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Herbivory and flooding impacts on planted bottomland hardwood seedlings

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Bottomland hardwoods forests (BLHW) are increasingly subject to active management for water quality improvement, streambank stabilization, to mitigate for urban expansion and to improve habitat for wildlife. Since the majority of remaining BLHW are degraded, restoration attempts are becoming commonplace within the Western Gulf Coastal Plain (WGCP) of the US. However, restoration success in terms of obtaining high stem densities of desirable species has been mixed, with managers observing survival rates <15 per cent for planted oak and hickory seedlings in some situations due to a variety of limitations. Over two growing seasons, we investigated the effectiveness of portable electric fences, individual tree shelters and 2.4-m woven wire high fences for mitigating herbivory by white-tailed deer (*Odocoileus virginianus*) and feral swine (*Sus scrofa*). Treatments fell within degraded forested areas and abandoned agricultural fields where we tested four species of interest: Nuttall oak (*Quercus texana* Buckley), Shumard oak (*Q. shumardii* Buckley), bur oak (*Q. macrocarpa* Michx.) and pecan (*Carya illinoinensis* K. Koch). Where herbivory occurred, mitigation techniques produced a higher survival rate ($\bar{X} = 17.6$ per cent) than unprotected areas ($\bar{X} = 9.1$ per cent). In areas of high white-tailed deer density, prominent browsing was evident, resulting in two-growing-season height growth of seedlings being less in non-fenced ($\bar{X} = 2.33$ cm) and electric ($\bar{X} = 4.33$ cm) fenced plots compared with high fences ($\bar{X} = 13.02$ cm) and individual tree shelters ($\bar{X} = 24.23$ cm). Additionally, we observed a negative relationship between survival and the number of days seedlings that were inundated with flood waters during the growing season. Matching species of interest to the site conditions, specifically the local hydrologic regimes, should carry a high priority in planning a restoration project within BLHW in the WGCP.

Introduction

Bottomland hardwood forests (BLHW) are complex ecosystems that not only are important vegetation types for a diverse range of wildlife but also provide important ecosystem services such as water quality enhancement, erosion control, water storage and nutrient cycling (Hodges, 1997; Kellison and Young, 1997; Sweeney *et al.,* 2002). Tree species that can survive and thereby increase the ecological function of BLHW are flood tolerant or moderately flood tolerant and are able to withstand variation in soil moisture ranging from inundation to droughty conditions. In particular, tree species, such as black willow (*Salix nigra* Marshall; Pezeshki *et al.,* 2007), river birch (*Betula nigra* L.), red maple (*Acer rubrum* L.; Sweeney *et al.,* 2002) and flood tolerant oaks (*Quercus* spp.) and hickories (Carya spp.; Battaglia *et al.,* 2008), can aid in river bank stabilization, provide aboveground vertical structure and, in some cases, provide seasonal mast for wildlife consumption. Typically, the natural composition of southwestern BLHW reaches a climax successional stage consisting mainly of an elm-ash-sugarberry (*Ulmus americana—Fraxinus pennsylvanica—Celtis laevigata* or *occidentalis*) complex (Hodges, 1997; Allen *et al.,* 2001) while retaining a minor oak-hickory component of 12–25 mature, mast producing trees per hectare (Goodrum *et al.,* 1971).

BLHW are a subject of much interest for restoration due to land-use conversion (i.e. to agriculture), selective removal of valuable timber species such as oaks, and changes to hydrological regimes due to reservoir impoundment and river channelization. Factors limiting the majority of restorations have been identified and classified as controllable and uncontrollable factors (Hodges, 1997; Allen *et al.,* 2001). Controllable factors include seed stock quality, species selection to match site characteristics, vegetation competition and planting procedures (Allen *et al.,* 2001; Stanturf *et al.,* 2001). Natural factors, such as the annual variation in flooding, drought and herbivory (Allen *et al.,* 2001), cannot be controlled but can be understood at the site level to determine how they may impact a particular site. Understanding these details at the site level increases restoration success by providing

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information to select more appropriate species or mitigation measures on that site (Hodges, 1997). In recent decades, there has been increased interest in identifying the primary factors that influence the success of forest restoration projects (Sweeney *et al.,* 2002; Heimann and Mettler-Cherry, 2004; Lockhart *et al.,* 2005). Heimann and Mettler-Cherry (2004) determined that elevation, flood duration and soil texture were the first and most important factors to consider when determining hardwood species composition for restoration of BLHW ecosystems. However, many agree that vegetative competition and herbivory are the main controllable factors to increase restoration success (Sweeney *et al.,* 2002; Stanturf *et al.,* 2004; Henderson *et al.,* 2009).

In the south central region of the US within the WGCP and the Lower Mississippi Alluvial Valley (LMAV), herbivores of seedlings include: beaver (*Castor canadensis*; Stanturf *et al.,* 2000), nutria (*Myocastor coypus*; Stanturf *et al.,* 2000), rabbit (Sylvilagus spp.; Stanturf *et al.,* 2000), voles (*Microtus pinetorum*; Crosby and Self, 2016), white-tailed deer (*Odocoileus virginianus*; Henderson *et al.,* 2009; Stanturf *et al.,* 2000) and feral swine (*Sus scrofa*; Mayer *et al.,* 2000; Stanturf *et al.,* 2004). Specifically, white-tailed deer and feral swine are the most important herbivores at most restoration sites, causing negative impacts on seedling performance and survival (Alverson *et al.,* 1988; De Steven, 1991; Mayer *et al.,* 2000). Each have wide distributions with varying densities throughout the southern US (Mayer *et al.,* 2000; Russell *et al.,* 2001).

Feral swine have increased their national distribution from viable populations in 27 states in 2000 (Mayer *et al.,* 2000) to viable populations in at least 37 states in 2014 (Müller *et al.,* 2011, United States Department of Agriculture 2015). Mayer *et al.* (2000) observed significant predation due to feral swine uprooting and eating rootstocks of seedlings during the first year after planting in a wetland restoration area in west-central South Carolina. Significant herbivory by white-tailed deer also causes increased mortality and stunted growth of hardwood seedlings within naturally and artificially regenerated restoration projects (De Steven, 1991; Russell *et al.,* 2001; Henderson *et al.,* 2009; Stanturf *et al.,* 2009). These species can limit restoration success at many sites, but the degree of impact varies depending on local population densities, tree species and other factors. Consequently, understanding ways to predict and mitigate negative impacts of herbivory on BLHW seedlings can help to improve restoration success.

Various techniques are available and have been used to protect seedlings during early establishment, but they vary widely in cost, ease of implementation and efficacy (Seamans and VerCauteren, 2006). Methods include the reduction of populations of herbivores as well as various arrays of permanent electric fences, permanent and temporary high fence structures, shelters or small fences that protect individual seedlings (Sweeney *et al.,* 2002; VerCauteren *et al.,* 2006). Electric fences constructed with polytape and polyrope (i.e. conductive wires within synthetic ribbons or ropes) have been popular for temporarily protecting wildlife food plots, but few investigations have examined their efficacy for reforestation (VerCauteren *et al.,* 2006). For rodents such as voles, various pesticides have also been deployed for protection (Sharew and Kays, 2006).

The goal of this project was to identify effective and practical procedures to mitigate the impacts of herbivory on hardwood seedling survival at bottomland hardwood restoration sites. Our specific research objectives were: (1) quantify the effects white-tailed deer and feral swine had on the survival of four mast-producing hardwood species; (2) compare the effectiveness of portable electric fences for protecting hardwood seedlings compared with more traditional techniques, namely woven wire high fences and individual tree shelters and (iii) quantify seedling growth in relation to non-forested and forested areas and various wildlife mitigation techniques.

Methods

Study area

We conducted two nested split-split-plot designed BLHW restoration experiments at four properties within the Blackland Prairie and Post Oak Savannah ecoregions covering three drainage basins. The northern most property is the Cooper 4D Ranch located in Hopkins County (Hopkins); moving south, there is the Lyons-McKenney Ranch in Hunt County (Hunt), Richland Creek Wildlife Management Area in Freestone County (Freestone 2015), and the Johnson Ranch in Anderson County (Anderson). All are located in east Texas within the WGCP (Figure 1). The first experiment continued for 2 years replicated over the four study locations using Shumard oak, bur oak and pecan 1–0 bare root seedlings, and the second continued for 1 year at Richland Creek Wildlife Management Area (Freestone 2016) using Nuttall oak (*Quercus texana* Buckley), Shumard oak and pecan 1–0 bare root seedlings. The four study locations contained Kaufman clay soils with 0–1 per cent slope that were frequently flooded, range in flood intensity and range in watershed characteristics that are typical of BLHW in eastern Texas. Each receives about 100–115 cm of precipitation annually.

Experimental design

The nested split-split-plot design included two areas differing in canopy cover type (i.e. non-forested (0 per cent canopy cover) and forested areas that had been thinned to ~50 per cent canopy cover) nested within each of the locations to examine the differences in herbivory occurrence for reforesting abandoned agricultural fields or pasturelands (non-forested areas) and improving existing stands to contain more mast-producing trees for wildlife (forested area). Whole-plot treatments included non-fenced plots and three wildlife mitigation techniques: 2.4-m woven wire high fences, Tubex USA® 60 cm twin walled polypropylene co-polymer individual tree shelters, and Gallagher® 3-wire portable electric fences (Figure 2). Nuttall oak, Shumard oak, bur oak and pecan were used for the subplot treatments because they are native to the region, provide good canopy structure and produce large mast that is heavily used by wildlife.

Three blocks were used within each canopy cover type to account for the minor changes *in site* characteristics that are not a direct focus of this project (e.g. soil micro-nutrients, elevation and time of planting). Two blocks at each location consisted of all mitigation treatments and one block consisted of all mitigation treatments excluding a high fence (Figure 2). The non-forested area at the Hunt county study location lacked non-fenced whole-plots due to residual roots obstructing the

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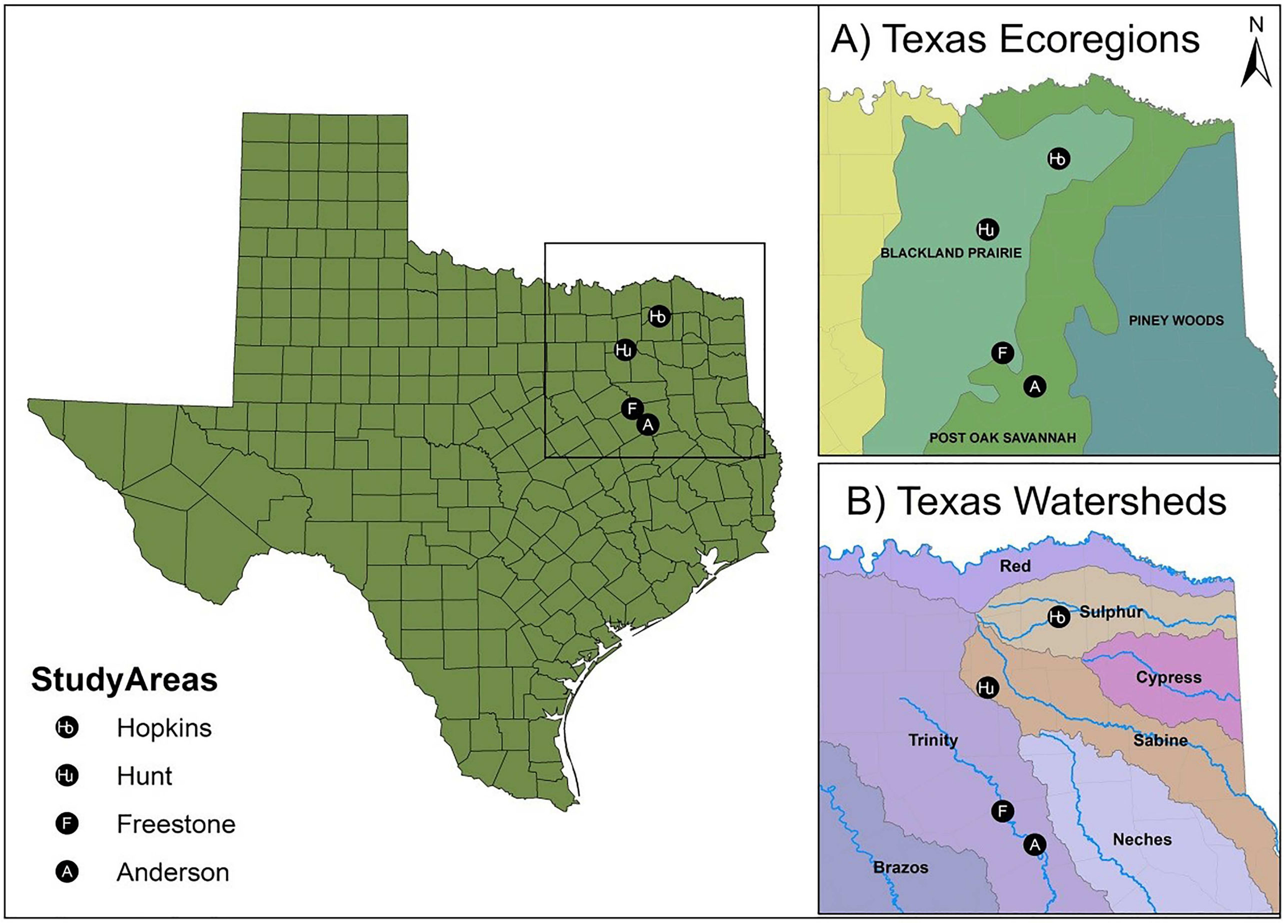

Figure 1 Locations of four study sites used for bottomland hardwood restoration studies in the (A) Blackland Prairie and Post Oak Savannah ecoregions and (B) Sulphur, Sabine and Trinity River basins of east Texas, US, in 2015 and 2016.

area planned to be ripped during site preparations. The subplot level consisted of 21, 1–0 bare root seedlings of each species within each fenced mitigation treatment, and 42, 1–0 bare root seedlings of each species within the non-fenced treatments. Two changes were made for the replanted 2016 Freestone location; (1) Nuttall oak replaced bur oak due to nursery availability and (2) only two blocks contained individual tree shelters within the forested area. Each canopy cover type at a site contained 882 seedlings (819 seedlings in 2016 Freestone, forested area).

High fences, ≥2.4 m, are considered a proven technique to mitigate wildlife damage in a variety of applications with nearly 100 per cent efficacy (Seamans and VerCauteren, 2006; VerCauteren *et al.*, 2006). Individual tree shelters are commonly used in orchard plantings as well as forest restorations because they are considered low maintenance and promote height growth (VerCauteren *et al.*, 2006). Portable electric fences are a relatively new technique in the forestry industry but have been extensively used for temporary applications such as seasonal food plots or gardens. This technique has potential for long-term use due to their versatility and durability (Seamans and VerCauteren, 2006; VerCauteren *et al.*, 2006; Reidy *et al.*, 2008). Using these mitigation techniques provides an opportunity to test a relatively new option for habitat restorations, portable electric fences, against more commonly used techniques, high fences and individual tree shelters.

The portable electric fence arrays and individual tree shelters were installed at the time of planting, while the woven wire high fence was constructed before planting operations began. High fences contained iron corner posts secured with concrete and *t*-posts every 7 m for interior support between corners. They spanned 36.5 m by 27.4 m with an interior fence splitting the 36.5 m side to create two 18.3 m by 27.4 m plots side by side. Electric fences contained one outside polytape wire, 45.8 cm off the ground, spanning 18.3 m by 27.4 m and two interior polyrope wires, 24.4 cm and 61.0 cm off the ground, spanning 16.5 m by 25.6 m (Gallagher USA Electric Fencing, Riverside, MO, US). Individual tree shelters were 60-cm tall, diameter averaged 10.1 cm and held in place by wooden stakes (Tubex USA®, Conservation Services, Waynesboro, VA, US). Seedlings within fenced treatments were not left-over night without their prescribed fence in full function. To ensure fence function over time and to document wildlife species responsible for any incursions, PRIMOS® Truth Cam 46 Ultra HD motion-activated trail cameras were deployed overlooking each of the fenced treatments (PRIMOS Hunting, Flora, MI, US).

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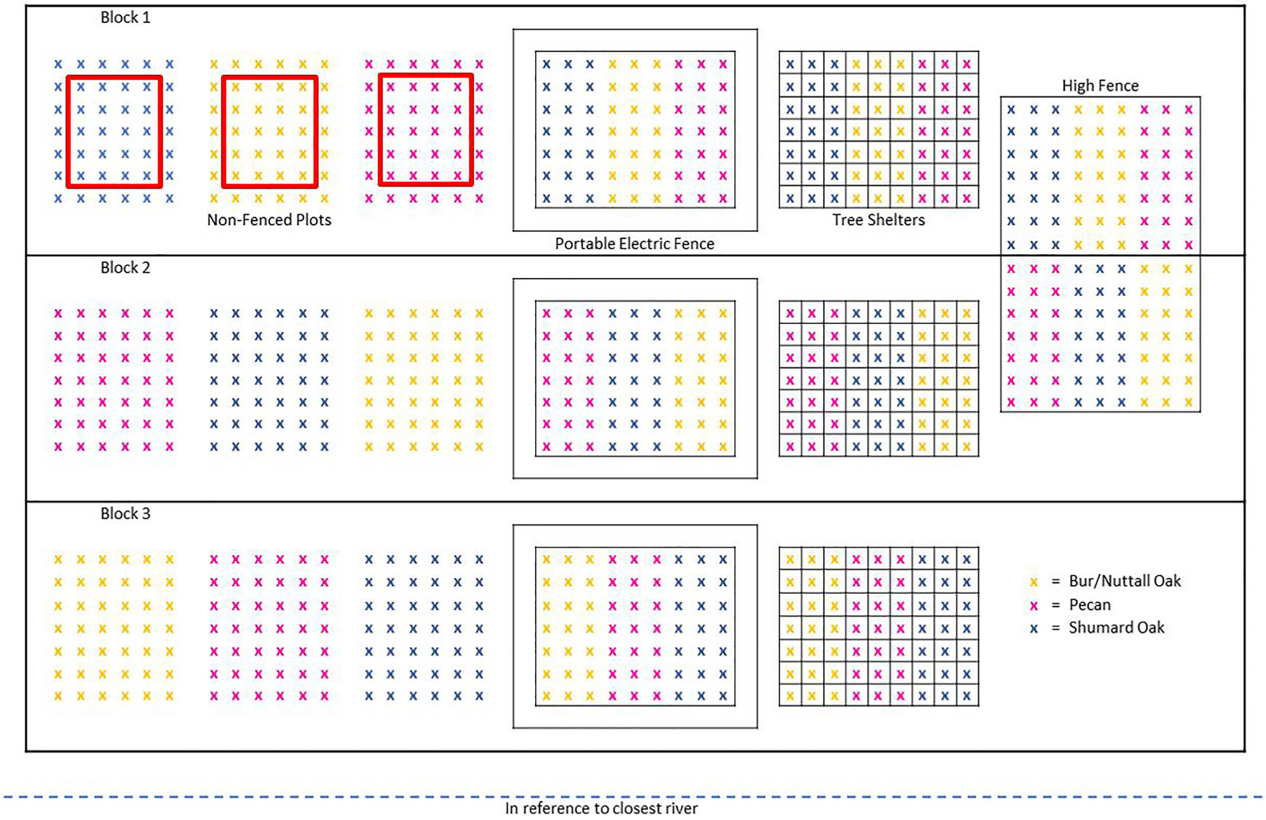

Figure 2 Theoretical representation of the three block, nested split-split-plot design within one of the canopy cover types. Each 'x' represents a single seedling within each whole plot; 42 seedlings per non-fenced plot and 21 seedlings of each species per fenced plot. All seedlings within fenced treatments were measured and the interior 20 seedlings were measured within non-fenced plots to account for possible edge effects. The study was in east Texas, US.

Treatment implementation

A variety of silvicultural practices (e.g. site preparation and low thinning) were used to reflect general practices for hardwood reforestation in the region and to ensure consistent conditions across sites. Texas Parks and Wildlife Department employees conducted the ripping within each non-forested area with a tractor drawn shank at ~35 cm into the soil creating a continuous 35-cm trench or rip across the target area to break up potential compaction (Löf *et al.*, 2012). Each fenced treatment had seven rows 18.3-m long with 3.6 m between each row to fit 21 seedlings of each species while having 1.8 m between seedlings. Each non-fenced subplot had the same number of rows and spacing but each row was only 14.7-m long to fit 42 seedlings of one species.

Each forested area was cruised prior to thinning to determine what diameter limits were needed to achieve the ~50 per cent canopy cover target. Low thinning diameter limits at each site were as follows: remove trees with DBH < 28 cm at Hopkins, <15 cm at Hunt, <28 cm at Freestone and <38 cm at Anderson. The Texas A&M Forest Service low-thinned each of the forested areas with a skid-steer tree mulching fecon machine following the set diameter limits and removing non-desirable trees (i.e. non-mast producing species) below this limit. Residual basal area at each site was 6.0 m^2 ha^{-1} at Hopkins, 4.1 m^2 ha^{-1} at Hunt, 3.7 m^2 ha^{-1} at Freestone and 10.6 m^2 ha^{-1} at Anderson.

Bare root (1–0) seedlings were planted during the dormant season (e.g. January to February) using a 30-cm KBC planting bar. Planting procedures and seedling storage procedures followed those suggested by Allen *et al.* (2001). We clipped Shumard oak seedlings by removing 30 per cent of the stem at planting to reduce shoot to root ratio and increase survival (M. E. Symmank, Texas Parks and Wildlife Department, unpublished data; Dey *et al.*, 2008). Planting began at the most southern property (Anderson) and ended at the most northern property (Hopkins). Seedlings were planted in a block by block fashion to control for planting conditions, such as temperature and soil moisture at time of planting, that could affect survival. Within the non-forested area, seedlings were planted adjacent to rip lines (i.e. ca. 15–30 cm from rip trench).

Our stocking density was 1495 seedlings ha^{-1} across treatments. A variety of research throughout the LMAV and the Atlantic Coastal Plain (ACP) have shown that an acceptable minimum density after 3 years is between 309 and 494 seedlings ha^{-1} to meet the desired forest conditions for diversity and structure (Allen *et al.*, 2001; Stanturf *et al.*, 2001; LMVJV Forest Resource Conservation Working Group, 2007; Stanturf *et al.*, 2009). At that rate, we would need 21–33 per cent survival in our research plots after 3 years to achieve minimum acceptable stocking density (Allen *et al.*, 2001). The recommended stocking densities for the LMAV and ACP are a good starting point for restoration projects in the WGCP but may not be suitable for the WGCP region since there are differences in soil characteristics, species composition and hydrology between BLHW in the WGCP and the LMAV and ACP (Hodges, 1997; Hupp, 2000). It should be noted that these densities apply to restoration for wildlife, aesthetics or other landowner objectives. Timber production in hardwood plantations requires higher densities to achieve more desirable stem forms and induce self-pruning.

A foliar-active treatment of Makaze® herbicide with active ingredient glyphosate (41 per cent) was spot applied around each seedling in a 90-cm radius on all plots annually in late-April to early May to decrease mortality caused by competing vegetation (Allen *et al.,* 2001; Dey *et al.,* 2008). Individual seedlings were covered using PVC pipe (15-cm diameter by 90-cm tall) during the application process to protect them from incidental exposure to the herbicide. Grasses and other vegetation tall enough to come into contact with the planted seedlings once the PVC pipe was removed were manually separated from the seedling and pressed down prior to spraying to avoid drift of herbicide from recently sprayed vegetation to the planted seedlings.

Seedling growth and survival measurements

Data were collected on three occasions for the seedlings planted in 2015: 2 months post-planting, 12 months post-planting (after the first growing season) and 24 months post-planting (after the second growing season). Data were collected on two occasions for the seedlings replanted at Freestone in 2016: 2 months post-planting and 12 months post-planting (after the first growing season).

During each sampling occasion, we recorded survival, height and diameter 25 mm above the root collar for living seedlings. If dormant, survival of each seedling was determined by scratching the base of the seedling to determine if the cambium was green. We also recorded cause of mortality if seedlings were dead and/or missing using animal sign and bite mark identifiers when available. Possible causes of mortality included general environmental conditions (e.g. extended periods of flooding, periods of dryness, excessive competition, disease, insects, poor planting or other unidentifiable environmental stressors), damage by feral swine (e.g. uprooted through wallowing or stems uprooted or broken due to gnawing and browsing), browsed by white-tailed deer and browsed by other or unknown species of wildlife.

All seedlings within a fenced mitigation treatment were used for growth measurements, while in non-fenced whole-plots, only the interior 20 seedlings were used for growth measurements to provide a buffer to control for edge effects, such as shade cast on the plots from adjacent untreated areas. All seedlings within all treatments were used for analysing survival.

Growth and survival data analysis

We combined height and diameter data to derive volume index (VI) and stand VI (SVI) for each data collection period. VI was calculated as basal diameter squared multiplied by height. This index assisted us in understanding seedling development over time (Leite *et al.,* 2016). SVI represented the sum of all seedling volumes within a sub-subplot divided by the area of the plot to get a volume per unit area (m^3 ha^{-1}) and was calculated to compare both survival and growth simultaneously using a single metric. In addition to raw measurements, we determined changes in response variables (i.e. height, diameter, VI and SVI) over time.

We used PROC UNIVARIATE in SAS (v.9.2, SAS Institute, Inc., Cary, NC) to test for normality and homogeneity of the variances within all response variables (height, diameter, VI, SVI and percent survival). We arcsine square root transformed percent survival to normalize the survival data (Ahrens *et al.,* 1990). We analysed differences in the response variables using mixed model ANOVAs (PROC MIXED) at $\alpha = 0.10$ to identify differences that are useful in making management decisions on state properties. Eleven sources (four main effects, six two-way interactions and one three-way interaction) of variation were analysed for the seedlings planted at the original four locations in 2015 and seven sources (three main effects, three two-way interactions and one three-way interaction) for seedlings planted at Freestone in 2016. We used Tukey's multiple comparison test and Saxton's pdmix800 macro for SAS to identify differences within significant sources of variation for each response variable (Saxton, 1998).

Wildlife surveys

We conducted infrared triggered trail camera surveys (Jacobson *et al.,* 1997; Demarais *et al.,* 2000; Holtfreter *et al.,* 2008; Williams *et al.,* 2011) to provide baseline data on the population densities of white-tailed deer and feral swine at each of the study locations. Surveys were conducted late August to early September using PRIMOS® infrared triggered trail cameras (PRIMOS Hunting). We used 11 cameras to conduct 14-day surveys at each site for a total area of 445 ha at the Hopkins, Hunt and Anderson study properties. The Freestone survey included two separate 324 ha surveys using eight cameras around each canopy cover type (non-forested and forested area) since the two canopy cover areas were spread apart and could not be included within one 445-ha survey. Freestone's non-forested area was 5.6 km south of the forested area. Cameras were placed within 50 m of the predetermined location, 1 m off the ground, facing due north and set to trigger when movement was detected. Camera locations were pre-baited using 22.6 kg of shelled corn 4 days prior to the start of surveys to acclimate wildlife to the camera sites.

Estimates of the density of white-tailed deer followed Jacobson *et al.* (1997) (revised by Demarais *et al.* (2000) and McKinley *et al.* (2006)). We used individually identifiable branched antlered bucks and buck to doe ratios. Density estimation for feral swine was similar to Holtfreter *et al.* (2008) and Williams *et al.* (2011).

In addition to density estimates, we conducted a deer browse survey (Lay, 1967) in December, 2016, within Hunt's forested area type to describe the impacts of white-tailed deer in an area less prone to flooding. We established sixteen 1/250-ha circular plots within different treatments: four within the high fences, six within the portable electric fences and six within the non-fenced area. Within each 1/250-ha plot, the number of branch tips available and the number of branch tips browsed were recorded by species for each mitigation treatment. Species were then categorized by browsing preference: first, second and third choice. The average number of tips browsed and tips available were reported by mitigation treatment and species (Lay, 1967).

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Flood duration estimation

We estimated the number of days seedlings were inundated at each study location to aid in explaining variation in survival and growth between study locations and the non-forested and forested areas. Flood depth estimates were recorded two ways: (1) through images captured by wildlife cameras that were deployed to monitor fence function and (2) personal observation when visiting study locations to conduct site maintenance. We placed marked *t*-posts in front of at least one trail camera per site as a reference to estimate water depth. We recorded location, date, time and depth of each observed flood and compared the estimated depths to the nearest United States Geological Survey (USGS) surface water gauge to determine at what depth on the USGS gauge each location's seedlings would be considered submerged. Once estimated, we summed all days over the course of the project where USGS gauges exceeded the estimated depth for seedling inundation. Archived gauge data were obtained back to January 2015 via https://waterdata.usgs.gov.

Results

Survival—2015 planted seedlings

After 2 months, plots within the forested area ($\bar{X}$ = 94.5 per cent) had a lower survival rate ($P = 0.0968$) than plots within the non-forested area ($\bar{X}$ = 99.8 per cent). Most of the mortality was due to higher feral swine predation on seedlings within forested area treatments (Freestone = 20.6 per cent and Anderson = 6.9 per cent mortality due to feral swine). Within the forested area, pecan ($\bar{X}$ = 91.2 per cent) had lower survival than Shumard oak ($\bar{X}$ = 96.9 per cent) and bur oak ($\bar{X}$ = 95.3 per cent) due to feral swine predation.

Survival dropped dramatically after the first growing season. Number of live seedlings decreased from $n = 6416$ 2 months post-planting to $n = 1384$ at one year. Survival varied at the site, canopy cover type, mitigation treatment and species levels after the first growing season of 2015 ($P < 0.0001$).

Environmental conditions, especially flooding, were a major contributor (70.2 per cent) to mortality. Herbivory from feral swine was also a moderate contributor (9.0 per cent) to mortality. Total survival dropped from 96.2 per cent after 2 months post-planting to 20.8 per cent after the first growing season. Freestone and Anderson, both along the Trinity River, produced lower survival rates (5.3 and 7.8 per cent, respectively) than Hopkins (32.6 per cent) and Hunt (47.9 per cent). Anderson, Freestone and the non-forested area at Hunt were submerged for large portions of the growing season: 81, 89 and 30 days, respectively (Table 1). Overall, canopy cover types differed with non-forested areas ($\bar{X}$ = 13.7 per cent) producing a lower survival rate than the forested area ($\bar{X}$ = 30.8 per cent).

After two growing seasons, the number of living seedlings decreased an additional 461 to total 923 live seedlings (Figure 3). Most of the additional mortality was due to environmental conditions. Minimal occurrences of herbivory were observed over the course of the second year. Once again, all the main effects were significant predictors of percent survival (Table 2). Overall survival decreased from 20.8 per cent after the first growing season to 13.8 per cent after the second growing season. Anderson, Freestone and the non-forested area at Hunt were submerged for an additional 44, 46 and 12 days, respectively, during the 2016 growing season (Table 1). Percent survival for Hunt's non-forested and forested areas decreased from 11.4 and 74.5 to 4.6 and 59.7 per cent, respectively. Across all sites, survival was lower for all species in the non-forested area ($\bar{X}$ = 7.3 per cent) compared with the forested area ($\bar{X}$ = 22.7 per cent). Percent survival also differed by mitigation treatment within each canopy cover type (Figure 3).

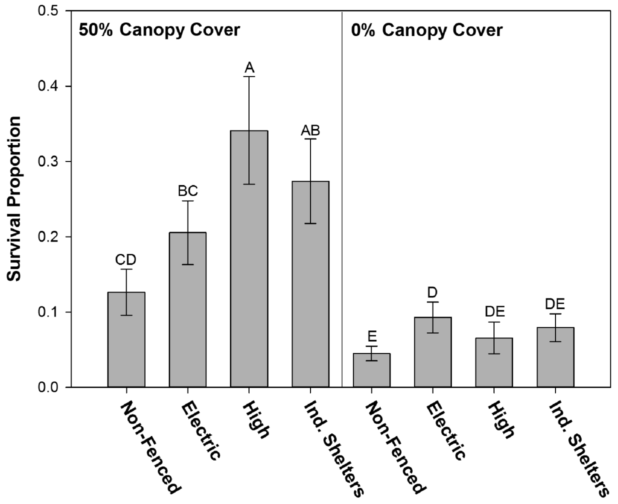

Figure 3 Mean percent survival of all species (bur oak, Shumard oak and pecan) planted in 2015 across 2 canopy covers and 4 herbivory mitigation treatments at 4 sites in east Texas, US (letters denote difference across treatments at $\alpha = 0.10$).

Survival—Freestone 2016 replant

All seedlings planted at the Freestone County study location in January 2016 survived the first 2 months post-planting. After the first growing season, all main effects were significant for survival. Survival was higher in the non-forested area ($\bar{X}$ = 36.2 per cent) than in the forested area ($\bar{X}$ = 30.7 per cent). Individual tree shelters, presumably designed to reduce browse and increase survival, within the forested area ($\bar{X}$ = 22.0 per cent) produced the lowest survival rate (Figure 4). By species, Nuttall oak ($\bar{X}$ = 71.5 per cent) and pecan ($\bar{X}$ = 62.5 per cent) produced a higher survival rate than Shumard oak ($\bar{X}$ = 4.2 per cent), as may be expected since Shumard oak is the least flood tolerant of these species. Herbivory was not a factor in causing additional mortality, as all seedling mortality appeared to be a result of environmental conditions endured over the first growing season.

Growth parameters—2 months post-planting

Initial seedling height, diameter and VI 2 months post-planting varied among sites, mitigation treatments and tree species. Because these parameters varied in the initial surveys, we used changes in height, diameter and VI rather than raw values for further analyses.

Initial height by site ranged from $\bar{X}$ = 31.38 cm (Anderson) to $\bar{X}$ = 28.57 cm (Freestone), with diameter ranging from $\bar{X}$

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Table 1 Number of days seedlings were submerged using estimated USGS surface water gauge height *t* each study location. The study was in east Texas, US.

River basin	Submergence at estimated USGS gauge height (m)	USGS gauge ID number	Research site	Dormant season days	Growing season days
Trinity	9.45	08065000	Anderson	70	125
Trinity	9.75	08062700	Freestone	71	135
Trinity	9.75	08062700	Freestone 2016	39	46
Sabine	3.65	08017300	Hunt (non-forested)	18	42
Sabine	5.18	08017300	Hunt (forested area)	1	5
Sulphur	5.18	07342500	Hopkins	2	2

Table 2 Mixed model ANOVA results (degrees of freedom [df], *F*-statistic [*F*] and *P*-value [*P*]) analysing arcsine square root transformed percent survival after two growing seasons (seedlings planted in 2015) and after one growing season (seedlings planted in 2016 at the Freestone County site, east Texas, US).

		Seedlings planted in 2015		Freestone 2016 replant	
Source	df	F	P	F	P
Site	3	85.25	<0.0001	–	–
Canopy type	1	104.93	<0.0001	5.26	0.0301
Mitigation treatment	3	12.4	0.001	4.93	0.0271
Species	2	27.29	<0.0001	263.04	<0.0001
Site∗canopy type	3	83.69	<0.0001	–	–
Site∗mitigation treatment	9	6.72	<0.0001	–	–
Site∗species	6	3.19	0.0052	–	–
Canopy type ∗ mitigation treatment	3	3.06	0.0295	6.88	0.0015
Canopy type ∗ species	2	1.59	0.2066	4.62	0.0192
Mitigation treatment ∗ species	6	1.41	0.2121	2.90	0.0268
Canopy type ∗ mitigation treatment ∗ species	6	0.92	0.481	1.56	0.1987

= 0.521 cm (Anderson) to $\bar{X}$ = 0.449 cm (Freestone). Larger differences were seen at the mitigation treatment level with seedlings within electric fences ($\bar{X}$ = 28.06 cm) and high fences ($\bar{X}$ = 28.57 cm) being shorter than non-fenced seedlings ($\bar{X}$ = 29.99 cm), while seedlings within individual tree shelters ($\bar{X}$ = 34.50 cm) were the tallest. Not surprisingly, seedlings of different species varied in initial size. Pecan seedlings ($\bar{X}$ height = 24.38 cm, $\bar{X}$ diameter = 0.454 cm) were shorter and thinner than Shumard oak seedlings ($\bar{X}$ height = 26.72 cm, $\bar{X}$ diameter = 0.465 cm), which were shorter and thinner than bur oak seedlings ($\bar{X}$ height = 37.95 cm, $\bar{X}$ diameter = 0.521 cm).

Significant main effects for SVI included site ($P < 0.0001$), mitigation treatment ($P = 0.0008$) and tree species ($P < 0.0001$). At this point, feral swine killed and uprooted 181 (48 per cent) of the non-fenced seedlings in the forested area at the Freestone study location. There, they seemed to prefer pecan (122 seedlings, 67.4 per cent) over bur oak (43 seedlings, 23.8 per cent) and Shumard oak (16 seedlings, 8.8 per cent). During this period, they also breached one of the three electric fence arrays within the forested area at the Anderson study location killing and uprooted 63 of the seedlings (33.3 per cent of total seedlings within electric fence) but did not show any type of preference towards a single species.

Growth parameters—first growing season

All species had similar change in height over the first growing season in 2015 ($P = 0.9508$). Change in height differed by mitigation treatment ($P = 0.0115$) with seedlings within individual tree shelters ($\bar{X}$ = 10.03 cm) increasing more in height compared with seedlings not within a fence ($\bar{X}$ = 2.44 cm), electric fence ($\bar{X}$ = 3.51 cm) or high fence ($\bar{X}$ = 2.76 cm). There were no other significant main effects in 2015. Additionally, there were no significant main effects for changes in seedling diameter or VI after the first growing season.

All main effects of site ($P < 0.0001$), canopy cover type ($P = 0.0182$), mitigation treatment ($P = 0.0543$) and species ($P < 0.0001$) were significant for change in SVI. Mean SVI decreased within all main effects due to varying mortality among study locations: Anderson ($\bar{X}$ = –0.0139 m^3 ha^{-1}) < Freestone ($\bar{X}$ = –0.0094 m^3 ha^{-1}) < Hopkins ($\bar{X}$ = –0.0073 m^3 ha^{-1}) = Hunt ($\bar{X}$ = –0.0053 m^3 ha^{-1}).

Growth parameters—second growing season

Over the course of the second growing season in 2016, changes in height differed among mitigation treatments ($P = 0.0144$) and species ($P = 0.0482$). Pecan ($\bar{X}$ = 5.50 cm) and Shumard oak

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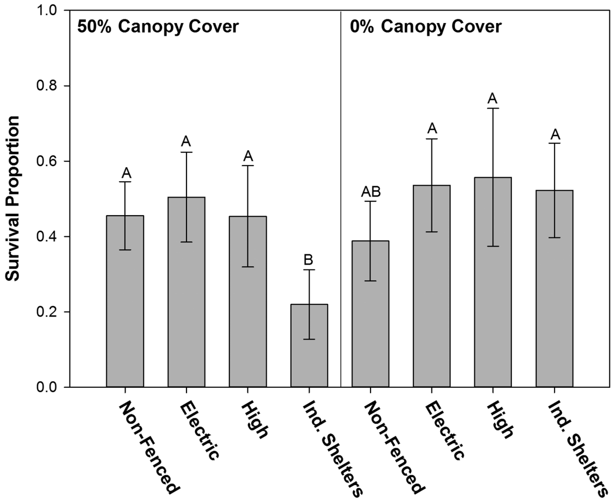

Figure 4 Mean percent survival of Nuttall oak, Shumard oak and pecan seedlings planted in 2016 across 2 canopy covers and 4 herbivory mitigation treatments at the Freestone study location in east Texas, US (letters denote difference across treatments at $\alpha = 0.10$).

($\bar{X}$ = 7.70 cm) outgrew bur oak ($\bar{X}$ = 2.42 cm), while seedlings within individual tree shelters ($\bar{X}$ = 8.18 cm) outgrew seedlings within high fences ($\bar{X}$ = 6.11 cm), electric fences ($\bar{X}$ = 2.08 cm) and non-fenced plots ($\bar{X}$ = 1.14 cm). Once again, there were no significant main effects for change in diameter or VI at $\alpha = 0.10$.

Significant main effects for changes in SVI include canopy cover type ($P = 0.0002$) and mitigation treatment ($P = 0.0029$). Mean SVI in the non-forested area was $\bar{X}$ = −0.0003 m^3 ha^{-1}, while in the forested area, it was a positive $\bar{X}$ = 0.0003 m^3 ha^{-1}. High fence was the only mitigation treatment to produce a positive SVI ($\bar{X}$ = 0.0013 m^3 ha^{-1}), which was greater than SVIs produced by individual tree shelters ($\bar{X}$ = −0.0001 m^3 ha^{-1}), electric fences ($\bar{X}$ = −0.0002 m^3 ha^{-1}) and non-fenced ($\bar{X}$ = −0.0006 m^3 ha^{-1}) mitigation treatments. Change in height over the first growing season had a relatively high covariate parameter estimate of blocking (3.2198), others not reported were ≤ 0.

Growth parameters—two growing season growth

From March 2015 to December 2017, total change in height among mitigation treatments was the only significant main effect in terms of change in height, diameter and VI (Table 3). Trees protected by individual tree shelters put on more height ($\bar{X}$ = 18.89 cm) than those protected by high fences ($\bar{X}$ = 9.55 cm), electric fences ($\bar{X}$ = 5.67 cm) and non-fenced plots ($\bar{X}$ = 3.10 cm). Significant interactions included site by canopy cover type, site by mitigation treatment, canopy cover type by species and mitigation treatment by species (Table 3).

Within Hunt's forested area, there was obvious white-tailed deer browsing in the non-fenced and electric fence mitigation treatments creating a greater range in total height change among mitigation treatments: individual tree shelter ($\bar{X}$ =24.23 cm) was greater than high fence ($\bar{X}$ = 13.02 cm) which was greater than electric fence ($\bar{X}$ = 4.33 cm) and non-fenced ($\bar{X}$ = 2.33 cm). Alternatively, total change in height within the non-forested area was on the low end of the range for all mitigation treatments: individual tree shelter ($\bar{X}$ = 11.43 cm) was greater than high fence ($\bar{X}$ = 6.64 cm) which was greater than electric fence ($\bar{X}$ = 1.50 cm). High fences and individual tree shelters theoretically excluded all white-tailed deer and provided 100 per cent protection to the seedlings, while electric fences varied in efficacy and were breached by white-tailed deer and feral swine during the study period.

Across all study locations, total change in diameter and volume showed multiple significant interactions in the mixed model ANOVA (Table 3), but the Tukey's post hoc analysis did not determine where the differences were within an interaction. It is possible that some of these interactions were due to collinear or correlated factors or that the sample sizes were too small when the data were broken down into specific groups and sub-groups. However, change in bur oak VI (9.17 cm^3) at Hopkins was greater than pecan (5.33 cm^3) and Shumard oak (3.18 cm^3) seedlings at Hopkins and pecan seedlings (2.43 cm^3) at Anderson.

The total change in SVI was significant for all main effects, like the results after the first growing season (Table 3). Overall, SVI was negative due to mortality reducing the number of seedlings. This produced similar results for total change in SVI (Table 3) and survival (Table 2) after two growing seasons. Additional differences were the result of growth at each canopy cover type, mitigation treatment and species levels. Two-year change in height and VI had relatively high covariate parameter estimates of blocking (6.0068 and 3.6171, respectively), others not reported were ≤ 0.

Growth parameters—Freestone 2016—2 months post-planting

Significant main effects for seedling height 2 months post-planting included canopy cover type ($P < 0.0001$), mitigation treatment ($P = 0.0045$) and species ($P < 0.0001$), while species was the only significant main effect for diameter, VI and SVI (all with $P < 0.0001$). Covariance parameter estimates of blocking were near zero, confirming that blocking was not significant for these response variables at this scale.

Species was the only significant main effect for SVI, which again is due to the physical characteristics of the species of interest since all seedlings survived up to this point. Like the original four study locations, further analyses were conducted on the change of each response variable over the course of the first growing season because of these differences. Initial VI 2 months post-planting had a relatively high covariate parameter estimate of blocking (2.8094), others not reported were ≤ 0.

Growth parameters—Freestone 2016—first growing season

Significant main effects for height included mitigation treatment and species (Table 4, Figure 5). Seedlings within individual tree shelters outgrew seedlings within electric fences, high fences and non-fenced plots. At the species level, pecan outgrew Nuttall oak, while Shumard oak sample size ($n = 14$) was small, so inferences could not be made.

Significant main effects for change in diameter included canopy cover type and species (Table 4). The non-forested area ($\bar{X}$ = 0.013 cm) produced a positive change driven by Nuttall

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Table 3 Mixed model ANOVA results (degrees of freedom [df], *F*-statistic [*F*] and *P*-value [*P*]) for seedlings planted in January 2015 analysing the total change in seedling height, diameter, VI and SVI over 2015 and 2016 growing seasons in east Texas, US.

		Total change in height (cm)		Total change in diameter (cm)		Total change in VI (cm^3)		Total change in SVI (m^3 ha^{-1})	
Source	df	F	P	F	P	F	P	F	P
Site	3	0.68	0.5617	1.31	0.2712	1.02	0.3835	24.27	<0.0001
Canopy type	1	0.15	0.6992	0.08	0.7727	0.87	0.3509	9.72	0.0021
Mitigation treatment	3	9.86	0.0025	0.20	0.8926	2.28	0.1414	7.52	0.0064
Species	2	1.73	0.1774	0.96	0.3846	0.65	0.5235	45.13	<0.0001
Site∗canopy type	3	4.46	0.0041	15.93	<0.0001	10.79	<0.0001	6.01	0.0006
Site∗mitigation treatment	9	5.51	<0.0001	1.39	0.1901	0.85	0.5711	8.03	<0.0001
Site∗species	4	1.48	0.2063	2.26	0.0613	4.44	0.0015	1.33	0.244
Canopy type ∗ mitigation treatment	3	1.75	0.1552	0.97	0.4082	2.84	0.0373	1.11	0.3471
Canopy type ∗ species	2	4.49	0.0115	0.11	0.893	0.98	0.3771	0.03	0.972
mitigation treatment ∗ species	6	3.74	0.0011	1.36	0.2303	1.96	0.0686	1.46	0.1921
Canopy type ∗ mitigation treatment ∗ species	6	1.62	0.1376	5.54	<0.0001	3.04	0.0061	0.85	0.5363

Table 4 Mixed model ANOVA results (degrees of freedom [df], *F*-statistic [*F*] and *P*-value [*P*]) for seedlings planted in January 2016 at the Freestone study location analysing seedling change in height, diameter, VI and SVI after one growing season. The study was in east Texas, US.

		Change in height (cm)		Change in diameter (cm)		Change in VI (cm^3)		Change in SVI (m^3/ha)	
Source	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Canopy type	1	0.00	0.9448	15.21	0.0001	4.72	0.0302	10.67	0.0031
Mitigation treatment	3	12.18	0.0016	0.43	0.7356	1.82	0.2144	3.78	0.0527
Species	2	7.21	0.0008	9.38	<0.0001	2.23	0.1088	69.65	<0.0001
Canopy type∗mitigation treatment	3	0.90	0.4403	0.37	0.7774	0.63	0.5987	6.95	0.0014
Canopy type∗species	2	5.80	0.0032	3.27	0.0387	9.17	0.0001	33.85	<0.0001
Mitigation treatment∗species	6	1.76	0.1054	1.41	0.2069	0.42	0.8677	2.29	0.0655
Canopy type∗mitigation treatment∗species	5	3.06	0.0097	2.58	0.0254	0.43	0.8286	2.29	0.0655

oak within high and electric fences, while the forested area ($\bar{X} = -0.052$ cm) produced a negative change driven by Shumard oak within electric and non-fenced areas. At the species level, all mean changes in diameter were negative but again Shumard oak consisted of a small sample and no inferences could be made. Canopy cover type was the only significant main effect for VI after the first growing season. Again, the non-forested area ($\bar{X} = 2.435$ cm^3) produced a positive change driven by Nuttall oak within high and electric fences, while the forested area ($\bar{X} = -1.230$ cm^3) produced a negative change driven by Shumard oak within electric and non-fenced areas.

All main effects and interactions were significant for SVI (Table 4). Again, this index accounts for mortality within species replications as well as single seedlings dramatically changing size over the first growing season. Patterns of SVI change by mitigation treatment were similar for each species individually.

Wildlife surveys

All study locations had similar, moderate densities of feral swine (Table 5), while the Hopkins County study location and Freestone County's forested area had low white-tailed deer densities compared with the moderate white-tailed deer densities at the other study locations (Alverson *et al.*, 1988; Russell *et al.*, 2001). Density estimates for white-tailed deer had higher variation ($\bar{X} = 0.15$ individuals ha^{-1}, $\sigma = 0.10$ individuals/ha) than feral swine across study locations ($\bar{X} = 0.12$ individuals ha^{-1}, $\sigma = 0.02$ individuals/ha; Table 5).

The Hunt County study location contained the highest density of white-tailed deer (Table 5) and experienced obvious visual signs of heavy browsing within the forested area (Figure 6). The white-tailed deer browse survey determined areas protected by high fences, more so than electric fences, had more available biomass and higher diversity of preferred browse species compared with non-fenced areas (Table 6).

Flood duration

On average, seedlings were dormant from 1 December to 31 March of each year. Inundation duration and intensity varied by study location and by canopy cover type within the Hunt County study location (Table 1). Overall, mean days of inundation ranged from 103 days $year^{-1}$ (Freestone) to about 2 days $year^{-1}$ (Hopkins). Peak inundation periods occurred, on average across

Table 5 Results of 14-day trail camera survey to estimate abundance using one camera per 41 ha conducted at each study location from late August to early September 2015 in east Texas, US.

			White-tailed deer			Feral swine		
	Hectares surveyed	Images analysed	% Images with deer	Est. Abun.	Density (per ha)	% Images with swine	Est. Abun.	Density (per ha)
Hopkins	445	7378	6.3	22	0.049	24.5	54	0.121
Hunt	445	3467	42.6	123	0.276	24.0	55	0.124
Freestone (forested area)	324	3587	1.5	16	0.049	67.7	30	0.093
Freestone (non-forested)	324	3910	26.4	55	0.170	37.8	37	0.114
Anderson	445	5547	33.1	83	0.187	23.2	71	0.16

Table 6 Results of deer browse survey within Hunt's forested area Fall, 2017, including preference, mean tips browsed and mean tips available for each mitigation treatment. Recorded occurrences of Shumard oak, bur oak and pecan are seedlings planted as part of the project in east Texas, US.

		High fence ($n = 4$)		Electric fence ($n = 6$)		Non-fenced ($n = 6$)	
Common name	Pref.	Tips browsed	Tips available	Tips browsed	Tips available	Tips browsed	Tips available
Green Briar *Smilax* spp.	1	0	9.0	1.3	2.2	1.5	2.2
Poison Ivy/Oak *Toxicodendron* spp.	1	0	6.0	–	–	–	–
Blackberry *Rubus* spp.	1	0	6.5	0.2	1.8	–	–
Honey locust *Gleditsia* spp.	1	0	5.0	2.2	2.8	0.0	3.0
Shumard Oak *Quercus shumardii*	**2**	**0**	**3.0**	**2.3**	**2.5**	**0.2**	**1.0**
Bur Oak *Q. macrocarpa*	**2**	**0**	**3.5**	**1.7**	**1.7**	**0.5**	**0.5**
Water Oak *Q. nigra*	2	0	10.5	–	–	–	–
Southern Red Oak *Q. falcata*	2	0	0.3	–	–	–	–
Grape Vines *Vitis* spp.	2	0	0.3	–	–	–	–
Red Mulberry *Morus rubra*	2	0	0.3	–	–	–	–
Virginia Creeper *Parthenocissus quinquefolia*	2	0	0.5	–	–	–	–
Sumac *Rhus* spp.	2	–	–	2.7	4.8	–	–
Hawthorn *Crataegus* spp.	2	–	–	1.5	1.7	–	–
Ash *Fraxinus* spp.	3	0	0.3	–	–	–	–
Sugarberry *Celtis laevigata*	3	0	48.8	10.5	10.7	4.8	5.8
Persimmon *Diospyros virginiana*	3	0	0.3	0.0	2.8	–	–
Hercules Club *Zanthoxylum clava-herculis*	3	0	0.8	–	–	–	–
Pecan *Carya illinoinensis*	**3**	**0**	**2.0**	**3.3**	**3.3**	**.**	**.**

Planted seedlings are shown in bold.

sites, during the mid-2015 growing season, 2015 growing season to dormant season transition, and mid-2016 growing season.

Freestone and Anderson study locations along the Trinity River showed similar patterns of inundation (Table 1) and survival. The Anderson County study location was ∼33 km south of the study location in Freestone County allowing more time for the accumulated runoff to dissipate and resulting in fewer days inundated. Both experienced flood depths near 3.5 m at times during the study.

Hunt was along the Sabine River and its non-forested area was subject to more flash flooding (i.e. rapid inundation after receiving less precipitation in the area) than the other locations. Inundation events lasted a maximum of 4 days at depths near 2 m. Canopy cover types differed in elevation by about 2 m, resulting in the non-forested area flooding 10-times more often than the forested area on the same property (Table 1). This section of the Sabine River was part of the headwaters for Lake Tawakoni and the study area hydrology was affected by the water levels within the reservoir. This section also does not have steep banks such as the Trinity and Sulphur Rivers. Hopkins was on a section of the Sulphur River that is less affected by inundation. The hydrology in this portion of the river was driven by the water release rates of the Cooper Lake dam positioned ∼13-km upstream.

The simple linear regression between survival and duration of growing season inundation shows a negative relationship after the first growing season and in total, after two growing seasons (Figure 7). The longer seedlings are inundated during the growing season the less likely they are to survive.

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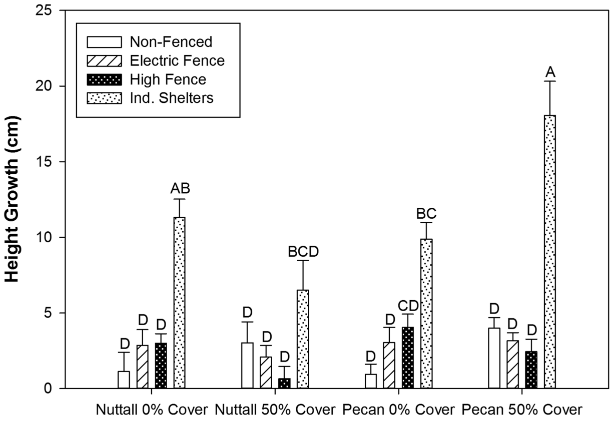

Figure 5 Replanted 2016 Freestone location: mean total change in height (with standard error) for Nuttall oak and pecan within each mitigation treatment at the different canopy cover types after one growing seasons. In total, 14 Shumard were alive and removed from this analysis. The study was in east Texas, US.

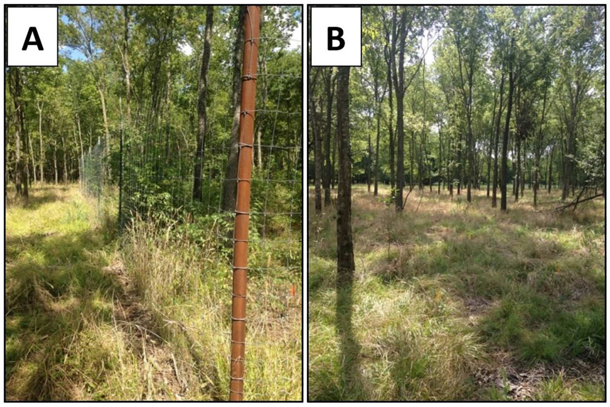

Figure 6 Evidence of white-tailed deer browse activity at Hunt study location within the forested area, (A) dense vegetation with increased number of preferred browse species within 2.4-m woven wire high fence, (B) non-fenced area consisting of reduced herbaceous layer, Photo from Hunt County, Texas, US, summer 2016.

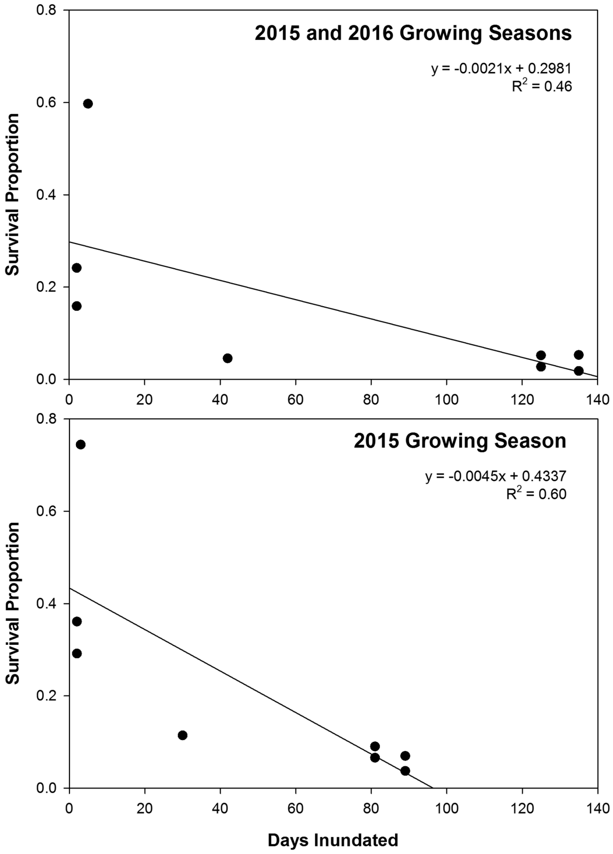

Figure 7 Simple linear regression results showing relationship of hardwood seedling survival with number of days inundated during the 2015 growing season (bottom pane) and after the 2015 and 2016 growing season (top pane). The study was in east Texas, US.

Discussion

There are many limitations (e.g. prolonged inundation, droughts, wildlife and nursery stock variability) to overcome in an effort to obtain a desired density of preferred tree species for BLHW restoration projects. Planting desirable species and decreasing the presence of competing vegetation, though important, may not be sufficient in the WGCP to successfully produce the desired species composition for BLHW (Allen *et al.*, 2001; Stanturf *et al.*, 2004). We observed high seedling mortality across species and treatments despite applying competition control across our treatments. Mortality from herbivory was not observed within the 1 year, Freestone County 2016 study plots, so survival variability was a result of environmental conditions over the first growing season. Additionally, white-tailed deer herbivory did not cause a notable amount of mortality over the project duration, even with densities ranging from average to high. Overall, seedlings protected by a mitigation treatment were about twice as likely to survive as non-fenced seedlings after two growing seasons. Over the course of our 2-year study, two of the four locations experienced excessive amounts of mortality within the forested area due to herbivory by feral swine. Feral swine herbivory occurred within non-forested areas but not to the extent that was observed within forested area. Evidence provided by the Hopkins and Freestone forested area showed that feral swine have the potential to limit the establishment of hardwood seedlings at some sites.

White-tailed deer did not cause mortality but their effects were visually present at Hunt's forested area. The unprotected areas had noticeably less herbaceous and woody vegetation available than portable electric fences, which had noticeably less herbaceous and woody vegetation available than high fenced areas after the two growing seasons. This phenomenon provides evidence that white-tailed deer have the potential to reduce seedling height. Additionally, high fences did not allow any white-tailed deer or feral swine to enter the plots. This, along with images collected from trail cameras monitoring the plots and the lack of animal sign, showed that our high fence at the Hunt County study location and the other study locations were 100 per cent effective at excluding wildlife. Individual tree shelters protected the desirable seedlings while doubling the rate of height

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growth compared with high fences. The rate of height gain was approximately six-times that observed for electric fences and non-fenced plots in the Hunt County forested area.

Trail cameras revealed that individual tree shelters allowed minor occurrences of herbivory, showing a higher efficacy within the non-forested area (0.4 per cent mortality due to herbivory) compared with the forested area (4.0 per cent mortality due to herbivory). Electric fences showed a lower efficacy than individual tree shelters but still provided some degree of protection compared with the herbivory rates in non-fenced plots. Inundation and falling limbs provided avenues for wildlife to breach the fence and access these areas for limited times. Also, they provided a higher efficacy in the non-forested area (2.8 per cent mortality due to herbivory) compared with the forested area (10.3 per cent mortality due to herbivory) probably due to increased debris in forested sites. Regardless of location, electric fences required routine maintenance. Mitigation treatments varied greatly by cost: individual tree shelters cost about $2250 per 1000 seedling plot, portable electric fence $3440 per 1000 seedling plot with 1.8 by 3.6 m spacing, and 2.4 m woven wire high fence $6775 for materials and $4510 for labour per 1000 seedling plot with 1.8 by 3.6 m spacing (VerCauteren *et al.,* 2006).

When herbivory occurred, feral swine seemed to prefer pecan seedlings over bur oak and bur oak over Shumard oak the majority of the time. On a single occasion 2 months post-planting, feral swine breached one electric fence treatment, killed all but three seedlings within and showed no species preference. The rooting signs left behind by feral swine suggested that seedling predation may have been an indirect result of rooting around one particular snag potentially targeting insects or other food material (Campbell and Long, 2009; Barrios-Garcia and Ballari, 2012). Environmental conditions acting on each study location, more specifically frequent inundation that persisted into the mid to late growing season, were a more important cause of mortality (Broadfoot and Williston, 1973). Environmental conditions caused equal amounts of mortality across non-fenced and mitigation treatments. In the study initiated in 2015, seedlings within the non-forested area were affected more than seedlings within the forested area. The non-forested area soils receive more direct sunlight compared with the forested area soils, potentially causing different rates of change in soil moisture or more intense drought conditions and stress to seedlings within the non-forested area (Allen *et al.,* 2001). Three of the four non-forested areas were inundated for >40 days during the growing season causing >90 per cent mortality, while only two of the four forested areas were. Thus, the response may be related to the duration of inundation, particularly at the Hunt site (Broadfoot and Williston, 1973). Establishing a canopy cover using rapidly growing species such as eastern cottonwood (*Populus deltoids* Bart. ex Marsh.) can increase survival of under-planted oak and hickory species by reducing stress caused by varying soil moisture conditions (Schoenholtz *et al.,* 2001; Gardiner *et al.,* 2004) suggesting that the forested areas could have alleviated some of the stress caused by the environmental conditions our study sites endured.

Seedlings planted within a forested area and protected by either a high fence or individual tree shelters had the best chance of survival. Within this combination, individual tree shelter seedlings grew twice as tall as seedlings within high fences which grew three- to four-times taller compared with electric fences and non-fenced plots after two growing seasons. It is possible in this study that tree shelters modified the climate immediately surrounding the seedling similar to a greenhouse, perhaps even trapping respired CO_2 and thus improving leaf-level gas exchange. Electric fences produced comparable survival rates to non-fenced areas and individual tree shelters but lower survival than the more traditional 2.4-m fence.

Although pecan seedlings seemed to be preferred by feral swine, they had the highest survival rate overall, suggesting that pecan was more suited to the environmental conditions present throughout the study. Pecan trees are considered more (weakly to moderately) tolerant to inundation compared with bur oak (intolerant to weakly tolerant) and Shumard oak (weakly tolerant; Whitlow and Harris, 1979;Allen *et al.,* 2001;Stanturf *et al.,* 2004). Surprisingly, bur oak had higher survival than Shumard oak even though bur oak is considered less flood tolerant (Whitlow and Harris, 1979; Stanturf *et al.,* 2004). This phenomenon could be a result of our bur oak seedlings being initially larger than Shumard oak at the time of planting (Stanturf *et al.,* 2004).

Individual tree shelters required more maintenance compared with high fences, but less than portable electric fences. Flooding dislodged shelters leaving the seedlings vulnerable. At times, this phenomenon caused physical damage to seedlings and deposited sediment on tree shelters, decreasing the amount of light that was able to penetrate them. Individual tree shelters also alter the internal environment (e.g. increase temperature, relative humidity and CO_2 concentration) to enhance growing conditions (Burger *et al.,* 1992; Kjelgren and Rupp, 1997). However, they can create extreme conditions, such as heat stress, that increases mortality. Recently, tree shelter companies have released improved tree shelters that include vents specifically designed to create an optimum balance between the ambient environment and the shelter's internal environment (Tubex USA®, Conservation Services). Floods causing physical damage to seedlings or tree shelters creating extreme environments could be why survival rates for Freestone 2016 were lowest within the individual tree shelter plots after the first growing season.

Electric fences required the most upkeep due to falling limbs, trees and debris that washed up during flooding. This broke the poly-wires and disrupted the connection between the energizer and fences, decreasing the overall integrity of the fences and providing opportunities for feral swine and white-tailed deer to breach the fence. The forested area also decreased the reliability of the solar energizers. During times of dense canopy, battery charges would become too weak to power each fence. Overall, these events decreased the efficacy of the fences over time. In addition, past research has shown that animals, given enough time, can learn how to breach fences without receiving a shock (VerCauteren *et al.,* 2006). This could be why portable electric fences did not perform as well as the more common mitigation techniques we tested.

Replanted 2016 Freestone location showed similar trends in terms of change in height by mitigation treatment after one growing season. However, there were confounding results in terms of survival by mitigation treatment with individual tree shelters having the lowest percent survival after one growing season. This phenomenon could be related to Nuttall oak being less shade tolerant than bur oak, internal conditions being too

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extreme and/or environmental conditions being more favourable outside the shelters for the species planted on our site (Burger *et al.,* 1992; Kjelgren and Rupp, 1997; Allen *et al.,* 2001).

When small and vulnerable, seedlings need assistance to overcome the major (i.e. variety of environmental conditions) and minor (i.e. herbivory due to feral swine) threats to survival. The faster seedlings reach a free to grow stage (>1.5 m), the more likely they are to reach maturity, produce large mast and overcome the stresses related to herbivory, browse pressure and flooding (Allen *et al.,* 2001). This study showed that individual tree shelters reduced the prevalence of both threats. They may cause a negative response for specific species within different forest types, for example Nuttall oak within a forested setting with ~50 per cent canopy cover or more. They allow seedlings time to establish themselves and prepare for environmental and wildlife impacts that may be significant over the initial 3 years of establishment (LMVJV Forest Resource Conservation Working Group, 2007).

Conclusion

Matching species of interest to the site conditions, specifically local hydrologic regimes, should be a high priority in planning a restoration project within BLHW in the WGCP. This study showed that mitigation for herbivory is possible in varying degrees using portable electric fences, individual tree shelters and high fences. Feral swine have potential to cause high mortality rates within a site, but population density was not a reliable predictor of mortality from feral swine. White-tailed deer did not cause high rates of mortality but caused reduced height gain over time at one study location. This has a significant impact on seedling establishment as reduced height gain causes seedlings to remain vulnerable to inundation, erosion and drought (Côté *et al.,* 2004). If seedlings cannot overcome continuous browsing by white-tailed deer year after year, they eventually die (Côté *et al.,* 2004).

In the WGCP, it is possible to achieve acceptable rates of survival. Once a diverse group of species are selected for a restoration project, it is important to take into consideration the likelihood of extreme weather events, whether that is noting at what level rivers and streams adjacent to the area overtop their banks or the frequency at which dormant or growing season flooding occurs (Broadfoot and Williston, 1973; Dey *et al.,* 2012). If inundation is a factor, staggering planting over the course of many years will allow for compensation for the losses within one planting year. These recommendations go hand in hand with increased monitoring of sites. Additional monitoring, multiple times per season, will allow managers to notice herbivory damage by feral swine and white-tailed deer and allow them the opportunity to protect seedlings via tree shelters.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

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Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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