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ORIGINAL ARTICLE

Nursery stock quality as an indicator of bottomland hardwood forest restoration success in the Lower Mississippi River Alluvial Valley

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Abstract

Seedling morphological quality standards are lacking for bottomland hardwood restoration plantings in the Lower Mississippi River Alluvial Valley, USA, which may contribute toward variable restoration success. We measured initial seedling morphology (shoot height, root collar diameter, number of first order lateral roots, fresh mass, and root volume), second year field heights and diameters, survival, browse, and top dieback of five species – cherrybark oak (*Quercus pagoda* Raf.), green ash (*Fraxinus pennsylvanica* Marsh.), Nuttall oak (*Q. nuttallii* Palmer), sweet pecan (*Carya illinoensis* (Wangenh.) K. Koch), and water oak (*Q. nigra* L.). Seedlings were obtained from three regional nurseries (Arkansas, Louisiana, and Mississippi), planted on three sites (Arkansas, Louisiana, and Mississippi), and treated with or without chemical weed control. Site × nursery interaction and weed control (without interactions) usually affected survival, whereas site × weed control interaction and nursery (without interactions) influenced second year heights and diameters. Weed control generally increased survival rates, as well as second year height and diameter. Effects of initial morphological characteristics on field survival and height and diameter growth were generally dependent on the other morphological parameters. Target morphological characteristics were identified as 99, 84, and 82 in height/diameter ratios (equal units) for cherrybark oak, green ash, and Nuttall oak, respectively; mean initial height of 40–43 cm in sweet pecan; and mean initial fresh mass/root volume of 2.7 g ml^{-1} in water oak. Seedlings with means above these values may be more susceptible to dieback or mortality after outplanting, likely associated with excessive shoot relative to root biomass.

Keywords: *Afforestation, competition control, field performance, growth, hardwood seedling quality.*

Introduction

There has been increased planting worldwide of temperate deciduous hardwood seedlings to facilitate restoration projects aimed at soil and resource conservation, provision of wildlife habitat, and timber production (Dey et al., 2010; Maltoni et al., 2010; Ross-Davis et al., 2005). Many of these projects designed to restore native forest habitat involve afforestation of open fields that were formally in agronomic crop production or under grazing. Survival of hardwood seedlings on these sites is often poor (Dey et al., 2008; Jacobs et al., 2004; Maltoni et al., 2010), which has been attributed to factors including poor nursery stock quality, competing vegetation, deer browsing, exposure to flooding, and/or transplant stress due to water or nutrient limitations (Cogliastro et al., 1990; Gordon et al. 1995; Martin & Baltzinger, 2002; Stanturf et al., 2004; Ward et al., 2000).

The Lower Mississippi Alluvial Valley (LMAV), the geologic floodplain of the Lower Mississippi River, comprised the largest extent of bottomland hardwood forest in the USA at the time of European settlement (Hefner & Brown, 1985). Conversion to agriculture in the LMAV reduced hardwood forests from about 10 to 2 million ha by 1978 (Hefner & Brown, 1985). Recently, there has been increased interest to afforest these sites to remove flood-prone areas from agriculture and maintain important

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ecological functions of these bottomland forests (Gardiner et al., 2002;Gardiner & Lockhart, 2007; Lockhart et al., 2003, 2008). Afforestation activities in the LMAV are further stimulated by the availability of governmental cost-share programs that help supplement planting costs (Gardiner et al., 2002). By 2005, approximately 194,000 ha of former agricultural land had been afforested in the LMAV since the mid-1980s (Gardiner & Oliver, 2005). The 2002 Farm Bill expanded the Wetlands Reserve Program to allow the enrollment of up to 101,200 ha annually and a maximum of 920,700 ha total (USDA-NRCS, 2007).

The earlier scenarios have created increased demand for hardwood bareroot seedlings for afforestation in the LMAV. Many new forest tree seedling nurseries have been established in this area, and some ornamental nurseries have expanded operations to include production of hardwood planting stock to meet this demand. However, no definitive guidelines for optimal seedling morphological quality of bottomland hardwoods in this region have been developed or published (Gardiner et al., 2002), thereby limiting capacity to dictate ideal morphological specifications of nursery stock. These trends have created potential for concern regarding quality of seedlings currently available for afforestation in the LMAV, which has been exacerbated by poor survival and growth of many hardwood plantations in the region (Lockhart et al., 2003; Stanturf et al., 2001). In addition, many afforestation sites in the LMAV receive little or no weed control measures, which may further limit survival and growth. Thus, a need exists for a concerted research effort to better define quality specifications for bottomland hardwood nursery stock to aid managers and policymakers in developing guidelines that help facilitate successful plantation establishment.

Initial nursery morphological characteristics of hardwood seedlings could serve as important predictors of subsequent field performance when evaluated as parameters in statistical analysis (Dey & Parker, 1997; Jacobs et al., 2005b). There is still considerable variation in reported literature, however, regarding optimal seedling quality attributes of hardwoods (Wilson & Jacobs, 2006). Morphological variables, such as seedling shoot height and diameter, have been demonstrated to serve as good predictors of field success (Dey & Parker, 1997) and are relatively simple to measure. Initial shoot height, however, has provided inconsistent ability to predict seedling field performance for some species (Jacobs et al., 2005b; Thompson & Schultz, 1995). Various root system characteristics may have greater potential to predict outplanting performance given the reliance of many hardwood species on carbohydrate and nutrient reserves stored largely in root systems, as well as the capacity of large root systems to exploit soil resources (Dey & Parker, 1997; Maltoni et al., 2010; Ponder, 2000). The balance of root to shoot biomass (assessed via ratios), which is indicative of seedling ability to withstand transplant stress (Dey et al., 2008; Jacobs et al., 2009), may also be an important morphological indicator yet has not been adequately explored in hardwood seedling quality studies. Furthermore, this type of experimentation has thus far been predominantly restricted to upland afforestation sites (Dey et al., 2010); responses may vary for species adapted to bottomland sites of the LMAV and under the intense vegetative competition characteristic of these areas.

We measured initial morphological characteristics of cherrybark oak (*Quercus pagoda* Raf.), green ash (*Fraxinus pennsylvanica* Marsh.), Nuttall oak (*Q. nuttallii* Palmer), sweet pecan (*Carya illinoensis* (Wangenh.) K. Koch), and water oak (*Q. nigra* L.) seedlings obtained from three nurseries (Arkansas, Louisiana, and Mississippi) and planted in field sites in the same three states with and without weed control. Our objectives were to (1) characterize bareroot seedling morphology from different regional nurseries, (2) examine seedling survival and growth across a range of outplanting sites, (3) test the effects of weed control on plantation establishment, and (4) determine target seedling initial morphology for each species. We present comprehensive data for two-year field responses for the studied species. Preliminary results were previously published for green ash and water oak (Corbin et al., 2004; Jacobs et al., 2005a).

Materials and methods

Experimental design

The experiment was established as a randomized complete block design with three field sites, three nurseries, two weed control levels, and three blocks (replications). Each of the five species was established as a separate experiment. Within each study site, each species was matched with suitable site conditions. See Table I for site location, soil series, taxonomic class, depth, drainage, and slope. Precipitation patterns during the course of the two-year study period were generally representative of normal conditions with deviation of -0.8%, 0.7%, and -4.9% for the Arkansas, Louisiana, and Mississippi sites, respectively (NOAA National Climate Data Center, http://www.ncdc.noaa.gov).

Each experimental unit (site $\times$ nursery $\times$ weed control $\times$ replication, within a species) consisted of 50 seedlings planted in a 9.14 m $\times$ 18.29 m plot (henceforth referred to as "treatment-replicate plot"). Seedlings within each treatment-replicate plot were

Table I. Site characteristics.

Site Spp.	Soil series	Taxonomic class	Depth and drainage	Slope	Vegetative biomass (kg/ha)	
					No WC	With WC
Chicot County, AR (33° 03′ N, 91° 22′ W)						
CHO	Robinsonville loam	Coarse-loamy, mixed, superactive, nonacid, thermic Typic Udifluvents	Very deep, well drained	0–5%	2031.3 ± 1064.8	25.2 ± 3.3
SWP					1536.6 ± 446.4	27.4 ± 7.5
WAO					1515.1 ± 429.6	19.8 ± 4.3
GRA	Perry clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Very deep, poorly drained	0–3%	2481.4 ± 558.2	24.6 ± 2.8
NUO					2110.1 ± 276.6	44.5 ± 9.9
Madison Parish, LA (32° 26′ N, 91° 25′ W)						
CHO	Dundee loam	Fine-silty, mixed, active, thermic Typic Endoaqualfs	Very deep, somewhat poorly drained	0–8 %	2171.9 ± 749.0	222.0 ± 131.4
SWP					1661.8 ± 553.6	66.8 ± 8.4
WAO					3488.1 ± 134.5	66.5 ± 2.2
GRA	Sharkey clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Very deep, poorly to very poorly drained	0–5 % (usually < 1%)	4820.9 ± 3496.3	181.3 ± 22.6
NUO					2630 ± 93.8	152.1 ± 11.1
Bolivar County, MS (33° 53′ N, 91° 00′ W)						
CHO	Commerce silt loam	Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts	Deep, somewhat poorly drained	0–5 % (usually < 1%)	4106.8 ± 559.9	102.0 ± 36.0
SWP					1273.9 ± 315.9	118.1 ± 34.9
WAO					1362.3 ± 232.4	105.8 ± 29.5
GRA	Sharkey clay	Very-fine, smectitic, thermic Chromic Epiaquerts	Very deep, poorly to very poorly drained	0–5 % (usually < 1%)	2759.4 ± 274.7	287.8 ± 26.3
NUO					4069.9 ± 2071.6	199.0 ± 21.4

Note: Site location (latitude, longitude), soil series name, taxonomic class, depth and drainage, and slope. On each site, cherrybark oak (CHO), sweet pecan (SWP), and water oak (WAO) were planted on the same soil series as each other; green ash (GRA) and Nuttall oak (NUO) were planted on the same soil series as each other. Soil series were determined on site; descriptions were obtained from USDA-NRCS (2008). Vegetative biomass is mean (±SE) of each species on each site with and without weed control (WC) treatments (n = 3).

arranged in 5 rows of 10 trees each at 1.83 m spacing. On each site, treatments (3 nurseries × 2 weed control treatments) were randomly assigned to treatment-replicate plots and there were three replicates of these six treatments on each site; there was a 3.66 m buffer between each experimental plot. Thus, each species on each site contained 900 seedlings and occupied a total area of 0.534 ha (76.8 m × 64.5 m).

Plant materials and measurements

One-year-old (1 + 0 bareroot) seedlings of five species commonly planted in LMAV afforestation programs – cherrybark, green ash, Nuttall oak, sweet pecan, and water oak – were obtained from the following three regional nurseries: Arkansas Forestry Commission (AR), Louisiana Department of Forestry (LA), and the Mississippi Forestry Commission (MS). Seedlings were lifted on 30 and 31 January 2003, transported to the USDA Forest Service Bottomland Hardwoods Laboratory in Stoneville, Mississippi, USA, and stored in refrigerated lockers (4°C) until measured. In the laboratory, each seedling was individually tagged and measured for the following variables of initial morphology: shoot height, root-collar diameter, fresh mass, number of first-order lateral roots (FOLR; roots >1 mm at junction with taproot), and root volume (by water displacement) (Burdett, 1979). Height/diameter ratios (H/D ratios) were calculated by measuring height and root-collar diameter in equal units. Seedlings were then re-packaged and returned to refrigerated storage.

After laboratory measurements, seedlings were randomly sorted for planting at the three different sites. All sites were planted using hardwood planting shovels (16.5 cm wide × 25.4 cm long). The Mississippi site was planted on 18 and 19 February 2003, and the Arkansas and Louisiana sites were planted on 26 February 2003.

In March 2003 (following planting and prior to bud burst), each seedling was measured for initial field height (from ground level) and diameter (at ground level). Seedling heights and diameters were re-measured and at the end of the first (December 2003) and second (December 2004) growing seasons and mortality was noted. At the same time, individual trees were also assessed for evidence of top dieback (Jacobs et al., 2004) or presence/absence of browse damage by white-tailed deer (*Odocoileus virginianus* Zimmermann).

Weed control treatments

Weed control treatments consisted of either no control or complete weed control. Complete weed control consisted of a pre-emergent application of Goal 2XL (oxyfluorfen) applied at 1.1 kg active ingredient (ai) ha^{-1} in early March 2003, broadcast applications of Select 2EC (clethodim) applied as needed throughout the growing season at a rate of 0.95–1.28 kg ai ha^{-1} depending on target weed species, and direct applications of Derringer (glufosinate-ammonium) applied at a rate of 1.19 g ai l [water]$^{-1}$ as needed throughout the growing season. The effectiveness of weed control treatments was assessed in October 2003. All herbaceous plants (weeds) were clipped and removed from six 1-m^2 sampling plots (one with and one without weed control randomly placed within each of the 3 blocks) per species site. Biomass samples were dried to a constant temperature and mass was determined (Table I).

Data analysis

Treatment-replicate means of all trees were used to examine initial morphology (laboratory measurements) and proportions of survival, browse, and dieback. Treatment-replicate means of all surviving trees were used to analyze second year heights and diameters. For the analysis of initial morphology by postplanting category, individual trees were separated into one of the following four categories: top dieback, browsed, dead, or none of the aforementioned (also referred to as "undamaged"). Browse damage and top-dieback were not differentiated for green ash seedlings, but damage was noted if either factor was present. Means were calculated for each of the categories for data analysis.

Analyses of variance (ANOVA) were performed using the mixed-model procedure (PROC MIXED) in SAS (Version 9.1, SAS Institute Inc., Cary, NC, USA). Block (replicate) was treated as a random effect. Residuals were tested for normality and homogeneous variance, and data were transformed according to the Box-Cox recommendation when necessary. Proportional data were transformed to the arcsine or arcsine of the square root as necessary. Values that were transformed for statistical analysis are reported as back-transformed midpoint and lower and upper limits of the 95% confidence interval as predictors of the mean and upper and lower 95% confidence limits, respectively, on the original scale (Schabenberger & Pierce, 2002). All pair-wise comparisons among means were performed using Fisher's least significant difference (LSD) at $\alpha = 0.05$.

Results are presented as the highest-order significant interaction or as main effects if no interactions were significant. In the examination of initial morphology by category, only variables that have no significant interactions with site or nursery are reported as means by category or weed control × category (when significant). In other words, this research sought to identify "target" initial morphological characteristics that are applicable across all sites and nurseries.

Results

Field survival, browse, and dieback

Second year field survival of all species was significantly affected by site, nursery, weed control (except green ash), and site × nursery interaction (except cherrybark oak) (Table II). Cherrybark oak and green ash survival was greatest in seedlings from the AR nursery across all sites, and sweet pecan survival was greatest in seedlings from the LA nursery across all sites (Figure 1). Nuttall oak and water oak survival did not show the same consistent trends between nurseries and sites. Survival was greater in plots receiving weed control than those that had not in all species except green ash (Figure 1).

Browse and dieback were significantly affected by site for all species; nursery affected browse in water oak and dieback in all species except water oak (Table II). Notable interactions with weed control occurred for some species (Table II). Browse damage to seedlings was generally greater in plots receiving weed control or else there was no detectable difference (Figure 2). Dieback, however, was generally greater in plots not receiving weed control or else there was no detectable difference (Figure 2).

Second year heights and diameters

Second year height and diameter were significantly influenced by site, nursery, weed control, and site × weed control interaction for all species, with the exception that cherrybark oak diameter was not significantly different between nurseries (Table II). Sweet pecan heights were additionally influenced by nursery × weed control interaction. Second year heights and diameters were always greater in plots receiving weed control, except on the Mississippi site for cherrybark oak, sweet pecan, and water oak (Figures 3 and 4). Where weed control was significant, the magnitude of the difference varied by species in the general order of Nuttall oak > green ash > water oak > cherrybark oak > sweet pecan (Figures 3 and 4).

Initial morphology and relation to field performance

For all species, seedling height, diameter, H/D ratio, FOLR, fresh mass, and root volume all differed significantly only by nursery ($p < 0.0001$ for each), but there were no consistent trends in nursery rankings between species or initial morphology (Table III). In water oak, browse was greatest in seedlings from the MS nursery (Figure 2), which had the greatest height, diameter, fresh mass, and root volume (Table III). In all species, survival was lowest (Figure 1) and dieback was greatest (Figure 2) in seedlings from the MS nursery, which always had the greatest height but never had the lowest number of FOLR or root volume (Table III).

When category (e.g. no damage, browse, dieback, dead) was added to the ANOVA model, both nursery and category were always significant ($p < 0.05$) for each morphological variable. Evaluation of additional interactions associated with category revealed that nursery × category was significant for nearly all species and parameters; for water oak, site × category was also significant for most parameters (Table IV).

For cherrybark oak, nondamaged seedlings had the lowest H/D ratios (99.1) and greatest number of FOLR (9.5), and dead seedlings initially had the lowest number of FOLR (7.2; Table V). In green ash seedlings, the lowest H/D ratios (84) also occurred in nondamaged seedlings, followed by those that incurred browse or dieback (92.4) and those that had died (98.8). For Nuttall oak, seedlings that experienced dieback or no damage had the lowest H/D ratios (81.7–83.5), and those that had died had the greatest H/D ratios. Without weed control, Nuttall oak seedling heights were greatest in those that experienced dieback (70.8 cm) and lowest in those that experienced browse (58.3 cm); with weed control, heights were also greatest in those that had experienced dieback (70.0 cm) and lowest in those that had died (60.8). Nuttall oak seedling diameters followed the same trends as height without weed control; with weed control, those that had died had the lowest diameters (6.9 mm). In sweet pecan seedlings with or without weed control, heights were greatest in those that incurred dieback and lowest in those that experienced browse or death. In water oak seedlings, none of the aforementioned variables emerged where category was constant across all sites and nurseries. As so, we explored other relationships (ratios of height, diameter, and fresh mass to FOLR and root volume). Of these new variables, only the fresh mass/root volume ratio emerged as significantly different among categories ($p < 0.0001$) without any interaction between category and site or nursery. Water oak seedlings that incurred no damage or browse had fresh mass/root volume ratios of 2.7 g ml^{-1}, while seedling that experienced dieback or death had ratios greater than this value.

Table II. ANOVA results for second year field performance.

Species	Site	Nursery	WC	S × N	S × WC	N × WC	S × N × WC
Survival							
CHO	<**0.0001**	**0.0001**	**0.0387**	0.8483	0.6310	0.2563	0.0826
GRA	**0.0014**	<**0.0001**	0.3579	**0.0111**	0.1044	0.7077	0.5862
NUO	**0.0003**	**0.0315**	<**0.0001**	**0.0325**	0.4673	0.4305	0.7787
SWP	<**0.0001**	<**0.0001**	<**0.0001**	**0.0412**	0.6077	0.7119	0.1013
WAO	<**0.0001**	**0.0337**	<**0.0001**	**0.0140**	0.7115	0.1900	0.2425
Browse							
CHO	<**0.0001**	0.7424	0.3763	0.3915	0.6701	0.2544	0.8320
NUO	**0.0013**	0.6945	**0.0078**	0.1041	0.0728	0.3719	0.2452
SWP	<**0.0001**	0.9434	<**0.0001**	0.0995	**0.0155**	**0.0491**	0.5802
WAO	<**0.0001**	**0.0279**	0.2746	0.7373	<**0.0001**	0.7536	0.9812
Dieback							
CHO	**0.0006**	<**0.0001**	**0.0238**	0.8195	0.2011	0.6909	0.6316
NUO	**0.0006**	<**0.0001**	**0.0002**	0.4870	**0.0372**	**0.0016**	0.5969
SWP	**0.0008**	<**0.0001**	0.7373	0.6125	0.0940	0.5822	0.7494
WAO	**0.0007**	0.2863	0.0955	0.2720	0.2808	0.2201	0.9011
Damage (browse + dieback)							
GRA	**0.0004**	<**0.0001**	<**0.0001**	0.1683	**0.0126**	<**0.0001**	0.0918
Height							
CHO	<**0.0001**	**0.0214**	<**0.0001**	0.4564	<**0.0001**	0.9616	0.1183
GRA	<**0.0001**	<**0.0001**	<**0.0001**	0.3879	<**0.0001**	0.7176	0.4945
NUO	<**0.0001**	<**0.0001**	<**0.0001**	0.7395	<**0.0001**	0.1925	0.4624
SWP	<**0.0001**	<**0.0001**	<**0.0001**	0.1557	**0.0054**	**0.0171**	0.5208
WAO	<**0.0001**	**0.0011**	<**0.0001**	0.2629	<**0.0001**	0.2197	0.8375
Diameter							
CHO	<**0.0001**	0.1768	<**0.0001**	0.2262	<**0.0001**	0.4522	0.4212
GRA	<**0.0001**	<**0.0001**	<**0.0001**	0.8582	<**0.0001**	0.0518	0.6252
NUO	<**0.0001**	<**0.0001**	<**0.0001**	0.6697	<**0.0001**	0.1777	0.1425
SWP	**0.0108**	<**0.0001**	<**0.0001**	0.1454	<**0.0001**	0.6927	0.3546
WAO	<**0.0001**	**0.0136**	<**0.0001**	0.1193	<**0.0001**	0.1562	0.8631

Notes: Bold font indicates significant effects.
Analysis of variance (ANOVA) results of second year proportions of survival, browse, and top dieback, as well as height and diameter of cherrybark oak (CHO), green ash (GRA), Nutall oak (NUO), sweet pecan (SWP), and water oak (WAO) for the effects of site (S), nursery (N), weed control (WC), and all interactions.

Discussion

Survival, browse, dieback, and growth

Chemical weed control generally increased seedling survival and growth (Figures 1, 3, and 4). However, the effectiveness of weed control depends on species, planting stock, site, and management objectives (e.g. increasing survival or growth). Weed control increased survival after two years in all species, except for the fastest-growing species, green ash. The greatest apparent increases in survival (due to weed control treatments) were seen in the slowest-growing species, sweet pecan and water oak. Conversely, the greatest increases (due to weed control) in heights and diameters after two years were noted in the fastest-growing species, green ash and Nuttall oak, and least in the slowest-growing species, sweet pecan.

Federal cost-share funds are typically not provided for weed control on afforestation plantings in the LMAV. Herbicide applications are estimated at $US 27–37 ha^{-1} (Gardiner & Oliver, 2005), while the Conservation Reserve Program only provides up to $US 4 ha^{-1} year^{-1} for maintenance (USDA-FSA, 2009). Thus, these treatments are often not employed, which may result in less productive or failed plantations.

Vegetation management may minimize capture of site resources by competing vegetation (Chang et al., 1996; Nambiar & Sands, 1993) and act to stimulate growth of desired crop plants and facilitate successful plantation establishment, as demonstrated here and elsewhere (Ezell & Catchot, 1998; Ezell et al., 1999). However, benefits of weed control must be weighed against monetary costs and potential environmental contamination (Plese et al., 2009). Complete weed control, as applied in this study, may be unnecessary and competition control may only be needed until tree seedlings are free-to-grow (Jacobs et al., 2004). Thus, additional research should be designed to

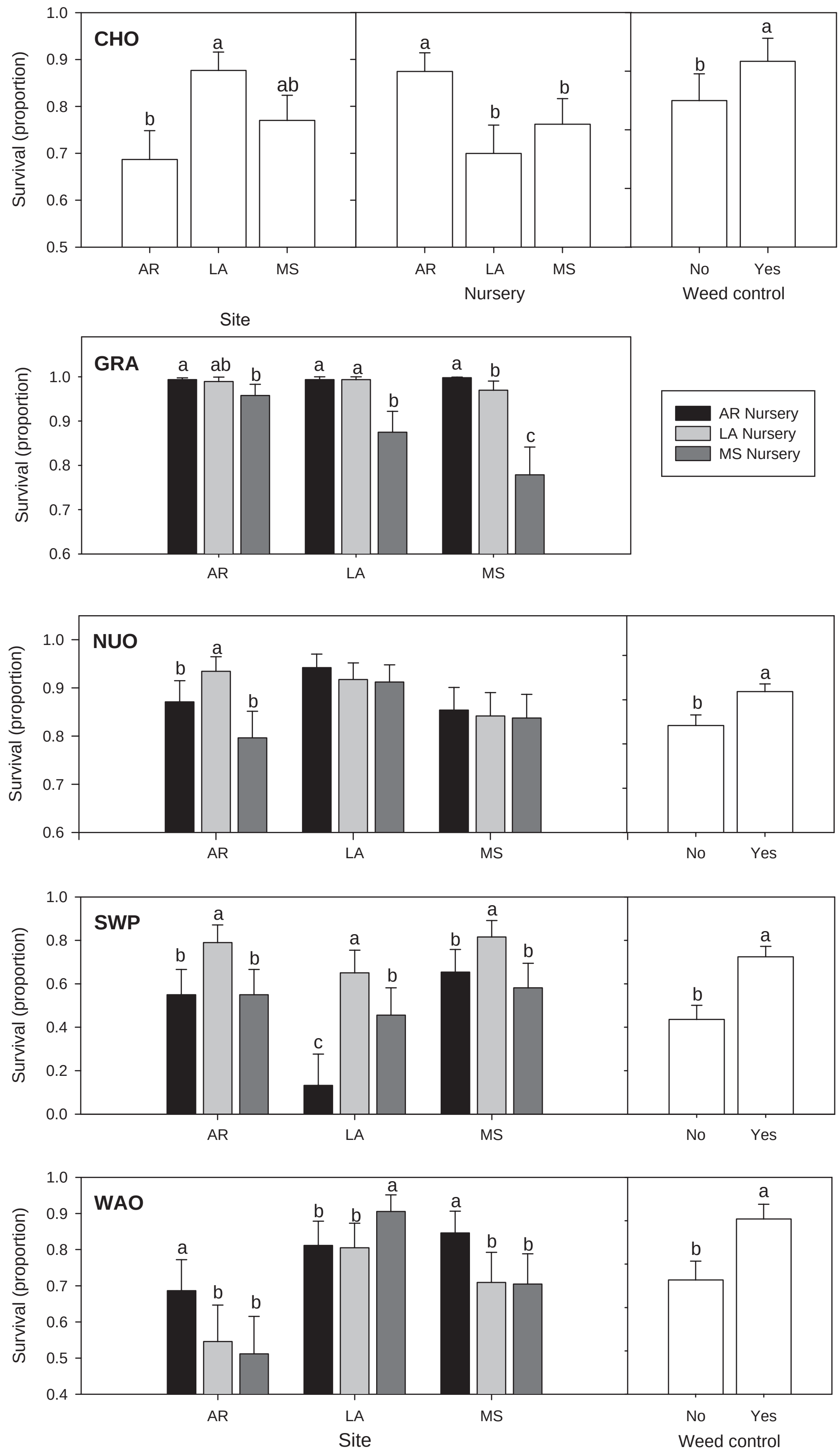

Figure 1. Second year seedling field survival for cherrybark oak (CHO), green ash (GRA), Nuttall oak (NUO), sweet pecan (SWP), and water oak (WHO) by site, nursery, weed control treatment, and/or site × nursery interaction where significant differences were detected. Columns represent back-transformed midpoint of the 95% confidence interval, and bars represent back-transformed upper 95% confidence limit. Columns marked with same letter are not statistically different according to Fisher's Least Significant Difference test at $\alpha = 0.05$. In graphs showing site × nursery interaction, letters show significant differences among nurseries at each site.

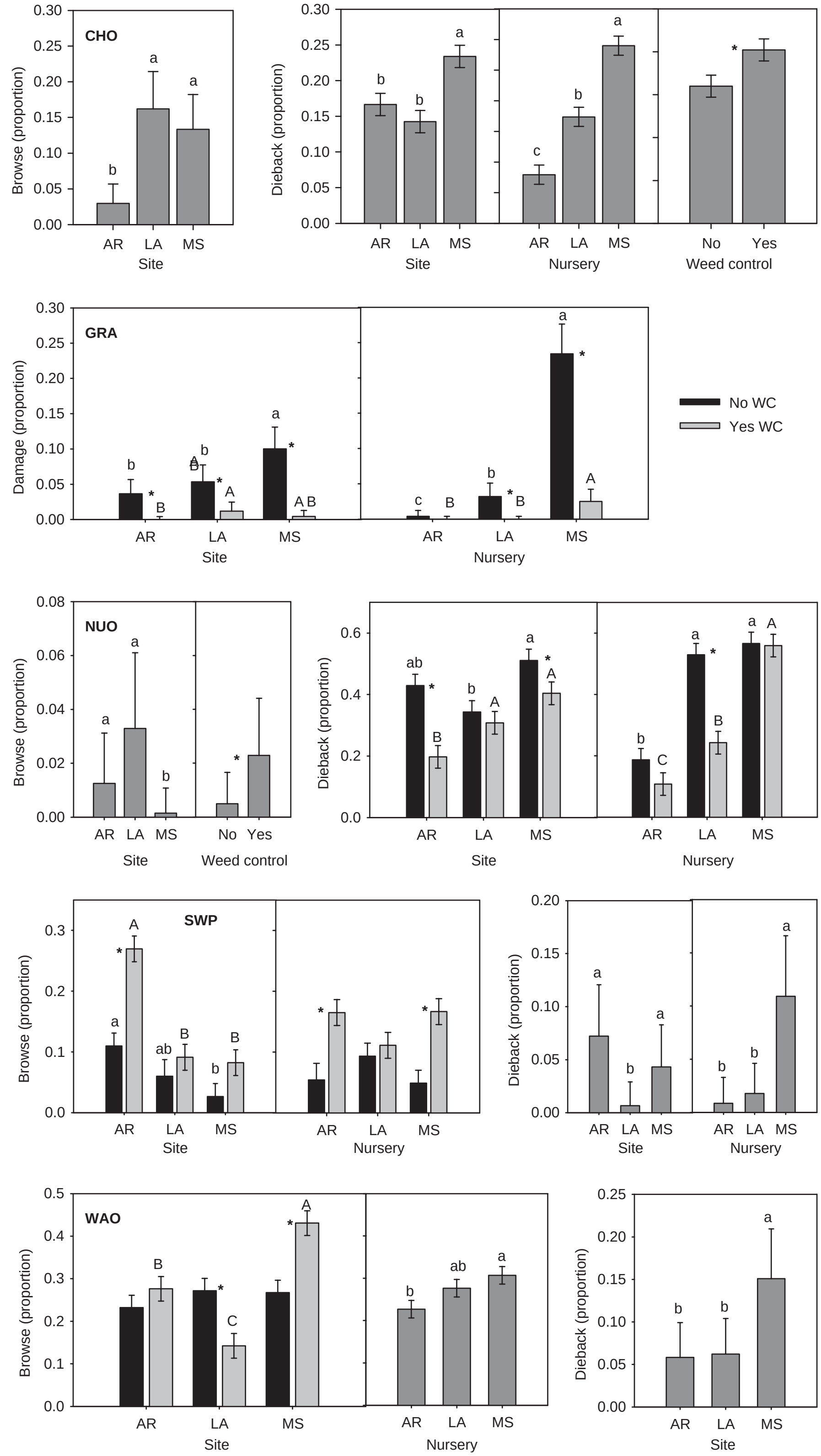

Figure 2. Second year seedling browse and dieback of cherrybark oak (CHO), Nuttall oak (NUO), sweet pecan (SWP), and water oak (WHO) or damage (browse + dieback) of green ash (GRA) by site, nursery, weed control treatment, or any significant interaction. Columns represent means or back-transformed midpoint of the 95% confidence interval. Double bars represent ±1 SE and positive bars only represent back-transformed upper 95% confidence limit. Columns marked with same letter are not statistically different according to Fisher's Least Significant Difference test at $\alpha = 0.05$. Where site (or nursery) × weed control treatment interaction is significant, lower case letters show means separation between sites (or nurseries) without weed control, and capital letters show means separation between sites (or nurseries) with weed control. Asterisk indicates a significant difference between weed control treatments on the same site (or from the same nursery).

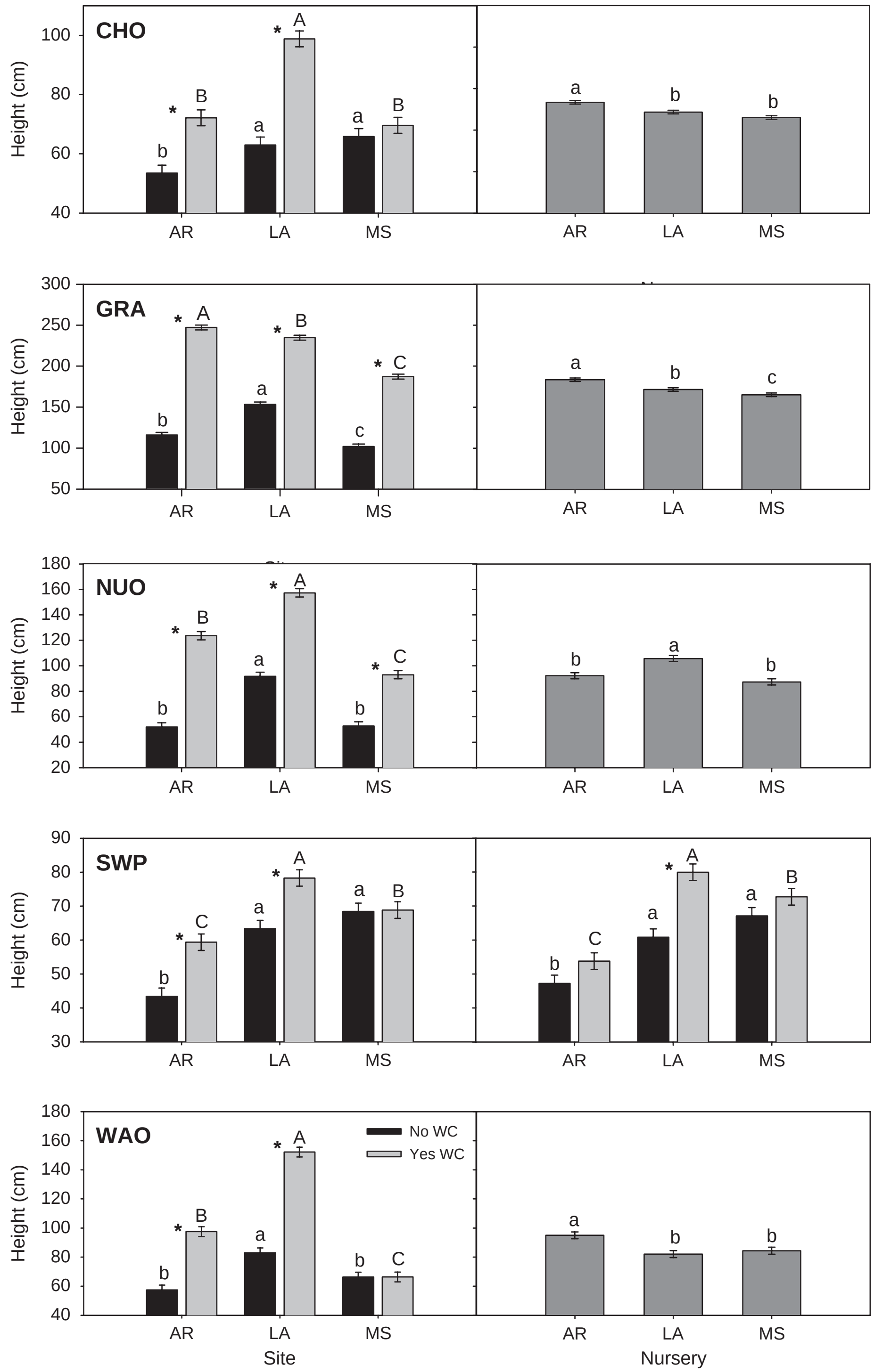

Figure 3. Second year seedling height of cherrybark oak (CHO), green ash (GRA), Nuttall oak (NUO), sweet pecan (SWP), and water oak (WHO) by site × weed control treatment interaction and nursery or nursery × weed control treatment. Columns represent means or back-transformed midpoint of the 95% confidence interval. Double bars represent ±1 SE and positive bars only represent back-transformed upper 95% confidence limit. Columns marked with same letter are not statistically different according to Fisher's Least Significant Difference test at $\alpha = 0.05$. Where site (or nursery) × weed control treatment interaction is significant, lower case letters show means separation between sites (or nurseries) without weed control, and capital letters show means separation between sites (or nurseries) with weed control. Asterisk indicates a significant difference between weed control treatments on the same site (or from the same nursery).

more specifically examine protocols for herbicide application and/or identify alternative vegetation control methods.

The effects of nursery on browse and dieback presumably stem from differences in initial morphology, physiology, and nutritional status. Interestingly,

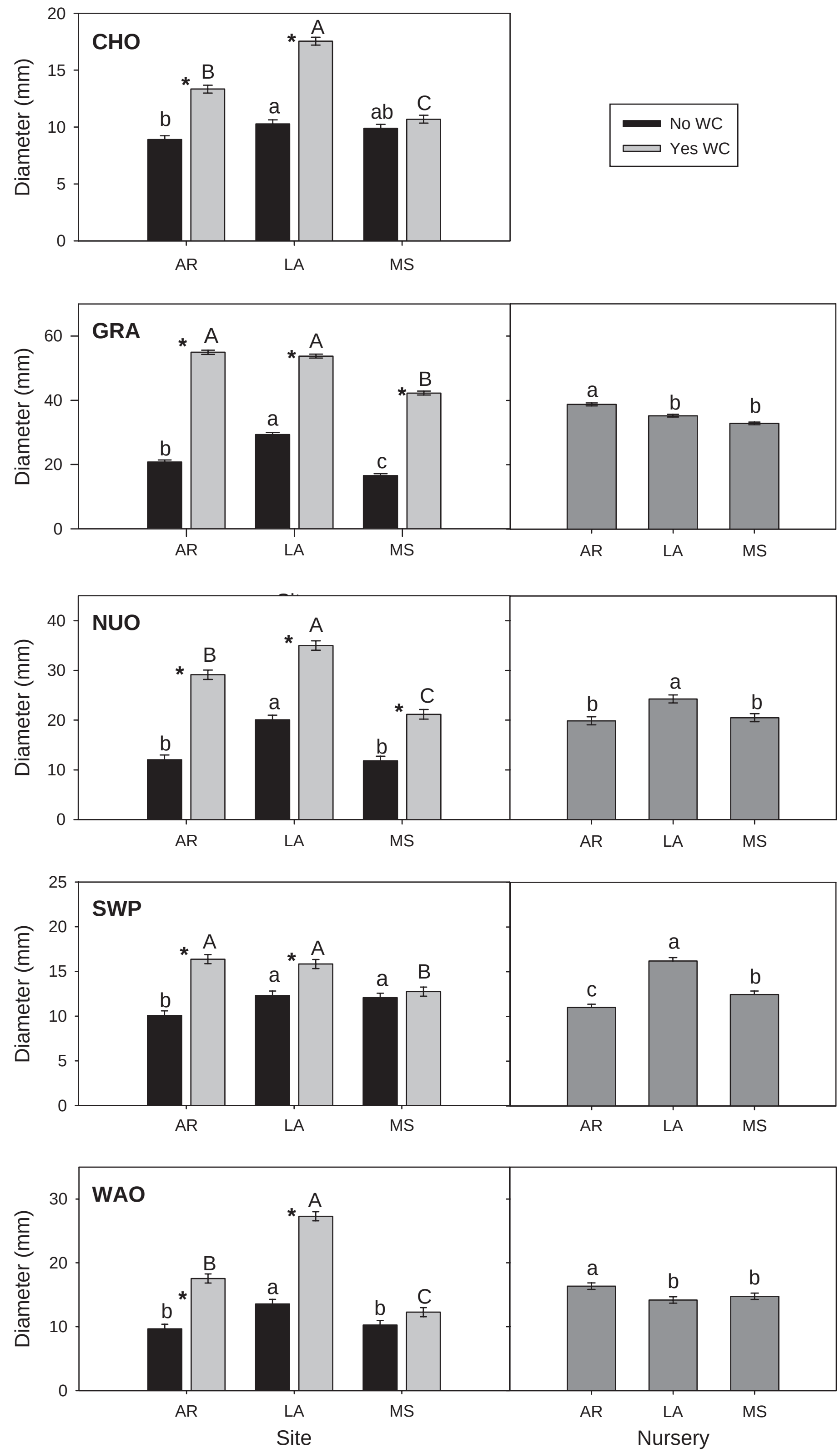

Figure 4. Second year seedling ground line diameters of cherrybark oak (CHO), green ash (GRA), Nuttall oak (NUO), sweet pecan (SWP), and water oak (WHO) by site × weed control treatment interaction and nursery. Columns represent means or back-transformed midpoint of the 95% confidence interval. Double bars represent ±1 SE and positive bars only represent back-transformed upper 95% confidence limit. Columns marked with same letter are not statistically different according to Fisher's Least Significant Difference test at $\alpha = 0.05$. Where site × weed control treatment interaction is significant, lower case letters show means separation between sites without weed control, and capital letters show means separation between sites with weed control. Asterisk indicates a significant difference between weed control treatments on the same site.

Table III. Initial seedling morphology.

Spp.	Nursery	Height (cm)	Diameter (mm)	H/D ratio (equal units)	FOLR (count)	Fresh mass (g)	Root volume (ml)
CHO	AR	47.4 ± 0.35b	5.0 ± 0.07c	98 ± 1.1c	8.7 ± 0.1b	27.3 ± 0.76c	13.1 ± 0.31b
	LA	59.3 ± 0.35a	5.9 ± 0.07b	107 ± 1.1a	8.4 ± 0.1b	45.7 ± 0.76a	16.4 ± 0.31a
	MS	59.7 ± 0.35a	6.1 ± 0.07a	103 ± 1.1b	9.4 ± 0.1a	33.3 ± 0.76b	15.6 ± 0.31a
GRA	AR	46.7 ± 0.73c	7.1 ± 0.10b	67 ± 0.6c	6.8 ± 0.2a	29.8 ± 0.92b	22.0 ± 0.60a
	LA	62.7 ± 0.73b	7.2 ± 0.10b	93 ± 0.6b	6.6 ± 0.2a	25.4 ± 0.92c	16.5 ± 0.60c
	MS	75.3 ± 0.73a	8.4 ± 0.10a	94 ± 0.6a	5.8 ± 0.2b	33.1 ± 0.92a	18.4 ± 0.60b
NUO	AR	51.1 ± 0.34c	6.4 ± 0.10c	84 ± 0.8b	7.2 ± 0.2c	30.3 ± 1.26c	16.4 ± 0.53c
	LA	73.1 ± 0.34b	10.7 ± 0.10a	72 ± 0.8c	13.3 ± 0.2a	75.9 ± 1.26a	34.4 ± 0.53a
	MS	76.8 ± 0.34a	8.5 ± 0.10b	95 ± 0.8a	8.9 ± 0.2b	50.8 ± 1.26b	20.8 ± 0.53b
SWP	AR	23.5* [22.9, 24.0]c	3.9 ± 0.07c	64 ± 0.9b	11.5 ± 0.2c	18.1* [17.3, 18.9]c	15.7* [15.0, 16.4]c
	LA	38.3* [37.4, 39.3]b	9.1 ± 0.07a	43 ± 0.9c	16.2 ± 0.2a	82.6* [79.1, 86.3]a	68.0* [65.0, 71.1]a
	MS	63.7* [62.2, 65.3]a	7.1 ± 0.07b	94 ± 0.9a	13.5 ± 0.2b	46.1* [44.1, 48.1]b	32.1* [30.7, 33.5]b
WAO	AR	54.1* [52.8, 53.5]b	5.3 ± 0.06b	109 ± 0.9b	8.3 ± 0.1a	39.1 ± 0.77b	13.1 ± 0.26b
	LA	53.9* [52.5, 53.2]b	4.7 ± 0.06c	118 ± 0.9a	5.1 ± 0.1c	22.4 ± 0.77c	7.8 ± 0.26c
	MS	65.1* [63.2, 64.1]a	6.6 ± 0.06a	104 ± 0.9c	7.3 ± 0.1b	45.4 ± 0.77a	17.1 ± 0.26a

Note: Mean (± SE) height, root collar diameter, height/diameter ratio (H/D ratio), number of first-order lateral roots (FOLR), fresh mass, and root volume of cherrybark oak (CHO), green ash (GRA), Nuttall oak (NUO), sweet pecan (SWP), and water oak (WAO) from the Arkansas (AR), Louisiana (LA), and Mississippi (MS) nurseries (Nurs.). Asterisk (*) indicates back-transformed midpoint of 95% confidence interval [lower confidence limit, upper confidence limit]. For each response variable, different letters indicate statistically significant differences among nurseries for a given species according to Fisher's Least Significant Difference test at a = 0.05.

Table IV. ANOVA results for second year field performance with significant ($p < 0.05$) interactive effects indicated.

Species	Parameter	Site (S) × C	Nursery (N) × C	WC × C	N × S × C	N × WC × C	S × WC × C	N × S × C × WC
CHO	Height		X	X				
	Diameter		X					
	Fresh mass		X				X	
	Root volume	X	X	X			X	
	FOLR							
	H/D ratio							
GRA	Height		X			X		
	Diameter		X			X		
	Fresh mass		X			X		
	Root volume		X					
	FOLR		X					
	H/D ratio							
NUO	Height		X	X				
	Diameter		X	X				
	Fresh mass		X					
	Root volume		X					
	FOLR		X					
	H/D ratio		X					
SWP	Height		X	X				
	Diameter	X	X					
	Fresh mass	X	X					
	Root volume		X					
	FOLR		X					
	H/D ratio							
WAO	Height	X	X					
	Diameter	X	X		X			
	Fresh mass	X	X		X			
	Root volume	X	X					
	FOLR	X	X					
	H/D ratio					X		X

Table V. Initial morphology and field damage.

Variable	WC	Category	Mean	SE	
Cherrybark oak					
FOLR		None	9.5	0.3a	
		Browse	8.6	0.3b	
		Dieback	8.8	0.3b	
		Dead	7.2	0.3c	
H/D ratio		None	99.1	1.7b	
		Browse	105.5	1.8a	
		Dieback	106.4	1.8a	
		Dead	104.7	1.7a	
Green ash					
H/D ratio		None	83.9	1.7c	
		Damage	92.4	1.8b	
		Dead	98.8	1.9a	
Water oak					
FM/RV ratio (g ml^{-1})		None	2.7	0.04b	
		Browse	2.7	0.06b	
		Dieback	2.9	0.03a	
		Dead	3.0	0.03a	
Nuttall oak					
Height (cm)	No	None	62.2	59.7	64.7bc
		Browse	58.3	53.3	63.1c
		Dieback	70.8	68.7	73.0a
		Dead	64.5	62.3	66.7b*
	Yes	None	65.1	62.6	67.6b
		Browse	66.5	63.1	69.9ab*
		Dieback	70.0	67.8	72.2a
		Dead	60.8	58.4	63.1c
Diameter (mm)	No	None	7.9	7.4	8.4b
		Browse	6.8	6.0	7.6c
		Dieback	8.8	8.4	9.3a
		Dead	7.4	7.1	7.9bc*
	Yes	None	8.1	7.6	8.6a
		Browse	8.2	7.5	9.0a*
		Dieback	8.5	8.1	9.0a
		Dead	6.9	6.5	7.3b
H/D ratio		None	81.7	79.2	84.3b
		Browse	83.8	79.5	88.1ab
		Dieback	83.5	81.2	85.9b
		Dead	88.3	85.9	90.7a
Sweet pecan					
Height (cm)	No	None	43.3	40.9	45.9b*
		Browse	36.8	34.1	39.7c
		Dieback	50.1	46.0	54.6a
		Dead	36.7	35.0	38.5c*
	Yes	None	39.5	37.4	41.7b
		Browse	36.0	33.9	38.1c
		Dieback	46.3	42.4	50.5a
		Dead	34.0	32.5	35.6c

Note: Mean ($\pm$SE) or back-transformed midpoint of 95% confidence interval and lower (LCL) and upper (UCL) confidence limits by category of initial morphological variables that had no significant interactions with site or nursery. Means with the same letter are not significantly different between categories in same weed control (WC) treatment according to Fisher's Least Significant Difference test at $\alpha = 0.05$. Where category $\times$ WC interaction is significant, asterisk indicates that mean is significantly greater than the other WC in the same category.

there were no significant interactions between site and nursery, as was seen for survival. Browse differed by site, but browse patterns were inconsistent between species on each site. Unlike another study, which reported no difference in frequency of browse between chemical weed control treatments (Jacobs et al., 2004), this study detected an increase in sweet pecan browse in several plots receiving weed control over those that had not, which may have been associated with easier access to seedlings.

Initial morphology and field performance

For survival analysis by category, the significant site × nursery and site × nursery × category interactions, respectively, support the idea that the target seedling concept varies by outplanting site (Landis, 2003). However, in this study, all sites were flat, former agricultural land and we could not identify distinct differences between sites that could be used in recommendations to specifically match target seedling morphology to site. It is possible that differences could be attributed to varying soil types (Table I). However, cherrybark oak, sweet pecan, and water oak were planted on different soil types on each site and there were no replications of soil type over several sites. Green ash and Nuttall oak were planted on the same soil series on both the LA and MS sites but responses were often significantly different between these two sites. Thus, variation between sites cannot definitively be attributed to soil classification, although the pedomorphological features used to classify soils may or may not affect seedling growth. Microsite differences in rooting volume, moisture holding capacity, or organic matter content across sites may have had greater impact. Nonetheless, we opted to identify variables that held true across all sites and nurseries without ignoring significant differences found between sites or nurseries.

Previous studies examining morphological quality attributes of hardwood nursery stock have shown variable results regarding optimal morphological characteristics, yet generally field performance potential improves with increasing seedling size (Dey et al., 2008, Dey et al., 2010; Wilson and Jacobs, 2006). For example, northern red oak (*Quercus rubra* L.) seedlings with root collar diameter >8 mm and shoot heights >50 cm were more competitive than smaller stock when planted on a variety of sites (Johnson, 1992). Similar results were reported by Maltoni et al. (2010) examining European ash (*Fraxinus excelsior* L.) in northern Italy; they recommended planting seedlings with stem height 40–50 cm and a well-developed root system of at least 40 cm in length. Earlier recommendations specific to the LMAV suggested that desirable seedlings for bottomland hardwood field planting should have a shoot height ranging from 76 to 91 cm and a diameter of 6 to 10 mm (Kennedy, 1981, McKnight & Johnson, 1980). Most seedlings used in this study did not meet height standards, and only green ash and Nuttall oak seedlings consistently met diameter standards (Table III). Nonetheless, our data suggest that it may be better to plant much shorter trees and that height recommendations should vary by species. Initial mean diameters of the highest performing nurseries fell within the recommended range (6–10 mm) in sweet pecan and green ash, but exceeded the upper limit (>10 mm) in Nuttall oak and fell below the lower limit (<6 mm) in cherrybark oak and water oak.

Past research has also emphasized the need to examine relationships between morphological variables to fully characterize stock quality (Jacobs et al., 2005b; Wilson & Jacobs, 2006). For example, although Dey and Parker (1997) found that initial diameter was the best predictor of field response in red oak seedlings, it accounted for $<25\%$ of the total variation in second year field growth. In most cases in our study, the effects of initial height, diameter, fresh mass, and root volume on field survival and height and diameter growth did not stand alone; rather, they were dependent on the other morphological characteristics. H/D ratios (by category), however, held true across all sites, nurseries, and weed control in cherrybark oak, green ash, and Nuttall oak seedlings. The target H/D ratios (equal units) were identified as the following: 99 for cherrybark oak, 84 for green ash, 82 for Nuttall oak; seedlings with H/D ratios greater than these values may be more susceptible to browse, dieback, or mortality. Similarly, water oak should be planted with fresh mass/root volume ratios of 2.7 g ml^{-1}, and seedlings with ratios greater than this may be more susceptible to dieback or mortality. Interestingly, these recommended ratios (i.e. initial H/D- and fresh mass/root volume ratios) did not differ significantly between trees grown with or without weed control, indicating that a well-balanced morphology may be more important to early survival than competition for light, water, and other resources. Trends seen in survival between different nurseries suggest that larger root systems (i.e. greater FOLR and root volume) contributed to survival when seedlings were not excessively tall but could not compensate for very large shoots, which can induce water deficits and increase initial transplant stress because root water uptake cannot meet transpirational demand from shoots soon after planting (Dey et al., 2008; Jacobs et al., 2009; Nambiar & Sands, 1993). Water oak, a semi-evergreen species, may incur additional transplant stress due to its foliage that may remain physiologically active throughout the winter (Goodman et al., 2009). For this reason, fresh mass/root volume ratio may have been more influential than H/D ratio for this species because fresh mass accounted for all remaining foliage.

Conclusions

Weed control increased survival in all species except green ash, and was most effective in the relatively slow-growing species. Weed control also increased height and diameter growth in all species on most sites, but growth was promoted most effectively in fast-growing species. In some instances, weed control increased frequency of browse and decreased tendency for dieback. Vegetation management, therefore, shows potential to improve afforestation success, but effectiveness may vary by species, site, nursery stock, and management objectives. Potential benefits should be considered in respect to monetary costs and environmental consequences.

Both site and nursery significantly affected field survival, dieback and browse frequency, and final heights and diameters after two years. Seedlings from nurseries with the greatest survival and second year field heights and diameters generally had the lowest H/D ratios. Analysis of initial morphology between seedlings that had browse, dieback, death, or no damage over the first two years revealed that variables analyzed individually generally varied between categories over the three different sites and between nurseries. However, relationships between variables (e.g. initial H/D ratio in cherrybark oak, green ash, and Nuttall oak and fresh mass/root volume ratio of water oak) were consistent among the categories across all sites and nurseries. This information may help refine nursery cultural treatments and grading techniques that maximize seedling performance on afforestation sites in the LMAV. It should be noted, however, that seedlings in this study were not sorted by initial morphological characteristics and outplanted with this as a basis for the experimental design, as in some previous stock quality trials (Jacobs et al., 2005b; Thompson & Schultz, 1995). Using this approach in future studies may provide more comprehensive results regarding relevance of individual morphological characteristics compared with the random sorting method used in the current trial.

Although these recommendations are the result of a range of each of the initial morphological variables and combinations and planted over three sites, this study cannot be considered comprehensive of all possible seedling and site conditions likely to be encountered in forest restoration programs of the LMAV. Combinations of both morphological and physiological factors may need to be studied to fully characterize hardwood seedling quality (Wilson & Jacobs, 2006). To this end, ratios appear to be more comprehensive measures of seedling vigor than single variables; target H/D or fresh mass/root volume ratios have been identified to improve outplanting success in these five species.

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