

RESEARCH ARTICLE

Site and management factors determining the fate of hardwood trees planted on reclaimed coal mines in the Illinois Basin, USA

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Despite decades of research and practice restoring forests on surface coal mines, success is still variable, and failures often occur. To better understand how variation in site factors and management affects the success of restoration of coal mines, we conducted a survey of tree performance for mine sites in the Illinois Basin across Indiana, USA, reclaimed between 2008 and 2018. We explored the impacts of climate and soil conditions on the survival and growth of planted trees, as well as the cover of associated vegetation. Average overall survival (21%) was relatively low compared to typical unmined sites. Organic matter had one of the most consistent and largest effects on most oak species, with the highest performance between 3 and 5%. Soil phosphorus content was the most important factor determining whether a planting totally failed and affected the growth of White oak (*Quercus alba*) and Swamp white oak (*Q. bicolor*), though its effect on White oak was nonlinear. Rainfall in the year of planting had large positive effects on the survival and growth of Persimmon (*Diospyros virginiana*), and Black walnut (*Juglans nigra*) and temperature in the year of planting had large positive effects on the growth of Bur oak (*Q. macrocarpa*) and Persimmon. Planting a diverse mix of species is the best option both for approximating natural conditions, and for avoiding problems from the failure of individual species. While conditions vary, successful forest restoration on former coal mines can occur; this study reveals some of the most important factors affecting such success.

Key words: anthropogenic disturbance, ecological restoration, forest regeneration, hardwood species, limiting site factors, mine reclamation

Implications for Practice

- To optimize survival and growth of hardwood seedlings planted on reclaimed coal mines, soils should contain sufficient phosphorus (at least 15 ppm) and organic matter (between 3 and 5%). Species have varying growth responses to pH levels, but survival generally increases at lower pH.
- Managers must be prepared for poor survival in dry summers unless irrigating. Planting species that can tolerate drought may help to alleviate losses.
- Planting a diversity of species is the safest prescription, and managers should consider using some species that are not valuable timber trees. Persimmon, Sycamore, Black locust, White pine, and Baldcypress all had higher survival than the 42 other surveyed species. These species also occupy different niches and serve important ecological functions.

These expansions cause a host of ecological issues. For example, mining is associated with deforestation and loss of native vegetation (Sonter et al. 2014), changes in soil properties (Showalter et al. 2007; Macdonald et al. 2015), water pollution, including acid mine drainage (Rotherham et al. 2012), and loss of wildlife habitat (Rotherham et al. 2012). Since the environmental movements of the 1970s, governments and companies have increasingly required reclamation of areas disturbed by mining; laws in several countries, including in North America, Europe, Australia, and China, require such reclamation (Macdonald et al. 2015; Shao et al. 2023). In the United States, for example, the Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public Law 87-95) was passed to address concerns regarding environmental problems

Author contributions: DFJ conceived and designed the study and supervised; CHR performed the experiment, curated data, analyzed the data, and wrote the manuscript; DFJ edited and revised the manuscript.

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Introduction

Areas impacted by mining for coal and other minerals are expanding globally due to higher demand for minerals, shifts toward surface mining, and advances in technology allowing for mining of deeper coal deposits (Sonter et al. 2014).

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doi: 10.1111/rec.14380

associated with coal mining (U.S. Congress 1977). Coal mine operators are required to submit a bond to cover the costs of reclaiming the site. Release from this bond occurs only if the land, at the end of a set period, meets the stated environmental conditions.

Reclamation research has increased correspondingly (Shao et al. 2023). While remediation of pollution, restoration of landform, and erosion control are generally necessary first steps to reclamation, they have created conditions that are often adverse for reclamation with trees, including establishment of aggressive ground cover species, intensive grading, and compaction of replaced topsoil materials (Chaney et al. 1995; Franklin et al. 2012).

Reconstructed topsoil may have physical and chemical properties that fail to promote tree growth, though physical properties have been identified as the most limiting (Andersen et al. 1989; Scullion & Malinovsky 1995; Rodrigue & Burger 2004). Performance of forest trees planted on reclaimed mines is therefore often deficient compared with those growing in native forest sites or on cropland afforestation (Fig. 1), which has often resulted in land use changes of reclaimed sites relative to the original native vegetation. In Brazil, for example, reforestation that occurs after land abandonment is often focused on plantation forestry, rather than restoration of native forests (Sonter et al. 2014). Many sites in the eastern United States reclaimed after the initiation of reclamation laws were established as grasslands or unmanaged forest, which have lower

economic value relative to native forests (Burger et al. 2005; Groninger et al. 2006).

Abiotic and biotic factors that limit early establishment success of newly planted seedlings on mine reclamation sites include high soil pH (Skousen et al. 2009; Evans et al. 2013), low soil fertility (Andersen et al. 1989), lack of organic matter (OM) (Sheoran et al. 2010; Zhang et al. 2019), soil compaction (Bateman & Chanasyk 2001), competition from weeds (Franklin et al. 2012), and animal browse (Skousen et al. 2009). Competing vegetation is often identified as the most influential of these factors (Andersen et al. 1989; Bockstette et al. 2017), followed by soil compaction (Casselmann et al. 2006). Competition has a complex relationship with seedling establishment; herbaceous cover can have facilitative or competitive effects (Franklin et al. 2012). Soil variables such as pH and compaction may be affected by the overburden used to create the minesoils, which may depend on the coal seam mined (Casselmann et al. 2006). OM is an essential source of nutrients and water-holding capacity and is the most limiting factor for microbial activity (Scullion & Malinovsky 1995; Sheoran et al. 2010; Zhang et al. 2019). Certain micronutrients also affect tree performance; magnesium (Mg), for example, can inhibit uptake of other nutrients or become toxic in high amounts (Scullion & Malinovsky 1995), though this depends on the amounts of other nutrients present in the soil, such as its ratio with calcium (Ca) (Ericsson et al. 1995). Climatic variables such as rainfall may also be limiting factors, often determining



Figure 1. A hand-planted reclaimed mine in southern Indiana, United States (center circle). The planted trees were 8 years old at the time of field sampling and were, in large part, a failure. Compare this to the matrix of natural forest in the background, as well as pre-SMCRA stands immediately surrounding the reclaimed site. A machine-planted section directly across the road (bottom right circle), which also has lower soil compaction, is performing better.

how severely compaction and competition affect seedlings (Larson et al. 1995; Franklin et al. 2012).

Progress has been made in identifying silvicultural treatments to overcome many of these challenges. For example, scientifically derived recommendations for rooting medium, ground covers, tree species selection, and tree planting techniques have been developed for the Appalachian region of the United States (Adams 2017), some of which have been adapted for use in the Midwest United States. When soil is already compacted, ripping or disking can alleviate the issue (Evans et al. 2013). Weed control, usually through herbicide, can enhance tree performance in the presence of competition (Andersen et al. 1989; Franklin et al. 2012; Bockstette et al. 2017). These practices can help to yield productive forests established at similar costs to other post-mining uses (e.g. pasture and wildlife habitat; Burger 2002).

Few studies, however, have evaluated the long-term establishment success of coal surface mine reclamation plantings and linked tree performance to site factors or management (Andersen et al. 1989), and many existing studies in the United States have concentrated on the Appalachian coal region (Adams 2017; Sena et al. 2018; Dement et al. 2020). The low number of recent reports limits the ability of managers to make confident prescriptions for success across the typical range of mine reclamation sites encountered.

We conducted a survey of tree performance for mine sites reclaimed between 2008 and 2018 in the Illinois Basin of southwestern Indiana, United States. This study provides a comprehensive analysis of how variation in site factors and management affects the operational success of mine reclamation tree plantations established during this period in Indiana, United States. Specific objectives were to assess the influence of (1) environmental and geological characteristics of mine reclamation sites, (2) reclamation methodology, (3) silvicultural management, and (4) climatic conditions at the time of planting on the survival and growth of planted trees.

Methods

Planting Records

We focused on 11 years of reclamation plantings (i.e. 2008–2018), providing a total sample size of 48 sites that were distributed across the Illinois basin in southwestern Indiana, United States (Fig. 2). We distinguished among sites with varying reclamation history, including sites abandoned prior to reclamation laws, but later reclaimed by the state (with either compacted soil or “loose fill”) and sites reclaimed to pasture or farmland to satisfy bond release in accordance with reclamation laws and later planted with trees under a state program offered to landowners. We use the term “Abandoned Mine Land” (AML) for sites that were mined before the introduction of SMCRA, and we divided AML sites into those with compacted fill or loose fill. Reclamation of AML sites with loose fill was influenced by the Forestry Reclamation Approach developed by the Appalachian Regional Reforestation

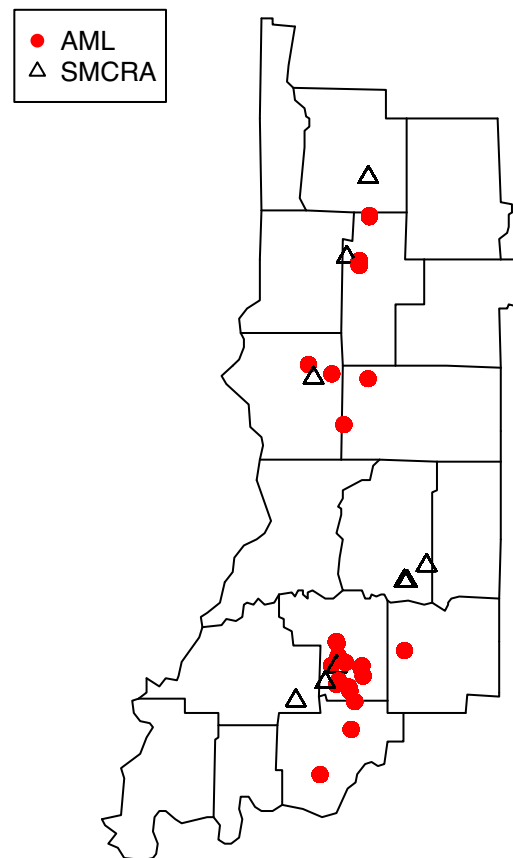


Figure 2. Distribution of 33 different private and Indiana Department of Natural Resources (IDNR) properties across Indiana where the 48 reclamation plantings in this study were surveyed. Lines denote county borders, and colors represent different reclamation programs (AML vs. SMCRA).

Initiative (Adams 2017). We use the term “SMCRA” for all other sites. AML sites vary in the time that elapsed between abandonment and reclamation and in site history, not all of which was documented. Some sites were formerly forested by mine companies or the state to varying extents. Old spoil piles were often planted with White pine. However, state reclamation work eliminated these trees before the trees in the current study were planted.

Mine reclamation planting records were obtained from the Indiana Department of Natural Resources Division of Reclamation (Jasonville, IN, U.S.A.). Planting records included Geographic Information System database and shape files with the following information: (1) location and size of unit, (2) planting start/end date, (3) reclamation program, (4) planting method (hand or mechanical planting), and (5) total number of trees planted (by hand and/or mechanical) and associated species. We obtained permission to conduct field surveys on 48 of 58 sites (83%) identified for the period selected.

Herbicide use varied by site and included no herbicide use, broadcast treatment of 41% glyphosate (Cornerstone, Winfield

United, Plainfield, IL, U.S.A.) at 0, 2.3, or 9.4 L/ha and sulfometuron methyl (Oust, DuPont, Wilmington, DE, U.S.A.) at 0, 36.5, 54.8, or 146.2 mL/ha, broadcast treatment of glyphosate (2.3 L/ha) and simazine (Aquazine, Syngenta, Basel, Switzerland) or sulfometuron methyl (146.2 mL/ha), as well as 2.3 L/ha glyphosate and 36.5 mL/ha sulfometuron methyl sprayed in 91-cm circles around planted trees at one site. For analysis, herbicide use was simplified to a binary categorical variable (yes/no). Planting method distinguished between mechanical (tractor-hauled coulters with trencher and packing wheels) and hand tools (shovels, post-hole diggers, dibbles, and augers). Due to different soil and topographical conditions at hand plantings and machine plantings, we separated these areas into different sites, even if they were planted in proximity in the same year (this occurred at seven locations). Plantings of different species in successive years in the same area were counted as different sites so that each individual planting could be distinguished (this occurred at six locations). If the same species was replanted on the same site in successive years, we did not use it due to the inability to distinguish ages. If a planting had different soil classifications in different areas, we separated these areas into different sites (this occurred at two locations). At one planting, we split the area into two sites because one part was fenced and had different vegetation control than the other.

Because performance of planted tree seedlings is often tied to weather conditions following planting, we used county-level climate data from National Oceanic and Atmospheric Administration (NOAA) “Climate at a Glance” time series resource to assess rainfall during May–October after planting as well as maximum and mean temperature during May–September after planting (NOAA Centers for Environmental Information 2022).

Sampling

Plantations were sampled using six 0.04 ha plots (20 m × 20 m), established randomly throughout each site. Within each plot, the total number of living trees was determined for each species planted (volunteers were excluded), and the height of each tree was measured to the nearest cm.

Vegetation percent cover was estimated within each plot, distinguishing between (i) grasses, sedges, and rushes; (ii) herbaceous vegetation; and (iii) naturally regenerating trees, shrubs, and woody vines. These categories were added together to create a “total cover” classification (possible range from 0% to 300%). A relative cover variable was also created for each class by dividing the cover of one class by the total vegetative cover.

Chemical and physical soil properties were analyzed for each site. Twenty paired soil samples (two soil samples 15 cm apart and 0–15 cm in depth) were collected from 10 random locations and composited within each site. Soil analysis was conducted by A&L Great Lakes Laboratories (Fort Wayne, IN, U.S.A.). Samples were analyzed for soil pH, soluble salts, OM content, and soil fertility (phosphorus [P], potassium [K], Ca, and Mg). We calculated total available nitrogen (N) by summing total nitrates and ammonium. Soil compaction was measured by soil penetrometer at depths of 7.5 and 15 cm. Five cone penetrometer measurements were taken at each of 10 randomly selected

locations throughout each site (a central point and four points 13 cm away in each cardinal direction). These penetrometer readings were then combined across all locations to get a site-wide average. Because water content can affect penetrometer readings, we obtained volumetric water content at the same time compaction was measured. Volumetric water content during these measurements ranged from 14.4 to 54.2% with an average of $18.1\% \pm 18.2\%$ (mean $\pm$ SD).

Statistical Analysis

Each site had six plots, which were considered the experimental unit for survival analyses. We dropped three sites from the final site factors analyses that had artificial soils with high amounts of coal fines and two plots that had been mowed and plowed, destroying trees and vegetation. We also dropped a third plot that had been plowed but not mowed from the vegetation analysis. We dropped one site at which tree shelters were used from the Persimmon analysis because the shelters caused such high growth that this site had some influential points. Mine reclamation establishment success was defined by a combination of seedling survival and growth, the former calculated with the following formula:

$$\text{Survival percentage} = \left(\frac{\text{density of surviving trees in each plot}}{\text{density of planted trees}} \right) \times 100.$$

We analyzed growth for 11 species that had wide enough occurrence to provide results, including: Persimmon, Black walnut, Bur oak, Pin oak (*Quercus palustris*), Swamp white oak, White oak, Shingle oak (*Q. imbricaria*), Northern red oak (*Q. rubra*), Silky dogwood (*Cornus amomum*), Swamp chestnut oak (*Q. michauxii*), and Sweetgum (*Liquidambar styraciflua*). Growth was defined by a mean annual increment (MAI). MAI was obtained by the following formula:

$$\text{MAI} = \left(\frac{\text{total tree height} - \text{standard initial height}}{\text{tree age}} \right).$$

“Standard” average initial heights were obtained for each tree species by consulting the nursery that provided the seedlings. Due to many plots with no surviving trees, we divided the analysis of survival into a logistic regression, in which the number of plots with surviving trees out of the total plots on each site was used as the response variable, and a linear mixed model analysis to evaluate percent survival on plots with at least one surviving tree.

Fixed factors included (1) planting method (mechanical vs. hand planting), (2) percent OM, (3) soil fertility variables (listed above), (4) soil pH, (5) degree of compaction at a depth of 7.5 or 15 cm, (6) total rainfall during the June after planting or total rainfall during the May–October after planting, (7) maximum temperature during the May–September after planting or mean temperature during this period, and (8) age of the planting as a fixed blocking factor. In addition, we included (9) a single factor that combined coal seam, program (AML vs. SMCRA),

and soil fill type (compacted vs. loose fill) because these variables were not fully crossed. We conducted linear mixed models separately for each species to evaluate MAI. No analytical comparisons were made between species because the sites and factors did not have equal representations of each species. We varied the use of variables for compaction at 7.5 or 15 cm, June rainfall or total growing season rainfall, and mean or maximum growing season temperature in these models based on goodness of fit using Akaike Information Criterion or consistent Akaike Information Criterion (AIC or cAIC), or the estimate for the survival logistic regression model. We also varied the use of coal seam, program, and soil fill type based on goodness of fit. Some species did not have enough sample size at each level of planting method, coal seam, program, or soil fill type to include these factors. Variance Inflation Factors (VIF) were used to determine factors that caused multicollinearity, which were dropped if VIF exceeded 4.5 (excepting factors involved in interactions or higher-order variables). Each plot was considered a replicate for the survival models, and each tree was considered a replicate for the increment models, while site was used as a random intercept for all survival models and plot was used as a random intercept for all increment models.

We used linear mixed models to determine the effects of our fixed variables on the total cover of competing vegetation. We used mixed models to determine the effects of all our vegetation cover variables, including total or relative forb cover, total or relative grass cover, total or relative woody cover, or total vegetative cover (depending on goodness of fit), as well as herbicide use and its interaction with vegetation cover variables, on survival. We used the same variables in linear mixed models to examine their effect on the MAI of each species. These variables could not be included in the other models, since vegetation cover would be correlated with the other factors, such as soil nutrients.

R version 4.1.2 (R Core Team 2018) was used for all statistical tests. The lme4 package was used to create all linear mixed models (Bates et al. 2015). We used Least Absolute Shrinkage and Selection Operator (LASSO), methods to perform variable selection from among our fixed variables for every model except the logistic regression, but we included age as our fixed blocking factor in every model (Friedman et al. 2010). Due to potential concern about differences in soils between sites of different ages, we examined the correlation coefficients for the correlation between age and each soil variable. Both compaction variables and Ca had a coefficient of 0.4, which is generally considered to be on the border of moderate and low correlation (Overholser & Sowinski 2008); cation exchange capacity (CEC), OM, and N had a coefficient of 0.3, and the other variables had lower coefficients. Because the assumptions of our mixed models (homogeneity of variance and linearity of error) were not met, and transformations could not fix this issue, we used bootstrapping from the package lmeresampler to get estimates and *p* values for our models (Loy et al. 2022). The effect-size package was used to provide eta-squared effect sizes based on the degrees of freedom and *t*-values provided by the bootstrapping results (Ben-Shachar et al. 2020). This package was also used to provide Cohen's *d* values from the odds ratios produced by the binary survival model. In the results we present the

test outcomes and effect sizes for all species where a factor had a significant ($p < 0.05$) effect, regardless of the effect sizes. Effect sizes were interpreted as large, medium, or small based on thresholds given by Cohen (1988).

Results

Survival

Survival ranged from 0 to 107%. The survival variable was indirectly calculated based on the density of surviving planted trees, and some errors were bound to occur. In the instance of higher than 100% survival, it is likely that the spacing was slightly closer than planned on that plot, and that most of the trees survived. It is unlikely that volunteers contributed to higher survival estimates, as we were able to exclusively tally planted trees based on species, spacing, and age. Twenty-nine percent of the plots had no surviving trees at all (0% survival). Of those with at least one surviving tree, mean survival was 21%.

Phosphorus was the most significant variable explaining the logistic regression survival model. The relationship between P and the probability of at least one surviving tree ($p < 0.001$, Cohen's *d*: 2.1) was positive. All plots with P greater than 15 ppm had at least one surviving tree (Fig. 3). Rainfall in the summer after planting also had a large positive effect on the probability of at least one tree surviving ($p < 0.001$, Cohen's *d*: 1.7).

Soil OM content had a large effect on survival for plots with at least one surviving tree ($p = 0.028$, η^2 : 0.14, CI: 0.13); peak survival for plots with at least one tree occurred at 6.0% OM. Three sites with engineered soil had to be dropped from the analysis due to their high OM (17.4–39.9%) and low survival, causing them to be outliers.

pH also had a large effect on survival on plots with at least one tree ($p = 0.025$, η^2 : 0.16, CI: 0.15), whereby survival decreased with increasing pH. June rainfall had a medium positive effect on survival in plots with at least one tree ($p = 0.018$, η^2 : 0.10, CI: 0.09).

Age, which we used as a fixed blocking factor, had a significant effect on plots with more than one surviving tree ($p = 0.008$, η^2 : 0.20, CI: 0.17).

While we could not estimate survival by species, we were able to get an idea of how the species performed relative to each other by creating an index of change in relative importance (Table 1). We did this by dividing the proportion of a species among all surviving trees by the proportion of that species among all planted trees. If a species increased its proportion relative to the total population of trees across all sites (e.g. had greater survival than most other species), then the number would be greater than 1. Not all of these were planted in high enough number to analyze their growth, but for those that were, we present the results below.

Growth: Species Differences

The mean and range of each species are represented in Figure 4, which provides a qualitative comparison, although no analytical comparisons were made between species (see Section 2.3).

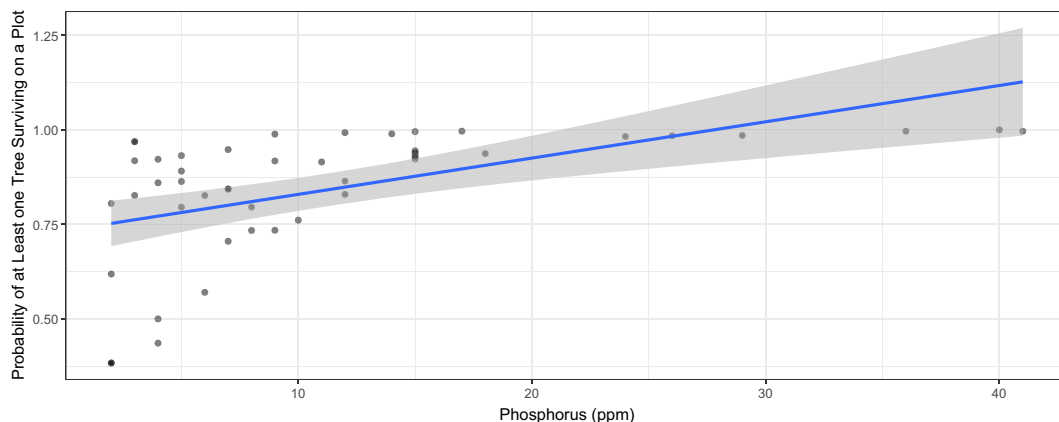


Figure 3. Probability of at least one tree surviving on a plot across the gradient of phosphorus in the soil at surveyed reclaimed mine sites. The final model did not include a higher order term, but note that the model predicts 100% probability of at least one tree surviving greater than 28 ppm. None of the plots in our experiment where phosphorus was over 15 ppm were a total failure.

Table 1. Index of change in relative importance by species. Numbers greater than 1 indicate that species comprised a greater proportion of all trees surviving at all sites than at planting. Numbers less than one indicate species comprised a smaller proportion than at planting.

Species	Change in relative importance
Persimmon (<i>Diospyros virginiana</i>)	1.23
Sycamore (<i>Platanus occidentalis</i>)	1.21
Black locust (<i>Robinia psuedoacacia</i>)	1.21
White pine (<i>Pinus strobus</i>)	1.19
Baldcypress (<i>Taxodium distichum</i>)	1.19
Swamp chestnut oak (<i>Quercus michauxii</i>)	1.17
Shagbark hickory (<i>Carya ovata</i>)	1.17
Silky dogwood (<i>Cornus amomum</i>)	1.17
Northern red oak (<i>Q. rubra</i>)	1.15
Swamp white oak (<i>Q. bicolor</i>)	1.10
Redbud (<i>Cercis canadensis</i>)	1.09
Shingle oak (<i>Q. imbricaria</i>)	0.98
Pecan (<i>Carya illinoensis</i>)	0.97
Black walnut (<i>Juglans nigra</i>)	0.96
White oak (<i>Q. alba</i>)	0.96
Bur oak (<i>Q. macrocarpa</i>)	0.96
Kentucky coffeetree (<i>Gymnocladus dioica</i>)	0.95
American plum (<i>Prunus americana</i>)	0.95
Sweetgum (<i>Liquidambar styraciflua</i>)	0.94
Pin oak (<i>Q. palustris</i>)	0.94
Black oak (<i>Q. velutina</i>)	0.93
Hazelnut (<i>Corylus americana</i>)	0.90
Gray dogwood (<i>Cornus racemosa</i>)	0.90
Cherrybark oak (<i>Q. pagoda</i>)	0.88
Other (23 species)	0.67

Growth: Rainfall and Temperature

Rainfall in June after planting had a large positive effect on Persimmon (Fig. 5, $p < 0.001$, η^2 of 0.19, CI: 0.11) and Black walnut growth rate ($p = 0.022$, η^2 of 0.17, CI: 0.15). Maximum temperature in the summer after planting had the largest positive effect on Persimmon growth rate other than age ($p < 0.001$, η^2 of 0.23, CI: 0.12), while mean temperature in the summer after

planting had the largest positive effect on Bur oak other than age ($p = 0.002$, η^2 of 0.25, CI: 0.17).

Growth: Organic Matter

OM affected growth of all oak species, and Black walnut. OM had a large positive effect on Black walnut growth ($p = 0.005$, η^2 of 0.29, CI: 0.23) and a medium positive effect on Pin oak growth ($p = 0.034$, η^2 of 0.13, CI: 0.12) and White oak growth ($p = 0.036$, η^2 of 0.07, CI: 0.07). OM had a medium nonlinear effect on Bur oak growth ($p = 0.038$, η^2 of 0.09, CI: 0.09), Shingle oak growth ($p = 0.048$, η^2 of 0.13, CI: 0.13), and Northern red oak growth ($p = 0.002$, η^2 of 0.08, CI: 0.06), and had a large nonlinear effect on Swamp chestnut oak ($p < 0.001$, η^2 of 0.42, CI: 0.24) and Swamp white oak growth (the largest effect other than age, $p = 0.009$, η^2 of 0.28, CI: 0.23). The peak growth occurred at 3.5% for Shingle oak, 3.6% for Northern red oak, 3.7% for Swamp chestnut oak, 4.1% for Bur oak, and 4.6% for Swamp white oak (Fig. 6).

Growth: Soil Nutrients, Cation Exchange Capacity, and pH

Total available N had a large positive effect on Northern red oak growth ($p = 0.003$, η^2 of 0.20, CI: 0.15) and Swamp chestnut oak growth ($p = 0.047$, η^2 of 0.16, CI: 0.16); and the largest effect on Pin oak growth ($p < 0.001$, η^2 of 0.34, CI: 0.19). Total available N ($p = 0.033$) was the only variable to affect Sweetgum and had a medium positive effect on growth (η^2 of 0.12, CI: 0.11). At 2 ppm, Sweetgum growth was 12 cm/year, and growth increased to 53 cm/year at 15 ppm.

Phosphorus had a large positive effect on Swamp white oak growth ($p = 0.015$, η^2 of 0.23, CI: 0.20). Phosphorus had a medium nonlinear effect on White oak growth ($p = 0.042$, η^2 of 0.13, CI: 0.13). The peak growth occurred at 12 ppm. Four trees were dropped from the analysis of White oak growth, which changed the results of these analyses. One was the only White oak at a site where Ca concentration was an outlier at 5100 ppm.

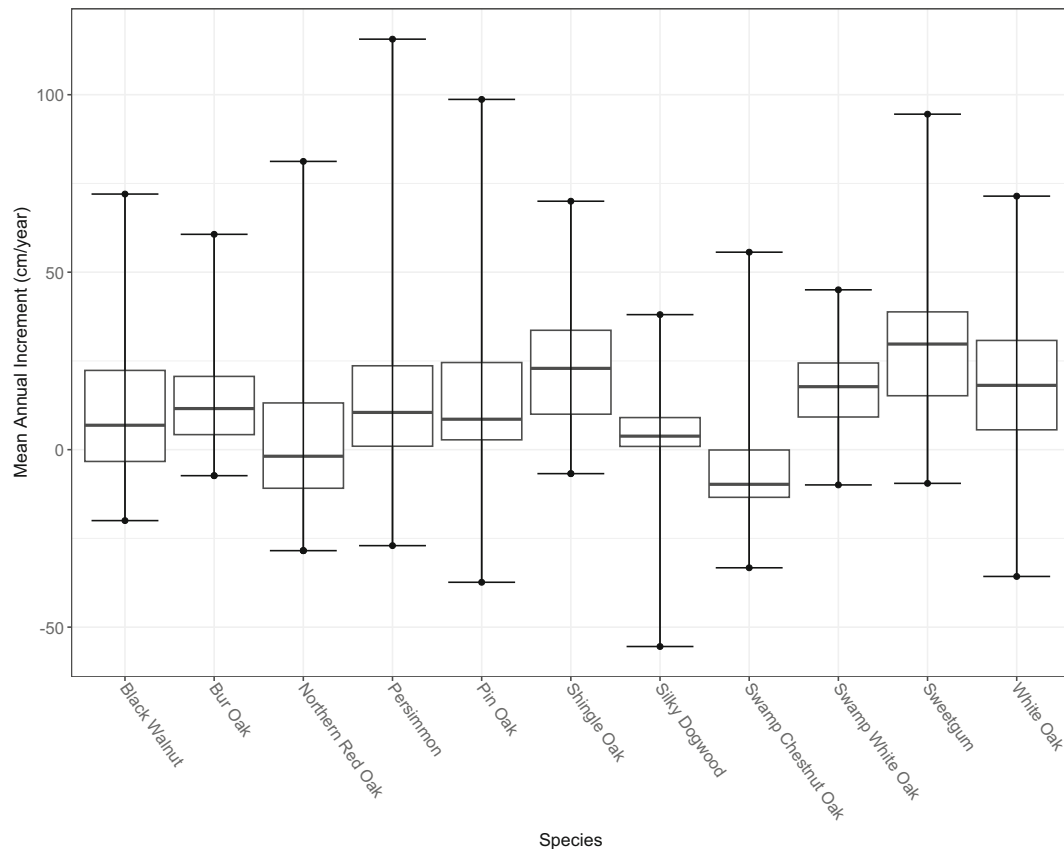


Figure 4. Mean annual increment and range of each species analyzed. Bars represent means, and whiskers represent minimum and maximum values. Species codes are as follows: BWN = Black walnut, BUO = Bur oak, NRO = Northern red oak, PER = Persimmon, PNO = pin oak, SHO = Shingle oak, SDW = Silky dogwood, SWO = Swamp white oak, SWG = Sweetgum, WHO = White oak.

The other three were the only White oaks at another site where P was 41 ppm, higher than at any other site (other than one artificial soil site, which was already dropped).

K, which ranged between 48 and 119 ppm, had a medium positive effect on Persimmon ($p = 0.003$, η^2 of 0.12, CI: 0.09) and White oak ($p = 0.014$, η^2 : 0.13, CI: 0.11) annual growth rate. Mg, which ranged between 70 and 390 ppm ($p = 0.042$), had a medium negative effect (η^2 : 0.13, CI: 0.13) on the growth of White oaks, and a large negative effect on the growth of Northern red oaks oak ($p < 0.001$, η^2 : 0.22, CI: 0.12). Growth decreased with increasing Mg concentrations. Ca had a large negative effect on White oak growth ($p = 0.006$, η^2 : 0.15, CI: 0.12). CEC had a large negative effect on Shingle oak growth ($p = 0.038$, η^2 of 0.16, CI: 0.15).

pH had a large effect on Swamp white oak ($p = 0.036$, η^2 : 0.26, CI: 0.25) and Northern red oak ($p < 0.001$, η^2 : 0.24, CI: 0.16) growth rate. pH had the largest effect on Northern red oak growth after coal seam. Growth for both these species increased with higher pH. pH also had the largest effects on Swamp chestnut oak ($p < 0.001$, η^2 of 0.54, CI: 0.31) and Black walnut growth rate ($p < 0.001$, Fig. 7, η^2 of 0.68, CI: 0.23); however, for these species, growth increased with decreasing (more acidic) pH.

Growth: Planting Method

Planting method had a medium significant effect on Swamp white oak ($p = 0.005$, η^2 of 0.13, CI: 0.11) annual growth rate. Hand planting resulted in a loss of height (-14 ± 10 cm/year), while machine planting resulted in positive growth rates (15 ± 1 cm/year). Planting method had a large significant effect on Swamp chestnut oak annual growth ($p < 0.001$, η^2 : 0.50, CI: 0.26). Hand-planted trees had positive growth rates (mean: 11 ± 4 cm/year) while machine-planted trees lost height (-7 ± 1 cm/year).

Growth: Soil Compaction

Soil compaction at a depth of 7.5 cm had a large negative effect on Black walnut growth ($p = 0.002$, η^2 of 0.38, CI: 0.27) and a medium negative effect on White oak growth ($p = 0.019$, η^2 : 0.13, CI: 0.11). Soil fill type had a larger effect than any other variable on Shingle oak annual growth ($p = 0.040$, η^2 : 0.19, CI: 0.18). Sites with loose fill had a mean growth of 34 ± 6 cm/year, while sites with compacted fill only had a mean growth of 21 ± 2 cm/year.

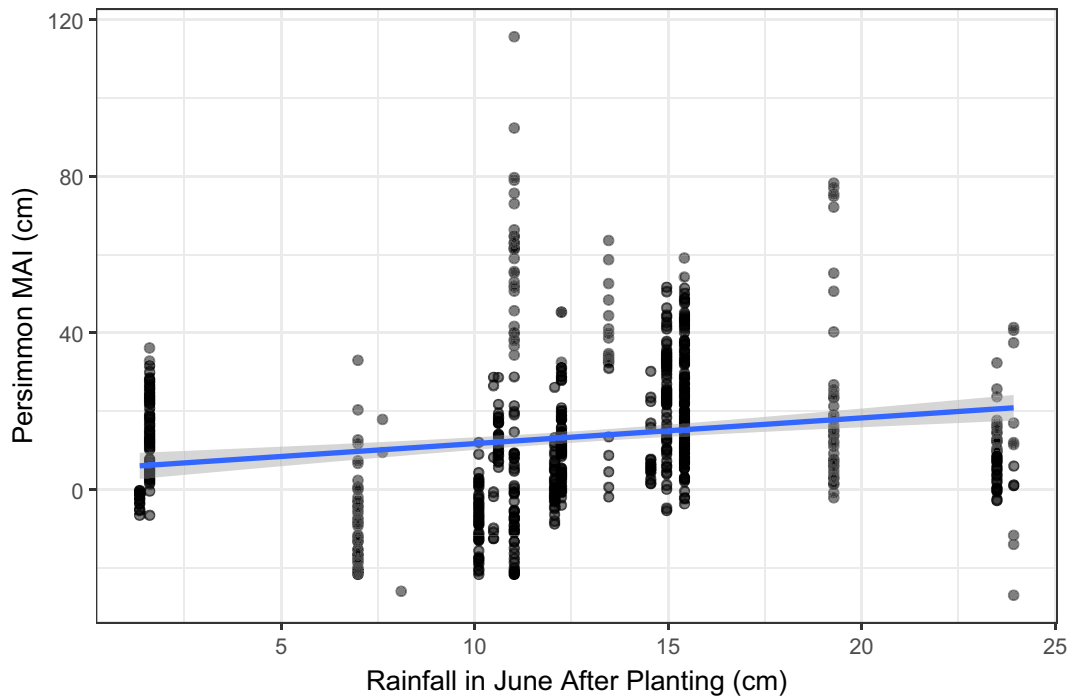


Figure 5. Mean annual increment of Persimmon height across the gradient of rainfall in the June after planting at surveyed reclaimed mine sites.

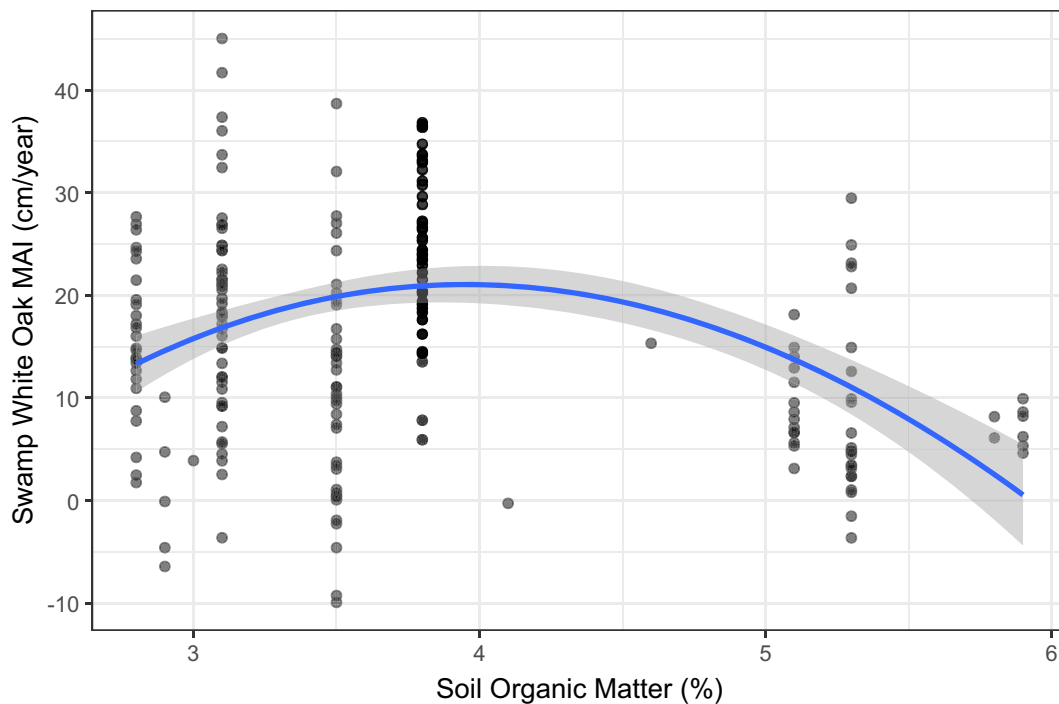


Figure 6. Mean annual increment of Swamp white oak height across the gradient of soil organic matter at surveyed reclaimed mine sites. Shading represents SE. The relationship was nonlinear and survival peaked at 4.6% according to the model.

Growth: Coal Seam and Reclamation Program

The combination of coal seam, soil fill type, and program had the largest effect of any variable on White oak growth. A post hoc test revealed that White oaks at seam 6 AML sites

with loose fill had higher growth (40 ± 6 cm/year) than those at seam 3 AML sites with compacted fill ($p = 0.004$, η^2 : 0.21, CI: 0.14), which decreased in height (-25 ± 19 cm/year).

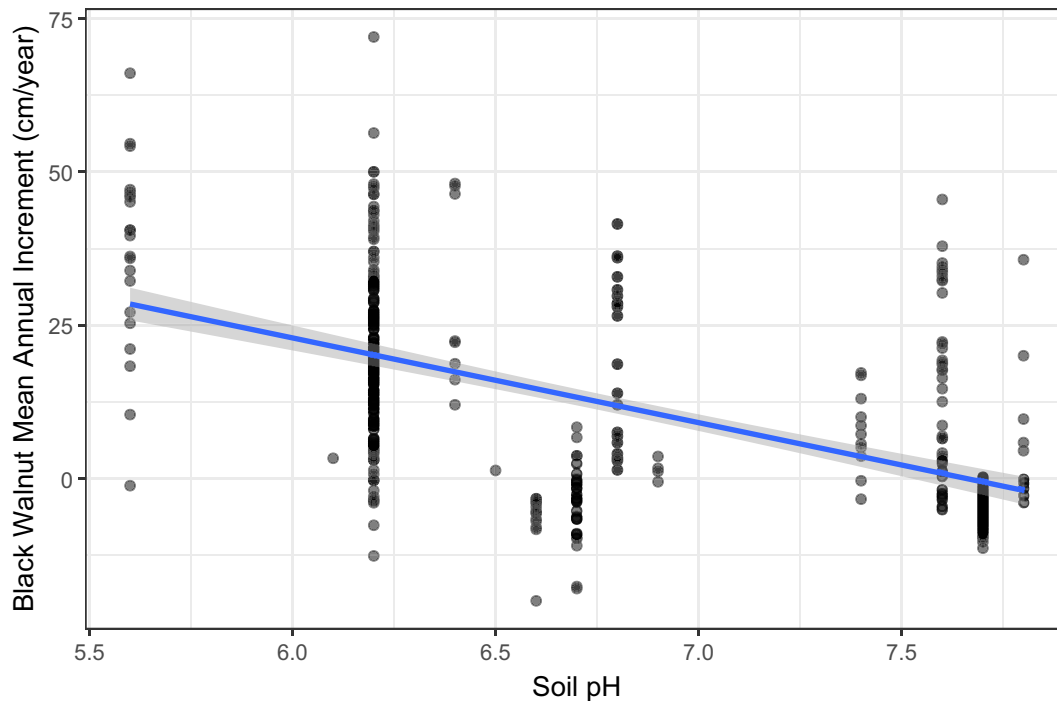


Figure 7. Mean annual increment of Black walnut height across the pH gradient at surveyed reclaimed mine sites.

Reclamation program had a medium effect on Persimmon annual growth ($p = 0.012$, η^2 : 0.08, CI: 0.07). AML sites had a mean growth of 15 ± 2 cm/year, while SMCRA sites only had a mean growth of 7 ± 3 cm/year.

Coal seam had effects on Northern red oak growth and Pin oak growth. A post hoc test revealed that Northern red oaks at seam 2 sites had the highest mean growth (36 ± 5 cm/year). Northern red oaks at seam 5 sites, which had a mean growth of -7 ± 3 cm/year, decreased rather than increased in height and had significantly lower growth than oaks at seam 2 ($p < 0.001$) and 6 ($p = 0.001$), while Northern red oak at seam 6 (6 ± 5 cm/year) had lower growth than those at seam 2 ($p = 0.008$). The effect sizes for seam 5 Northern red oak growth compared to seam 2 as a reference were larger than any other effect size for Northern red oak (η^2 : 0.41, CI: 0.14), and the effect sizes for seam 6 compared to seam 2 (η^2 : 0.26, CI: 0.14) and seam 6 compared to seam 5 (η^2 : 0.22, CI: 0.17) were also large. A post hoc test revealed that the pin oaks at seam 3, which decreased in height (-48 ± 22 cm/year), had lower growth than those at seam 2 (19 ± 6 cm/year, $p = 0.005$) and those at seam 6 (23 ± 7 cm/year, $p = 0.014$). The effect sizes for seam 3 compared to seam 2 as a reference were large (η^2 : 0.27, CI: 0.18), as were the effect sizes for seam 3 compared to seam 6 (η^2 : 0.26, CI: 0.19). Pin oaks at the other two seams had intermediate (though positive) growth.

Growth: Age of the Planting

Age, which we used as a fixed blocking factor, had a large significant effect on Persimmon ($p < 0.001$, η^2 of 0.35, CI: 0.13),

Bur oak ($p < 0.001$, η^2 of 0.25, CI: 0.15), Swamp white oak ($p < 0.001$, η^2 : 0.54, CI: 0.30), Northern red oak ($p < 0.001$, η^2 of 0.16, CI: 0.11), Swamp chestnut oak ($p < 0.001$, η^2 of 0.53, CI: 0.24), and Pin oak growth ($p < 0.001$, η^2 of 0.24, CI: 0.19).

Growth: Vegetation Models

Vegetation cover had no significant effects on Swamp chestnut oak growth. In the original vegetation models for Black walnut no vegetation variables were significant. In the original model for Sweetgum total cover had a large negative effect on Sweetgum growth ($p = 0.014$, η^2 of 0.22, CI: 0.19), and in the original model for Pin oak bare ground cover had a large positive effect on Pin oak growth ($p < 0.001$, η^2 : 0.18, CI: 0.12). However, these results were influenced by only one site, which had a high amount of bare ground and a high growth rate. If this site was removed, grass cover interacted with herbicide use to have a large significant effect ($p = 0.041$, η^2 of 0.18, CI: 0.18) on Black walnut mean annual growth (Fig. 8). However, it should be noted that sites where herbicide was used had from 0 to 100% grass cover, but the range of grass cover at sites where herbicide was not used was 1–52%. Higher grass cover was associated with lower growth when herbicide was used, but was associated with higher growth when herbicide was not used. When the site with high bare ground was removed, total cover was no longer significant for Sweetgum, and bare ground no longer had any effect on Pin oak.

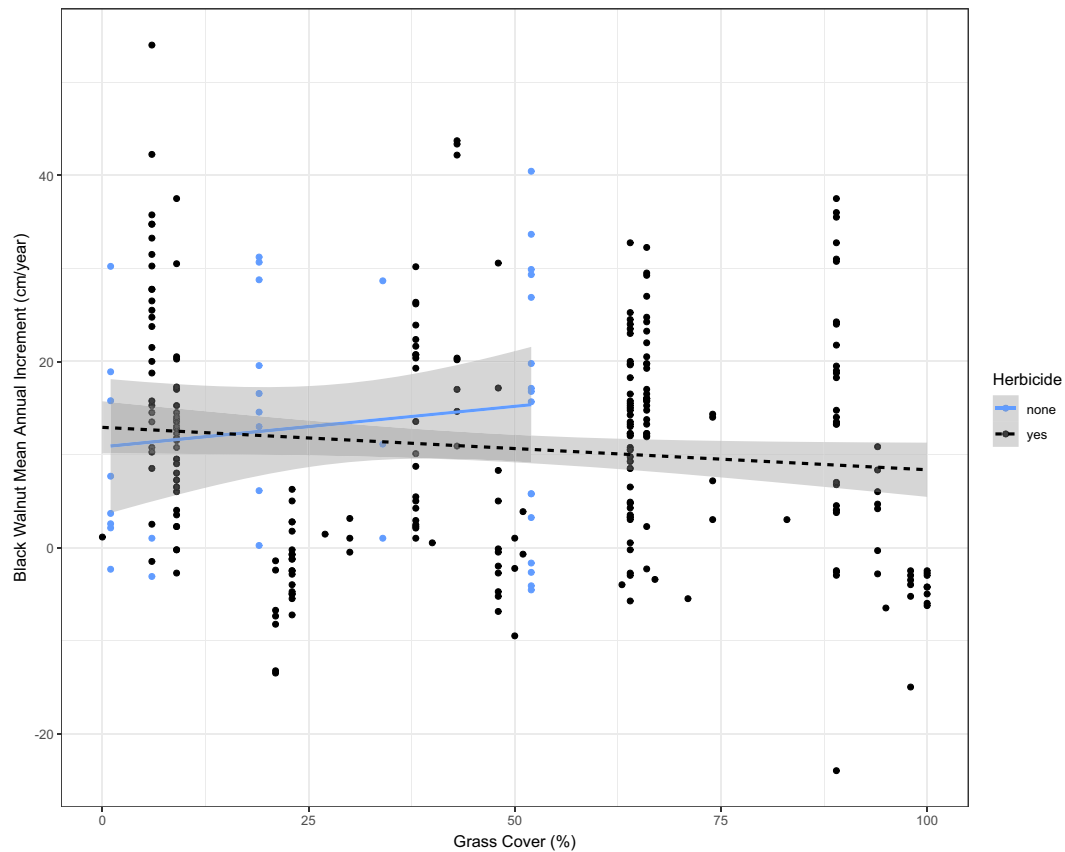


Figure 8. The interaction of grass cover and herbicide use on mean annual increment of Black walnut height at surveyed reclaimed mine sites.

Herbicide had a small negative effect on Silky dogwood ($p = 0.014$, η^2 : 0.02, CI: 0.02). Herbicide reduced mean growth of Silky dogwoods from 11 to 4 cm/year.

Total plant cover had a large negative effect on Shingle oak annual growth ($p = 0.006$, η^2 : 0.19, CI: 0.16) and a medium negative effect on Bur oak growth ($p = 0.038$, η^2 of 0.13 CI: 0.13).

Forb cover had a medium negative effect on Persimmon growth ($p < 0.001$, η^2 of 0.11, CI: 0.08) and a very small negative effect ($p = 0.035$, η^2 : 0.01, CI: 0.01) on Silky dogwood mean annual growth; relative cover of forbs had a small negative effect on Bur oak growth rate ($p = 0.041$, η^2 of 0.05 CI: 0.05).

Relative woody cover had a large positive association with Swamp white oak growth ($p = 0.037$, η^2 of 0.19, CI: 0.18) and White oak annual growth ($p = 0.030$, η^2 : 0.12, CI: 0.11).

Grass cover had a negative effect on Northern red oak growth in plots sprayed with herbicide as well as in plots without herbicide; however, the effect was much greater if herbicide was not used ($p = 0.027$, η^2 of 0.02, CI: 0.02). Forb cover had the same interaction with herbicide ($p = 0.013$, η^2 : 0.02, CI: 0.02), as did woody plant cover ($p = 0.031$, η^2 of 0.02, CI: 0.02), and cover of bare ground ($p = 0.006$, η^2 : 0.03, CI: 0.03). In the case of bare ground, MAI was unaffected by the amount of bare ground cover if herbicide was used.

Vegetation Cover

Total vegetation cover had the most normal distribution of any other vegetation measure, so we used it as our dependent variable. This measure represented the sum of the cover of grass, forbs, and woody vegetation (excluding planted trees), and as such, can be over 100% (maximum possible cover would be 300%, in the case that each of the three classes had complete cover). The actual range was between 3 and 214%, while mean total cover across all plots at all sites was 120%. Soil P, which ranged from 2 to 41 ppm, had a large negative effect on total cover ($p = 0.018$, η^2 : 0.16, CI: 0.14). However, this was influenced by one site, which had low plant cover and high P. If this site was removed, there were no site factors that significantly affected vegetation cover. There were no effects of vegetation cover or herbicide on tree survival.

Discussion

Average overall survival (21%) was relatively low compared to typical unmined sites. Jacobs et al. (2004) conducted a survey of 87 afforestation plantations (ages 1–5 year) in Indiana, excluding reclamation sites, and found that the average survival of planted trees was 65%. We recommend maintaining OM between 3 and 5% due to its nonlinear effect on overall survival, and the growth of most oak species, including Bur oak, Swamp

white oak, Shingle oak, Northern red oak, and Swamp chestnut oak. This recommendation for OM (and other soil variables discussed herein) reflects data from sites of varying ages, and these values may have changed over time at the older sites. However, we found low correlation between age and soil variables (see Section 2.3), suggesting the effect of stand age on these parameters was nominal in our study. Oaks have been found to be sensitive to OM or other factors associated with organic content, such as pore space (Scullion & Malinowszky 1995). Black walnut, pin oak, and White oak had linear positive relationships with OM. The range of OM content where Black walnut was planted was optimal for many of our species (2.9–4.1%). The range of OM where Pin oak and White oak were planted was 1.9–5.1% and 1.8–5.3%, respectively. Despite the higher order variable being dropped during model selection, the highest growth rates for these species were observed at intermediate values of OM (i.e. 3–4%).

Phosphorus was the most important variable predicting whether any trees could survive on a plot and had a positive effect on Swamp white oak growth. The reason for negative influence of P on White oak and total vegetation cover was less clear, but P less than 12 ppm is evidently a hindrance to tree growth and survival.

Rainfall during the summer after planting also determined the ability of a plot to support any surviving trees. Rainfall in June affected overall survival, and growth rate for Persimmon and Black walnut. At sites with at least one surviving tree, survival increased from an average of 20% to 51% between the plantings with the lowest June rainfall (1 cm) to the highest (32 cm). Another reclamation study in Ohio also found that rainfall was a key factor (Larson et al. 1995). When planting was followed by two wet years, soil ripping was not necessary, and competing vegetation did not negatively affect survival; however, when a drought followed planting, survival greatly decreased on topsoil, unless the soil was ripped, or the plots were not planted with grass or legumes (Larson et al. 1995). Most species will perform better in years with more rain, but because rainfall cannot be controlled or predicted, species mixes and sites can be adapted for resilience to low precipitation, e.g. adding drought-resistant species.

Swamp white oak only had height growth if machine planted; it had reduced height in hand-planted plots. However, Swamp chestnut oak had greater growth rates when hand planted. It is likely that the success of Swamp chestnut oak when hand planted was at least partly due to the wetter terrain for which hand planting was often used, though why this would not also apply to Swamp white oak is unclear. Hand planting was also used on steep terrain, which may have contributed to the failure of Swamp white oak when hand planted. Jacobs et al. (2004) found that machine planting resulted in greater plantation success in Indiana, which they mainly attributed to herbicide being more likely to be used on machine-planted sites; they also noted that holes created during hand planting are often too shallow for hardwood seedlings. Hand planting has potential to be successful, however, if performed with skill and care.

Compaction was negatively associated with Black walnut and White oak growth, and the tendency of Shingle oak to perform better at sites with loose fill indicates that compaction affected it as well. Poor soil structure has been identified as one of the most important factors affecting grass revegetation on reclaimed mines (Doubleday 1974). We expected compaction to affect more tree species, as much so as rainfall and OM, though the effects of compaction can be ameliorated by soil moisture (Day 1999) and OM content (Ekwue & Stone 1995). Compaction at the depth measured could be addressed by ripping or disking (Fields-Johnson et al. 2014), but deeper compaction (>20 cm) can only be addressed when filling the site (Back et al. 2024).

pH affected Swamp white oak and Northern red oak growth, which were better in more basic (less acidic) soils. This was unexpected as high pH is often associated with a failure for trees to dominate a site, favoring herbaceous species instead (Casselmann et al. 2006; Skousen et al. 2009; Franklin et al. 2012). pH more predictably affected overall survival, and Swamp chestnut and Black walnut growth, which performed better in more acidic soils. In fact, pH had a larger effect on survival (for plots with at least one tree) than any variable other than age. These results correspond with many studies involving hardwoods on reclaimed mine sites (Showalter et al. 2007; Evans et al. 2013), but contradict some other studies on Black walnut that reported better performance in more basic soils (Skousen et al. 2009). Black walnut is desired by landowners due to its high timber value. Our results indicate that Black walnut can grow in soil with acidic conditions (between 5.5 and 6.5 pH) and low compaction (<1.0 kPa at a 7.5-cm depth). However, these results should be used with caution because performance of Black walnut on mined lands has proven unpredictable (Skousen et al. 2009).

Mg had a negative effect on White oaks and Northern red oaks; and Ca had a negative effect on White oaks. Similar results have been found for Mg and oaks in England and Japanese larch in Wales (Bending et al. 1991; Scullion & Malinowszky 1995). Bending et al. (1991) suggested that Mg may inhibit availability of micronutrients by increasing soil pH beyond 7.5. While too much Mg can cause toxicity when Ca levels are insufficient, the Ca:Mg ratio at our sites (range: 1.7–45.3) always displayed a sufficient level of Ca to prevent this from occurring. It may be that the levels of both these nutrients together (and perhaps other ions) were high enough to cause salt stress. Salt stress due to Mg can be caused when it forms Mg sulfates (Doubleday 1974). At low pH, iron and manganese sulfates may also form. High salinity is less common in areas with greater rainfall. Replacing the positive cations in our White oak model with a measure of CEC did not reveal any further results, as might be expected if salinity were the issue; however, CEC did have a significant negative effect on Shingle oak.

K affected Persimmon and White oak mean annual growth, which showed positive relationships. According to our model, at 48 ppm, Persimmons are predicted to grow at a rate of 11 cm/year, but this linearly increases to 14 cm/year at 119 ppm (which, though the maximum value measured, is still only considered a moderate amount by the laboratory that performed our soil analysis). While this nutrient is often the least limiting of the

macronutrients (N, P, and K) on reclaimed mine sites (Doubleday 1974), it is evidently important for Persimmon and White oak.

Grass cover was the most common vegetation variable to affect tree growth, and it often interacted with herbicide use. Oddly, Black walnut growth was positively correlated with grass growth when herbicide was not used but had the opposite relationship when herbicide was used. The fact that maximum grass cover was 52% at sites where herbicide was not used, whereas sites where it was used represented the full range of grass cover, likely obscured the true effect that untreated grass might have had if cover were higher. Simultaneous low seedling growth and grass cover at the herbicide-free sites could indicate a confounding environmental effect, if adverse conditions were responsible for low cover. Northern red oak growth was negatively associated with grass cover regardless of treatment, but herbicide reduced the effect. A previous literature review on the use of ground cover during reclamation found that herbaceous competition had a negative effect on seedling survival when cover was greater than 62%, but survival was variable below this number (Franklin et al. 2012), due to grass having both competitive and facilitative effects (Franklin et al. 2012; Macdonald et al. 2015). Control of vegetative competition with herbicide has been found to increase tree success (Franklin et al. 2012). The effects of grasses are dependent on type; cool-season grasses, or aggressive non-native grasses, tend to have negative effects on tree establishment, while warm-season grasses and native grasses are not as prone to these effects (Skousen et al. 2009; Franklin et al. 2012; Macdonald et al. 2015). We did not distinguish between warm- and cool-season grass cover in our measurements, but our results do corroborate past evidence that herbicide can be successfully used after planting to avoid competition between grasses and seedlings. In the case of Black walnut, herbicide may not be necessary under a certain threshold, mirroring Franklin et al. (2012), and our results also show herbicide should be avoided around Silky dogwoods.

Factors affecting the success of reforestation of reclaimed coal mines are complex, and the entire literature on this subject should be considered when making management decisions. Due to the expansive scale of this study and the varied nature of our sites, we can make broad conclusions, but every individual management decision must be made within its own context. However, this study highlights several important factors. First, climate after planting (i.e. rainfall and temperature), though it cannot be controlled, is an important limiting factor in mineland reclamation. While higher precipitation after planting is almost always desirable, effects of temperature are less clear. Higher temperatures increase the growth of several species but may increase water stress. Secondly, OM should be maintained between 3 and 5%, especially when planting oaks. Thirdly, machine planting resulted in a higher rate of survival and growth. Hand planting needs to be performed correctly and likely needs quality control. Fourth, while additions of N and modifications of pH may aid trees, Mg does not need to be added, especially for White

oaks and Northern red oaks. Comparing the levels of these nutrients in foliage and the soil and examining salinity may reveal the source of the problem.

While hardwood species are desired on these sites, grasses, forbs, and other vegetation perform a valuable function, including erosion control, carbon storage, and wildlife habitat. Conifers may also be considered as an option; we found many Virginia pines (*Pinus virginiana*) volunteering on several sites. Many conifers are more adapted to disturbed, mineral soils than hardwoods (Neale & Wheeler 2019) and have been used in the reforestation of degraded land in the Midwestern United States since the 1930s (Lesko et al. 2024). However, they are not native to the area studied and develop different soil and understory characteristics than hardwoods (Duffy et al. 2024). A diverse mix of species continues to be the best option, both for approximating natural conditions and for avoiding problems from the failure of individual species. It is certainly possible to grow successful hardwood forests on some of these sites, and the results of this study reveal some areas that can be improved.

Acknowledgments

We are highly grateful to K. Turpin (Indiana Department of Natural Resources Division of Reclamation) for collaborations that were essential to ensure the success of this project. We also appreciate the assistance of many Purdue University technicians during the collection of field data, especially S. Engwall; several statistics consultants from the Department of Statistics at Purdue University, especially A. Ramsethu; and the landowners that allowed access to their property. This research was funded by the Indiana Department of Natural Resources Division of Reclamation, National Science Foundation Center for Advanced Forestry Systems Award 1916587, and USDA National Institute of Food and Agriculture McIntire-Stennis Cooperative Forestry Program Accession IND90000830MS. Two reviewers and M. Daws provided constructive comments that improved the manuscript.

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Coordinating Editor: Mathew Daws

Received: 17 June, 2024; First decision: 22 August, 2024; Revised 6 January 2025 and 1 November 2024; Accepted: 8 January, 2025