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Silviculture

Overstory Retention and Stock Type Impact Survival and Growth of Underplanted Shortleaf Pine Beneath a Hardwood Canopy

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This study was established to evaluate underplanting as a method of reestablishing a shortleaf pine (*Pinus echinata* Mill.) component to a dry upland hardwood stand in the Piedmont region of the southeastern United States. Replicated treatment plots were harvested to retain four levels (approximately 0, 3, 7, and 10 m² of basal area per hectare) of residual overstory density. One-year-old containerized seedlings with both smaller (93.4 cm³) and larger (113.1 cm³) plugs and bareroot seedlings were underplanted beneath the residual overstory treatments. After five growing seasons, seedling survival averaged 61% and was not meaningfully affected by residual overstory density. Seedling height growth ranged from 1.42 m to 2.61 m and was inversely related to residual overstory density. Containerized seedlings with larger plugs had the highest survival (77.4%) and best height growth (2.11 m), followed by containerized seedlings with smaller plugs (64.3%, 1.76 m) and bareroot seedlings (40.2%, 1.85 m). The results of this study indicated that underplanting containerized seedlings, particularly those with higher plug volume and greater plug depth, was a suitable option for reestablishing shortleaf pine on drier, hardwood dominated upland sites in the Piedmont. However, even low levels of overstory retention suppressed seedling height growth after a few years.

Study Implications: The study was conducted on a dry upland site typical of the North Carolina Piedmont. Retaining up to 10 m² ha⁻¹ of oak and hickory overstory basal area did not strongly affect survival among underplanted shortleaf pine seedlings after five growing seasons. However, overstory cover as low as 3 m² ha⁻¹ had negative effects on height growth of underplanted seedlings over the same time period. Height growth declined as overstory density increased. Containerized seedlings had better survival than bareroot seedlings. Further improvements in survival and height growth were realized by planting containerized seedlings with higher plug volume and greater plug depth.

Keywords: underplanting, shortleaf pine, pine-hardwood mixtures, stock type, Piedmont

Shortleaf pine (*Pinus echinata* Mill.) was once a prominent component in the forests that developed postagricultural abandonment throughout the Piedmont region of the southeastern United States (Mattoon 1915). The expansion of shortleaf pine following agricultural abandonment can largely be attributed to its early successional life history traits. Abundant seed crops every three to six years in this region (Lawson 1990) allowed shortleaf pine to colonize available growing space. Following establishment, shortleaf pine was well adapted to persist on dry, eroded substrates, as a result of its low nutritional demands and conservative early growth strategy focused on root development (Lawson 1990). Shortleaf pine was also capable of surviving frequent surface fire through a combination of sprouting at the seedling developmental stage and bark thickness as an adult (Lilly et al. 2012). Collectively, these traits allowed shortleaf pine to outcompete other species for canopy growing position allowing it to meet its high light demands (Lawson 1990).

Since this era of expansion, several factors have contributed to the decline of shortleaf pine throughout its native range (Little 1971, Moser et al. 2007, Oswalt 2012). The contraction of shortleaf pine has been broadly linked to forest succession stemming from fire suppression or the expansion of lobolly pine (*P. taeda* L.) plantations

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(Guldin and Black 2018). In the Piedmont, littleleaf disease caused by *Phytophthora cinnamomi* Rands. contributed extensively to the decline of shortleaf pine (Campbell and Copeland 1954), a trend that is likely continue in the future (Rummer and Hafer 2014). Urbanization in the Piedmont has also contributed to the decline of shortleaf pine and is expected to restrict the use of prescribed fire as a restoration tool (Rummer and Hafer 2014). Additionally, shortleaf pine is currently most prevalent in the Piedmont as a large-diameter component to aging stands (Moser et al. 2007), suggesting that current forest management practices in the region are failing to naturally regenerate shortleaf pine. As such, artificial regeneration will likely be required for reestablishing shortleaf pine in the Piedmont region.

Much of the existing research examining artificially regenerating shortleaf pine has focused on promoting pure, even-aged stands. However, apart from stands that became established on abandoned agricultural lands, shortleaf pine is typically found in the Piedmont as a component of oak (*Quercus* spp.) and hickory (*Carya* spp.)–dominated pine-hardwood mixtures (Schafale and Weakley 2012). Research focused on establishing shortleaf pine-hardwood mixtures is comparatively sparse, and almost exclusively limited to sites from the western portion of its range. There are notable differences in climate, topography, edaphic conditions, disturbance regimes, and land use history across the native range of shortleaf pine (McNab and Avers 1996, Guldin and Black 2018). Littleleaf disease is also prevalent across much of the Piedmont (Campbell and Copeland 1954, Mistretta 1984), but is absent west of the Mississippi River. These collective differences may contribute to variable responses of shortleaf pine to silvicultural manipulation throughout its range. Thus, studies examining the response of shortleaf pine to silvicultural treatments across a broader suite of biotic and abiotic conditions are needed to guide restoration efforts in other parts of the historical range of shortleaf pine.

Underplanting is an artificial regeneration practice where seedlings are planted beneath overstory trees (Helms 1998). This provides forest managers the opportunity to influence the density and species composition of both the overstory and reproduction cohorts, as well as the timing of regeneration. A meta-analysis of underplanting studies revealed that seedling survival and growth generally increase as overstory stocking is reduced (see Paquette et al. 2006), and thus indicate an inverse relationship between underplanted seedling survival and growth and overstory stocking. These trends were attributed to increases in light availability following stocking reduction and protection from wind, temperature extremes, and browse provided by intermediate levels (40%–60% of original overstory basal area) of overstory shelter (Paquette et al. 2006). A similar inverse relationship between overstory stocking and seedling growth has been found between underplanted shortleaf pine seedlings and an overstory of predominantly oak and hickory basal areas ranging from 0 to 22 m^2 ha^{-1} (Guldin and Heath 2001, Jensen et al. 2007, Kabrick et al. 2011, 2015, Schnake et al. 2016). Trends in the survival of shortleaf pine seedlings underplanted beneath a hardwood overstory have been less consistent. Overstory retention has been found to not affect survival (Guldin and Heath 2001, Kabrick et al. 2011, 2015), positively influence survival following the first growing season (Schnake et al. 2016), or have varying effects with the best survival occurring beneath the highest and lowest levels of overstory stocking and the poorest survival occurring beneath intermediate levels (Jensen et al. 2007).

The results of this previous research suggest that underplanting may be a suitable method for establishing a shortleaf pine component in stands with hardwood-dominated overstories but reductions in underplanted seedling growth are likely under increasingly higher levels of overstory stocking. These studies and others (Shelton and Murphy 1997, Shelton 2004) also suggest that although shortleaf pine is considered intolerant of shade, young seedlings can both survive and grow under some shade for several years. Further research is needed to explore whether there are overstory stocking levels under which managers can achieve both survival and adequate height growth for underplanted seedlings to effectively compete for growing space.

Stock type is one factor that may influence seedling performance. Comparisons between bareroot and containerized stock types have shown that containerized seedlings often have better survival and growth than bareroot seedlings on adverse sites but similar performance on higher quality sites and under more favorable planting conditions (Boyer 1989, Barnett and McGilvray 1993, South et al. 2005, Grossnickle and El-Kassaby 2016). Container size has also been found to be important in comparisons between containerized stock, with seedlings in larger containers often having similar (Dominguez-Lerena et al. 2006, Pinto et al. 2011b, Aghai et al. 2014) or better (Amidon et al. 1982, Haywood et al. 2012) survival and greater growth, although the differences are not always significant or long-lasting (Pinto et al. 2011b). In many cases, the differences between bareroot and containerized stock, and between containerized stock with different plug sizes, are attributed to the more intact root systems and the presence of planting medium in the plug that provides moisture and nutrients after planting (Grossnickle and El-Kassaby 2016).

The limited number of studies comparing stock type for shortleaf pine have also yielded mixed results. Barnett and Brissette (2004) found better survival and growth of containerized seedlings on a poor site but similar performance on a higher-quality site. Rhuele et al. (1981) reported better performance of bareroot seedlings on drier sites, but the opposite on higher-quality sites. Gwaze et al. (2006) reported no significant difference in survival or growth between 1-0 bareroot and containerized stock planted in a former nursery bed. However, none of these studies explored the potential influence of hardwood overstory retention. Given that site harshness appears to influence stock type performance, and that overstory retention can moderate site harshness (Langvall and Ottosson Löfvenius 2002, Agestam et al. 2003, Guldin and Barnett 2004, Pommerening and Murphy 2004, Paquette et al. 2006), additional research is needed to assess whether differences in survival and growth between the containerized and bareroot stock types available in the Central Appalachian Piedmont exist when seedlings are underplanted on a drier site beneath varying levels of overstory density.

In 2012, we initiated a study to evaluate the effectiveness of underplanting as a method of reestablishing a shortleaf pine component in an upland hardwood stand on a dry, rocky site in the North Carolina Piedmont where the natural shortleaf pine component had been diminished. Three commercially available shortleaf pine stock types (bareroot, smaller plug seedlings, and larger plug seedlings) were underplanted beneath varying levels of hardwood overstory retention (0, 3, 7, and 10 m^2 of basal area per hectare). The first objective of this research was to determine the effect of residual overstory density on underplanted shortleaf pine seedling survival and growth. The second objective was to investigate the survival and growth of two commonly available containerized stock types relative to common bareroot stock type. The third objective was to determine the effects of container plug size on field performance of the two different containerized stock types after outplanting. The goal of this study was to provide forest managers in the Piedmont with guidance on whether underplanting using commonly available sources of shortleaf pine seedlings in this region may be a possible method for reestablishing a shortleaf pine component to upland hardwood stands while retaining overstory hardwood cover.

Materials and Methods

Study Area

The study site is in the Piedmont physiographic region in Durham County, North Carolina, USA (36°9′25.75″N, 78°48′54.32″W), on the North Carolina Department of Agriculture & Consumer Services' Umstead Research Station. Elevation ranges from 132 to 148 m along a ridge with east and west aspects. Slopes are less than 10%. Precipitation at the site averages 1,158 mm annually and is evenly distributed throughout the year. The average growing season length is 194 days (Perry 1996, State Climate Office of North Carolina, North Carolina State University 2015). Mean temperatures at the site range from 3.1°C in January to 25.3°C in July (State Climate Office of North Carolina, North Carolina State University 2015).

Soils of the site are typical of the Central Appalachian Piedmont, a region mostly within the borders of the US states of Virginia and North Carolina characterized as a moderately dissected plain of rolling hills underlain by metephophic formations of thick saplrolites and deep soils with heavy clay subhorizons (McNab and Avers 1996, Rummer and Hafer 2014). Lignum silt loam soils dominate the upper portions of the ridge and Helena sandy loam is found on the lower hillslopes (Kirby 1976). Both soil series are deep and moderately well drained clayey, mixed, thermic Aquic Hapludults. However, like many sites in the Central Appalachian Piedmont, the soils are thin and rocky following at least one cycle of agricultural clearing, cultivation, and abandonment since the 1770s (Trimble 1974). The site index for shortleaf pine on both soils is 20.1 m at base age 50 years (Coile and Schumacher 1953). The site index for southern red oak (*Q. falcata* Michx.) is 21.9 m and 20.7 m for Lignum silt loam and Helena sandy loam at base age 50 years, respectively (Olson 1959).

Eroded sites with moderate to poor drainage and with a history of agricultural use and abandonment often present high hazard for littleleaf disease (Campbell and Copeland 1954). We used the methods described in Cambpell and Copeland (1954) to determine that the conditions of the Helena sandy loam and Lignum silt loam on our site presented only a moderate hazard for littleleaf disease. Although we would have preferred a low-risk site, the study area is not located within the mapped occurrence of littleleaf disease (Mistretta 1984). Littleleaf disease has also not been documented on the large state-owned forest where this study was conducted (NCDA&CS Research Stations, Forest Management Program, pers. commun., 2020). As such, we considered the overall risks low and did not expect littleleaf disease to affect our results.

The forest cover of the study site prior to harvest was typical of Piedmont subtype of the Dry Oak-Hickory Forest Community (Schafale and Weakley 2012), which commonly forms on the driest environments produced under normal Piedmont topography and edaphic conditions. The overstory was dominated by white oak (*Q. alba* L.), southern red oak, hickory species and lesser amounts of northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), post oak (*Q. stellata* Wangenh.), blackjack oak (*Q. marilandica* Munchh.), willow oak (*Q. phellos* L.), yellow-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), white ash (*Fraxinus americana* L.), elm species (*Ulmus* spp.), black cherry (*Prunus serotina* Ehrh.), American beech (*Fagus grandifolia* Ehrh.) and a limited (<20% of the overstory) pine component composed of loblolly pine, Virginia pine (*P. virginiana* Mill.), and shortleaf pine. The midstory was sparse and dominated by hophornbeam (*Ostrya virginiana* [Mill.] K. Koch), hickory spp., elm spp., red maple (*Acer rubrum* L.), eastern red cedar (*Juniperus virginiana* Mill.), with a minor component of eastern redbud (*Cercis canadensis* L.), flowering dogwood (*Cornus florida* L.), American holly (*Ilex opaca* Aiton), blackgum (*Nyssa sylvatica* Marsh.), and advance regeneration of oak. Much of the stand developed following agricultural abandonment in the 1940s. Past agricultural use included crop production and woodland grazing. Portions of the stand which were woodland grazed contained dominant overstory oaks and hickories that became established as early as the 1880s.

Experimental Design and Treatments

This replicated study uses as a randomized complete block design. Four residual overstory basal area (RBA) treatments were implemented by installing twenty-eight 0.16 ha circular (22.7 m radius) plots on the study site. The RBA treatment plots were organized into seven replicated blocks to account for local variability in slope position, soil productivity, and our estimation of past agricultural use across the site (Figure 1). Each block of RBA treatment plots contained one randomly assigned replicate of treatments retaining approximately zero (RBA 0), 3 (RBA 3), 7 (RBA 7) and 10 (RBA 10) m^2 of basal area per hectare. The site was whole-tree harvested to the residual basal area targets in August and September of 2012 using wheeled feller-bunchers and skidders. The sparse residual midstory vegetation was hand-felled with brush saws in the weeks following the harvest. Skid trails and piles of logging debris were not permitted within the 0.16 ha circular plots.

Residual overstory trees were dispersed throughout each plot and were selected based on species, form, size, location, and visual assessment of health. A majority (90%) of the retained overstory was composed of oak and hickory trees (mean diameter at breast height [dbh] 25 cm) because of their typical association with shortleaf pine in the Piedmont region (Schafale and Weakley 2012). Other deciduous species including American beech, elm species, red maple, sweetgum, and yellow-poplar, composed 8% of the retained overstory and averaged approximately 20 cm dbh. The remaining 2% of the overstory was coniferous and included loblolly pine, shortleaf pine, and eastern red cedar and averaged approximately 25 cm dbh.

A broadcast burn was applied in November 2012 to prepare the site for planting. The burn was conducted with air temperatures averaging 13°C, relative humidity less than 30%, and predominantly light (1.4 to 3.6 m/sec) NW winds. Overall

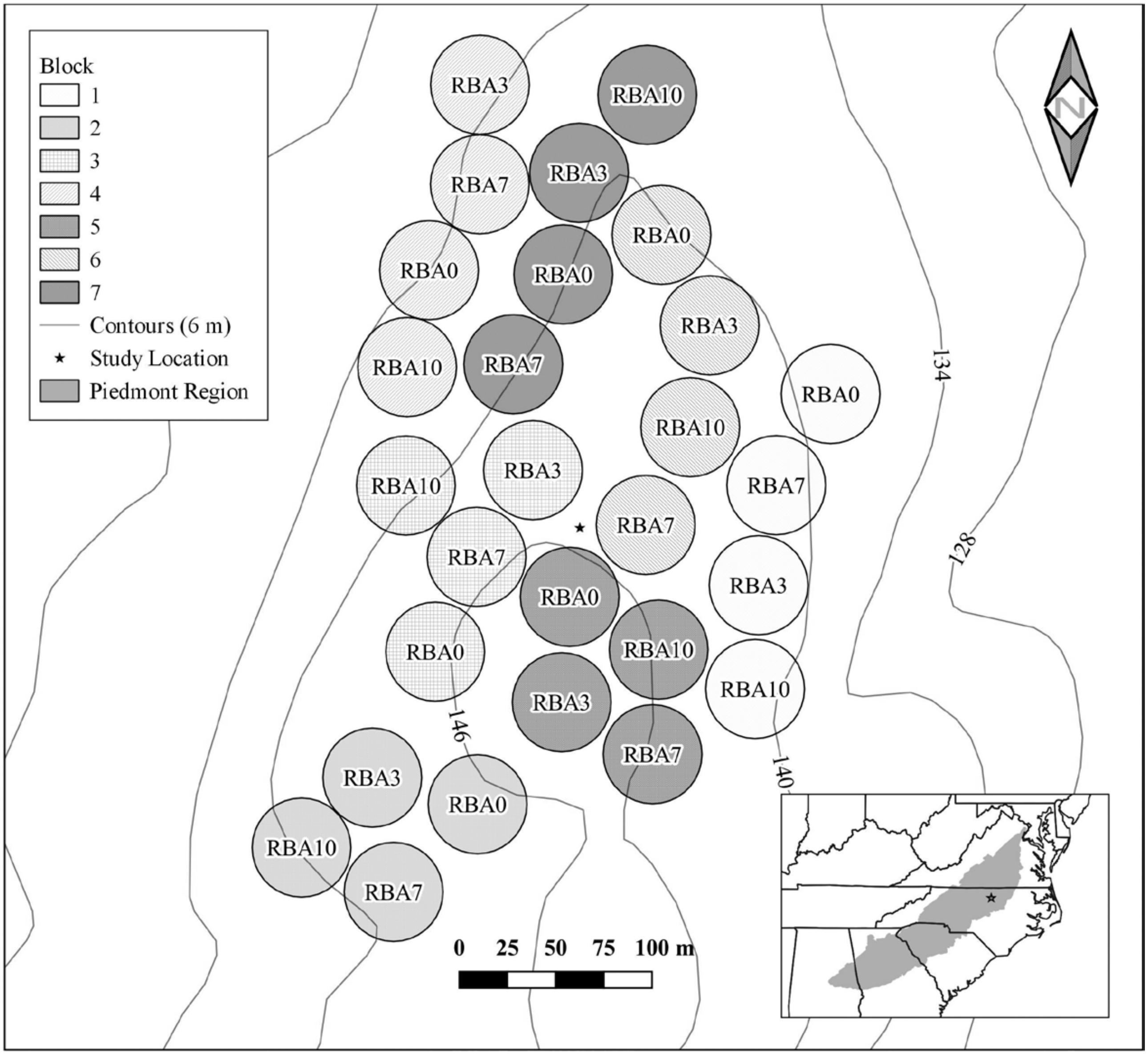

Figure 1. The site was located on the Umstead Research Station, Durham County, NC (36°9′25.75″N, 78°48′54.32″W). The different shades of circles represent different blocking groups based on site variability. Each of the seven blocks contained one replicate each of the four residual overstory treatments (RBA 0, RBA 3, RBA 7, and RBA 10 m²/ha⁻¹). The inset map displays the study site location relative to the Piedmont physiographic region of the southeastern United States.

fuel consumption was low and confined mostly to piles of debris located outside of the 0.16 ha plots. The vegetative response to the harvest and burn was similar across the site. Herbaceous vegetation was dominated by dogfennel (*Eupatorium leptophyllum* DC.), bluestem species, (*Andropogon* spp.), poverty oatgrass (*Danthonia spicata* [L.] P. Beauv. Ex. Roem. & Schult.), rosette grass (*Dichanthelium* spp.), and sedges (*Carex* spp.). Vines, briars and shrubs included muscadine (*Muscadinia rotundifolia* Michx.), greenbrier (*Smilax* spp.), blueberry (*Vaccinnium* spp.), and abundant blackberry (*Rubus* spp.). Sumac spp. (*Rhus* spp.) and exotic species autunm olive (*Elaegnus umbellata* Thunb.) and paulownia (*Paulownia tomentosa* Thunb.) were also present among the postdisturbance vegetation. Herbaceous and shrub cover were not quantified in this study, although we observed that vegetation following the harvest and burn tended to be patchy and sparse at the time of planting, and increased in cover through subsequent growing seasons with an inverse relationship to overstory cover.

Three seedling stock type treatments (Table 1) were implemented within a 0.04 ha circular (11.34 m radius) measurement plot established at plot center of each RBA treatment plot (Figure 2). The stock types established included bareroot seedlings, containerized seedlings with shorter plugs designed to be planted in shallow, rocky soils (smaller plug) and containerized seedlings with a higher volume and deeper plug (larger plug). The bareroot and containerized seedlings were produced using different seed sources and in different nurseries (Table 1). The two containerized seedling stock types were likely grown from the same seed source, but this could not be fully verified. The risk of loblolly pine-shortleaf pine hybrids among the containerized seedlings with larger plugs was

Table 1. Seed source, nursery location, plug sizes, and initial seedling height and ground line diameter (GLD) of the bareroot and containerized seedling stock used in this study.

Stock Type	Seed Source	Nursery Location	Plug Dimensions (D × H, cm)	Plug Volume (mL)	Initial Seedling Height (cm)	Initial Seedling GLD (cm)
Bareroot	1st Generation Improved Orchard Mix, Statewide, Virginia	Virginia	N/A	N/A	24.1[a]	0.38[a]
Smaller plug	Likely the same as larger plug but unverified	Georgia	3.8 × 12.1	93.4	23.9[a]	0.36[a]
Larger plug	1st Generation Improved Orchard Mix, Southern Appalachian Mountains	North Carolina	4.1 × 8.9	113.1	11.9[b]	0.28[b]

Initial seedling heights and GLD measurements not connected by the same letter are significantly (α = 0.05) different, as reported in Schnake et al. (2016).

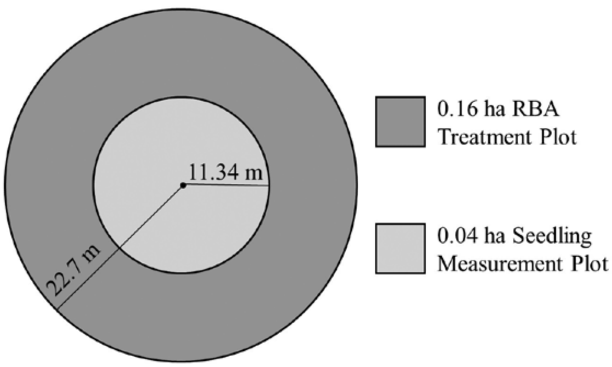

Figure 2. Residual overstory basal area treatment plot and seedling measurement plot originating from plot center.

low (Crane et al. 2019), but we are unable to assess the percentage of hybrids among our bareroot stock or the containerize seedlings with smaller plugs if they indeed came from a different and unknown source. Propagation methods differed between all three nurseries and may have contributed to the significant differences in initial size of the seedlings reported by Schnake et al. (2016) (Table 2). The containerized stock types were grown in a planting medium composed of peat, perlite, vermiculite, and slow-release fertilizers, although the mixtures of each may have differed by nursery. Differences in seedling source, nursery location, and propagation methods prevent us from conducting a traditional stock type comparison (Pinto et al. 2011a); nevertheless, the objective of this study was not a formal stock type comparison but to examine the performance of three widely available shortleaf pine seedling options when underplanted beneath a hardwood overstory in the Central Appalachian Piedmont.

Between January 19 and February 8, 2013, each seedling measurement plot was underplanted with 36 (890 stems/ha^{-1}) bareroot seedlings, 36 containerized seedlings with smaller plugs, and, because of limited availability, 20–22 (544–494 stems/ha^{-1}) containerized seedlings with larger plugs. To ensure the seedlings were distributed as evenly as possible throughout the seedling measurement plots, planting crews divided the measurement plots into four approximately equal quadrants and planted nine bareroot and containerized seedlings with smaller plugs and five of the containerized seedlings with larger plugs within each quadrant. The rocky soils of the study site prevented planting at a uniform spacing, but trees were spaced at least 1 m apart, in approximate rows that alternated by stock type, and in soils deep enough to ensure proper planting depth. Proper seedling care and planting methods were practiced during the transport, storage, and planting of these seedlings (USDA 1996).

Initial seedling groundline diameters (GLD) and heights were measured and recorded, and each seedling was tagged with a unique identification number shortly after planting in 2013 (Table 2). Seedling survival was again assessed, and GLD and heights were remeasured using digital calipers and an adjustable height pole, between December 2018 and January 2019, after the fifth growing season.

A regeneration survey was conducted in June 2020, during the seventh growing season of this experiment. Four circular 0.0004 ha (1.14 m radius) regeneration plots were randomly established within 11.34 m radius of plot center of each of the 28 RBA treatment plots. All saplings (>1.37 m height) belonging to the same cohort as the underplanted shortleaf pine were counted by species within each regeneration plot. Heights and diameters of regeneration were not collected in this early regeneration survey. Tree regeneration was abundant across all treatments, but highest in the RBA 0 and RBA 3 treatments. Tree regeneration was dominated by species that were present prior to harvest, but particularly yellow-poplar, hophornbean, and loblolly pine (Table 2).

Statistical Analyses

The effects of residual overstory basal area and stock type on mean survival and height growth were analyzed using a split-plot design. Residual overstory basal area served as the whole plot factor, whereas stock type was the split-plot factor. A blocking factor representing the seven groups of replicates of each treatment was included to account for local variability in soil, aspect, topographic position, and potential differences in past agricultural land use across the site. However, these are not variables of interest in this experiment and block was considered a fixed effect because of the proximity of the blocks and overall limited range of site conditions. The response variable of mean height growth was calculated by subtracting initial height from the height collected following the fifth growing season for each seedling and calculating the mean for each replicate/RBA/stock type combination. We limited our growth analysis to height because of many of the seedlings not having reached heights to possess a dbh and because we considered height to be a more important metric for a shade intolerant species.

A straight-line windstorm in June 2013 resulted in one RBA 10 plot being removed from analysis. Additionally, at least 35% of the underplanted seedlings experienced redheaded pine sawfly (*Neodiprion lecontei* [Fitch]) damage over the first five growing seasons. Approximately 31% of the seedlings were also browsed, primarily by white-tailed deer (*Odocoileus virginianus*), following a February 2014 winter storm. Unfortunately, we were unable to confidently determine the presence of past biotic damage or the specific cause of mortality

Table 2. Sapling (<0.1.37 m height) regeneration belonging to the same cohort as the underplanted shortleaf pine during the seventh growing season by residual overstory basal area treatment. SE, standard error.

Common Name	Mean Stems/ha^{-1} (SE)			
	RBA 0	RBA 3	RBA 7	RBA 10
Shortleaf pine	2,118 ± 331	1,059 ± 241	1,500 ± 307	1,677 ± 282
American holly	0 ± 0	0 ± 0	0 ± 0	88 ± 74
Autumn olive	706 ± 396	353 ± 138	0 ± 0	0 ± 0
Black cherry	0 ± 0	0 ± 0	88 ± 74	0 ± 0
Blackgum	0 ± 0	0 ± 0	0 ± 0	88 ± 74
Eastern red cedar	88 ± 74	88 ± 744	177 ± 102	177 ± 102
Eastern redbud	706 ± 423	177 ± 106	0 ± 0	0 ± 0
Elm spp.	88 ± 74	0 ± 0	265 ± 163	88 ± 74
Flowering dogwood	353 ± 295	353 ± 171	265 ± 123	88 ± 74
Hickory spp.	530 ± 1,951	706 ± 271	177 ± 102	88 ± 74
Hophornbeam	1,147 ± 390	2,824 ± 613	2,383 ± 763	1,677 ± 439
Loblolly pine	1,236 ± 328	1,412 ± 301	177 ± 102	618 ± 172
Paulownia	0 ± 0	0 ± 0	88 ± 74	0 ± 0
Post oak	530 ± 163	0 ± 0	0 ± 0	0 ± 0
Red maple	706 ± 366	1,236 ± 523	530 ± 195	0 ± 0
Southern red oak	88 ± 74	353 ± 171	88 ± 74	88 ± 74
Sumac spp.	177 ± 148	265 ± 161	88 ± 74	0 ± 0
Sweetgum	353 ± 175	88 ± 744	353 ± 175	177 ± 102
Virginia pine	353 ± 139	0 ± 0	353 ± 139	265 ± 123
White ash	618 ± 378	0 ± 0	0 ± 0	0 ± 0
White oak	1,236 ± 361	2,471 ± 704	177 ± 148	530 ± 195
Yellow-poplar	5,119 ± 857	5,825 ± 106	1,942 ± 595	706 ± 316
Total sapling density	**16,150**	**17,209**	**8,649**	**6,354**

Data collected from four circular 0.0004 ha (1.14 m radius) regeneration plots randomly established within each 0.04 ha measurement plot.

for many seedlings. We were therefore unable to include browse or sawfly damage levels as covariates in this analysis or opportunistically test for the effects of residual overstory basal area or stock type on sawfly or browse incidence. However, mean occurrence of both deer browse and sawfly defoliation was assessed among seedlings for which damage type could be determined (Table 3). This summary is presented only to allow inferences of general trends. Mean survival and height growth were calculated from all seedlings for which survival and height could be assessed after the fifth growing season, regardless of whether they experienced browse or sawfly damage.

We explored the fixed effects of the whole-plot residual overstory basal area and split-plot stock type treatment differences on percent survival (equation 1) and height growth (equation 2) of underplanted shortleaf pine seedlings after five growing seasons through an analysis of variance (ANOVA) using linear mixed-effects models. The analysis was completed using the MIXED and PLM procedures of SAS software, Version 9.4 (SAS Institute, Inc., Cary, NC).

$$S_{ijklm} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \delta_k + (\alpha\delta)_{ik} + \mathrm{E}_{ijkl} \quad (1)$$

$$H_{ijklm} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \delta_k + (\alpha\delta)_{ik} + \mathrm{E}_{ijkl} \quad (2)$$

where S is percent survival, H is mean height growth (m), μ is the overall mean, α_i (i = 0, 3, 7, 10 m^2 ha^{-1}) are the RBA treatment, β_j (j = bareroot, smaller plug container, larger plug container) are the stock type treatment, $(\alpha\beta)_{ij}$ represents the interaction between RBA and stock type treatments, δ_k (k = 1, …, 7) represents fixed bock effects, $(\alpha\delta)_{ik}$ represents whole-plot random error from the effect of the block and RBA interaction (assumed iid ~ $N(0,\sigma^2_{ik})$), E_{ijkl} represents random error between split-plots (assumed iid ~ $N(0,\sigma^2)$, and N = 81.

Standard model diagnostics were used to verify that the assumption of normality of errors and homogeneity of variance were appropriately satisfied. A critical value of α = 0.05 was used to determine statistical significance of effects. We used a Kenward-Roger approximation for degrees of freedom given the slight imbalance of this design (Schaalje et al. 2002). Tukey's honest significant difference (HSD) was conducted as a post hoc mean separation test to conduct pairwise comparisons between treatment levels.

Results

Percent Survival

After five years, residual overstory basal area and stock type significantly (p = .0437) interacted to affect underplanted seedling survival (Table 4). Survival of containerized seedlings with larger plugs averaged 77.4% and survival did not statistically differ across the RBA 0 (78.4%), RBA 3 (63.4%), RBA 7 (79.7%), and RBA 10 (87.6%) treatments (Figure 3). Containerized seedlings with smaller plugs had mean survival of 64.3%, and survival again did not differ significantly across the RBA 0 (67.1%), RBA 3 (50.0%), RBA 7 (61.9%), and RBA 10 (78.1%) residual overstory basal area treatments (Figure 3). Bareroot seedlings had the lowest mean survival (40.2%) and survival did not differ significantly across the RBA 0 (30.7%), RBA 3 (36.3%), RBA 7 (44.3%), and RBA 10 (49.4%) residual overstory basal area treatments (Figure 3). Underplanted seedling survival did not differ significantly by block (Table 4).

The differences in survival between the containerized seedlings with larger plugs and bareroot seedlings were significant across a majority of pairwise comparisons of stock type and residual overstory basal area treatment levels (Figure 3). The exception was that containerized seedlings with larger plugs in the

Table 3. Observed occurrence of seedlings damaged by deer browse or defoliation by redheaded pine sawfly over five years by stock type and residual overstory basal area.

Residual Overstory Basal Area	Large Plug		Small Plug		Bareroot	
	Browse (%)	Sawfly (%)	Browse (%)	Sawfly (%)	Browse (%)	Sawfly (%)
RBA 0	44	24	35	30	11	14
RBA 3	24	53	27	51	15	36
RBA 7	37	39	34	40	19	35
RBA 10	53	33	48	30	25	32

Table 4. Type III analysis of variance table with Kenward-Rogers approximation for degrees of freedom for main effects (residual overstory basal area [RBA] and stock type), their interaction, and block on seedling survival and seedling height growth after five growing seasons (df = numerator df, denominator df, significant *p*-values (α = 0.05) indicated in bold).

Variable	Source	df	*F* Ratio	Prob > *F*
Percent survival	RBA	3, 17	3.45	**0.0400**
	Stock Type	2, 46	103.11	**<0.0001**
	RBA*Stock Type	6, 46	2.38	**0.0437**
	Block	6, 17	1.45	0.2537
Mean height growth	RBA	3, 17	12.02	**0.0002**
	Stock Type	2, 46	29.80	**<0.0001**
	RBA*Stock Type	6, 46	0.94	0.4746
	Block	6,17	0.51	0.7944

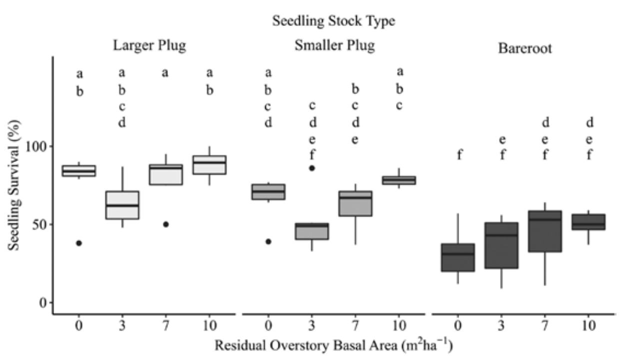

Figure 3. Tukey-Kramer adjustment for multiple comparisons of estimated marginal means for the interaction of residual overstory basal area (RBA) and stock type on percent seedling survival after five growing seasons. Treatments not connected by the same letter are significantly (α = 0.05) different.

RBA 3 treatment had higher survival than bareroot seedlings in the RBA 7 and RBA 10 treatments, but the differences were not statistically significant.

Differences in survival between the containerized seedlings with smaller plugs and bareroot seedlings varied by the residual basal area treatment levels being compared. The survival of containerized seedlings with smaller plugs was highest in the RBA 0 and 10 treatments where survival was statistically higher than bare root seedlings (Figure 3). However, survival among the containerized seedlings with smaller plug was lower in the RBA 3 and RBA 7 treatments and did not significantly differ from bareroot seedlings (Figure 3).

The differences between the two containerized stock types were mostly insignificant across residual overstory basal area treatments. The exception to this trend was smaller plug seedlings had statistically lower survival in the RBA 7 treatment compared with larger plug seedlings. However, the low survival among smaller plug seedlings in the RBA 3 and RBA 7 treatments corresponded with the low survival among the larger plug seedlings in the RBA 3 treatment (Figure 3).

Height Growth

Height growth was significantly (p = .0002) and inversely related to residual overstory basal area (Table 4). The greatest height growth occurred in the RBA 0 treatment (2.61 m). Although height growth among the RBA 0 treatment was significantly higher than the RBA 7 (1.53 m) and RBA 10 (1.44 m) treatments, it did not statistically differ from height growth in the RBA 3 treatment (2.05 m). Height growth in the RBA 3 treatment was higher than in the RBA 7 and RBA 10 treatments, although the difference was not significant. Height growth in the RBA 7 and RBA 10 treatments was statistically similar (Figure 4).

Height growth differed significantly by stock type (p < .0001) (Table 4) with the larger plug containerized seedlings demonstrating significantly greater mean height growth (2.11 m) than both the bareroot (1.85 m) or smaller plug containerized seedlings (1.76 m) (Figure 4). The interaction between residual overstory basal area and stock type did not significantly affect underplanted shortleaf pine seedling height growth over five growing seasons (Table 4). Height growth also did not vary significantly by block (Table 4).

Discussion

Limitations

We encourage readers to view our results with a few important caveates. First, herbaceous or woody vegetation was not quantified during the lifespan of this experiment. The concept that the overstory and understory layers of a forest apply effects on one another is well-documented in literature (Gilliam and Roberts 2014). However, Clabo and Clatterbuck (2020) observed that survival and height growth of shortleaf pine seedlings underplanted in clusters beneath 3.5–5 m^2 ha^{-1} of predominantly oak and hickory basal area were not significantly improved by conducting site preparation and release treatments to favor shortleaf pine. Nevertheless, we cannot dismiss the possibility that understory competition may have influenced underplanted shortleaf pine seedling survival and growth.

A second caveat relates to our split-plot experimental design. With only seven replicates of each whole-plot residual overstory basal area treatment, local variability in edaphic conditions in a replicate could heavily influence the results for that replicate's treatment. Although all the replicates were located within a relatively small

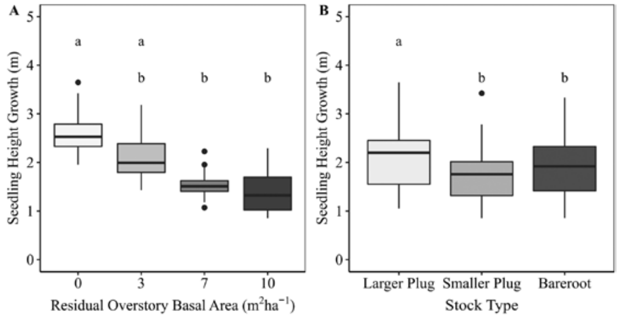

Figure 4. Tukey-Kramer adjustment for multiple comparisons of estimated marginal means for main effects (A) residual overstory basal area (RBA) and (B) stock type on seedling height growth after five growing seasons. Treatments not connected by the same letter are significantly (α = 0.05) different.

study area, there were subtle but potentially important differences in site conditions across replicates. We therefore cannot rule out the possibility that some of this variability influenced our results, despite our analytical approach which included blocking. The close arrangement of the replicates within the study site may also have created an issue with edge effects from neighboring treatments. The measurement plots in which the seedlings were underplanted were purposely established within the center of the replicates to limit the potential of influence from adjoining treatments. Although we are confident edge effects had little impact on the microclimate and light levels of our measurement plots, we are unable to verify that the potential of influence was eliminated.

Another potentially important caveat to our findings are the underlying differences in seed source and seedling propagation methods among stock types. Performance differences between genotype, phenotype, and seedlings produced in different locations using different propagation methods are well documented in the literature (Pinto et al. 2011a). Indeed, shortleaf pine is not immune to these confounding effects and previous studies have indicated that family and stock type can interact and influence the performance of shortleaf pine seedlings (Barnett and Brissette 2004, Sword Sayer et al. 2005, Gwaze et al. 2006). As such, we cannot rule out the possibility that the differences in survival and growth found among the three stock types evaluated in this study were confounded by preplanting differences. Inferences related to the differences between stock types are therefore best limited to the seedling sources and associated stock types used in this experiment, which are all commonly available in the Central Appalachian Piedmont region.

A final caveat of this study is that we are unable to isolate the effects of browse or sawfly, which affected 31 and at least 35% of our seedlings, respectively. In hindsight, we are not surprised that we experienced high-levels of sawfly damage given that infestations often occur on infertile sites where short statured (<4.5 m height) pines are growing beneath or near overstory hardwoods and among high-levels of competing vegetation (Benjamin 1955, Wilson and Averill 1978). Our site featured these very conditions both at the replicate level, and when viewed as a whole. Browse and sawfly damage can negatively affect pine seedling survival and growth (Wilson and Averill 1978, Shelton and Cain 2002). As such, impacts from sawfly, deer, or both may have masked important relationships between seedling survival and growth, residual overstory basal area, and stock type. That said, insect and deer damage are common during plantings and thus may represent a realistic scenario in restoration treatments.

Survival

Our analysis revealed that residual overstory basal area did not strongly affect survival for any of the three stock types tested in this study. Although each stock types achieved their greatest survival beneath 10 m^2 ha^{-1} of residual overstory basal area, the increased survival was not a statistically significant improvement over survival beneath successively lower levels of overstory retention. As such, we conclude that our results correspond with other studies demonstrating that overstory retention does not strongly affect underplanted shortleaf pine seedling survival (Guldin and Heath 2001, Kabrick et al. 2011, 2015).

Although residual overstory basal area did not significantly affect underplanted seedling survival, the nature of the relationship between survival and residual overstory basal area appeared to vary by stock type. We suspect this drove the significance of the interaction between residual overstory basal area and stock type in our model. Containerized seedlings with larger plugs had poor survival in the RBA 3 treatment, but otherwise demonstrated a positive relationship between seedling survival and residual overstory basal area. Smaller plugged seedlings also had poorer survival in the RBA 3 treatments, but additionally had poor survival in the RBA 7 treatments. Although survival ultimately increased between the RBA 0 and RBA 10 treatments, we do not consider this evidence of a positive relationship among the smaller plug seedlings. Bareroot seedlings had the most consistent positive relationship with residual overstory basal area, although we again stress that these relationships were not significant for any stock type.

Survival among containerized seedlings with larger plugs was approximately 37 percentage points higher than survival among bareroot stock. When compared by residual overstory basal area treatment, survival among the larger plug seedlings was approximately 27 to 48 percentage points higher than survival among bareroot seedlings. As such, our results provide clear evidence that the containerized seedlings with larger plugs had greater survival than bareroot seedlings, and that this trend occurred across all residual overstory basal area treatment levels.

Differences between the smaller plug seedling and bareroot seedlings, and between the two containerized stock types, were less apparent. Survival among containerized seedlings with smaller plugs was approximately 24 percentage points higher than survival among bareroot seedlings. There was a 38-percentage-point difference in survival between the two stock types in the RBA 0 treatment, where survival was lowest among bareroot seedlings. The difference between stock types in the RBA 10 treatment, where bareroot seedling survival was highest, was still 29 percentage points. These differences were statistically significant, and we speculate they would also be operationally significant to many forest managers. The differences between the stock types decreased to 14 and 18 percentage points among the RBA 3 and RBA 7 treatments, respectively. Although these were not statistically significant differences, we suspect they would be considered operationally meaningful to forest managers, especially when bareroot survival was below 50% for both treatments. Consequently, we consider the overall trend to be evidence indicating that containerized seedlings with smaller plugs had a biologically meaningful and higher survival rate than the bareroot seedlings planted in this experiment.

Survival among the containerized seedlings with larger plugs was an average of 13 percentage points higher than survival among the smaller plug seedlings. However, the differences were not always statistically significant. When compared by residual overstory basal area treatment, the larger plug seedlings averaged approximately 11, 14, 18, and 9 percentage points higher survival than smaller plug seedlings in the RBA 0, RBA 3, RBA 7, and RBA 10 treatments, respectively. The 18-percentage-point difference in survival under the RBA 7 treatment was the only statistically significant difference between the two stock types. However, we again expect that although not always statistically significant in our analysis, the differences in mean survival between these stock types would be considered operationally meaningful. As such, we infer that our overall results of an average 13-percentage-point difference in survival provides evidence of meaningful dissimilarity of survival between the two containerized stock types.

In support of the above interpretations of our analysis, we note that the relatively few similarities measured between the stock types occurred where survival among the containerized stock was lowest, and survival among bareroot stock was highest. In explaining this trend, we think it is again important to acknowledge the potential collective effects of deer browse, sawfly damage, and competing vegetation on our results. We observed the highest occurrence of sawfly damage in the RBA 3 treatment and specifically among the two containerized stock types. We also observed the highest densities of sapling recruitment in the RBA 3 treatment. We speculate that both could have contributed to low survival rates in the RBA 3 treatment and therefore may have influenced our results. Seedling mortality driven by competition between vegetation would be expected (Aschehoug et al. 2016) as would the negative effects of sawfly infestation on survival (Wilson and Averill 1978). Indeed, Clabo and Clatterbuck (2020) recently noted that sawfly likely contributed to mortality among shortleaf pine seedlings underplanted in clusters beneath a hardwood overstory in eastern Tennessee, USA. However, we remain unable to formally test whether either or both have influenced our results related to the interacting effects of residual overstory basal area and stock type on underplanted seedling survival.

Higher survival among both containerized stock types was expected given the harsh site conditions and is similar to the survival trends reported following the first growing season of this study (Schnake et al. 2016). The superior survival of containerized stock measured in this study is also similar to the findings reported in stock type comparisons of southern yellow pines planted on adverse sites (Boyer 1989, Barnett and McGilvray 1993, Barnett and Brissette 2004). The approximately 13-percentage-point higher survival of larger plug seedlings over smaller plug seedlings after the fifth growing season supports the findings of previously reported container size comparisons which found that increasing plug size improved survival on harsh sites (Amidon et al. 1982, Chirino et al. 2008, Haywood et al. 2012).

We attribute the differences in seedling survival between containerized and bareroot stock after five growing seasons to the intact root system and presence of the growing medium at the time of planting. However, we again acknowledge that preplanting differences between these stock types may also have influenced our survival results. Nonetheless, plugs have been found to be a source of both water and nutrition for transplanted seedlings (Grossnickle and El-Kassaby 2016). We suspect that increased moisture availability and nutrition from the mix of vermiculate, perlite, peat, and fertilizer that composed the growing medium promoted seedling survival. Specifically, we suspect they reduced planting stress and accelerating seedling establishment (Grossnickle 2005). Indeed, there were significant differences in survival between the containerized and bareroot stock, particularly in RBA 0 treatments where moisture stress was likely highest, following the first growing season (Schnake et al. 2016). This trend of higher containerized survival continued through the fifth growing season.

Height Growth

Residual overstory basal area had a significantly negative effect on underplanted shortleaf pine seedling height growth after five growing seasons. Height growth was greatest where there was no overstory cover and decreased as residual overstory increased. However, the significance of the suppressing effects of residual overstory tapered off beyond approximately 3 $m^2\ ha^{-1}$. Overall, our results supports the findings of previous studies where shortleaf pine was underplanted beneath a residual hardwood overstory (Guldin and Heath 2001, Jensen et al. 2007, Kabrick et al. 2011, 2015), as well as trends measured among naturally regenerated shortleaf pine growing in multiaged forests with pine-hardwood overstories with densities ranging from 0 to 13.8 $m^2\ ha^{-1}$ (Shelton and Murphy 1997, Shelton 2004). An inverse relationship between seedling height growth and residual basal area is generally attributed to resource competition created by the residual overstory trees. Although we did not explore modes of competition in this study, we speculate that above and belowground competition from both woody and herbaceous vegetation may have diminished height growth.

Our height growth results also show that the trend of marginally higher height growth in the RBA 3 treatment reported following the second growing season of this study (Schnake et al. 2016) has reversed. Height growth is now marginally higher in the RBA 0 treatment, and thus support Kabrick et al.'s (2015) finding that the inverse relationship between residual overstory basal area and shortleaf pine seedling height growth increases over time. We hypothesize that the combination of crown expansion and increased utilization of site resources by the overstory trees has suppressed the height growth of underplanted shortleaf pine seedlings over the course of five growing seasons even at a low residual basal area. Future measurements will be necessary to determine if this trend continues. These results are marginally different than those reported by Paquette et al. (2006) for underplanting studies in the temperate deciduous biome where height growth was often highest beneath intermediate levels of residual overstory. We attribute conflicting results to shortleaf pine being more intolerant of shade than many of the midtolerant deciduous species underplanted in most of the studies from the temperate deciduous biome analyzed by Paquette et al. (2006).

The marginally higher survival and significantly greater height growth of the containerized seedlings with larger plugs compared with those produced with smaller plugs concurs with other container size comparisons (Dominguez-Lerena et al. 2006, Chirino et al. 2008, Pinto et al. 2011b, Aghai et al. 2014). We note that preplanting differences in seed source and nursery propagation may again have influenced seedling performance but suspect that the differences in container size also contributed to our results. Larger containers often provide more space for root development as well as improved water and nutrient availability after transplanting (Hsu et al. 1996, Matthes-Sears and Larson 1999, Aghai et al. 2014, Grossnickle and El-Kassaby 2016). All these characteristics can reduce transplant shock and aid seedling establishment (Grossnickle 2005). Container depth may be particularly important, as demonstrated by Chirino et al. (2008) who reported that containerized seedlings produced with deeper plugs had deeper tap roots, which improved seedling water status on dry sites. Planting depth has also been shown to influence early seedling survival and growth of bareroot shortleaf pine seedlings (South et al. 2012), further demonstrating that ensuring roots reach deeper substrates where they are less likely to dry out is important for shortleaf pine.

Our results support the notion that increasing plug volume and depth can aid in survival and growth on dry sites, as the larger plug seedlings, which had higher volume and deeper plugs, achieved significantly greater survival and height growth than the other two stock types through the fifth growing season. We suspect that the additional growing medium associated with the higher volume plug and their extra depth likely reduced planting stress at our dry, rocky site and accelerated the establishment of these seedlings relative to the other stock types. The earlier coupling of the seedling with the planting environment (Grossnickle 2005) likely contributed the superior performance of the containerized seedlings with larger plugs on this site.

Conclusions

Underplanting seedlings beneath a residual hardwood overstory is a viable method of reestablishing shortleaf pine in an upland hardwood stand on thin and rocky soils in the Central Appalachian Piedmont. Underplanted seedlings of each stock type were alive, established, and accruing height growth after five growing seasons, even when growing under as much as 10 m^2 ha^{-1} of predominantly oak and hickory overstory basal area. However, as little as 3 m^2 ha^{-1} of overstory retention moderately suppressed underplanted seedling height growth over the first five years of the study, and height growth was significantly suppressed under more than 3 m^2 ha^{-1} of overstory basal area.

We found that the two containerized stock types used in this experiment achieved greater survival than the bareroot stock. As such, landowners underplanting the bareroot stock on similarly harsh sites may need to consider planting at higher densities to account for the likely poorer survival. However, although the larger plug seedlings, which had higher plug volume and deeper plug depth, outperformed the other two stock types in both survival and growth on this dry, rocky site, the differences in height growth between the larger plug and bareroot seedlings were similar. It is debatable whether the difference in growth between the bareroot and containerized seedlings with smaller plugs used in this experiment is operationally meaningful in the context of reestablishing shortleaf pine into an otherwise hardwood-dominated forest stand.

Although planting appears to have been relatively successful at our dry, rocky site, landowners are again cautioned that such sites often present high hazards for littleleaf disease (Campbell and Copeland 1954). We make no claim that retaining overstory hardwoods or establishing any of the three shortleaf pine seedling options used in this study will overcome littleleaf disease. However, we are confident recommending that landowners underplanting shortleaf pine on similarly harsh, but appropriate sites for shortleaf pine should consider planting the containerized seedlings with larger plugs used in this study. These seedlings appeared to offer the best combination of survival and growth under the residual overstory basal area treatments explored in this experiment.

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