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SETBACKS AND SURPRISES

Weed control and overstory reduction improve survival and growth of under-planted oak and hickory seedlings

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Weed control and overstory reduction are important silvicultural treatments for improving survival and growth of under-planted oak and hickory seedlings. Mast-producing trees in the bottomland forests of the blackland prairie and Post Oak Savannah ecoregions of Texas have declined in abundance. Oaks and hickories have been replaced by more shade-tolerant species, including green ash (*Fraxinus pennsylvanica* Marshall) and sugarberry (*Celtis laevigata* Willd.), which do not produce significant hard mast for priority wildlife species. A split-plot experiment design was installed on three sites at Richland Creek Wildlife Management Area in Freestone County, Texas, studying the effects of canopy coverage and competition control on survival and growth of bur oak (*Quercus macrocarpa* Michx.), Shumard oak (*Quercus shumardii* Buckl.), and pecan (*Carya illinoinensis* (Wagenh.) K. Koch) seedlings. Uprooting by hogs shortly after planting resulted in greater than 90% mortality of pecan on the two lower elevation sites. Year one survival of Shumard oak was significantly higher than bur oak. However, bur oak was more preferred by hogs than Shumard oak. Year one growth of bur oak was significantly greater than Shumard oak. Severe flooding during the second growing season caused complete mortality on the lower two sites. None of the species were well suited to such prolonged (3–4 months) inundation as seedlings. On the remaining site, density reduction and weed-barrier mats improved growth and survival while herbaceous weed control with herbicides actually reduced both growth and survival.

Key words: bur oak, overstory reduction, pecan, Shumard oak, under-planting, weed control

Implications for Practice

- Unexpected disturbances such as flooding and herbivory play as large a role in restoration success as silvicultural treatments designed to match the ecology of under-planted seedlings.
- Seedling survival and growth are difficult to predict across or even within a species due to the interactions of silvicultural treatments and unexpected disturbance.
- Even in situations with overall high and unacceptable seedling mortality, some combinations of species selection, silvicultural treatments, and a lack of severe disturbance may result in adequate survival. Identifying these a priori is a great challenge.

Introduction

Extensive removal of bottomland hardwood forests (BLH) in the southern United States for agriculture began in the early part of the nineteenth century (Stanturf et al. 2001). The Lower Mississippi Alluvial Valley has experienced the greatest loss of BLH in the United States where land clearing for agriculture and changes to hydrological regimes have resulted in a 70% reduction in area (Gardiner et al. 2010). These forests are unique and provide ecological functions important to wildlife species. The reestablishment of oak species (*Quercus* spp.) has been the focus of most restoration attempts (King & Keeland 1999). The establishment of oaks and hickories (*Carya* spp.) is desirable to increase habitat diversity and restore ecological functions such as hard mast production, foliage availability (Tallamy & Shropshire 2009), and cavity creation (Baumgartner 1939) that are important to fauna. Many of these restoration efforts have been unsuccessful for a variety of reasons. In some cases, species are no longer suitable because of changes to the hydrological regimes and associated processes (Kellison et al. 1998; Gordon et al. 2008). While many tree species tolerate flooding during winter and early spring months, few are adapted to withstand prolonged flooding during the growing season. While our study focuses on the U.S. south and east Texas

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in particular, many forested regions globally experience similar problems with seedling survival under conditions of drought and flooding (Sena Gomes & Kozlowski 1980; Nepstad et al. 1996; Glenz et al. 2006; Allen et al. 2015).

Herbaceous competition is another factor that may pose a threat to the survival of planted oak and hickory seedlings. Diggs and Schulze (2003) presented indirect evidence that grass biomass is typically higher on clay soils, due to better moisture and nutrient availability at grass rooting depths. Oak and hickory species possess growth rates slower than or equal to those of herbaceous competitors and can quickly be overtopped (Hodges & Gardiner 1993). Young oak and hickory seedlings focus their resources on root growth rather than shoot growth, and height growth is relatively slow until the root system is well-developed (Hodges & Gardiner 1993; Sparks 2005). There have been mixed results concerning survival and growth of BLH seedlings as related to herbaceous competition. Some studies have yielded greater survival and growth of hardwood seedlings in BLH receiving competition control versus no competition control (Nix 1989; Lockhart et al. 2000; Ezell & Hodges 2002). Other studies have shown greater survival in untreated plots, and noted benefits of herbaceous competition, including less soil-drying and protection from herbivory (Putnam et al. 1960; Janzen & Hodges 1985; Buckley et al. 1998).

The extent to which oaks and hickories existed historically in BLH in the Texas blackland prairie (BP) and Post Oak Savannah (POS) is uncertain (Sharpless & Yelderman Jr 1993; Bezanson 2000; Diggs et al. 2006) but state agencies, as well as private landowners, within these ecoregions are interested in increasing the oak and hickory components of these BLH. To identify a combination of integrated silvicultural treatments to improve survival and early growth of planted hard mast-producing seedlings, we tested the effects of a density reduction by mulching and different competition control methods (spot-application of glyphosate and fabric weed barrier mats) on three different tree species.

Methods

Study Sites

The Richland Creek Wildlife Management Area (RCWMA) is located on the floodplain of the Trinity River in Freestone County, TX, U.S.A. (31.93°N, −96.05°W) (Fig. 1). The RCWMA is 3,653 ha of mostly BLH. Richland Creek and the Trinity River form the northern boundary and all study sites were within 5 km of the Trinity River (Fig. 1). Elevation is approximately 77 m above mean sea level with microsite variations.

The area has hot, humid summers, and moderate winters with a mean annual temperature of 18.7°C and a mean monthly range from 1.8°C in January to 35.3°C in July. The frost-free growing season is approximately 263 days. This area receives on average annual precipitation of 1,025 mm (NOAA 2011). While precipitation can be distributed evenly throughout the year, prolonged droughts may occur during the growing season. Seasonal flooding occurs during winter and early spring months, and may extend well into the growing season.

In Texas, the POS ecoregion covers approximately 5.3 million hectares (Diggs et al. 2006), and is situated between the Pineywoods and BP ecoregions (Fig. 1). The POS generally begins where the 1,016 mm precipitation line occurs, west of the Pineywoods ecoregion (Larkin & Bomar 1983). Soils in the area are derived from sandstone, and thus are generally sandy, although clays and clay loams can occur in the BLH due to alluvial deposits from upstream areas with different parent materials. There are two cover types typically found in these BLH: the water oak (*Quercus nigra* L.)−post oak (*Quercus stellata* Wangenh.) type and the sugarberry (*Celtis laevigata* Willd.)−elm (*Ulmus spp*.) type (Diggs et al. 2006). In BLH in the POS, vines, grasses, and forbs are common and can be abundant (Diggs et al. 2006).

Immediately west of the POS, the BP covers approximately 4.6 million hectares (Fig. 1). The main belt was developed from marine sediment that upon weathering formed calcareous, heavy clay Vertisols found throughout this ecoregion. Similar to the POS, there are two cover types typically found in the BLH: the water oak−postoak type and the sugarberry−elm type (Diggs et al. 2006). Grasses and forbs are well-adapted to the environment and can be formidable competitors of tree seedlings for soil and light resources.

Soils with vertic characteristics can be found in floodplains of major streams in the BP and POS. Buol et al. (2011) reported Vertisols occurring on 6.5 million hectares in Texas. By definition, Vertisols have a large percentage of clay particles, that is greater than 30% in all subhorizons to a depth of 50 cm or more (Staff 2001). Clay soils can have a relatively high water content, and yet little of the water is available for plant uptake (Hillel 1971). The bulk density of Vertisols increases and may be extraordinarily high during dry periods. Dudal (1963) found Vertisols in Texas with bulk density values of 2.2 g/cm^3, making root elongation difficult for seedlings. When the rhizosphere dries out, soil cracking can damage tree roots (Dudal 1963; Ahmad 1988). Large cracks in Vertisols still present at the beginning of the wet season are responsible for high initial infiltration rates, which decrease substantially with increased wetting (Krantz et al. 1978; Virmani et al. 1982). The flat relief that is typically found in BLH, coupled with the reduced infiltration, creates surface drainage problems, especially when these soils are fully saturated (Kanwar 1982).

At least three high-grading timber harvests that occurred at RCWMA prior to Texas Parks and Wildlife Department ownership may have reduced oak and hickory abundance (Matt Symmank 2013, Texas Parks and Wildlife, personal communication). These areas are now dominated by cedar elm (*Ulmus crassifolia* Nutt.), green ash (*Fraxinus pennsylvanica* Marshall), and sugarberry. None of these species produce significant mast for priority wildlife, such as white-tailed deer (*Odocoileus virginianus*) and eastern wild turkey (*Meleagris gallopava*). Though scarce, bur oak (*Quercus macrocarpa* Michx.), overcup oak (*Quercus lyrata* Walter), pecan (*Carya illinoinensis* (Wagenh.) K. Koch), Shumard oak (*Quercus shumardii* Buckl.), and willow oak (*Quercus phellos* L.) are also found in the RCWMA.

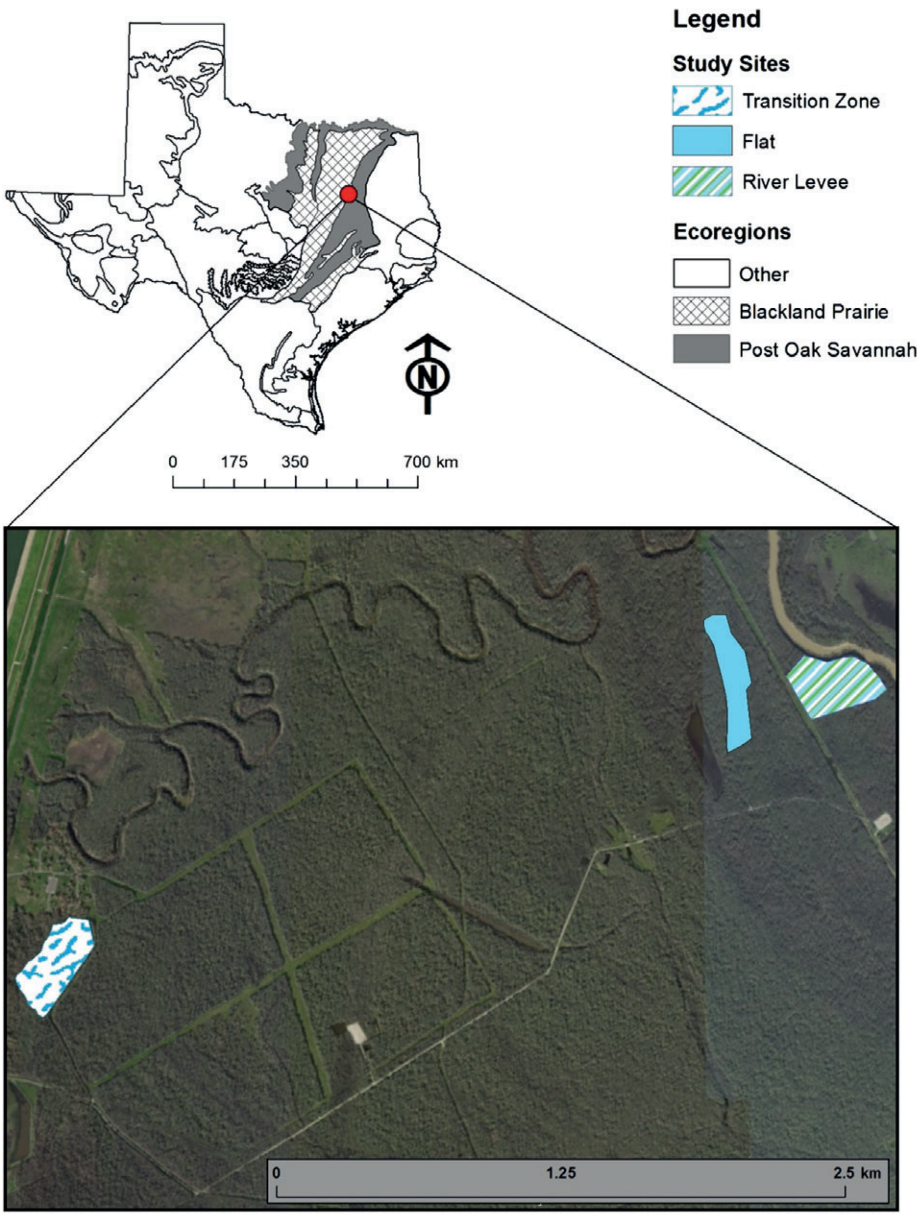

Figure 1. Study sites situated between the Blackland Prairie and the Post Oak Savannah. Three sites were used for a field trial examining the effects of herbaceous competition control and basal area reduction on planted seedling survival and growth at different positions on the floodplain at Richland Creek WMA in Freestone County, Texas, 2014–2016.

Three sites were chosen at different elevations on the floodplain to represent areas with different levels of flooding frequency (Fig. 1). Each site was approximately 8 ha. Common landform types found on active floodplains include fronts, flats, ridges, and slopes (Allen et al. 2001; Gardiner 2001). A front is an elevated sandy or silty textured natural levee that has formed parallel to the stream channel (Gardiner 2001). Floodwaters continue down the back of the levee into the flat where they deposit finer textured sediment (Gardiner 2001). Ridges are fronts or bars from historic stream channels. Slopes are the transitional areas found between the active floodplain and uplands (Allen et al. 2001). The easternmost site (levee) was on the river levee, directly adjacent to the Trinity River. A second site (flat) was located on a flat in the first bottom, and the westernmost site (transition) was situated in a transition zone between the second bottom and uplands. The levee and the flat each had soils from the Kaufman and Trinity series (both are very fine, smectitic, thermic Typic Hapluderts). These soils are very deep, moderately well-drained heavy clays with very slow permeability, and are typically found on floodplains with slopes ranging from 0 to 3%. Because the easternmost site was on the river levee, there was a greater percentage of sand that accumulated there during overbank flood events. The transition site had soils from the Kaufman series and the Lamar series (fine-silty, mixed, active, thermic Udic Haplustepts). The Lamar series is a very deep, well-drained, moderately permeable clay loam. This series is usually found in transition zones between level uplands and floodplains on slopes ranging from 5 to 12%. Both the Kaufman and Trinity series have clay content between 60 and 80% in the control section, making them clays. The Lamar series may be loam, clay loam, or silty clay loam.

Experimental Design

A split-split-plot design was used to examine the effects of density reduction, competition control methods, and tree species on growth and survival of planted seedlings. The design had a 2 (density reduction) × 3 (competition control method) × 3 (species) factorial structure replicated on the three sites. Each site was randomly divided into two sections constituting the whole plot (i.e. two whole plots per site, one mulched and one unmulched). Divisions were made perpendicular to any perceived gradient caused by the river. Randomly assigned whole plots received one of two levels of the density reduction treatment: density reduction by mulching and an untreated control. There were 900 seedlings monitored on each site, with 450 seedlings monitored in each whole plot. Within each whole plot, three levels of competition control were implemented constituting the subplot: a spot-application of glyphosate, fabric weed barrier mats, and an untreated control. Of the 450 seedlings in each whole plot, 180 seedlings received the spot-application of herbicide, 180 seedlings received no competition control, and 90 seedlings received the weed barrier mat treatment. Within each subplot three species constituted the sub–subplot (i.e. 60 of each species). Thus, there were 60 observational units randomly selected from operationally planted seedlings for each combination of treatments, except for the combinations receiving the weed barrier mat treatment, which each had 30 observational units. Seedlings included 1–0 (grow in a nursery bed for 1 year prior to lifting and planting) bur oak, Shumard oak, and pecan with an unknown provenance acquired from Arborgen nursery in Bluff City, Arkansas.

Treatments

In December 2013, a line-point inventory was conducted at the three sites to determine total basal area (Table 1). A density reduction by mulching, analogous to a low thin, was performed in February 2014 to remove a target of 50% of the basal area on four of the eight hectares in each site (Fig. 2). A multiterrain loader fitted on the front with a mulcher that used rotating blades similar to the DAF front-mounted brushcutter–mulcher 180 series was used to reduce the density on the sites. While we targeted a 50% reduction in basal area, this treatment was operational in nature and actual removals varied (Table 1). Only species undesirable for the landowner objective of hard mast production (species other than oaks or hickories) were removed beginning with the lowest diameter class and moving up. Bur oak, Shumard oak, and pecan seedlings were hand planted operationally in March 2014 on a 3 × 3 m spacing. Shumard oak seedlings were clipped to remove 30–50% of shoot height to reduce transpiration rates and increase vigor based on results from a study performed at the RCWMA in 2011 (Matt Symmank, Texas Parks and Wildlife, unpublished data). In May 2014, seedlings to be monitored in our study were selected at random. At the same time, heights of all monitored seedlings were measured to the nearest centimeter and basal diameters were measured to the nearest millimeter.

Table 1. Basal area of three sites on the Trinity River floodplain inside the RCWMA in Freestone County, Texas. Basal area was measured across each site in December 2013 before the density reduction treatment was applied, and within the areas receiving the density reduction treatment after treatment application in February 2014.

Site	*Transition (m^2/ha)*	*Flat (m^2/ha)*	*Levee (m^2/ha)*
Prebasal area reduction by mulching	10.48	16.93	16.59
Postbasal area reduction by mulching	7.82	8.97	10.40

Figure 2. Examples of (A) an unmulched area with no mulching treatment and (B) an area that was mulched to reduce basal area.

Beginning the last week of May 2014 and into the second week of June 2014, herbicide was applied to the seedlings in the herbicide treatments (Fig. 3). Due to early growing season flooding on these sites, this was the earliest we were able to

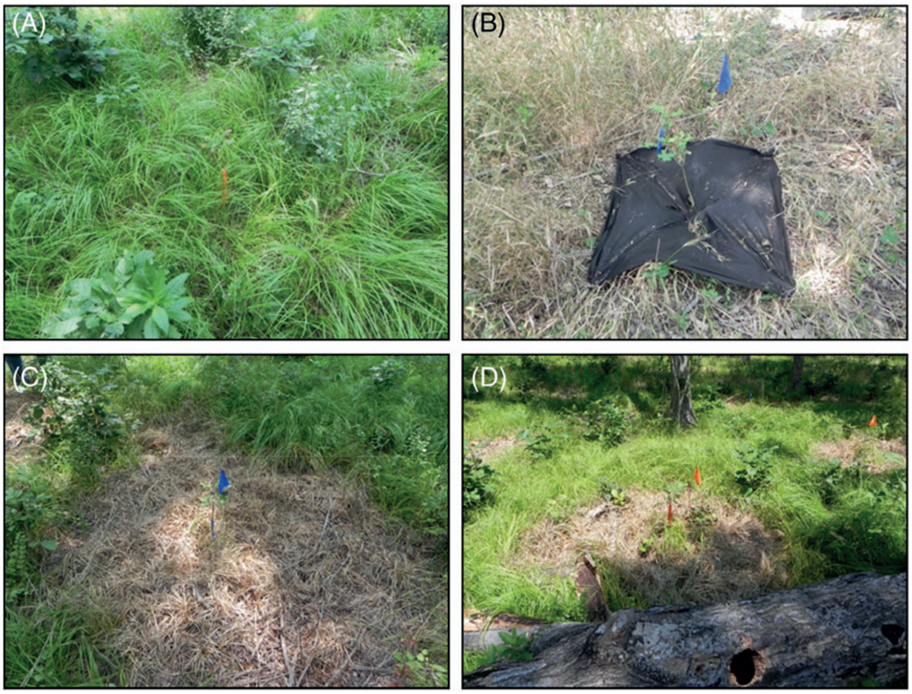

Figure 3. Typical examples of herbaceous competition and weed control effects in (A) an untreated experimental control, (B) a weed barrier mat treatment, (C) herbaceous weed control on a bur oak seedling, and (D) herbaceous weed control on a pecan seedling. Although the seedlings are difficult to see, in each photo they are marked by the colored pin flag or flagging.

apply herbaceous weed control following leaf-out of the competing herbaceous vegetation. Although it was our initial plan to use a pre-emergent herbicide such as sulfometuron, early growing season flooding also prevented this more typical herbaceous weed control treatment. Rodeo® (53.8% glyphosate) was the herbicide used to control herbaceous competition. A hand-held sprayer containing 15.6 mL/L water of Rodeo® and 15.6 mL/L water of Red River 90™, a nonionic low foam wetter/spreader adjuvant, was used. The planted seedlings had already leafed out and had to be protected from the herbicide spray. A container with a 45.7-cm diameter circular opening was used to cover the seedlings. The mix was sprayed around the container approximately 0.5 m from the outside edge of the container. This range was selected to provide complete weed control up to the seedling while minimizing the potential for drift of the herbicide onto the seedlings. A range of 50–130 mL of the mix was sprayed around each seedling, depending on the level of herbaceous competition. Beginning during the second week of June 2014, and into the first week of July 2014, 1 × 1 m Dewitt® 6-year, nonwoven, polypropylene hydrophilic treated fabric weed barrier mats were installed around seedlings receiving the weed barrier mat treatment.

Data Collection

Feral hogs (*Sus scrofa*) entered the levee and the flat shortly after planting and uprooted most (>90%) of the pecan seedlings. Afterwards, when selecting seedlings to be monitored in the study, less than 30 pecan seedlings could be located on each of the two lower sites, so no data were collected for pecan seedlings on those sites. Uprooting by hogs was minimal on the transition site, and growth and survival of pecan seedlings were monitored after one growing season on that site. During the second growing season the Trinity River flooded the levee and the flat, and completely covered the planted seedlings for several weeks. The two sites were inaccessible from late May to mid-August 2015. During this event the river reached the second highest stage on record at a nearby gage where data have been collected since September 1950, indicating an extreme level of flooding even for these lowland sites. Mortality was essentially complete (99.9%) for all of the seedlings on the levee and the flat, so only the transition site was analyzed for the second growing season. Survival, heights, and basal diameters of seedlings after one growing season were measured from late January to mid-February 2015. Survival was assessed by nicking the bark of each seedling to expose the cambium. If the cambium was green the seedling was recorded as alive. If the cambium was brown the seedling was recorded as dead. A volume index was calculated by squaring the diameters, then multiplying the product by the heights (Ruehle et al. 1984). The differences in heights and diameters between each year were calculated to determine growth per growing season. All data are presented as growth per growing season.

Statistical analyses after one growing season were performed to compare the effects of the treatments and their interactions across all three sites for bur oak and Shumard oak seedlings only, and additionally, statistical analyses were performed to compare the effects of competition control, species, and their interactions

Table 2. Survival for seedlings receiving density reduction and competition control treatments planted in March 2014 in Freestone County, Texas. Survival of monitored seedlings was measured in January–February 2015, following one growing season, and March–April 2016 following two growing seasons. Superscripts denote differences between all combinations of treatments, that is, between all columns and rows (describing the three-way interaction that was revealed in each statistical analysis) for each of the three analyses ($p < 0.10$). Standard errors are displayed in parentheses. Column and row headings used to represent density reduction and competition control method include: control = no density reduction, control, no competition control; herb, spot-application of herbicide; mats, fabric weed barrier mats. Pecan data are not presented in some cases due to excessive herbivory by feral hogs.

	Bur Oak		*Shumard Oak*		*Pecan*	
	Control	*Density Reduction*	*Control*	*Density Reduction*	*Control*	*Density Reduction*
2014	(%)	(%)	(%)	(%)	(%)	(%)
All sites						
Control	$46(4)^{bcd}$	$42(4)^{bc}$	$53(4)^{defg}$	$61(4)^{gh}$		
Herb	$31(3)^{a}$	$51(4)^{def}$	$49(4)^{cde}$	$58(4)^{fg}$		
Mats	$39(5)^{ab}$	$57(5)^{efg}$	$62(5)^{gh}$	$68(5)^{h}$		
2014 transition zone only						
Control	$62(6)^{abc}$	$80(5)^{defg}$	$58(6)^{abc}$	$93(3)^{hi}$	$53(6)^{ab}$	$57(6)^{ab}$
Herb	$60(6)^{abc}$	$95(3)^{i}$	$67(6)^{bcd}$	$90(4)^{ghi}$	$78(5)^{def}$	$72(6)^{cde}$
Mats	$47(9)^{a}$	$83(7)^{defgh}$	$93(5)^{ghi}$	$87(6)^{efghi}$	$80(7)^{defg}$	$90(6)^{fghi}$
2015 transition zone only						
Control	$10(4)^{ab}$	$47(6)^{d}$	$27(6)^{c}$	$80(5)^{f}$	$3(2)^{a}$	$35(6)^{cd}$
Herb	$5(3)^{ab}$	$13(4)^{b}$	$30(6)^{c}$	$73(6)^{f}$	$5(3)^{ab}$	$48(7)^{d}$
Mats	$3(3)^{ab}$	$47(9)^{cd}$	$37(9)^{cd}$	$73(8)^{ef}$	$53(9)^{de}$	$70(9)^{ef}$

on the transition site only after one growing season. The data examined for the transition site included bur oak, Shumard oak, and pecan seedlings. Survival and heights and diameters of seedlings on the transition site were measured again in March and April 2016. Statistical analyses were performed to compare the effects of the competition control, species, and their interactions on this site only after two growing seasons.

Data Analysis

All statistical analyses were completed using SAS software version 9.3 (SAS Institute, Cary, NC, U.S.A.). Logistic regression was used to examine the effects of density reduction, competition control method, seedling species, and interactions on seedling survival. A mixed model analysis was used to test the effects of density reduction, competition control method, seedling species, and interactions on annual seedling growth. Prior to running the mixed model analysis, a univariate analysis was performed on annual growth measurements to test the assumptions of normality, and a Levene's test was used to test homogeneity of variance. A cubed root transformation was applied to the volume index growth data that was collected from the transition site after two growing seasons, although all means reported in this manuscript are untransformed. The fixed effect variables were level of density reduction, level of competition control method, level of species, and fixed-effect interactions. The random effect variables were site and site interactions. Following the mixed model analyses, the estimated G matrix was determined to be not positive definite. This indicates that one or more variance components in the random statement were estimated to be zero, so all site by treatment interactions were removed from the model. An α of 0.10 was used to determine significance due to the operational nature of the experiment. Due to the large mortality rates, we would rather incorrectly state that a silviculture treatment improved survival when it did not (type I error) than incorrectly state that the treatment had no effect when it indeed did (type II error). Landowners are expecting high mortality, so even if there is a chance that a treatment can reduce that mortality, it may be worth pursuing.

Results

After two growing seasons, overall survival across all treatments and sites was 12%. Shumard oak seedlings had a higher survival percentage than the other species in all three analyses (all sites following one growing season, transition site following one growing season, transition site following two growing seasons, $p < 0.10$). Seedlings receiving the density reduction treatment had a higher survival percentage than seedlings receiving no density reduction in all three analyses ($p < 0.10$). The seedlings receiving the weed barrier mats had higher survival than the other competition control methods in all cases, except after one growing season in the transition site where their survival did not differ from seedlings receiving the herbicide treatment ($p < 0.10$). Though Shumard oak, density reduction, and weed barrier mats generally had the greatest survival, this was not always the case, as there were significant interactions among the three treatments (Table S1, Supporting Information). Because the two lower sites suffered severe mortality during the second growing season, the transition site will also be described separately for both years of data.

Across all sites after one growing season, analysis of survival revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S1). Shumard oak seedlings that received the weed barrier mat treatment and Shumard oak seedlings in the areas receiving the density reduction treatment and no competition control had the highest survival (61–68%) ($p < 0.10$) (Table 2).

Analysis of diameter growth across all sites after one growing season also revealed a significant three-way interaction

Table 3. Annual growth, after one growing season, of planted seedlings receiving density reduction and competition control treatments in Freestone County, Texas. Superscripts denote differences between all combinations of treatments, that is, between all columns and rows (describing the two-way and three-way interactions that were revealed in each statistical analysis) for each of the three analyses ($p < 0.10$). Standard errors are included in parentheses. Column and row headings used to represent density reduction and competition control method include: control, no density reduction; control, no competition control; herb, spot-application of herbicide; mats, fabric weed barrier mats.

	Bur Oak		*Shumard Oak*		*Pecan*	
	Control	*Density Reduction*	*Control*	*Density Reduction*	*Control*	*Density Reduction*
Transition site						
Annual diameter growth (mm)						
Control	0.1(0.1)^{abc}	0.7(0.2)^{efgh}	0.9(0.2)^{ghij}	0.0(0.2)^{a}	1.3(0.2)^{j}	1.0(0.2)^{hij}
Herb	0.2(0.2)^{abcd}	0.1(0.1)^{ab}	0.6(0.2)^{defgh}	1.0(0.2)^{hij}	0.8(0.2)^{fghi}	0.6(0.2)^{cdefg}
Mats	0.4(0.2)^{abcdefgh}	0.5(0.2)^{bcdefg}	0.4(0.2)^{abcde}	0.4(0.2)^{abcdef}	0.4(0.2)^{abcdef}	1.2(0.3)^{ij}
Annual volume index growth (cm^3)						
Control	2.7(1.0)^{ab}	6.9(1.3)^{defgh}	8.8(1.6)^{fgh}	2.9(1.3)^{ab}	13.3(2.5)^{i}	9.0(1.9)^{gh}
Herb	2.7(1.5)^{ab}	2.9(0.8)^{ab}	5.7(1.5)^{bcdefg}	9.9(1.5)^{h}	7.9(2.1)^{efgh}	3.8(1.0)^{abcd}
Mats	5.8(2.2)^{abcdefgh}	4.8(1.3)^{abcde}	0.7(0.7)^{a}	5.0(1.6)^{bcdef}	2.3(1.2)^{abc}	6.6(1.7)^{cdefgh}
Annual height growth (cm)						
Control	6.1(1.2)^{defg}	6.6(0.7)^{efg}	9.1(2.1)^{g}	6.2(1.3)^{defg}	5.4(1.1)^{cdef}	3.7(0.8)^{cde}
Herb	2.7(2.5)^{bc}	5.9(1.0)^{def}	5.7(1.3)^{cdef}	8.3(1.1)^{fg}	3.5(0.9)^{cd}	0.4(0.9)^{ab}
Mats	6.0(3.1)^{cdefg}	5.5(1.1)^{cdef}	−1.5(0.7)^{a}	6.5(2.2)^{defg}	−1.2(1.5)^{a}	0.1(1.3)^{ab}
All sites						
Annual diameter growth (mm)						
Control	0.2(0.1)^{cd}	0.4(0.2)^{d}	0.1(0.1)^{bcd}	−0.2(0.1)^{a}		
Herb	0.2(0.2)^{bcd}	0.0(0.1)^{ab}	0.3(0.2)^{cd}	0.4(0.1)^{d}		
Mats	0.4(0.2)^{d}	0.4(0.2)^{d}	0.0(0.1)^{abc}	0.4(0.1)^{d}		
Annual volume index growth (cm^3)						
Control	3.1(1.1)^{bc}	5.2(1.3)^{c}	2.8(1.1)^{bc}	0.8(0.8)^{a}		
Herb	2.8(1.0)^{bc}	1.9(0.7)^{ab}	2.6(0.9)^{bc}	4.1(1.1)^{c}		
Mats	3.3(1.0)^{bc}	3.4(1.0)^{bc}	−0.6(0.5)^{a}	3.1(0.8)^{bc}		

Annual height growth (cm)

	Control	*Density Reduction*	*Bur*	*Shumard*
Control	5.3(0.8)^{c}	3.9(0.6)^{a}	6.2(0.6)^{c}	3.4(0.7)^{b}
Herb	2.5(0.8)^{a}	3.7(0.6)^{b}	3.5(0.8)^{b}	2.9(0.6)^{b}
Mats	−0.2(0.8)^{a}	2.4(0.8)^{a}	3.0(0.9)^{b}	0.0(0.7)^{a}

between density reduction, competition control method, and species ($p < 0.10$) (Table S2). Diameter growth was low for all treatment combinations, and variance was relatively high (Table 3). The Shumard oak seedlings in the areas receiving no competition control, the Shumard oak seedlings in the area receiving the weed barrier mat treatment and no density reduction, and the bur oak seedlings in the areas receiving no density reduction and the glyphosate treatment had the least diameter growth ($p < 0.10$) (Table 3). All other treatment combinations had greater diameter growth, but were not different from one another ($p < 0.10$) (Table 3).

Analysis of height growth across all sites after one growing season revealed two significant two-way interactions: density reduction by competition control method, and competition control method by species ($p < 0.10$) (Table S2). The seedlings with the tallest height growth in the first interaction were in the areas receiving no density reduction and no competition control ($p < 0.10$) (Table 2). In the second interaction, the seedlings with the tallest height growth were the bur oak seedlings receiving no competition control ($p < 0.10$) (Table 2). Analysis of volume index growth across all sites after one growing season revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S2). Volume index is highly correlated with diameter, and like diameter growth, volume index growth was low for all treatments and variance was relatively high. The seedlings with the least volume index growth were in the same treatment combinations that had the least diameter growth. All other treatment combinations had greater volume index growth, but were not different from one another ($p < 0.10$) (Table 3).

After one growing season, analysis of survival of seedlings in the transition site only revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S1). Six treatment combinations had the highest survival (87–95%). Five of the six treatment combinations were in the areas receiving the density reduction treatment, and four of the six were comprised of Shumard oak seedlings (Table 2). Analysis of annual diameter growth in the transition site after one growing season revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S2). There were five treatment combinations with the greatest diameter

Table 4. Annual growth, after two growing seasons, of planted seedlings receiving density reduction and competition control treatments in Freestone County, Texas. Superscripts denote differences between all combinations of treatments, that is, between all columns and rows (describing the three-way interaction that was revealed in each statistical analysis) for each of the three analyses ($p < 0.10$), except in the case of volume index growth, where differences are between the main effects ($p < 0.10$). Standard errors are included in parentheses. Column and row headings used to represent density reduction and competition control method include: control, no density reduction; control, no competition control; herb, spot-application of herbicide; mats, fabric weed barrier mats.

	Bur	*Oak*	*Shumard*	*Oak*	*Pecan*	
	Control	*Density Reduction*	*Control*	*Density Reduction*	*Control*	*Density Reduction*
Transition site						
Height growth (cm)						
Control	0.6(1.1)^{bc}	7.5(1.9)^{cd}	8.3(2.7)^{cd}	24.2(2.4)^{f}	8.1(6.2)^{cde}	9.8(2.3)^{de}
Herb	−19.0(10.7)^{a}	2.1(2.9)^{bcd}	5.8(1.9)^{bcd}	9.6(1.2)^{d}	−2.5(4.0)^{b}	6.9(2.5)^{cd}
Mats	15.4(9.3)^{ef}	1.4(3.6)^{bc}	10.7(2.8)^{de}	15.4(3.8)^{e}	4.8(1.4)^{bcd}	7.1(1.8)^{cd}
Volume index growth (cm^3)						
Control	Density reduction					
2.1(0.9)^{a}	9.4(1.1)^{b}					
Bur	Shumard	Pecan				
1.9(1.0)^{a}	11.7(1.5)^{b}	4.3(1.2)^{a}				
Diameter growth (mm)						
	Bur Oak	Shumard Oak	Pecan			
Control	0.3(0.2)^{abc}	1.2(0.3)^{d}	0.0(0.4)^{ab}			
Herb	−0.3(0.3)^{a}	0.1(0.2)^{a}	0.7(0.3)^{bcd}			
Mats	0.7(0.3)^{bcd}	0.9(0.3)^{cd}	0.1(0.2)^{ab}			
Control	0.5(0.5)^{ab}	−0.1(0.2)^{a}	0.1(0.2)^{a}			
Density reduction	0.3(0.2)^{a}	1.0(0.2)^{b}	0.4(0.2)^{a}			

comprised of pecan and Shumard oak seedlings ($p < 0.10$) (Table 3). Three of the five combinations were in the areas receiving the density reduction treatment. The two combinations in the area receiving no density reduction, and one of the combinations in the area receiving the density reduction treatment received no competition control (Table 3).

Analysis of annual height growth after one growing season in the transition site revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S2). The seven treatment combinations with the tallest height growth were comprised of Shumard oak and bur oak seedlings. Four of the combinations received no competition control, and two of the combinations received the weed barrier mat treatment ($p < 0.10$) (Table 3). Analysis of annual volume index growth in the transition site following one growing season revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S2). The pecan seedlings in the area receiving no density reduction or competition control had greater volume index growth than any other treatment combination ($p < 0.10$) (Table 3).

As mentioned earlier, the analyses after two growing seasons only included data from the transition site, and included data from the pecan seedlings. The reduction to one site with no blocking resulted in no treatment replications, causing pseudoreplication. Due to the treatments being pseudoreplicated, the inferences on the treatment effects after two growing seasons are extremely limited, among other potential problems (Davies & Gray 2015). The nature of the flooding events on these sites, the environmental conditions in the particular years of the study, and the severity of herbivory impacts all make broad inferences difficult to draw from a study on a single site during a relatively (2 years) short period. Analysis of survival after two growing seasons revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table S1). Four treatment combinations displayed the highest survival (70–80%). All four combinations received the density reduction treatment. Three of the four combinations were the Shumard oak seedlings receiving all three levels of competition control ($p < 0.10$) (Table 2).

Analysis of year two annual diameter growth revealed two significant two-way interactions: density reduction by species, and competition control method by species ($p < 0.10$) (Table S2). Within the first interaction, Shumard oak seedlings in the area receiving the density reduction treatment and bur oak seedlings in the area receiving no density reduction had the greatest diameter growth ($p < 0.10$) (Table 4). All other combinations were not different from one another ($p > 0.10$) (Table 4). In the second interaction, of the four combinations with the greatest diameter growth, two were Shumard oak seedlings, and two received the weed barrier mat treatment ($p < 0.10$) (Table 4). Analysis of year two annual height growth revealed a significant three-way interaction between density reduction, competition control method, and species ($p < 0.10$) (Table 2). The Shumard oak seedlings in the area receiving the density reduction and no competition control had the tallest height growth ($p < 0.10$) (Table 4). Analysis of year two annual volume index growth revealed two significant main effects (Table S2). Seedlings in the area receiving the density reduction had greater annual volume index growth than seedlings in the areas receiving no density reduction ($p < 0.10$) (Table 4), and Shumard oak seedlings had greater volume index growth than bur oak seedlings or pecan seedlings ($p < 0.10$) (Table 4).

Discussion

Flooding causes mortality in tree seedlings in many forested regions around the world (Sena Gomes & Kozlowski 1980; Glenz et al. 2006). In our study, flooding of a severe and unexpected nature during the second growing season was too long in duration for the oaks on the levee and the flat, but survival of planted oak seedlings was high in some cases in the transition site. When operationally planting seedlings in fall or winter, it is not possible to predict the nature of flooding the following growing season. We also observed substantial mortality due to herbivory, with no clear or obvious reason as to why it occurred on some of our sites but not others, despite their close geographic proximity. Despite these unexpected setbacks and surprises, there remain some conclusions that can be drawn from this operational study. There were factors that affected survival and growth consistently throughout both growing seasons on the transition site and for the first year on all three sites. These factors were: herbaceous cover, density reduction, and the effects of the weed barrier mats on soil moisture retention.

Herbaceous Cover

Herbaceous weeds, if not too severe, can be beneficial to seedlings by making them more difficult to find by browsing animals (Putnam et al. 1960; Johnson & Biesterfeldt 1970). Herbaceous vegetation can also reduce negative effects of drought and/or flooding. Janzen and Hodges (1985) while examining the effects of herbicide on oak advance reproduction in BLH saw higher establishment and survival of new oak seedlings in plots that did not remove the herbaceous vegetation. During droughty periods, there were many large cracks in the soils, but where herbaceous vegetation or debris was present to cover the soil, the cracks were small or absent. In our study, after one growing season, across all sites, Shumard oak seedlings in the section receiving density reduction and no competition control were one of the three treatment combinations, which had highest survival. In the species by competition control interaction, height growth after one growing season across all sites was tallest for the bur oak seedlings receiving no competition control. In the density reduction by competition control interaction, height growth was tallest for seedlings receiving no density reduction and no competition control. The partial or complete removal of the midstory and/or herbaceous competition creates open areas that can make seedlings easier to find by browsing animals, as has been shown in studies examining wildlife effects on oak growth and survival (Buckley et al. 1998; Kolka et al. 1998; Truax et al. 2000; Oswalt et al. 2004). Increased browsing in these open areas could explain the lower height growth. Some of the seedlings receiving the herbicide treatment may have unintentionally been injured by the treatment application. The seedlings were covered with a large diameter container because the herbicide was foliar-active, but it is possible that some herbicide residue from the surrounding vegetation may have contacted the seedlings' leaves.

The treatment combinations with the tallest year two height growth were the Shumard oak seedlings in the area receiving the density reduction and no competition control. Gordon et al. (1995) reported that the heights of northern red oak seedlings (*Quercus rubra* L.) receiving annual competition control were shorter than northern red oak seedlings receiving no competition control by up to 27 and 33 cm during the fifth and sixth seasons, respectively. They attributed this to the competition control making the seedlings easier to find by deer. Rapid height growth is important for long-term survival of seedlings planted in BLH. This enables seedlings to get above herbaceous competition, out of the reach of browsing animals, and above seasonal floodwaters.

Density Reduction

All the species in our study were shade-intolerant, but during the first few years of seedling establishment canopy openness can elicit a neutral survival and growth response from oak seedlings (Collins & Battaglia 2002). Dulohery et al. (2000) reported no increases in survival of swamp chestnut oak (*Quercus michauxii* Nutt.) from canopy reduction during the first two years after planting. In our study across all sites after one growing season, two of the three combinations of treatments that yielded the highest survival percentage received the density reduction treatment. On the transition site after one growing season, five of the six combinations of treatments that yielded the highest survival percentage received the density reduction treatment. For year two, the treatment combinations with the highest survival all received the density reduction treatment. Volume index growth after two growing seasons was greater in the areas receiving the density reduction treatment than in the untreated areas. A study by Gardiner and Hodges (1998) showed maximum height and diameter growth for seedlings with similar shade tolerances occurred around 50% canopy coverage. After two growing seasons, Shumard oak seedlings had greater volume index growth than the other species. After two growing seasons the seedlings with the tallest height growth were also Shumard oak seedlings.

Weed Barrier Mats

Across all sites after one growing season, Shumard oak seedlings receiving the glyphosate treatment had lower survival than the Shumard oak seedlings receiving the weed barrier mat treatment. The weed barrier mats may have performed the same service as the debris Janzen and Hodges (1985) observed. There were four treatment combinations that yielded the highest survival after 2 years. One of these combinations was the pecan seedlings in the area receiving the density reduction and the weed barrier mat treatment (70%). Pecans have been shown to be less drought-tolerant than most oaks (Sparks 2005), and the weed barrier mats create an environment with less competition than seedlings receiving no competition control. The treatment combination with the second highest survival percentage was the pecan seedlings in the area receiving no density reduction and the weed barrier mat treatment (53%).

Pecan seedlings receiving the weed barrier mat treatment had higher survival than the other competition control methods applied to pecan seedlings in the areas receiving the density reduction treatment and in the areas receiving no density reduction. It is worth mentioning again that the seedlings planted in the experiment had an unknown provenance, and that this may have affected the survival and growth data. While it would be ideal to use seedlings with a local provenance, at the time of the experiment there were no seedlings with a local provenance available.

Management Recommendations

Despite the regional focus of this study, many forested regions face low seedling survival and high mortality as a result of drought and flooding (Sena Gomes & Kozlowski 1980; Nepstad et al. 1996; Davis et al. 1999; Glenz et al. 2006; Allen et al. 2015). While pecan is sometimes found on fronts, such as the river levee (Johnson & Biesterfeldt 1970; Sparks et al. 1998), except for the most flood-tolerant oak species, oaks generally begin to appear on the second bottom (Putnam et al. 1960; Wharton et al. 1982; Hodges 1997). Soils on the second bottom are more developed, with lower pH values, and experience less frequent growing season flooding (Gardiner 2001). The two lower sites, especially the site on the flat, had a thick understory of dwarf palmetto. Wharton et al. (1982) pointed out that dwarf palmetto is largely restricted to National Wetlands Technical Council bottomland hardwood zone IV. Vegetation commonly found in zone IV includes green ash, sugarberry, possumhaw (*Ilex decidua* Walter), and hawthorn (*Crataegus* spp.) (Wharton et al. 1982). All of these species were common on the levee and the flat.

While bur oak and Shumard oak are typically recognized as zone V species, large and mature trees of both species were present on both the levee and the flat, hence our assumption that these species would be suitable to these sites. It is possible that the mature bur oak and Shumard oak trees found on the sites in the first bottom were established at a time when changes to the hydrological regime were not as great as they are now, although there are no available data we are aware of to support this contention. Additionally, it is possible that these trees may have been established during periods of several droughty years in a row (Clark & Benforado 1981), which were not the conditions during our particular study period. Extended droughty conditions would have led to mortality of some mature trees, creating openings for the more drought-tolerant oak seedlings to become established. Many seedlings probably became established, but only a few were large enough to survive when the drought ended, and average conditions returned.

Oaks and pecans had relatively high survival (>45%) after two growing seasons in many of the treatments on the transition site. The lack of survival of the oaks within the sites on the levee and the flat was primarily a result of sustained flooding during the growing season. This is not an annual occurrence. The oak seedlings had relatively high survival across all sites after the first growing season. If following planting there were at least 5 years without sustained flooding during the growing season, some of the seedlings would likely be tall enough to avoid being completely overtopped by floodwaters, and have a chance of becoming established. However, the occurrence of extended flooding during the growing season cannot be predicted. If planting seedlings to increase large mast-production in the active floodplain is undertaken, then it may be advantageous to use dwarf palmetto and other tree species listed as primarily being found in zone III and zone IV as indicator species for appropriate sites. For example, where dwarf palmetto is common one could plant species typically found in zone IV such as Nuttall oak (*Quercus texana* Buckley), laurel oak (*Quercus laurifolia* Michx.), and willow oak, or species suited to zone III, such as water hickory (*Carya aquatic* Michx. f.) and overcup oak, as most zone III species can be found in zone IV (Clark & Benforado 1981; Conner et al. 1990). Each species' tolerance to the alkaline soils in this area should also be considered. Planting of zone V species should be restricted to areas where the occurrence of dwarf palmetto is uncommon. Higher elevations in the floodplain, such as hummocks on fronts and ridges, may be more suitable for planting less flood-tolerant species such as bur oak and Shumard oak. A removal of the canopy around these seedlings could then be performed if seedlings survived and looked vigorous after 1–2 growing seasons. Pecan seedlings may be well-adapted to the first bottom, especially on the river levee, if large populations of feral hogs are not present.

In the transition site between the floodplain and uplands, the density reduction had a beneficial effect on survival of seven of the nine species/competition control method combinations. Controlling herbaceous vegetation had no beneficial effects on survival of either of the two oak species. In fact, the spot-application of glyphosate around bur oak seedlings in the area receiving the density reduction treatment resulted in a survival percentage lower than the seedlings receiving no competition control. The weed barrier mats had a positive effect on survival of the pecan seedlings. The pecan seedlings receiving the weed barrier mats (in the areas receiving the density reduction treatment and the areas receiving no density reduction) had higher survival than the pecan seedlings receiving the glyphosate treatment, and those receiving no competition control.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. The *p*-values for the fixed effects and fixed effects interactions for survival of seedlings planted in March 2014 in Freestone County, Texas.
Table S2. The *p*-values for the fixed effects and fixed effects interactions for annual growth of seedlings planted in March 2014 in Freestone County, Texas.

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