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Establishing Pine Monocultures and Mixed Pine-Hardwood Stands on Reclaimed Surface Mined Land in Eastern Kentucky: Implications for Forest Resilience in a Changing Climate

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Abstract: Surface mining and mine reclamation practices have caused significant forest loss and forest fragmentation in Appalachia. Shortleaf pine (*Pinus echinata*) is threatened by a variety of stresses, including diseases, pests, poor management, altered fire regimes, and climate change, and the species is the subject of a widescale restoration effort. Surface mines may present opportunity for shortleaf pine restoration; however, the survival and growth of shortleaf pine on these harsh sites has not been critically evaluated. This paper presents first-year survival and growth of native shortleaf pine planted on a reclaimed surface mine, compared to non-native loblolly pine (*Pinus taeda*), which has been highly successful in previous mined land reclamation plantings. Pine monoculture plots are also compared to pine-hardwood polyculture plots to evaluate effects of planting mix on tree growth and survival, as well as soil health. Initial survival of shortleaf pine is low (42%), but height growth is similar to that of loblolly pine. No differences in survival or growth were observed between monoculture and polyculture treatments. Additional surveys in coming years will address longer-term growth and survival patterns of these species, as well as changes to relevant soil health endpoints, such as soil carbon.

Keywords: reforestation; shortleaf pine; restoration ecology; mine reclamation; Appalachia; loblolly pine

1. Introduction:

1.1. Surface Mine Reclamation and Reforestation

Surface mining is a major driver of land use change throughout Appalachia, including eastern Kentucky. While early surface mining reclamation practices often resulted in successful post-mining forest restoration, surface mines reclaimed prior to 1978 were often characterized by haphazardly-placed mine spoils that were prone to landslides and erosion, and significantly impaired water quality. Public Law 95-87, The Surface Mining Control and Reclamation Act of 1977 (SMCRA), ushered in a new era of surface mine reclamation, requiring a return of landforms to the approximate original contour, stabilized spoil placement to eliminate landslides, and establishment of herbaceous vegetation to control erosion. Revegetation was commonly performed by hydro-seeding competitive, fast-growing nonnative species such as tall fescue (*Schedonorus arundinaceus*) and lespedeza (*Lespedeza cuneata*). Surface mines reclaimed after SMCRA were often characterized by heavily compacted spoils with poor infiltration and aeration [1]. Aggressive groundcovers competed

with planted and volunteer tree seedlings for nutrients, water, and light, and the compacted soils were often not conducive to vigorous tree growth. As a result, many mining companies began implementing hay/pastureland or wildlife habitat as post-mining land uses. These reclamation practices present challenges to subsequent reforestation of reclaimed mine sites.

An estimated 600,000 ha of previously forested Appalachian land was surface mined and reclaimed to non-forest land (termed “legacy mined land”) [2], perpetuating negative landscape effects of surface mining, including forest fragmentation and spread of invasive species, as well as habitat and biodiversity loss [3]. In addition to these ecological challenges, this extensive land area is mostly unmanaged and economically unproductive. Thus, this broad area of unforested land presents opportunities for ecological improvement, including restoration of threatened and endangered forest species, habitat restoration, and carbon storage, as well as short-term (e.g., restoration industry jobs) and long-term economic opportunities (e.g., timber and non-timber forest products) [4].

A team of researchers, regulators, and industry practitioners have addressed the reforestation challenges on reclaimed mine sites by developing a set of recommendations known as the Forestry Reclamation Approach (FRA) [4,5]. When these guidelines are followed during initial mine reclamation, forest establishment can be successful, with high survival and hardwood growth rates similar to regenerating stands of high-quality forests [6–8]. Additionally, reclaimed surface mined lands that currently exist as grasslands or shrublands (legacy mines) can be rehabilitated using the FRA by controlling competing vegetation, mitigating soil compaction, and planting a diverse mix of native tree and shrub seedlings [9–11].

The FRA recommends planting both early- and late-successional species [5], however, the survival and growth of planted hardwoods on legacy mined land can be restricted by severe competition from grasses and shrubs, especially tall fescue, lespedeza, and autumn olive (*Elaeagnus umbellata*) [12]. In contrast, pines typically demonstrate high survival and growth rates on legacy sites [13], rapidly achieving canopy closure and shading out competitive invasive species in the understory. The potential for pines to act as a “nurse” crop on harsh legacy sites should also be evaluated. For example, pines could be planted in monoculture stands to improve soil quality through organic matter contribution and to eliminate invasive species from the understory, and subsequently underplanted with hardwoods, which could be released in stages. Alternatively, pines and hardwoods can be planted together initially, and pines can be selectively thinned as needed.

1.2. Shortleaf Pine Restoration

Shortleaf pine (*Pinus echinata*), an economically and ecologically valuable species native throughout the southeast US, is a potential candidate for mine reforestation. Shortleaf pine forest types have experienced significant declines throughout the southeast US due in part to insect and disease pressure, extensive timber harvesting, fire suppression and poor management [14–19]. Shortleaf pine is currently the focus of a major restoration effort (Shortleaf Pine Initiative: <http://shortleafpine.net/>) throughout its native range [20,21] because of the suite of ecosystem services they provide. Shortleaf pine restoration leads to increased levels of plant available nutrients over time [22], in spite of initial loss of nitrogen [23]. Shortleaf pine restoration also provides important habitat for the federally endangered red-cockaded woodpecker (*Picoides borealis*), and also positively impacts diversity and/or abundance of populations of taxa including butterflies, reptiles, amphibians [24], other birds [25,26] and small mammals [27]. Shortleaf pine stands, characterized by relatively frequent fire maintaining low basal area, also provide important habitat for endangered Indiana bats (*Myotis sodalis*) [28], as well as a number of other bat species [29].

Loblolly pine (*Pinus taeda*) is another economically valuable tree species that is distributed across the southeast US, although not native to Kentucky, generally preferring poorly drained, fine-textured soils. In mixed stands, loblolly pine is commonly associated with hardwoods (including white oak) and other pines (including shortleaf pine). Loblolly pine is shallow-rooted; the majority of lateral roots are found in the top 15–46 cm of soil, especially in shallow soils with a hardpan or high water table [30].

Shortleaf pine has a broader distribution throughout the southeast US, ranging much farther north than loblolly pine, and it tolerates a broader range of climate conditions. While shortleaf pine grows best on deep, well-drained floodplain soils, it is also competitive on dry, shallow ridgetop soils, and is commonly associated with a number of hardwood and other pine species. When found in mixed stands with loblolly pine, shortleaf pine tends to be dominant in drier ridgetop sites; this is commonly attributed to shortleaf pine preferring better soil aeration and being more tolerant of poor soil fertility than loblolly pine [30].

While techniques for establishing shortleaf pine in relatively high-quality sites, such as existing hardwood forests or agricultural fields [31–34], are relatively well-understood, establishment of shortleaf pine on compaction-mitigated legacy surface mines has not yet been rigorously evaluated [35,36]. Shortleaf pine is competitive on drier ridgetop sites with frequent fire [37], but legacy mine sites can be characterized by poor infiltration resulting in ponding, which may limit site suitability for shortleaf pine. In contrast, loblolly pine prefers poorly drained soils and is more tolerant of higher moisture conditions [37], and has demonstrated good growth and survival on legacy sites in Kentucky [13].

Over even larger spatial scales and longer temporal scales, climate change represents a major threat to forest tree species, especially for species already stressed by insects, disease, and management issues [38,39]. Because trees are sessile and have long generation times, they may be particularly susceptible to the effects of rapid climate change, less resilient to changing temperatures and moisture than animals or plants with shorter generation times [40]. An option for conservation and management of forest trees with respect to climate change may be assisted migration, intentionally planting species of interest in their projected future range under climate change. Shortleaf pine is an example of a species already under significant pressure, which may be particularly threatened by climate change. With climate change projections indicating that the distribution of loblolly pine will shift north over time into Kentucky [14], the species is likely to move into these sites whether planted or not, and may potentially outcompete native species such as shortleaf pine. Focusing shortleaf pine reforestation efforts in the northern part of its range, such as eastern Kentucky, may improve its resilience to climate change.

This project was initiated to evaluate growth and survival of shortleaf pine and loblolly pine on surface mined land in eastern Kentucky grown in monoculture and in polyculture with white oak (*Quercus alba*), northern red oak (*Quercus rubra*), and chestnut oak (*Quercus montana*). This paper presents first-year growth and survival data. Long-term project goals will be assessed by follow-up surveys 5–7 years after establishment, including species effects (i.e., shortleaf pine vs. loblolly pine) and planting effects (i.e., polyculture vs. monoculture) on reforestation success, including tree (e.g., growth and survival) and soil (e.g., carbon, pH, etc.) outcomes.

2. Methods and Materials

2.1. Plot Establishment and Data Collection

A 1.3 ha plot of legacy mined land in a portion of the University of Kentucky Robinson Forest (Breathitt County, KY) was selected for this experiment (Figure 1). Exotic shrubs, primarily autumn olive (*Elaeagnus umbellata*), were removed prior to ripping using a small bulldozer (John Deere 550G). Soil compaction was mitigated by cross-ripping (plowing) the ground with a Caterpillar D-9 bulldozer equipped with two, rear-mounted ripping shanks. The two shanks were spaced approximately 2.4 m apart on the tool bar so that the two shanks were located directly behind the bulldozer's tracks. Ripping shanks were immersed approximately 1 m deep into the soil and pulled through the ground, creating parallel rips across the entire site. The bulldozer operator then turned perpendicular to the first set of parallel rips and ripped the site a second time. The experiment was set up as a split-plot design with six whole plots, each measuring 39 m × 31.7 m. Three of the plots were randomly assigned to a shortleaf pine treatment and the other three to a loblolly pine treatment. Each whole plot was divided into two

22 m × 12.2 m subplots that were randomly assigned either the pine monoculture or pine-hardwood polyculture treatment (i.e., split plot factor) (Figure 2). One-year-old bare root seedlings sourced from the Kentucky Division of Forestry were planted in March of 2016. Seedlings were planted in rows on a 2 m spacing, with 45 pines per monoculture subplot, and 22 hardwoods (red oak, white oak, and chestnut oak) and 23 pines per polyculture subplot. The buffer space outside the border of the split plots but within the whole plots was planted with seedlings for the pine species assigned to the whole plot.

Height and ground-line diameter were recorded for each individual at time of planting (spring 2016), and measurements were repeated after one year (spring 2017). In addition, soil samples (composited from six subsamples) were collected in duplicate at random in each subplot both at planting and after one year, and samples were analyzed for the following parameters: soil pH, P, K, Ca, Mg, and Zn. Additional soil analyses conducted only in 2017 included the following: total N, sand, silt, clay, CEC, total C, and exchangeable K, Ca, Mg, and Na. Sand, silt, and clay were determined by the micropipette method [41]; pH was determined in a 1:1 soil:water solution [42]. P, K, Ca, and Mg, were analyzed by Mehlich-III extraction [43]. Cation exchange capacity was determined by the ammonium acetate method at pH 3 [44]. Exchangeable base concentration was evaluated after ammonium acetate extraction using ICP [43]. Total N (%) and total C (%) were determined on a LECO CHN-2000 Analyzer (LECO Corporation, St. Joseph, MI, USA).

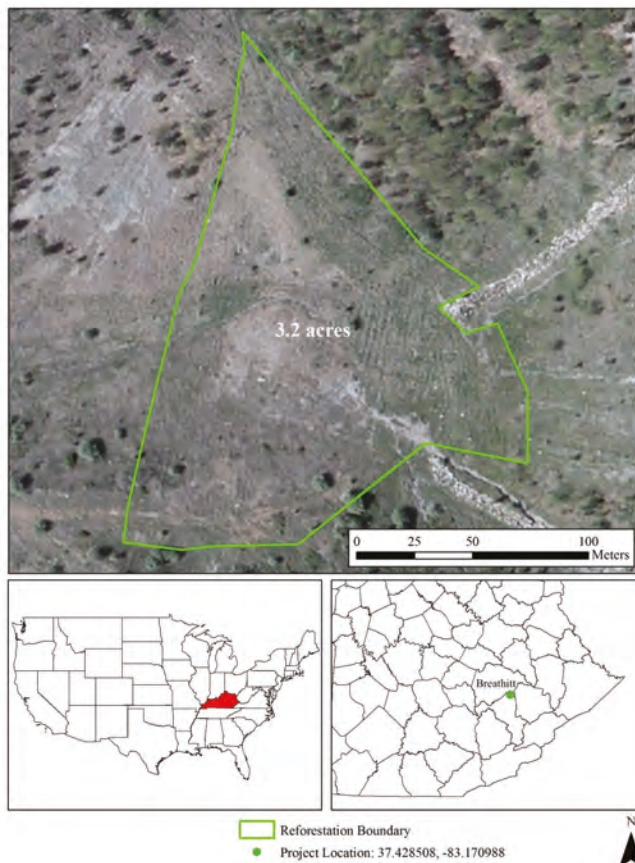


Figure 1. Plot location, Breathitt County, KY. (Figure credit: Kylie Schmidt).



Figure 2. Whole plot (1–6) and subplot configuration of shortleaf pine and loblolly pine monoculture and pine/hardwood polyculture plantings in rehabilitated legacy mined land in eastern Kentucky.

2.2. Statistical Methods

Statistical analyses were conducted in SAS 9.3. Soils data collected in both 2016 and 2017 were analysed by repeated measures ANOVA using PROC MIXED, with subplot as the experimental unit. Planting mix (polyculture vs. monoculture) and species (loblolly pine vs. shortleaf pine), and their interaction, were modelled as fixed effects, replicate (each treatment replicated 3 times) modelled as a random effect, and year modelled in the repeated statement. Soils data collected in 2017 only were analysed by ANOVA using PROC GLM, with planting mix, species, and their interaction modelled as effects, with three replicates.

Tree height change was averaged by species for each subplot, and subplot means were treated as the experimental unit. Differences in change in tree height were detected by split-plot ANOVA using PROC GLM, with species, planting mix, and their interaction, modelled as effects. Tree survival was analysed using PROC GLIMMIX, with survival proportions calculated for each subplot as the experimental unit, and species, planting mix, and their interaction modelled as effects. Significant differences detected by all ANOVAs were followed up by a student's *t*-test to detect pairwise differences.

3. Results

Soil chemical and physical data are reported in Table 1. Of the soil chemical data assessed in both 2016 and 2017, only pH was significantly different, increasing slightly from 5.74 to 6.18 ($p < 0.05$). K, Mg, and Zn were significantly higher in loblolly pine than in shortleaf pine, and Zn was significantly higher in monoculture than polyculture ($p < 0.05$). Total N and exchangeable Mg were higher in loblolly pine than shortleaf pine plots ($p < 0.05$).

Table 1. Soil data (means \pm SE) for soil samples collected from reforestation plots (three plots planted in loblolly pine and three plots planted in shortleaf pine) in Eastern Kentucky. Each plot was subdivided into pine-hardwood polyculture and pine-only monoculture subplots. Means with differing letters are significantly different, as detected by ANOVA and followed up by a student's *t*-test, at $p < 0.05$. "Exch" = "Exchangeable".

	Year		Pine		Planting Mix	
	2016	2017	Shortleaf Pine	Loblolly Pine	Monoculture	Polyculture
Soil pH	5.74b \pm 0.31	6.18a \pm 0.31	6.20 \pm 0.42	5.72 \pm 0.42	6.06 \pm 0.42	5.86 \pm 0.42
P (mg/kg)	6.92 \pm 1.27	7.67 \pm 1.27	6.79 \pm 1.56	7.79 \pm 1.56	7.83 \pm 1.56	6.75 \pm 1.56
K (mg/kg)	91.2 \pm 6.24	78.6 \pm 6.24	67.9b \pm 6.58	101.9a \pm 6.58	91.0 \pm 6.58	78.8 \pm 6.58
Ca (mg/kg)	996 \pm 408	1409 \pm 408	773 \pm 529	1633 \pm 529	1178 \pm 529	1227 \pm 529
Mg (mg/kg)	216.7 \pm 16.5	206.1 \pm 16.5	159.9b \pm 22.4	262.9a \pm 22.4	213.7 \pm 22.4	209.1 \pm 22.4
Zn (mg/kg)	3.09 \pm 0.08	3.06 \pm 0.08	2.28b \pm 0.08	3.87a \pm 0.08	3.39a \pm 0.08	2.76b \pm 0.08
Total N (%)	-	-	0.104b \pm 0.014	0.196a \pm 0.016	0.162 \pm 0.023	0.138 \pm 0.018
Sand (%)	-	-	62.7 \pm 3	53.7 \pm 4	58.0 \pm 4	58.4 \pm 4
Silt (%)	-	-	25.4 \pm 2	32.7 \pm 3	29.0 \pm 3	29.0 \pm 3
Clay (%)	-	-	12 \pm 9	13.6 \pm 1.2	12.9 \pm 1.2	12.6 \pm 0.9
CEC (meq/100 g)	-	-	7.46 \pm 1.13	12.94 \pm 1.20	10.84 \pm 1.65	9.56 \pm 1.13
Exch K (meq/100 g)	-	-	0.158 \pm 0.02	0.308 \pm 0.04	0.247 \pm 0.04	0.219 \pm 0.03
Exch Ca (meq/100 g)	-	-	3.58 \pm 1.68	7.95 \pm 2.09	6.63 \pm 2.13	4.90 \pm 1.85
Exch Mg (meq/100 g)	-	-	1.13b \pm 0.16	2.26a \pm 0.21	1.67 \pm 0.23	1.72 \pm 0.27
Exch Na (meq/100 g)	-	-	0.023 \pm 0.004	0.026 \pm 0.004	0.026 \pm 0.005	0.023 \pm 0.004
Total C (%)	-	-	0.022 \pm 0.004	0.034 \pm 0.002	0.029 \pm 0.004	0.027 \pm 0.003

After one growing season, most seedlings experienced positive growth in their height (77%) and diameter (72%). Negative height growth was related to deer and elk browse that sheared the tops off of the seedlings. Diameter growth did not differ between the two pine species, averaging 0.22 cm and ranging between -0.6 cm and 1.79 cm (Figure 3). Hardwood diameter growth was about half that of the pines with highest growth in white oaks (mean = 0.1 cm; range = -0.6 cm–1.1 cm) followed by chestnut oak (mean = 0.08 cm; range = -0.25 cm–0.5 cm), and red oak (mean = 0.06 cm; range = -0.8 cm–0.65 cm) (Figure 4). A similar species-specific pattern was observed in height growth. Individual loblolly pine seedling growth ranged from -11 cm to 69.3 cm and loblollies had the largest average height increase (16.02 cm), which was significantly greater than all the hardwoods but not shortleaf pine. Shortleaf pine height growth ranged from -19.8 cm to 72.5 cm with an average (10.51 cm) that was approximately 5.5 cm less than loblolly pine. Shortleaf pine height growth was not significantly different from loblolly pine growth but was significantly larger than two of the three hardwoods. White oak seedling height growth ranged from -32.2 cm to 52.5 cm. White oaks had the largest height growth among the hardwoods and was the only hardwood species to achieve a positive average height growth (5.65 cm). Although many red oak seedlings experienced positive height growth, ranging from -27.9 cm to 19 cm, their average was negative (-0.71 cm). Similarly, chestnut oak height growth ranged from -15.5 cm to 7.5 cm and averaged -1.19 cm. Despite the range of height growths among the hardwoods, none were significantly different from each other. Collectively, these results suggest that diameter growth was similar among all five species but that the pines grew taller than hardwoods, with the exception of no significant difference between shortleaf pines and white oaks.

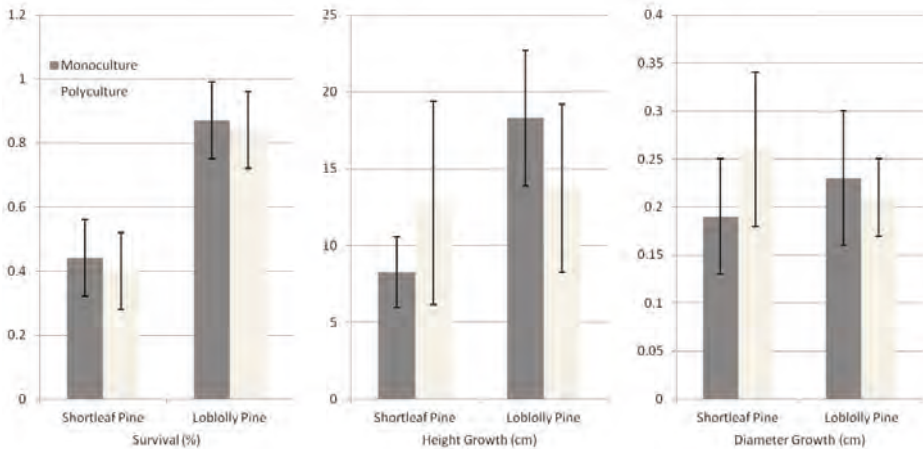


Figure 3. First-year growth and percent survival of shortleaf pine and loblolly pine planted in pine monoculture and pine-hardwood polyculture on rehabilitated legacy mine land in eastern Kentucky.

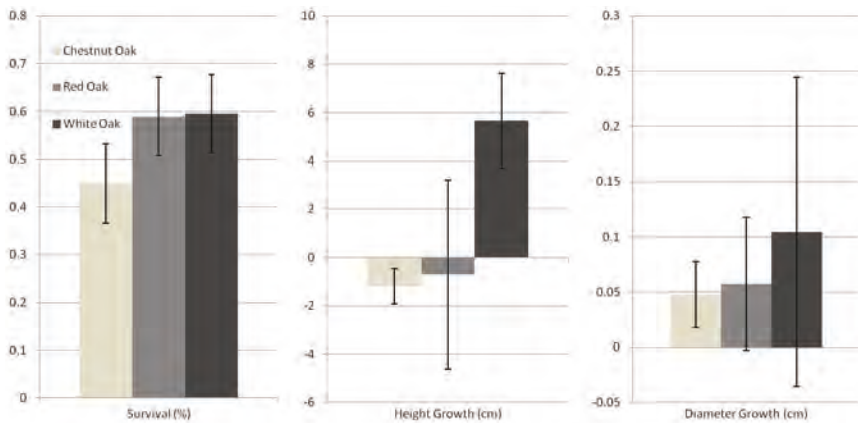


Figure 4. First-year growth and percent survival of white oak, chestnut oak, and northern red oak planted in pine-hardwood polyculture on rehabilitated mine land in eastern Kentucky.

4. Discussion

Planting mix (polyculture vs. monoculture) did not significantly influence tree growth or survival; however, growth and survival varied with species. Shortleaf pine survival (42%) was similar to that of planted hardwoods, but lower than that of loblolly pine (85%) ($p < 0.05$). Survival of shortleaf pine was lower than first-year survival reported by Angel (2008) of mixed hardwoods planted into mixed mine spoils with no vegetative competition in eastern Kentucky (69–98%) [6,45], lower than survival (65–75%) of seedlings planted into spoils seeded with groundcover species [46], and lower than first-year chestnut survival in legacy mined land in eastern Kentucky (72–97%) [9]. However, shortleaf pine survival was similar to survival of seedlings planted into mine spoil seeded with groundcover species (56%) [47], and greater than survival of shagbark hickory (*Carya ovata*) reported in the same study (24%) [47]. In contrast to relatively low shortleaf pine survival, loblolly pine survival (85%) was greater than first-year loblolly pine survival reported in Oklahoma by Dipesh et al. (2015) (76%) [48] and fourth-year survival of another loblolly pine planting near Robinson Forest

(77%) [13]. While first-year survival of shortleaf pine was relatively low, this planting could still be successful if ongoing mortality rates are low; subsequent surveys will be necessary to evaluate long-term suitability of shortleaf pine on these sites. Also, consistent with previous studies at Robinson Forest and elsewhere, first-year loblolly pine survival was high, supporting continued use of loblolly pine in mine reforestation efforts.

While first-year survival was lower, first-year growth of shortleaf pine (10 cm) was similar to that of loblolly pine (16 cm). Growth of loblolly pine dramatically outpaced growth of northern red oak in an adjacent site in legacy mined land in eastern Kentucky [49]. In that study, loblolly pine rapidly overgrew competing vegetation and shaded it out (in 4–8 yrs), leading to a bare understory characterized by a thick pine needle litter layer [13]. In contrast, the northern red oaks in Hansen et al. (2015) struggled against competing vegetation and were not successful in achieving canopy closure even after 10 years [13]. While loblolly pine has demonstrated its ability to rapidly outcompete nonnative vegetation in these conditions, this has yet to be seen with shortleaf pine. Further monitoring of our plots over the next several years should demonstrate whether shortleaf pine can compensate for its lower survival and be a reasonable candidate for reforestation on reclaimed surface mined land. Heavy competition from *Miscanthus* spp. and other herbaceous species (lespedeza and fescue) in these plots will likely be the most significant impediment to shortleaf pine survival and growth. Hardwood growth in this study was low, even negative in two species (chestnut oak and red oak), likely due to browse by deer and elk. Browse was observed on this site, as on many other similar plantings, and can significantly affect growth and survival [9,50,51]. Regardless of browse, hardwood growth tends to be low during the first 2–3 years after planting [45], with growth rates increasing after this 2–3 yr establishment period [6].

Higher survival of loblolly pine than shortleaf pine on our site is likely due to loblolly pine being favored by site soil moisture and chemistry conditions. Loblolly pine is more tolerant of poorly drained soils than shortleaf pine [37]. Large portions of the project site exhibited poor drainage and even standing water (which can frequently be the case on these sites [52,53]), suggesting that overall soil moisture conditions may be more favorable for loblolly pine than shortleaf pine. Chemically, soils were favorable across treatments, with pH, particle size distribution, nutrient levels, and CEC similar to those observed on soils favorable for tree growth and survival in another eastern Kentucky study [6]. However, the soils in loblolly pine plots in this study were chemically more favorable than the soils in shortleaf pine plots, with higher total N and exchangeable Mg.

The current study continues to provide support for the use of loblolly pine in surface mine restoration plantings; however, low first-year survival of shortleaf pine is concerning. Additional studies investigating survival and growth over time will provide additional valuable information about the potential for surface mines as shortleaf pine restoration sites. Also, the unique design of this project presents opportunity for investigation of more complex restoration ecology questions, specifically (1) whether pines planted in mixtures with hardwoods experience greater growth and survival than pines planted in monoculture and (2) whether rapid pine establishment can sufficiently reduce invasive species competition and improve soil health so as to act as a “nurse crop” for subsequent high-value hardwood species release. Finally, this experiment presents an opportunity for the long-term comparison of loblolly pine and shortleaf pine that will offer insights into restoration strategies involving these species, especially under climate change. Specifically, insights on whether restoration practitioners should consider species not historically native to a state or region (e.g., loblolly pine in Kentucky) suitable for restoration, given that climate change will shift their distributions.

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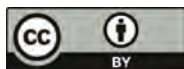
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