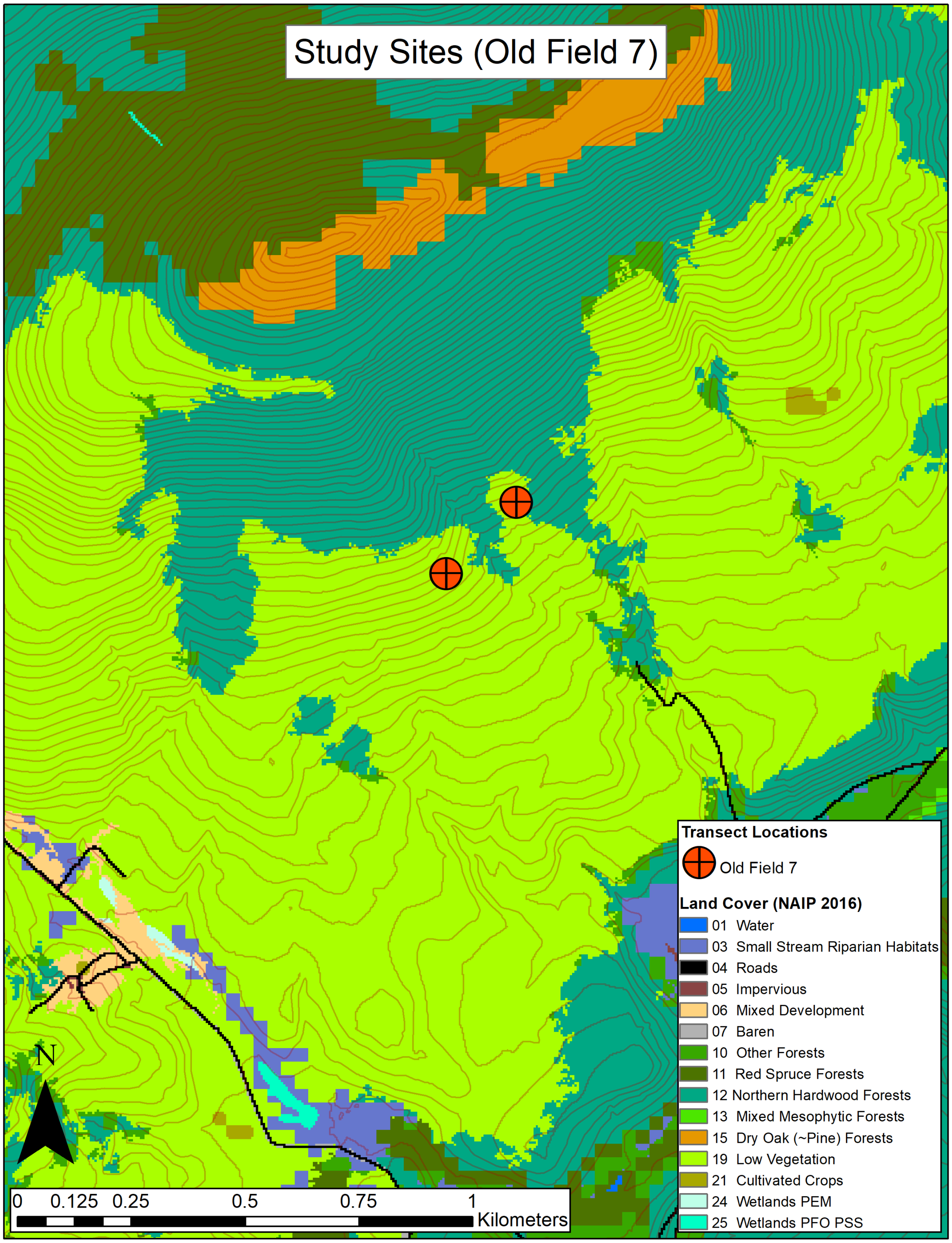


Figure A4. F7 location with 2016 land cover and 20 ft. contours. Map layers provided by West Virginia GIS Technical Center (https://wvgis.wvu.edu/data/data.php).

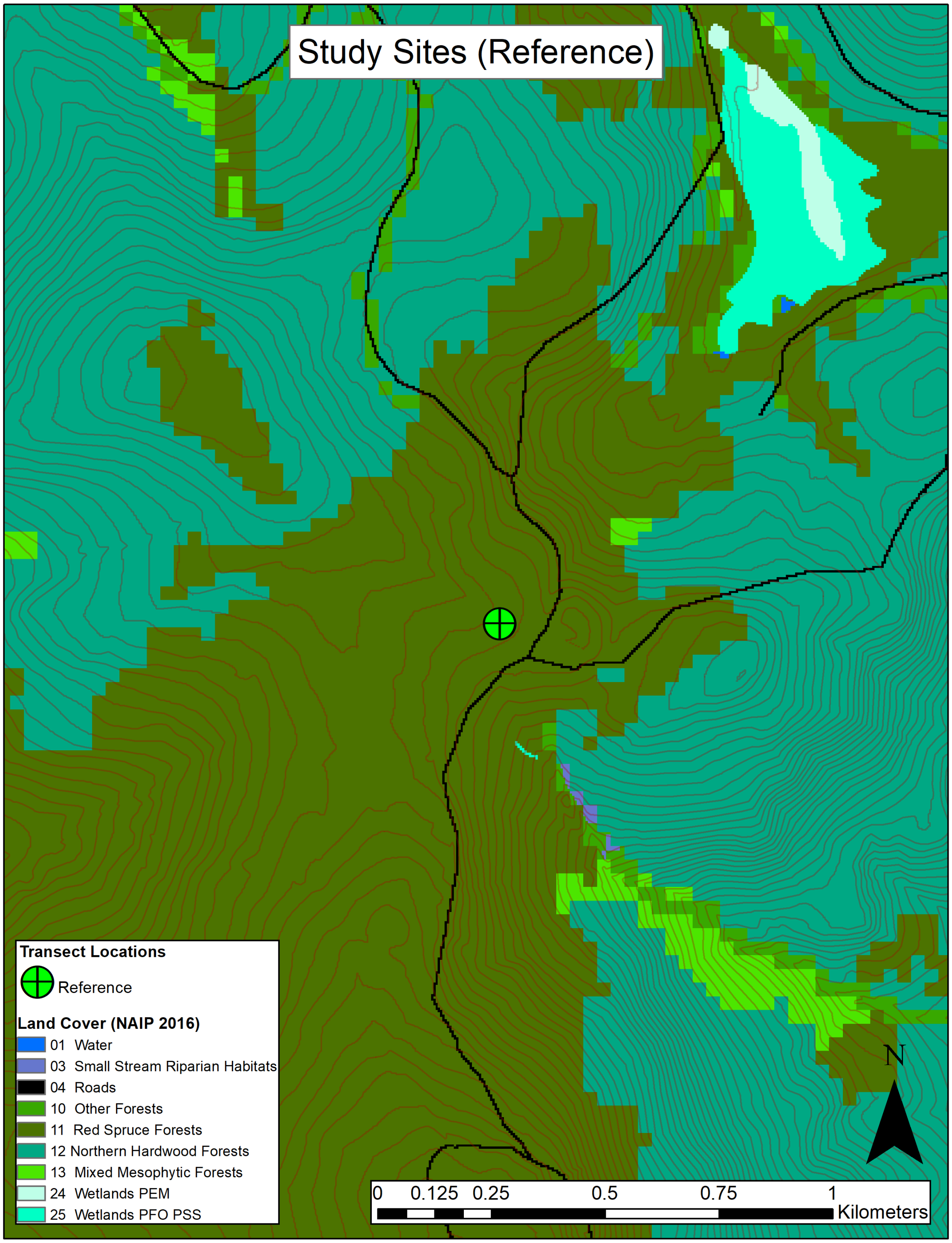
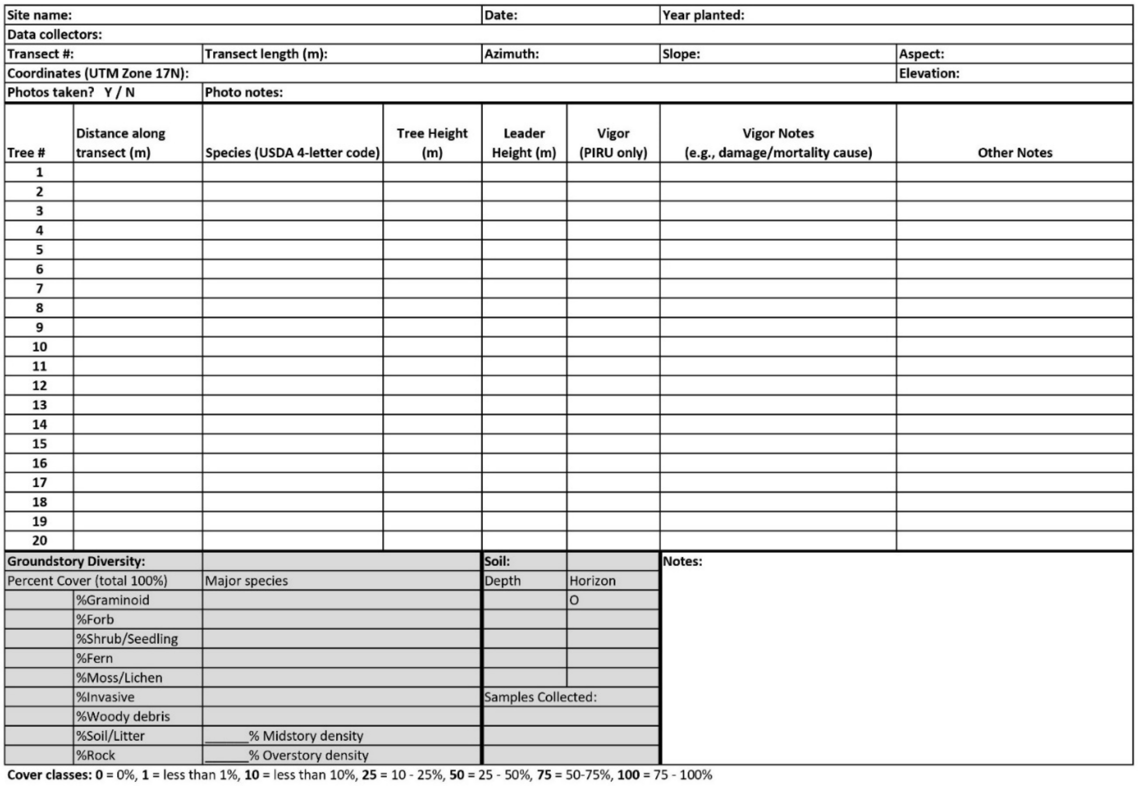


Figure A5. REF location with 2016 land cover and 20 ft. contours. Map layers provided by West Virginia GIS Technical Center (https://wvgis.wvu.edu/data/data.php).

Appendix B: Sample Data Sheet



Site name:		Date:	Year planted:	
Data collectors:				
Transect #:	Transect length (m):	Azimuth:	Slope:	Aspect:
Coordinates (UTM Zone 17N):				Elevation:
Photos taken? Y / N	Photo notes:			

Tree #	Distance along transect (m)	Species (USDA 4-letter code)	Tree Height (m)	Leader Height (m)	Vigor (PIRU only)	Vigor Notes (e.g., damage/mortality cause)	Other Notes
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

Groundstory Diversity:			Soil:		Notes:
Percent Cover (total 100%)		Major species	Depth	Horizon	
	%Graminoid			O	
	%Forb				
	%Shrub/Seedling				
	%Fern				
	%Moss/Lichen				
	%Invasive		Samples Collected:		
	%Woody debris				
	%Soil/Litter	______% Midstory density			
	%Rock	______% Overstory density			

Cover classes: 0 = 0%, **1** = less than 1%, **10** = less than 10%, **25** = 10 - 25%, **50** = 25 - 50%, **75** = 50-75%, **100** = 75 - 100%

Appendix C: Soil Data

Table C1. Soil data, part 1. For each site, each variable was averaged across all transects at depth 0-10 cm (D1 AVG), depth 10-25 cm (D2 AVG), and both depths combined (SITE AVG). Sites are listed by site type (Mined = M, old field = F) and year post-planting.

		Soil_wtr_pH	[P]	[K]	[Ca]	[Mg]	[Zn]	Total_N	Total_C	CEC
SITE	**UNIT>**	**pH**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**%**	**%**	**cmol/kg**
M1	SITE AVG>	5.439	2.688	73.094	565.313	271.031	8.303	0.134	3.613	11.778
	D1 AVG>	5.508	2.813	72.625	650.313	277.188	8.575	0.143	3.844	12.220
	D2 AVG>	5.370	2.563	73.563	480.313	264.875	8.031	0.124	3.381	11.335
M7	SITE AVG>	5.327	6.438	125.563	512.688	260.625	8.247	0.121	2.354	10.686
	D1 AVG>	5.334	9.250	144.500	547.688	255.313	9.469	0.147	2.581	11.199
	D2 AVG>	5.320	3.625	106.625	477.688	265.938	7.025	0.096	2.126	10.174
M10	SITE AVG>	5.093	6.000	106.531	479.813	249.313	6.484	0.185	3.282	12.546
	D1 AVG>	5.069	7.000	122.875	483.250	225.000	7.163	0.244	3.977	14.378
	D2 AVG>	5.118	5.000	90.188	476.375	273.625	5.806	0.125	2.588	10.714
F1	SITE AVG>	4.924	4.469	67.406	862.531	59.281	11.388	0.212	2.622	16.596
	D1 AVG>	4.879	7.000	85.063	850.313	68.938	14.463	0.293	3.605	18.111
	D2 AVG>	4.969	1.938	49.750	874.750	49.625	8.313	0.132	1.640	15.081
F7	SITE AVG>	4.676	3.906	69.563	266.594	45.500	4.144	0.245	2.551	14.343
	D1 AVG>	4.645	5.438	88.500	297.313	52.688	4.806	0.326	3.326	14.849
	D2 AVG>	4.708	2.375	50.625	235.875	38.313	3.481	0.164	1.872	13.836
F10	SITE AVG>	5.018	13.500	156.969	898.250	72.000	8.291	0.297	3.739	20.811
	D1 AVG>	5.098	18.563	209.188	1045.750	89.375	11.438	0.388	4.697	22.863
	D2 AVG>	4.938	8.438	104.750	750.750	54.625	5.144	0.205	2.782	18.760
REF	SITE AVG>	3.874	18.063	29.188	84.000	28.250	87.263	0.409	4.081	10.400
	D1 AVG>	3.818	15.250	36.875	99.000	34.125	145.425	0.446	4.996	9.818
	D2 AVG>	3.930	20.875	21.500	69.000	22.375	29.100	0.373	3.472	10.983

Table C2. Soil data, part 2. For each site, each variable was averaged across all transects at depth 0-10 cm (D1 AVG), depth 10-25 cm (D2 AVG), and both depths combined (SITE AVG). Sites are listed by site type (Mined = M, old field = F) and year post-planting.

		Sand	**Silt**	**Clay**	**Exch._K**	**Exch._Ca**	**Exch._Mg**	**Exch._Na**	**Sol_Salts**	**Base_Sat**
SITE	**UNIT>**	**%**	**%**	**%**	**cmol/kg**	**cmol/kg**	**cmol/kg**	**cmol/kg**	**mmhos/cm**	**%**
M1	SITE AVG>	40.233	40.438	19.330	0.271	3.544	2.785	0.011	0.045	54.755
	D1 AVG>	40.311	40.624	19.068	0.274	4.130	2.893	0.011	0.048	58.033
	D2 AVG>	40.155	40.253	19.593	0.268	2.958	2.678	0.010	0.042	51.478
M7	SITE AVG>	49.780	34.463	15.756	0.381	2.807	2.236	0.015	0.086	53.491
	D1 AVG>	51.590	33.599	14.808	0.460	3.340	2.441	0.015	0.087	55.448
	D2 AVG>	47.970	35.326	16.705	0.303	2.274	2.030	0.015	0.084	51.535
M10	SITE AVG>	49.156	35.437	15.408	0.371	2.726	2.327	0.018	0.070	46.043
	D1 AVG>	51.489	34.379	14.134	0.458	3.054	2.348	0.020	0.080	42.358
	D2 AVG>	46.824	36.495	16.683	0.284	2.398	2.306	0.016	0.060	49.729
F1	SITE AVG>	31.308	49.973	18.718	0.261	5.814	0.526	0.019	0.072	40.993
	D1 AVG>	33.378	50.879	15.741	0.331	6.044	0.658	0.020	0.088	40.323
	D2 AVG>	29.239	49.066	21.695	0.190	5.585	0.395	0.019	0.055	41.663
F7	SITE AVG>	28.092	53.067	19.091	0.297	1.648	0.365	0.435	0.095	14.699
	D1 AVG>	30.977	53.677	16.286	0.394	2.004	0.448	0.853	0.122	16.885
	D2 AVG>	25.568	52.533	21.896	0.200	1.293	0.283	0.018	0.067	12.513
F10	SITE AVG>	36.225	50.327	13.448	0.605	6.799	0.739	0.032	0.119	38.223
	D1 AVG>	39.606	48.384	12.011	0.841	8.736	1.004	0.033	0.150	45.516
	D2 AVG>	32.844	52.270	14.885	0.369	4.863	0.474	0.031	0.088	30.929
REF	SITE AVG>	65.538	26.974	28.008	0.405	0.278	0.139	8.179	0.088	1.863
	D1 AVG>	60.745	32.195	29.718	0.470	0.343	0.183	8.426	0.099	2.240
	D2 AVG>	68.733	23.493	26.298	0.340	0.213	0.095	7.931	0.078	1.485

LITERATURE CITED

Adams, M.B., ed. 2017. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. General Technical Report NRS-169, USDA Forest Service, Northern Research Station, Newtown Square, PA.

Barrett, L.R., and R.J. Schaetzl. 1998. Regressive pedogenesis following a century of deforestation: evidence for depodzolization. Soil Science 163:482-497.

Barton, C., C. Zipper, and J. Burger. 2017. Preface to The Forestry Reclamation Approach: guide to successful reforestation of mined lands. Pp. i – iii. *In*: Adams, Mary Beth, ed. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. General Technical Report NRS-169, USDA Forest Service, Northern Research Station, Newtown Square, PA.

Barton, C., K. Sena, T. Dolan, P. Angel, and C. Zipper. 2017. Restoring forests on surface coal mines in Appalachia: A regional Reforestation approach with global application. Chapter 8. Pp. 124-145. *In*: N. Bolan, M.B. Kirkham and Y.S. Ok (Eds), Spoil to Soil: Mine Site Rehabilitation and Revegetation. Taylor and Francis.

Beane, N.R., and J.S. Rentch. 2015. Using Known Occurrences to Model Suitable Habitat for a Rare Forest Type in West Virginia Under Select Climate Change Scenarios. Ecological Restoration 33:178-189.

Beane, N.R., J.S. Rentch, and T.M. Schuler. 2013. Using Maximum Entropy Modeling to Identify and Prioritize Red Spruce Forest Habitat in West Virginia. Research Paper NRS-23, USDA Forest Service, Northern Research Station, Newtown Square, PA.

Branduzzi, A.M. 2020. Enhancing Native Plant Diversity on Legacy Mined Lands. Master's thesis, University of Kentucky. Theses and Dissertations – Forestry and Natural Resources. https://uknowledge.uky.edu/forestry_etds/59/, accessed 3/27/2022.

Burns, R.M., and B.H. Honkala, tech. coords. 1990. Silvics of North America: 1. Conifers. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC.

Burger, J., D. Graves, P. Angel, V. Davis, and C. Zipper. 2017. Chapter 2: The Forestry Reclamation Approach. Pp. 2-1 – 2-8. *In*: Adams, Mary Beth, ed. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. General Technical Report NRS-169, USDA Forest Service, Northern Research Station, Newtown Square, PA.

Byers, E.A., J.P. Vanderhorst, B.P. Streets. 2010. Classification and conservation assessment of upland red spruce communities in West Virginia. West Virginia Natural Heritage Program, WVDNR.

Cavallin, N., and L. Vasseur. 2008. Potential for red spruce (Picea rubens Sarg.) establishment from natural seed dispersal in old fields adjacent to forest stands. Plant Ecology 199:33-41.

Central Appalachian Spruce Restoration Initiative. 2010. Action Plan of the Central Appalachian Spruce Restoration Initiative.

Cogbill, C.V., and G.E. Likens. 1974. Acid Precipitation in the Northeastern United States. Water Resources Research 10:1133-1137.

de Mendiburu, F., and M. Yaseen. 2020. agricolae: Statistical Procedures for Agricultural Research. R package version 1.4.0. https://myaseen208.github.io/agricolae/https://cran.r-project.org/package=agricolae

Fortney, R.H., and J.S. Rentch. 2003. Post logging era plant successional trends and geospatial vegetation patterns in Canaan Valley, West Virginia, 1945 to 2000. Castanea 68:317-334.

Groninger, J., J. Skousen, P. Angel, C. Barton, J. Burger, and C. Zipper. 2017. Chapter 8: Mine reclamation practices to enhance forest development through natural succession. Pp. 8-1 – 8-7. *In*: Adams, Mary Beth, ed. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. General Technical Report NRS-169, USDA Forest Service, Northern Research Station, Newtown Square, PA.

Hall, S.L., C.D. Barton, and C.C. Baskin. 2010. Topsoil Seed Bank of an Oak–Hickory Forest in Eastern Kentucky as a Restoration Tool on Surface Mines. Restoration Ecology 18:834-842.

Korstian, C.F. 1937. Perpetuation of spruce on cut-over and burned lands in the higher Southern Appalachian Mountains. Ecological Monographs 7:125-167.

Gentry, C.E., H.G. Halverson, and G.L. Wade. 1991. Mass of Ions Removed by Leaching Mine Spoil with Simulated Precipitation. Proceedings of the American Society of Mining and Reclamation 1991:87-96.

Jaccard, P. 1912. The Distribution of the Flora in the Alpine Zone. New Phytologist 11:37-50.

Littlefield, T., C. Barton, M. Arthur, M. Coyne. 2013. Factors controlling carbon distribution on reforested minelands and regenerating clearcuts in Appalachia, USA. Science of the Total Environment 465:240-247.

Lynch, J.A., V.C. Bowersox, and J.W. Grimm. 2000. Acid Rain Reduced in Eastern United States. Environmental Science & Technology 34:940-949.

Maharaj, S., C.D. Barton, T.A.D. Karathanasis, H.D. Rowe, and S.M. Rimmer. 2007. Distinguishing “new” from “old” organic carbon in reclaimed coal mine sites using thermogravimetry: II. Field validation. Soil Science 172:302-312.

McLaughlin, S.B., and M.J. Tjoelker. 1992. Growth and physiological changes in red spruce saplings associated with acid deposition at high elevations in the southern Appalachians, USA. Forest Ecology and Management 51:43-51.

Menzel, D.C. 1981. Implementation of the Federal Surface Mining Control and Reclamation Act of 1977. Public Administration Review 41:212-219.

Miller, J., C. Barton, C. Agouridis, A. Fogle, T. Dowdy, and P. Angel. 2012. Evaluating Soil Genesis and Reforestation Success on a Surface Coal Mine in Appalachia. Soil Science Society of America Journal 76:950-960.

Miller, W., and D. Miller. 1987. A micro-pipette method for soil mechanical analysis. Communications in Soil Science and Plant Analysis 18:1–15.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties, 2nd ed.; A.L. Page, R.H. Miller, and D.R. Keeney, Eds.; ASA-SSSA: Madison, WI, USA.

Odum, E.P. 1960. Organic Production and Turnover in Old Field Succession. Ecology 41:34-49.

Pickett, S.T.A. 1982. Population Patterns through Twenty Years of Oldfield Succession. Vegetatio 49:45-59.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Richter, D.D., D. Markewitz, C.G. Wells, H.L. Allen, R. April, P.R. Heine and B. Urrego. 1994. Soil Chemical Change during Three Decades in an Old-Field Loblolly Pine (Pinus Taeda L.) Ecosystem. Ecology 75:1463-1473.

Sena, K., C. Agouridis, J. Miller, and C. Barton. 2018. Spoil type influences soil genesis and forest development on an Appalachian surface coal mine ten years after placement. Forests 9:780.

Soil and Plant Analysis Council. 2000. Soil Analysis Handbook of Reference Methods; CRC Press: Boca Raton, FL, USA.

Southern Appalachian Spruce Restoration Initiative. 2015. Southern Appalachian Spruce Restoration Plan.

Spellerberg, I.F., and P.J. Fedor. 2003. A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the ‘Shannon–Wiener’ Index. Global Ecology and Biogeography 12:177-179.

Stickel, P.W. 1928. Physical characteristics and silvicultural importance of podsol soil. Ecology 9:176-187.

Stinner, B.R., D.A. Crossley, Jr., E.P. Odum and R.L. Todd. 1984. Nutrient Budgets and Internal Cycling of N, P, K, Ca, and Mg in Conventional Tillage, No-Tillage, and Old-Field Ecosystems on the Georgia Piedmont. Ecology 65:354-369.

Thomas-Van Gundy, M.A., and B.R. Sturtevant. 2014. Using Scenario Modeling for Red Spruce Restoration Planning in West Virginia. Journal of Forestry 112:457-466.

University of California, Davis, California Soil Resource Lab; University of California, Division of Agriculture and Natural Resources; Natural Resources Conservation

Service. 2019. SoilWeb. University of California; USDA-NRCS. https://data.nal.usda.gov/dataset/soilweb. Dataset accessed 2022-03-17.

Vanderburg, K.L., T.J. Steffens, D.G. Lust, M.B. Rhoades, B.C. Blaser, K. Peters, and M.J. Ham. 2020. Trampling and Cover Effects on Soil Compaction and Seedling Establishment in Reseeded Pasturelands Over Time. Rangeland Ecology & Management 73:452-461.

Westveld, M. 1931. Reproduction on pulpwood lands in the Northeast. Technical Bulletin No. 233, United States Department of Agriculture, Washington, D.C.

Zipper, C., J. Burger, J. Skousen, P. Angel, C. Barton, V. Davis, and J. Franklin. 2011. Restoring Forests and Associated Ecosystem Services on Appalachian Coal Surface Mines. Environmental Management 47:751-765.

Zipper, C.E., J.A. Burger, C.D. Barton and J.G. Skousen. 2013. Rebuilding Soils on Mined Land for Native Forests in Appalachia, USA. Soil Science Society of America Journal 77:337-349.

VITA

Benjamin Rhodes

Education History

University of North Carolina at Chapel Hill: Bachelor of Science in Environmental Sciences

Professional Positions Held

The Nature Conservancy in West Virginia – Ecological Restoration Coordinator

The Nature Conservancy in West Virginia – PHCWPMA Field Crew Leader

Conservation Corps of Minnesota & Iowa – Crew Leader

Publications

Rhodes, B., and M.P. Setshogo. 2012. An Evaluation of the Sustainability of Baobab Harvesting in the Gweta Area. Botswana Notes and Records 44:130-143.

Ziervogel, K., L. McKay, B. Rhodes, C.L. Osburn, J. Dickson-Brown, C. Arnosti, A. Teske. 2012. Microbial Activities and Dissolved Organic Matter Dynamics in Oil-Contaminated Surface Seawater from the Deepwater Horizon Oil Spill Site. PLoS ONE 7:e34816.