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# Hardwood Species Show Wide Variability in Response to Silviculture during Reclamation of Coal Mine Sites

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**Abstract:** Coal is a significant energy source for the United States, and reclamation of surface mined lands is required under the Surface Mining Control and Reclamation Act of 1977. Reforestation of mined lands is challenging due to soil substrate properties including soil compaction, herbaceous competition, and animal browse, necessitating silvicultural treatments to help overcome such limiting factors. We investigated the field performance of black walnut (*Juglans nigra* L.), northern red oak (*Quercus rubra* L.), and swamp white oak (*Quercus bicolor* Willd.) planted on two mine reclamation sites in southern Indiana, USA, and evaluated the interactions of nursery stocktypes (container and bareroot), herbicide application, and tree shelters. Two-year survival averaged 80% across all species and stocktypes. Container stocktype had greater relative height and diameter growth (i.e., relative to initial size at planting), whereas bareroot had greater absolute height and diameter growth corresponding to initial stocktype differences. Shelter use increased height growth and reduced diameter growth across both stocktypes. Swamp white oak (*Q. bicolor*) had the highest survival rate and field performance regardless of silvicultural treatment, whereas red oak (*Q. rubra*) and black walnut (*J. nigra*) showed strong early regeneration responses to silvicultural treatments. Container seedlings showed promise as an alternative to bareroot seedlings to promote early growth on mine reclamation sites. Species-specific responses documented here indicate the need to consider the ecology and stress resistance of target species in developing cost-effective silvicultural prescriptions.

**Keywords:** mine reclamation; *Quercus* species; herbivory; competing vegetation; forest regeneration; limiting site factors; target plant concept; ecological restoration

## 1. Introduction

In 2015, coal accounted for 28% of the United States' total primary energy production [1], the third most important fossil fuel source. Surface mining is the preferred removal method when the coal deposit, or seam, is within 60 m of the surface, due to lower economic costs and higher resource recovery compared to underground mining [2]. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public law 95-87) was enacted to address concerns regarding environmental problems associated with coal mining [3]. According to SMCRA, mining is considered a temporary land use; therefore, after surface mining operations are complete, land must be returned to a condition capable of supporting its pre-mining land cover [4]. Mine operators are required to submit a bond to cover the costs of reclaiming the site. Bond release occurs only if the land, at the end of a set time period (e.g., 5 years), meets the stated environmental conditions [4].

The main abiotic and biotic factors that limit early establishment success of newly planted seedlings on mine reclamation sites in the eastern USA include low soil fertility [5,6], soil compaction [7–10], competition from weeds [9,11–13], and animal browse [14–17]. Performance of trees planted on reclaimed mines is often deficient compared with trees growing in native forest sites or other afforestation settings [4,18]. Many sites in the eastern USA reclaimed after the initiation of SMCRA were established as grasslands, wildlife habitat (grasslands with a mix of woody wildlife forage), or unmanaged forest (ground cover grasses with a mix of black locust, pine species, and woody shrubs) rather than native hardwood forests, and currently have limited economic value [4,19,20]. Despite challenges under SMCRA, proper engineering and operational procedures to reclaim and prepare mine soils for forestry uses combined with an understanding of silvicultural practices to improve tree establishment and growth on these sites can yield productive forests at similar costs to other post-mining uses (e.g., pasture, wildlife habitat) [21,22], with productivity at least equal to native forests removed by mining [23].

Reforestation efforts use nursery seedlings grown as bareroot or container stocktypes. In the eastern USA, bareroot seedlings are the most common planting stocktype [24], partly associated with low production costs. However, fine root loss and/or desiccation during lifting, storage, and transport may lead to water stress, reduced leaf area [25,26], and shoot dieback [27,28] following planting of bareroot seedlings, particularly under stressful conditions of mine reclamation sites. Container seedlings represent an alternative to bareroot production that may improve field establishment success of hardwoods [29]. Following nursery lifting, container seedlings tend to be smaller than bareroot seedlings [24,28] though they often have a greater root-to-shoot ratio. Additionally, because root systems remain intact and surrounded by media at lifting, container seedlings typically show greater root proliferation and reduced transplanting stress [30–32]. For example, container northern red oak (*Quercus rubra* L.) seedlings have consistently demonstrated reduced transplant stress and greater relative growth rates than bareroot seedlings across a variety of regeneration sites in the eastern USA [27–29,33]. Davis and Jacobs [34] found that container seedlings were significantly less drought-stressed than bareroot seedlings during the summer following planting onto mine reclamation sites in Indiana.

Despite the potential for container seedlings to improve mine reclamation success, relatively little research has examined the influence of nursery stocktypes on seedling establishment for mine reclamation, particularly in the Midwest. Therefore, the objectives of this study were to (i) assess the overall field performance and stress resistance of container seedlings compared with that of traditional bareroot (1 + 0) seedlings for three hardwood tree species planted on two mine reclamation sites, and (ii) evaluate the interactions of nursery stocktypes with herbicide and shelter use.

## 2. Materials and Methods

### 2.1. Site Description

This study was established on two sites near Dugger, Indiana, USA. CR400 (39°01′ N, 87°15′ W) is 6 km south, and Dugger (39°03′ N, 87°21′ W) is 10 km west-southwest. CR400, last mined in the 1950s and considered an abandoned mine site, was reclaimed in 2013, which consisted of grading and "loosely" compacting the overburden with no topsoil cap added. The Dugger site, owned and operated by Peabody Coal Company until 1985, was reclaimed in 1996 using typical post-SMCRA techniques of heavy compaction and an aggressive seeding mixture [16]. Additionally, a 2.5 m tall polypropylene mesh deer fence was installed around the approximately 1 ha planting sites.

### 2.2. Plant Materials

Swamp white oak (*Quercus bicolor*), northern red oak (*Q. rubra*), and black walnut (*Juglans nigra*) were selected for use in this study based on operational knowledge indicating that they performed relatively well (swamp white oak) or inconsistently (northern red oak and black walnut) in Indiana mine reclamation. Two nursery stocktype treatments were used. The first stocktype was one-year-old bareroot seedlings (1 + 0, i.e., grown for one year without transplant) grown under standard nursery cultural practices at the Indiana Department of Natural Resources (IDNR) State Tree Nursery near Vallonia, IN, USA, (38°85′ N, 86°10′ W). The second stocktype, container seedlings, was grown at Woody Warehouse nursery in Lizton, IN, USA (39°53′ N, 86°35′ W). Containers were made of fiber cloth with no bottom and an approximate volume of 580 $cm^3$. Seedlings were processed for over-winter storage in coolers (3 °C) at Purdue University, John S. Wright Forestry Center (40°26′ N, 87°02′ W), West Lafayette, IN, USA; then, they were removed from storage in mid-April 2016. Seedlings of both stocktypes were presorted prior to planting to ensure that browsed, damaged, or abnormally sized seedlings were removed to minimize potential confounding effects from nursery to field.

### 2.3. Experimental Design and Treatments

At each site, a randomized complete block design with split-split plots and three blocks was used for this study (Figure 1). The whole plot treatment was herbicide (1 or 2 years). Species were randomly assigned to subplots with 80 seedlings per species in each. Sub-subplot treatments were stocktype (container or bareroot) and shelter (tree shelter or no shelter), randomly assigned to planted rows of seedlings within the species subplots, with each treatment combination represented (20 seedlings × 3 species × 2 herbicide treatments × 2 stocktypes × 2 browse treatments × 2 sites × 3 replicates). Seedlings were machine planted in April 2016 (i.e., tractor-hauled coulter with trencher and packing wheels) at 2.4 m between rows by 1.2 m within row spacing for a total of 2880 seedlings planted.

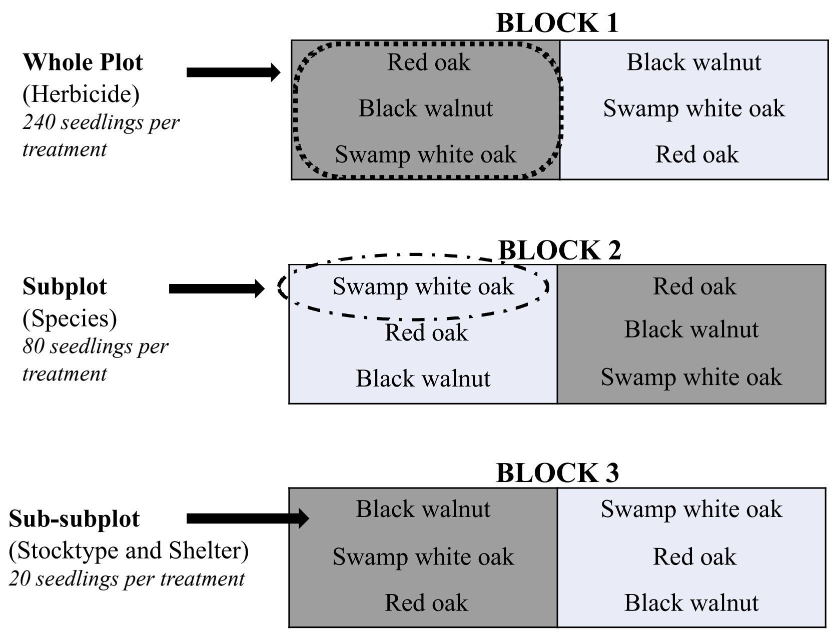


**Figure 1.** Example of the experimental design at one planting site using a factorial structure of 3 species × 2 herbicide treatments (1 year or 2 years of herbicide) × 2 nursery stocktype treatments (bareroot or container) × 2 browse control treatments (tree shelter or none). Light gray color indicates one year of herbicide, and dark gray indicates two years of herbicide.

On 17 May 2016, both sites were treated with the first herbicide treatment using a mixture of Pendulum AquaCap (BASF, active ingredient pendimethalin—38.7%), a pre-emergent for grasses and broadleaf weeds (3.9 L/ha), and Clethodium PS (Albaugh, Inc., active ingredient clethodium—26.4%), a grass-specific post-emergent (0.71 L/ha). Application was via tractor-mounted sprayer in a 1 m band centered on the planted row. Randomly selected plots at each site received the second year of vegetation control on 21 March 2017. Application was via 19 L backpack sprayer to planted rows in 1 m width. Trees were dormant at this time and a mixture of Pendulum AquaCap (BASF, 2.9 L/ha), RoundUp (Monsanto, active ingredient glyphosate—48.7%), a broad-spectrum systemic herbicide for grass and annual broadleaf weeds (0.95 L/ha), and Oust (Bayer, active ingredient sulfometuron methyl—75%) for control of annual/perennial grasses and broadleaf weeds (0.03 L/ha) was used. Shelter treatments were 30 cm tall × 15 cm diameter, white polyethylene, vented tree shelter tubes (Miracle Tube, Tree Pro, West Lafayette, IN, USA) to exclude damage from rabbits and voles.

### *2.4. Measurement Variables*

Prior to planting, a sub-sample of 12 seedlings from each nursery stocktype and species combination was destructively sampled to evaluate initial seedling morphology to characterize initial seedling quality. Seedlings were measured for height (from root collar to base of apical bud) and root collar diameter. Shoots were separated from roots at the root collar and placed into individual labeled paper bags. Samples were dried for 72 h at 70 °C, then weighed to the nearest 0.10 g for dry mass determination. Root-to-shoot ratios were calculated by dividing root dry mass by shoot dry mass.

Field measurements, including initial ground line diameter (GLD) and height to last live apical bud, were collected on 7 July 2016. Height, GLD, survival, and browse data were recorded over several days in mid-November 2016 and again over several days in mid-November 2017. Height was measured to the nearest 0.5 cm; GLD was measured using calipers to the nearest 0.1 mm. Relative height and diameter growth were calculated from field measurements by taking the absolute height or diameter for specific time periods relative to initial height or diameter of seedling (i.e., absolute height/initial height).

Pre-dawn leaf water potential was measured on three randomly selected seedlings per nested treatments, within each of the 3 species sub-plots at both sites, over one night of 5–6 October 2016, during a typical late season drought period (i.e., at least 7 days since the last rain event). Pre-dawn leaf water potential is used in determining chronic water stress of a plant and as a proxy for soil water [35]. A Scholander pressure chamber (Model 1000, PMS Instruments, Corvallis, OR, USA) was used to take pressure measurements. A 10× magnification hand lens was utilized to view the leaf petiole, and pressure was recorded at the point when xylem water was expressed from the petiole.

Browse assessments occurred with field measurements during each growing season. Browse damage was identified as deer, rabbit, or vole according to a visual inspection of the damage. Deer remove the shoot terminal buds and leave ragged edges. Rabbit herbivory is indicated by clean, angled shoot removal. Bark removal near the base is considered vole damage [17].

Soils were sampled from each site in April 2017 to determine organic matter; pH; bulk density; cation exchange capacity (CEC); total phosphorous, potassium, magnesium, and calcium; carbon:nitrogen ratio; and texture. In each plot, twelve soil cores, approximately 20 cm depth × 3 cm diameter, were collected along two transects perpendicular to planted rows and then bulked, thus there were six composite samples per site. Composite samples were sent to A&L Great Lakes Laboratory, Inc. (Fort Wayne, IL, USA) for analysis.

### *2.5. Data Analysis*

All data were checked for normality and homoscedasticity, and data were transformed if required to satisfy model assumptions (survival data only). Morphological data were analyzed using analysis of variance (ANOVA) with linear mixed models (lmer) in the 'lme4' package [36] for R (RStudio Team, Boston, MA, USA). Data were analyzed independently for each species. Fixed effects were site, stocktype, shelter, and herbicide, with block as the random effect. When treatment differences were found, the 'emmeans' package in R [37] was used to perform post-hoc pairwise comparison of 'estimated marginal means'. Survival data were analyzed similarly to morphological data except generalized linear mixed models (glmer), using the binomial family and logit transformation, in the 'lme4' package for R were used. The highest interactions between treatments were two-way as the models would not converge with three-way interactions. Leaf water potential data were analyzed using ANOVA with general linear models (glm). The 'emmeans' package in R was used to perform post-hoc pairwise comparisons for all treatment differences found to be significant. The significance level for all tests performed was $\alpha = 0.05$.

## 3. Results

### 3.1. Initial Stocktype Morphology and Soils

There were pre-planting stocktype differences among all species for height and diameter, with bareroot seedlings significantly taller and having a larger diameter than container seedlings, except for swamp white oak root collar diameters. Root and shoot dry weights followed the same trend, with bareroot seedlings having greater root and shoot dry weights for all species. However, only black walnut had a significantly different root:shoot (R:S) ratio, with container seedlings having a greater R:S ratio (Table 1).

**Table 1.** Pre-planting seedling morphological measurements.

| Species | Stocktype | Height (cm) | Diameter (mm) | Root Dry Mass (g) | Shoot Dry Mass (g) | R:S Ratio |
|---|---|---|---|---|---|---|
| BW | Bareroot | 70.8 ± 4.8 $^{a}$ | 13.7 ± 1.8 $^{a}$ | 19.8 ± 3.0 $^{a}$ | 14.3 ± 1.8 $^{a}$ | 1.4 ± 0.14 $^{b}$ |
| | Container | 27.7 ± 2.1 $^{b}$ | 8.9 ± 0.3 $^{b}$ | 3.6 ± 0.9 $^{b}$ | 1.5 ± 0.2 $^{b}$ | 2.2 ± 0.28 $^{a}$ |
| RO | Bareroot | 63.6 ± 3.8 $^{a}$ | 10.6 ± 0.6 $^{a}$ | 17.1 ± 2.0 $^{a}$ | 10.8 ± 1.4 $^{a}$ | 1.7 ± 0.15 $^{a}$ |
| | Container | 28.7 ± 0.7 $^{b}$ | 7.5 ± 0.3 $^{b}$ | 2.9 ± 0.4 $^{b}$ | 1.9 ± 0.2 $^{b}$ | 1.5 ± 0.13 $^{a}$ |
| SWO | Bareroot | 50.8 ± 4.8 $^{a}$ | 7.9 ± 0.4 $^{a}$ | 7.5 ± 1.4 $^{a}$ | 5.0 ± 1.0 $^{a}$ | 1.6 ± 0.13 $^{a}$ |
| | Container | 27.5 ± 1.2 $^{b}$ | 8.4 ± 0.4 $^{a}$ | 3.9 ± 0.5 $^{b}$ | 2.6 ± 0.3 $^{b}$ | 1.5 ± 0.06 $^{a}$ |

Notes: BW (black walnut), RO (northern red oak), SWO (swamp white oak). Species (means ± SE) were analyzed separately for each hardwood species and two stocktypes ($n$ = 12). Means in columns not followed by the same letter are significantly different ($p < 0.05$).

There were several differences in edaphic properties between the two planting sites (Table 2). CR400 had significantly greater percent organic matter (3.2%) compared to Dugger (2.8%). Additionally, CR400 had double the cation exchange capacity, phosphorous, calcium, and carbon-to-nitrogen ratio as the Dugger site.

**Table 2.** Site soil properties.

| | CR400 | Dugger |
|---|---|---|
| Organic matter (%) | 3.20 ± 0.01 $^{a}$ | 2.8 ± 0.01 $^{b}$ |
| Soil pH | 6.01 ± 0.24 $^{a}$ | 6.16 ± 0.14 $^{a}$ |
| Cation exchange capacity (meq/100 g) | 20.83 ± 1.28 $^{a}$ | 11.21 ± 0.45 $^{b}$ |
| Bulk density (g/cm$^3$) | 1.30 ± 0.01 $^{a}$ | 1.26 ± 0.01 $^{a}$ |
| Phosphorous (ppm) | 7.00 ± 0.97 $^{a}$ | 3.08 ± 0.50 $^{b}$ |
| Potassium (ppm) | 102.83 ± 4.19 $^{a}$ | 107.08 ± 5.84 $^{a}$ |
| Magnesium (ppm) | 280.42 ± 28.47 $^{a}$ | 308.33 ± 9.07 $^{a}$ |
| Calcium (ppm) | 2779.17 ± 149.17 $^{a}$ | 1250 ± 62.46 $^{b}$ |
| Carbon:nitrogen | 26.22 ± 0.87 $^{a}$ | 14.67 ± 1.25 $^{b}$ |
| Texture | Clay Loam | Silty Clay Loam |

Notes: Means (± SE), n = 6 bulked samples/site respectively. CR400 was abandoned mine land reclaimed in 2013, and Dugger was post-SMCRA (Surface Mining Control and Reclamation Act) reclaimed in 1995. Means in rows not followed by the same letter are significantly different ($p < 0.05$). meq, milliequivalents; ppm, parts per million.

### 3.2. Field Survival and Browse

Second year survival averaged 86% across all species with black walnut (85%), red oak (77%) and swamp white oak (97%). Black walnut and red oak had a similar stocktype × shelter interaction (Table 3), where only bareroot with shelter had the greatest survival (95% and 90%, respectively) compared to bareroot without shelter (83% and 80%) and container irrespective of shelter treatment (81% and 79%, Figure 2). A site × stocktype interaction was detected for red oak (Table 3), where container stocktype planted at CR400 had greater survival (92%) than bareroot (81%) or both stocktypes at the Dugger site (average of 68%). Swamp white oak had a marginally significant site × shelter interaction (Table 3); however, the pairwise comparison of least squares means indicated no significant differences for the interaction. A significant stocktype × herbicide interaction was found for swamp white oak, with survival of container stocktype having two years of herbicide (94%) significantly lower than bareroot with two years (99%) but similar to bareroot or container with one year of herbicide (average of 96%).

**Table 3.** ANOVA results for second year field performance.

| Parameters | Site (S) | Stocktype (St) | Shelter (Sh) | Herbicide (H) | S × St | S × Sh | S × H | St × Sh | St × H | Sh × H | S × St × Sh | S × St × H | S × Sh × H | St × Sh × H |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Survival | | | | | | | | | | | | | | |
| BW | 0.9706 | 0.885 | **0.004** | **<0.0001** | 0.653 | 0.4104 | **<0.0001** | **0.0011** | 0.0511 | 0.7996 | | | | |
| RO | 0.2116 | **0.0302** | 0.056 | 0.816 | **0.0009** | 0.5184 | 0.6775 | **0.0179** | 0.9481 | 0.8737 | | | | |
| SWO | 0.7456 | 0.5591 | 0.6589 | 0.1991 | 0.2862 | **0.044** | 0.4064 | 0.8843 | **0.009** | 0.5454 | | | | |
| Rel. Ht | | | | | | | | | | | | | | |
| BW | **<0.0001** | **<0.0001** | **0.0008** | **0.0002** | **0.0106** | **0.0182** | **0.014** | **0.0001** | **0.0227** | **<0.0001** | 0.2555 | 0.2555 | 0.7952 | **0.0004** |
| RO | **<0.0001** | **<0.0001** | **<0.0001** | 0.0913 | **<0.0001** | **0.0004** | **0.0217** | **0.0034** | 0.3748 | 0.79 | 0.0612 | 0.6504 | 0.4369 | 0.0564 |
| SWO | **<0.0001** | **<0.0001** | **0.0023** | **0.0092** | **<0.0001** | 0.1419 | 0.1801 | **0.0201** | 0.2024 | **0.0062** | 0.9399 | 0.2936 | 0.0995 | 0.6721 |
| Abs. Ht | | | | | | | | | | | | | | |
| BW | 0.5459 | **<0.0001** | 0.3529 | **<0.0001** | 0.7245 | 0.3067 | **0.0004** | **0.0062** | 0.6706 | **<0.0001** | 0.7732 | 0.0707 | **0.0417** | 0.1684 |
| RO | **0.0025** | **<0.0001** | **<0.0001** | **0.0005** | **0.0126** | **0.0017** | 0.7832 | 0.7742 | **0.0489** | **0.0015** | 0.1496 | 0.3222 | 0.5813 | **0.0023** |
| SWO | **0.0041** | **<0.0001** | **<0.0001** | 0.1213 | 0.0964 | **0.0226** | 0.482 | **0.0019** | 0.9164 | 0.0991 | **0.0322** | 0.4099 | 0.9148 | 0.3399 |
| Abs. Diam | | | | | | | | | | | | | | |
| BW | 0.5377 | **<0.0001** | **0.0372** | **<0.0001** | 0.2942 | 0.5884 | 0.0566 | **0.0252** | **<0.0001** | 0.0677 | 0.0582 | 0.0926 | 0.6337 | 0.806 |
| RO | **<0.0001** | **<0.0001** | 0.3374 | **0.0063** | 0.311 | 0.1836 | **<0.0001** | 0.6842 | **0.0023** | 0.8449 | **0.0082** | 0.1513 | 0.7684 | 0.072 |
| SWO | **<0.0001** | **<0.0001** | 0.1081 | **<0.0001** | **0.0236** | **0.003** | **<0.0001** | **0.0305** | **<0.0001** | **<0.0001** | 0.9727 | **0.0057** | **<0.0001** | 0.6874 |
| Tot. Diam | | | | | | | | | | | | | | |
| BW | 0.3781 | **<0.0001** | **0.0035** | **<0.0001** | 0.5961 | 0.886 | **0.0027** | 0.189 | **<0.0001** | 0.3661 | 0.1748 | 0.9196 | 0.2481 | **0.0223** |
| RO | **0.0128** | **<0.0001** | 0.977 | **0.0075** | 0.0591 | **0.0004** | **0.0024** | 0.1367 | 0.3825 | 0.6964 | 0.4437 | 0.4057 | 0.7513 | 0.2239 |
| SWO | **0.0013** | **0.0004** | **0.023** | **<0.0001** | 0.8843 | **0.0002** | **<0.0001** | **0.0062** | **0.0282** | **0.0154** | **0.0345** | 0.3005 | **<0.0001** | 0.4983 |

Notes: Analysis of variance results for second year survival, absolute height and diameter (*Abs. Ht* and *Abs. Diam*), and growth (*Rel. Ht* and *Rel. Diam*) for black walnut (BW), northern red oak (RO), and swamp white oak (SWO) for the effects of site, stocktype, shelter, herbicide and all interactions. Species were analyzed separately. Bold font indicates significant effect.

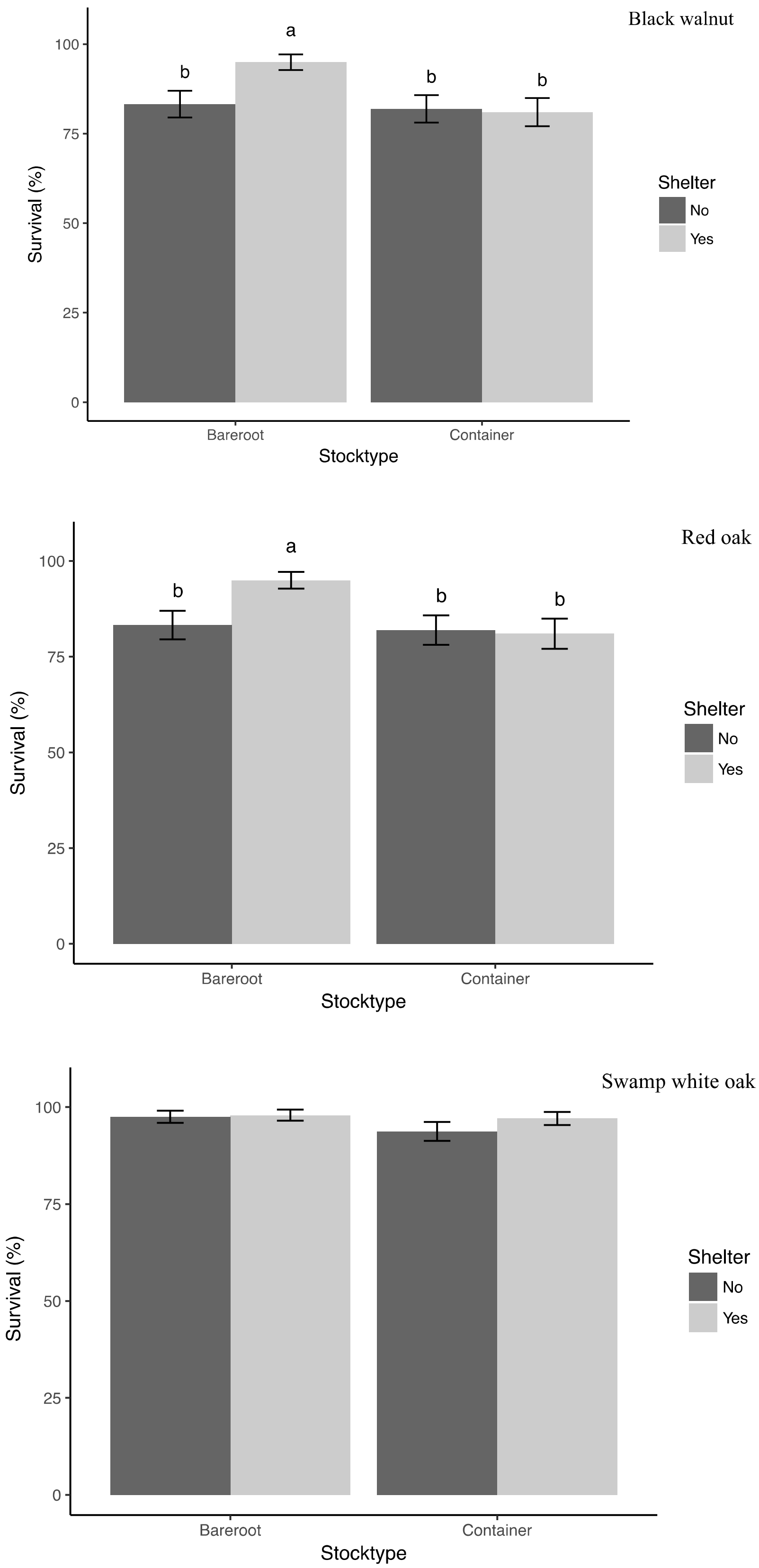


**Figure 2.** Percent survival after two years of black walnut, red oak, and swamp white oak for stocktype × shelter interaction. Columns represent means, and bars represent ±1 SD. Columns with different letters are statistically different according to Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$.

After two years, the total number of seedlings browsed was 81 out of 2880 seedlings planted (2.8%) despite fencing around both sites (Appendix A Table A1). Deer showed a clear preference for species, with red oak browse counts (36) greater than swamp white oak (14) and black walnut (0).

### *3.3. Height and Diameter Growth*

Stocktype had a significant influence on growth for all species, except red oak second year relative height growth, with container stock having greater relative height and diameter growth than bareroot stock. Higher level interactions varied among species for relative growth (Table 3).

All species had significant interactions of site × stocktype for second year relative height growth (Table 3). Container stock had significantly greater growth than bareroot for black walnut and swamp white oak, with no site differences between stocktypes for black walnut but significant differences for swamp white oak (Figure 3). Container stocktype had greater growth for all species at CR400, with container black walnut and swamp white oak having almost six times the growth of bareroot stock (Figure 3). An interaction of stocktype × herbicide was significant for all species' second year diameter growth (Table 3). A similar trend for diameter growth was found, with container having significantly greater diameter growth for all species and two years of herbicide, where growth differences became more pronounced but only with two years of herbicide use (Figure 3).

A significant interaction of site × shelter × herbicide on second year relative height growth was found for black walnut and red oak but not for swamp white oak (Table 3). At the Dugger site, shelter use and two years of herbicide significantly increased both black walnut and red oak relative height growth compared to other combinations. However, at CR400, there were no differences between treatment combinations for swamp white oak, but black walnut without shelter and one year of herbicide had greater relative growth than with shelter and one year or without shelter and two years herbicide.

### *3.4. Absolute Height and Diameter*

All species showed stocktype differences for absolute height and diameter (Table 3), with bareroot stock taller (10–20 cm) and larger (1–3 mm) than container stock after two years (Figure 4). The trend of taller and larger bareroot than container seedlings was consistent throughout all interactions.

In the second year, no species had a significant interaction of site × stocktype × shelter for absolute height, and each of the other three-way interactions was only significant for one species per interaction (Table 3). Black walnut and swamp white oak had a significant interaction of stocktype × shelter for second year absolute height. Both species followed the general trend of bareroot stocktype being taller than container; however, shelter affected black walnut bareroot stocktype and swamp white oak container stocktype. Interestingly, shelter use resulted in reduced absolute height for bareroot black walnut while absolute height increased for container swamp white oak.

### *3.5. Leaf Water Potential*

Site was the only significant treatment found for leaf water potential across all species (Table 4). The CR400 site had significantly higher water potential than Dugger (Figure 5). A significant interaction of site × herbicide was detected for swamp white oak. Dugger had significantly lower water potentials, and herbicide was only significant at Dugger, with one year of herbicide having the lowest water potential compared to two years of herbicide.

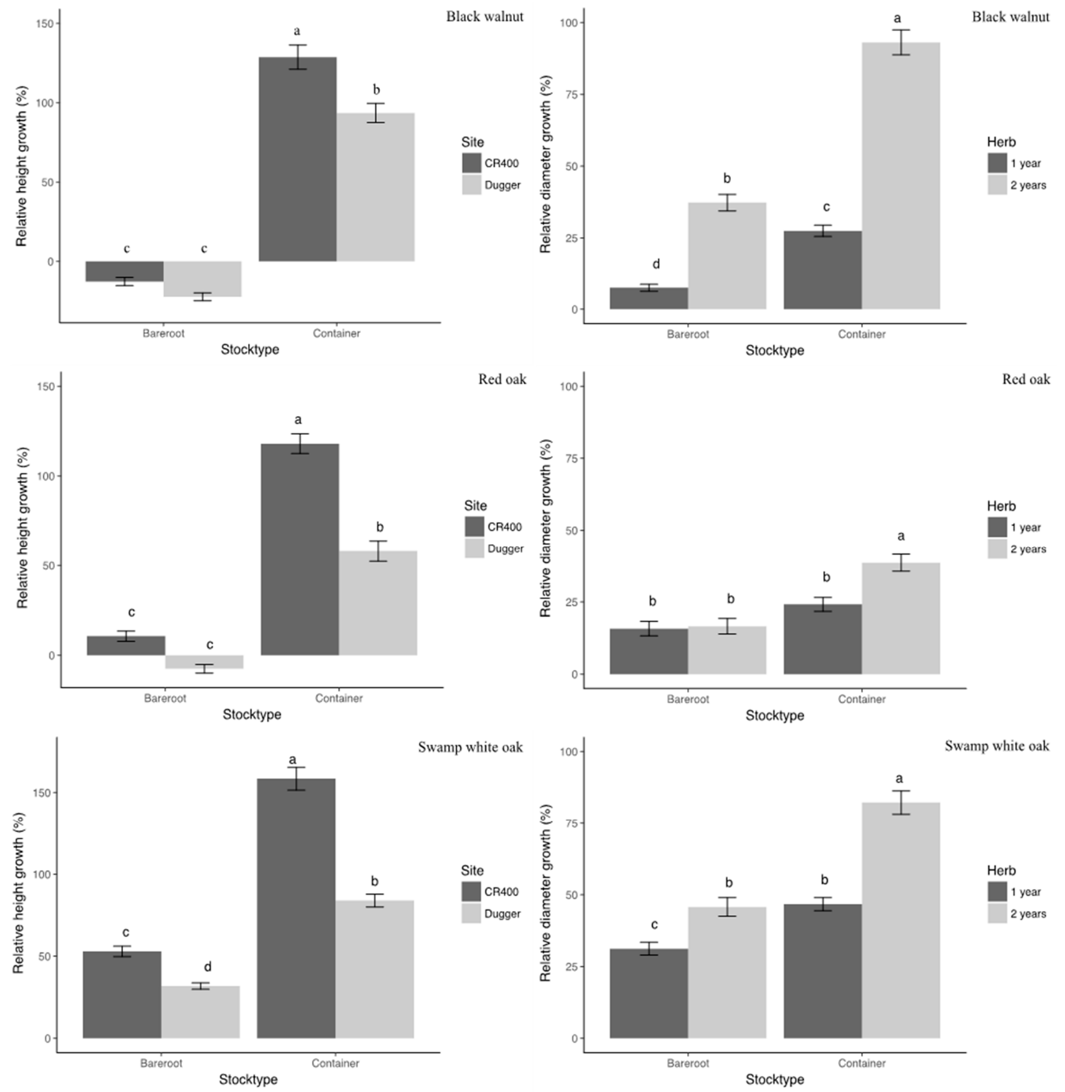


**Figure 3.** Relative height growth of black walnut, red oak, and swamp white oak for site × stocktype interaction (left side) after two years. Relative diameter growth for stocktype × herbicide interaction (right side) after two years. Columns are means, and error bars are (±SE). Columns with different letters are statistically different according to Tukey's Honestly Significant Difference (HSD) test at α = 0.05.

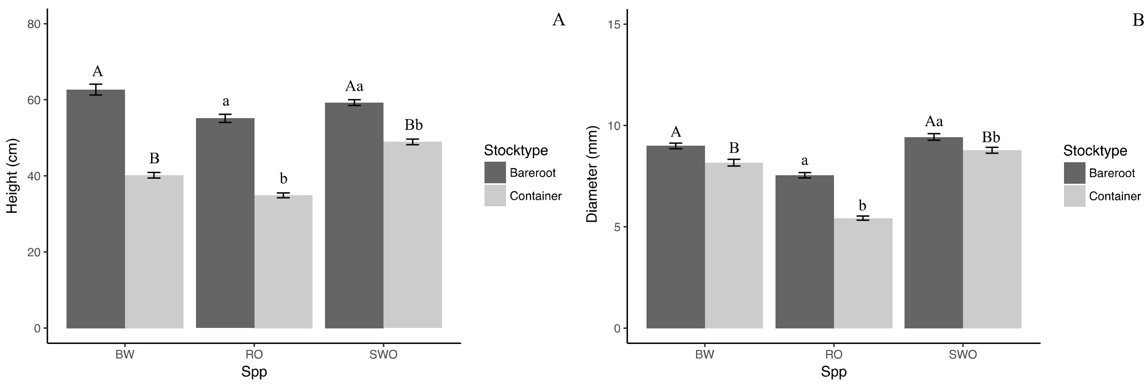


**Figure 4.** Second year absolute height (**A**) and diameter (**B**) for black walnut (BW), red oak (RO), and swamp white oak (SWO) by stocktype. Columns are means, and error bars are (±SE). Species were analyzed separately. Columns with different letters are statistically different according to Tukey's Honestly Significant Difference (HSD) test at α = 0.05.

**Table 4.** Analysis of variance test results for pre-dawn leaf water potential.

| Parameter | Site (S) | Stocktype (St) | Herbicide (H) | S × St | S × H | St × H | S × St × H |
|---|---|---|---|---|---|---|---|
| Leaf $\Psi_{pd}$ | | | | | | | |
| BW | **0.0219** | 0.3395 | 0.4401 | 0.6853 | 0.7181 | 0.0728 | 0.0804 |
| RO | **0.0016** | 0.9283 | 0.7008 | 0.1618 | 0.3144 | 0.8428 | 0.7475 |
| SWO | **<0.0001** | 0.7925 | 0.7613 | 0.2643 | **0.0062** | 1.0000 | 0.4476 |

Notes: by site (df = 1), stocktype (df = 1), herbicide (df = 1) and all possible interactions separated by species (BW, black walnut; RO, red oak; SWO, swamp white oak). Bold font indicates significant effect.

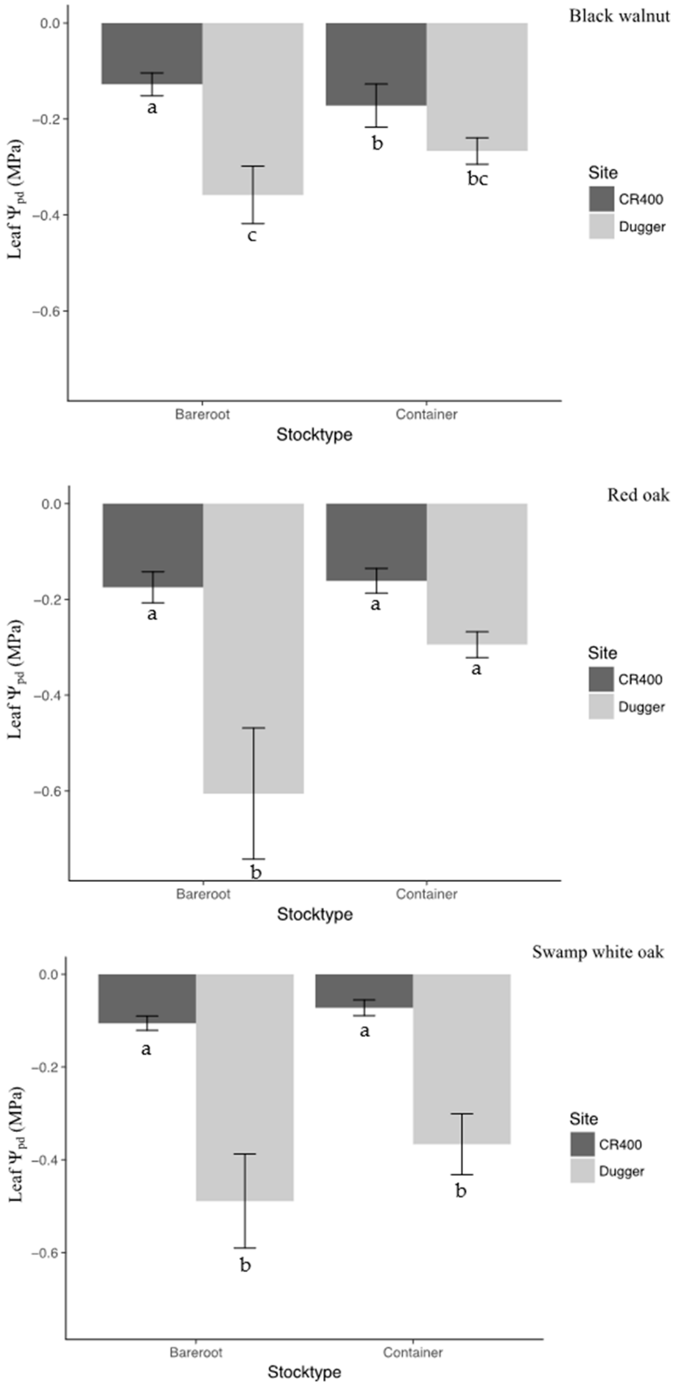


**Figure 5.** Mean leaf pre-dawn water potential ($\Psi_{pd}$) for each site and stocktype. Columns are means, and error bars are (±SE). Columns with different letters are statistically different according to Tukey's Honestly Significant Difference (HSD) test at $\alpha$ = 0.05.

## 4. Discussion

### 4.1. Survival

Seedling survival after two years averaged 80% overall, which is greater than that reported for afforestation [38] and other mine site plantings in Indiana [34,39]; however, our survival rates are similar to research results reported at the same Dugger site after two years (range of 57–97%) [16]. When protected by tree shelters, bareroot stocktype showed greater survival for black walnut and red oak as compared to container stocktype, which is counter to the hypothesis that container stock would have improved survival rates with shelters. Sweeney et al. [40] found no difference in survival between bareroot and container stocktypes protected by shelters in a riparian restoration area on the Eastern Shore of Maryland. Our results may be explained, in part, by the fact that there were no differences in root:shoot ratios between stocktypes, except for black walnut, where all stocktypes had a R:S ratio within the accepted range (1.0–3.0), which is shown to improve survival [41]. Bareroot stocktype typically experiences loss of root mass, particularly fine roots, in the lifting and packing process, which alters the R:S ratio and therefore impacts the ability of seedlings to hydraulically connect to the planting site [25,31]. R:S ratio is important for seedling survival as seedlings with balanced morphology likely have a large root system that avoids water stress after planting and therefore improves seedling survival, particularly on harsher sites [31,41]. Similarly, initiation of new root growth after planting (i.e., root growth potential) has been shown to improve seedling water status, and by extension survival, as the seedling is able to hydraulically connect with the planting site and begin exploring the soil profile [31,41]. While not measured in this experiment, it is likely that both stocktypes had high root growth potentials, leading to successful coupling of seedlings to the site, resulting in high survival rates. Additionally, careful handling of both stocktypes during transport and planting may have also contributed to the high survival rates found in this trial.

Two of the three species selected for this trial, black walnut and red oak, had significant stocktype × shelter responses whereby shelters improved bareroot seedling survival over unsheltered seedlings. Thus, shelter use appeared to have a species-specific stocktype response for survival. Ponder [42] found similar results for red oak planted in forest openings, but contrasting results for black walnut (i.e., lower survival when sheltered) planted in an old agricultural field. In our study, swamp white oak was not affected by shelter use and had high survival at both sites, which is in agreement with Walter et al. [43] where after five years, swamp white oak had 100% survival for bareroot and container stocktypes planted on an agricultural field. It should be noted that with bareroot seedlings, the average planting height was 60 cm, which is double the shelter height (30 cm). The mechanism causing increased survival of bareroot over container stock with short shelters is not entirely clear in this study. However, seedlings in tree shelters allocate resources to increasing height over diameter and root growth [44]. Bareroot seedlings that were taller than the shelters were likely less affected by the shelter environment, resulting in normal diameter and root growth patterns, which may be the reason for increased survival.

Planting sites were reclaimed using different methods and there were several significant edaphic differences (Table 2), but site was not a significant factor for survival. Site was important in pre-dawn leaf water potentials, with CR400 seedlings showing less water stress. As Grossnickle [31,41] showed, seedling water status is directly connected to survival, especially on harsher sites, yet there was not a relationship of increased survival of container stocktypes on the harsher Dugger site for any species. The maximum pre-dawn leaf water potential measured was around 0.8 MPa, less than the generally accepted range of 1.5–2.5 MPa for permanent wilting point [45], which may be why site was not a significant factor in seedling survival.

### 4.2. Growth

Stocktype was the greatest driver of seedling morphological differences after two years. As evidenced by the pre-planting sampling of seedling morphology, bareroot stocktype in all species was significantly taller and, except for swamp white oak, had larger diameters (Table 2). This trend follows what has been reported by Grossnickle and El-Kassaby [32] where bareroot stock tends to be taller and have larger diameters compared to container stock of the same age, implying that taller seedlings will maintain height advantage over time [46]. While the bareroot seedlings planted in this trial maintained an absolute height and diameter advantage over the two growing seasons, container seedlings reduced the difference during the two years (although still not matching bareroot seedlings). In contrast, Wilson et al. [28] showed that for red oak planted in a clearcut, container stocktype matched or even outperformed bareroot by the end of the first growing season. The positive trend in absolute height and diameter for container stock in this study suggests that within subsequent seasons the difference may be negligible or even surpass bareroot.

All species and stocktypes showed improved relative diameter growth after two years of herbicide use. Competing vegetation, particularly on post-SMCRA reclaimed sites, contributes to poor hardwood seedling survival and growth [4,9,11–13] as heavy herbaceous cover can trap seedlings and create a dense overstory that smothers smaller seedlings [47]. Additionally, herbaceous cover often outcompetes planted seedlings for soil moisture and nutrients [31]. Seedlings in heavy herbaceous cover seek to increase height to attain a greater portion of available light for photosynthate production, and this is likely at the cost of allocating reserves to diameter and root growth. Control of vegetation in direct competition likely improves soil water (although not indicated in our periodic water potential results) and nutrients available to planted seedlings thereby improving growth [31,46]. Therefore, herbicide is a justified management tool for mine reclamation sites to effectively mitigate the deleterious effects of competing vegetation, although herbicide use has been shown to increase browse incidence for planted seedlings [11,48]. Browse incidence in this experiment was not high (Appendix A Table A1), in part due to fencing and likely low populations of rabbits and rodents.

Relative growth in height and diameter for container stock with shelters agreed with the literature, whereby relative height growth was positively affected and relative diameter growth was negatively affected by shelters. Shelters have been shown to increase height growth and reduce diameter growth in *Quercus* species [44,49] due to alteration of above and belowground biomass allocation by protected seedlings. Seedlings in shelters allocate greater resources toward height growth, which reduces photosynthate available for root growth. Additionally, species have specific seasonal growth patterns that can be enhanced or suppressed by shelters. For example, *Quercus* species have polycyclic growth and under ideal conditions can have multiple growth flushes in a single growing season, as shown with *Q. robur* [44]. Notably, shelters used in this experiment were only 30 cm while most shelters in the literature are 120 cm, which possibly is a confounding factor in this experiment as all of the bareroot stock planted were on average 60 cm; this could have reduced any effect of shelters with this stocktype.

## 5. Conclusions

Establishment of hardwood tree seedlings on mine reclamation sites is challenging for land managers, and management prescriptions are unique to individual sites. Swamp white oak was the most successful species planted in this experiment as far as survival and growth. While species interactions were not examined statistically, the general pattern that emerged among species was that swamp white oak exhibited generally good performance regardless of silvicultural treatment; however, black walnut and northern red oak showed much stronger early regeneration responses to the silvicultural treatments tested in this study. Despite initial morphological differences, container stocktype showed greater or equivalent survival, relative growth, and drought resistance compared with bareroot stocktype, demonstrating efficacy for use on mine reclamation sites. Our results agree with the literature on stocktype × shelter interactions, where height growth increases and diameter growth decreases with shelter use. In this study, herbicide use was an effective tool in promoting growth of hardwood tree seedlings on reclaimed mine sites. Viewed altogether, our results support utilizing the "Target Seedling Concept" [50] in developing restoration prescriptions for reforestation of mine sites. Herbicide use in conjunction with container seedlings grown in larger sized containers would likely narrow the initial size differences to bareroot, providing a high performing stocktype capable of successful establishment on harsh mine sites while still being economically feasible.

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## Appendix A

**Table A1.** Browse incidence.

| | | | | Deer | Rabbit | Vole |
|---|---|---|---|---|---|---|
| **Site** | **Species** | **Stocktype** | **Shelter** | | | |
| CR400 | BW | Bareroot | No | 0 | 0 | 0 |
| | | | Yes | 0 | 0 | 4 |
| | | Container | No | 0 | 0 | 0 |
| | | | Yes | 0 | 0 | 0 |
| | RO | Bareroot | No | 7 | 0 | 1 |
| | | | Yes | 7 | 0 | 0 |
| | | Container | No | 5 | 0 | 0 |
| | | | Yes | 6 | 0 | 1 |
| | SWO | Bareroot | No | 1 | 0 | 1 |
| | | | Yes | 0 | 0 | 0 |
| | | Container | No | 2 | 0 | 0 |
| | | | Yes | 1 | 0 | 0 |
| Dugger | BW | Bareroot | No | 0 | 0 | 1 |
| | | | Yes | 0 | 0 | 0 |
| | | Container | No | 0 | 1 | 1 |
| | | | Yes | 0 | 0 | 0 |
| | RO | Bareroot | No | 9 | 6 | 2 |
| | | | Yes | 1 | 0 | 0 |
| | | Container | No | 0 | 7 | 0 |
| | | | Yes | 1 | 0 | 0 |
| | SWO | Bareroot | No | 4 | 2 | 0 |
| | | | Yes | 0 | 1 | 0 |
| | | Container | No | 3 | 2 | 1 |
| | | | Yes | 3 | 0 | 0 |
| | | | Total | 50 | 19 | 12 |

Notes: By site for species, stocktype, and shelter treatments by deer, rabbit, or vole. BW, black walnut; RO, red oak; SWO, swamp white oak.

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