Forest Ecology and Management 529 (2023) 120699

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Responses of natural and artificial pin oak (*Quercus palustris*) reproduction to a sequence of silvicultural release treatments in bottomland hardwood forests in southern Missouri

Isaac Hayford [a], Benjamin O. Knapp [a,*], John M. Kabrick [b]

[a] School of Natural Resources, University of Missouri, 203 ABNR Building, Columbia, MO 65211, USA
[b] USDA Forest Service, Northern Research Station, 202 ABNR Building, Columbia, MO 65211, USA

ARTICLE INFO

Keywords:
Artificial regeneration
Bottomland hardwood forests
Midstory removal
Natural regeneration
Overstory harvest

ABSTRACT

Developing competitive oak advance reproduction prior to canopy disturbance is understood to be important for oak regeneration success. In the early 2000s, a study was installed in southeastern Missouri to examine the effects of midstory and understory release on natural and artificial sources of pin oak (*Quercus palustris* Muenchh.) advance reproduction. The findings obtained three years after midstory and understory release indicated photosynthetically active radiation increased from 3 to 15 % and a corresponding increase in density of pin oak reproduction as well as the survival and growth of both natural and artificial pin oak reproduction compared to control. In 2010, eight years after the midstory and understory was removed, three different overstory harvests were applied to release the established pin oak advance reproduction. Here, we investigated the effects of the midstory and understory removal and the subsequent overstory harvests on underplanted and naturally regenerated oak advance reproduction. We also tested effects of a later midstory release on the density of natural pin oak advance reproduction. Results indicate that the survival of bareroot pin oak seedlings increased with increasing initial basal diameter. The survival of Root Production Method (RPM®) container pin oak seedlings, however, was not dependent on the size at the time of planting. The early understory removal with triclopyr herbicide was ineffective in ensuring survival of planted pin oak seedlings. Shelterwood increased the growth of oak advance reproduction but did not eliminate competition from other species. A late release also failed to increase the growth of oak advance reproduction. Given shelterwood also favored oak competitors in our study, multiple applications of midstory and understory competition control treatments following the shelterwood treatment will be imperative for successful oak regeneration.

1. Introduction

Bottomland hardwood forests are highly productive forested floodplains along streams and rivers and serve critical economic and ecological roles throughout the lower Midwest and southeastern United States. These forested floodplains are dominated by hardwood species but also include softwood species such as baldcypress (*Taxodium distichum* (L.) Rich.) (Allen et al., 2001). They are valued for timber production, recreational purposes, hunting, wildlife habitat, carbon storage, nutrient cycling, erosion control, and enhanced water quality through filtering and flushing of nutrients (Kellison and Young, 1997). Forest managers are interested in maintaining oaks (*Quercus* spp.) because they provide favorable habitat for wildlife and are often preferred for timber production. Maintenance of oaks requires managing forest regeneration and recruitment processes to boost their regeneration potential and long-term competitiveness through to maturity.

Regenerating oaks in bottomland hardwood forests is challenging, in part due to high potential productivity and abundance of competing tree species. Oaks have slow initial aboveground seedling shoot growth, which makes it difficult for them to compete with fast-growing vegetation in the midstory and understory layers (Hayford and Chhin, 2020). The low understory light levels common to mature bottomland hardwood forests typically favor more shade-tolerant tree species over common oak species, which are intermediate to very intolerant of shade (Clatterbuck and Meadows, 1993; Hodges and Gardiner, 1993). Other factors, including high rates of acorn predation, seedling herbivory, and

* Corresponding author.
E-mail address: knappb@missouri.edu (B.O. Knapp).

https://doi.org/10.1016/j.foreco.2022.120699
Received 27 September 2022; Received in revised form 21 November 2022; Accepted 24 November 2022
Available online 5 December 2022

anaerobic conditions from flooding have also been implicated as possible causes of oak regeneration challenges in bottomland hardwood forests (Holladay et al., 2006; Lorimer, 1993; Oswalt et al., 2006).

The success of oak regeneration and subsequent recruitment into the overstory is greatly increased by having sufficient numbers of large oak advance reproduction before overstory harvest (Lorimer, 1993). Although bottomland oaks are more prolific seed producers and generally grow faster than upland oaks, their regeneration potential is greatly increased where advance reproduction is present. Smaller oak seedlings cannot compete effectively as larger seedlings of shade-tolerant species or fast-growing, shade-intolerant competitors following release. For example, the probability of survival for nuttall oak (*Quercus texana* Buckley) in the Lower Mississippi Alluvial Valley bottomland forests improved 26 % three years post-planting when the initial basal diameter increased from 0.20 to 1.80 cm (Gardiner et al., 2009). Similar results have been reported for productive upland forests, where increased sizes of oak advance reproduction were critical to improving the likelihood of regeneration success (Belli et al., 1999; Spetich et al., 2002). According to Miller et al. (2017), the probability that northern red oak (*Quercus rubra* L.) advance reproduction with a 0.25 cm basal diameter will become dominant or codominant 20 years following a harvest is virtually zero, but this probability increases to 1 % and 8 % for 0.51 cm and 1.78 cm basal diameter, respectively. Previous studies have recommended that large advance reproduction, generally at least 122 cm in height, be in place prior to overstory release (Sander et al., 1976; Vickers et al., 2011).

Poor establishment of oak advance reproduction within bottomland forests may necessitate artificial regeneration for seedling establishment. Although natural regeneration is more cost-effective than artificial regeneration (Löf et al., 2019), there are instances in which natural reproduction is inadequate to meet management objectives (Rives et al., 2020; Dey et al., 2008). Artificial regeneration methods, including direct seeding of acorns or planting bareroot or container-grown seedlings, may differ in their likelihood of success for oak regeneration in bottomland hardwood forests. Dey et al. (2003) reported for pin oak (*Quercus palustris* Muenchh.) that the Root Production Method (RPM®, an example of container-grown seedling) resulted in greater survival and diameter growth compared to 1–0 bareroot seedlings three years after planting in a Missouri River bottomland. Survival of RPM® pin oak was more than 94 % after three years, whereas that of 1–0 bareroot seedlings was 54 %. Motsinger et al. (2010) also reported greater diameter and height growth of RPM® pin oak than 1–0 bareroot seedlings three years after planting, but there was no difference in survival between the two stock types. Overall, research on direct seeding of oaks in bottomland forests has shown variable results (Wittwer, 1991; Kennedy, 1993; Johnson, 1984; Motsinger et al., 2010). Planting seedlings generally yields greater survival than direct seeding and thus, managers prefer tree planting to direct seeding for regenerating oaks (Dey et al., 2008).

Following establishment, sustained growth of oak seedlings is required to develop large advance reproduction. Understory and midstory competition control may be used to increase seedling survival by increasing light availability on the forest floor and enhancing seedling growth rates. Dense understory and midstory of shade-tolerant vegetation reduce light levels to < 5 % of full sunlight and inhibit oak seedling development (Lorimer et al., 1994; Miller et al., 2004; Lhotka and Loewenstein, 2009). Midstory and understory removal has been found to increase light levels up to 15 % of full sunlight in mixed bottomland hardwood stands and increase the initial survival and growth of oak advance reproduction (Motsinger et al., 2010). However, to achieve the 20 to 50 % of full sunlight required by oak reproduction for maximum growth in the long term, subsequent reductions in overstory density are needed (Brose, 2008; Gottschalk, 1994).

Once advance reproduction is in place, overstory harvest can release the reproduction so that it can grow into the overstory. Overstory harvests from single-tree selection to clearcutting can be used to create a range of canopy openings to allow light to reach the seedling layer. Clearcutting is the most recognized and widely used silvicultural method for successfully regenerating bottomland oaks in the southern United States (Clatterbuck and Meadows, 1993; Meadows and Stanturf, 1997). However, interest in retaining legacy trees or habitat for wildlife has resulted in use of partial harvesting systems like irregular shelterwood, single-tree selection, and group selection. The shelterwood method is used to facilitate establishment of natural advance reproduction and provide adequate sunlight to encourage development of desirable species. The shelterwood method has been successfully used to develop large oak advance reproduction in the southern Appalachians (Loftis, 1990) but has produced variable results when used for bottomland oaks. To successfully regenerate bottomland oak species using the shelterwood method, it is essential that competing undesirable species in the midstory and understory layers are controlled, usually by chemical means (Meadows and Stanturf, 1997). The single-tree and group selection are less used to manage for oaks in mixed bottomland hardwood forests because they create only small openings that often fail to allow sufficient light to the understory (Kellison and Young, 1997; Meadows and Stanturf, 1997). Nevertheless, forest managers in this region are increasingly interested in applying these uneven-aged methods to oak stands for aesthetic purposes and wildlife habitat created by maintaining complex forest structure.

This study was designed to evaluate the effects of a sequence of silvicultural practices designed to first encourage the development and size of advance reproduction and then subsequently release it with overstory harvest. In 2002, a study was initiated at Duck Creek Conservation Area and Mingo National Wildlife Refuge in Stoddard County, MO to examine the effects of a complete midstory removal (all stems < 11.4 cm diameter) and understory competition control on the establishment and development of natural and artificial sources of pin oak advance reproduction in bottomland hardwood forests. Three years after midstory and understory competition control, photosynthetically active radiation increased from 3 to 15 %, with a corresponding increase in density of pin oak reproduction and improved survival and growth of both natural and artificial pin oak reproduction compared to control (Motsinger et al., 2010). In 2010, eight years after the original midstory and understory removal treatments, three different overstory harvest methods were applied to release the established pin oak advance reproduction. The first method used single-tree selection to reduce the overstory density by about 10 to 15 %. The second used group and single-tree selection to reduce the overstory density by about 50 %, and the third treatment used a shelterwood method that retained a residual overstory density of 30 to 40 %. In addition, some study plots received an additional midstory release treatment in 2010, around the time of overstory harvest. The objectives of this study were to: 1) compare the effects of midstory and understory removal (applied around the time of planting) and subsequent overstory harvest (eight years after planting) on the survival, size, and growth of bareroot and RPM® container-grown pin oak advance reproduction; 2) determine the effect of initial size of bareroot and RPM® seedlings on the likelihood of survival through time; and 3) determine the benefit of additional midstory release at the time of overstory harvest for natural reproduction of oaks.

2. Methods and materials

2.1. Study area

This study was conducted within two mature greentree reservoir management pools in Stoddard County, southeastern Missouri (N37°01′00.00′’, W090°06′03.50′’). One pool was located at Duck Creek Conservation Area managed by Missouri Department of Conservation and the other at Mingo National Wildlife Refuge managed by the U.S. Fish and Wildlife Service. Both areas were in the Mingo Basin, which is the largest remnant tract of bottomland hardwood forest in the Upper Mississippi Alluvial Valley (Krekeler et al., 2006). The study areas were managed for waterfowl habitat and hunting since 1955 and were flooded almost every year for short periods during the fall waterfowl migration and hunting season in November and December (Fredrickson et al., 1977). The study area was flat (slopes range from 0 to 1 percent), and soils consisted of poorly drained, slowly permeable Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs). The soils are characterized by high available water capacity (total plant available water is 43 cm), low fertility, low organic matter, high runoff, and occasional flooding. The 30-year (1991–2020) mean annual temperature and precipitation for the area were respectively 14.5 °C and 1286 mm (PRISM Climate Group, prism.oregonstate.edu). Prior to treatment application in 2003, pin oak was identified as the dominant species in these two sites, comprising approximately 54 % of the basal area. The other abundant overstory and midstory species included sweetgum (*Liquidambar styraciflua* L.), overcup oak (*Quercus lyrata* Walt.), red maple (*Acer rubrum* L.), American elm (*Ulmus americana* L.), willow oak (*Quercus phellos* L.), persimmon (*Diospyros virginiana* L.), and cherrybark oak (*Quercus pagoda* Raf.). The advance reproduction layer was predominantly composed of red maple, green ash (*Fraxinus pennsylvanica* Marsh.), sweetgum, American elm, pin oak, and willow oak (Motsinger et al., 2010).

2.2. Experimental design and treatments of the original study

The experimental design and treatments applied in the original study have been described by Motsinger et al. (2010). The study used a randomized complete block design with six blocks, three of which were in Mingo National Wildlife Refuge and the other three at Duck Creek Conservation Area. Each block was approximately 4 ha and contained nine experimental units, each 0.45 ha, with dimensions of 67 by 67 m (Fig. 1). Blocks were established on sites considered suitable for the flood tolerance of pin oak; locations where water ponded for long periods during the growing season were excluded.

One of nine treatments was randomly assigned to each experimental unit within each block (Table 1). The original treatments included one untreated control along with a factorial combination of four levels of pin oak stock types and two levels of competition control treatments. The four levels of pin oak stock type included: 1) natural reproduction, 2) direct seeded, 3) 1–0 bareroot seedlings, and 4) Root Production Method or RPM® container-grown seedlings. Within each experimental unit, one 0.08-ha circular plot was established for sampling and monitoring reproduction (Fig. 1B). In April 2003, 40 acorns were sown by hand at

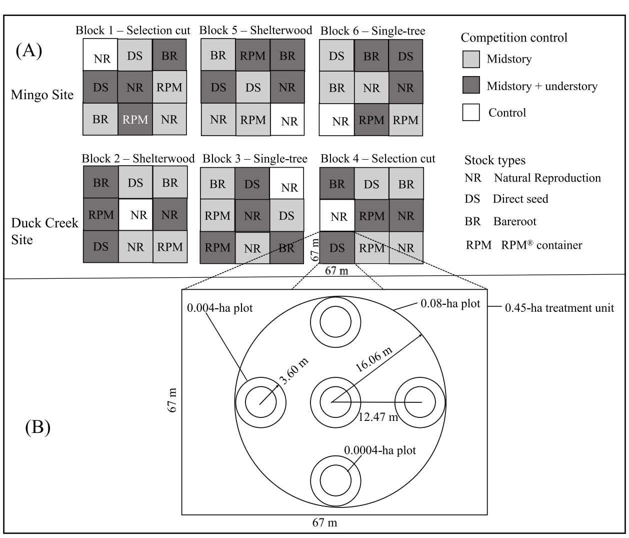

Fig. 1. Experimental layout showing (A) the six blocks in the two different sites (Mingo and Duck Creek) and the treatment combinations, and (B) the sampling design used in the study. Illustrations are not to scale; in panel A, the overstory treatment was not applied to the untreated competition control unit.

Table 1
Treatment combinations compared in the original study.

Stock	Control	Midstory removal	
		With understory removal (Midstory + understory)	Without understory removal (Midstory)
Natural reproduction	X	X	X
Direct seed		X	X
1–0 Bareroot		X	X
RPM® container		X	X

7.5 cm depth in the direct seeded treatment, with each acorn approximately 5 m apart in concentric circles around the plot center. The acorns were purchased from the George O. White State Nursery in Licking, Missouri. Acorns had been collected during the preceding autumn and screened for soundness, stratified, and stored according to standard nursery practices. Also in April 2003, 22 each of 1–0 bareroot and RPM® container-grown pin oak seedlings obtained from George O. White State Nursery in Licking, Missouri and Forest Keeling Nursery in Elsberry, Missouri, respectively, were planted in designated treatment units (Fig. 1). RPM® is a nursery culture technique to produce large container-grown seedlings that have dense, fibrous root systems. After 1 to 2 growing seasons in the nursery, RPM® seedlings develop large root systems, attain basal diameters > 2 cm and heights > 1.5 m (Dey et al., 2004). The bareroot and RPM® seedlings were planted approximately 6 m apart in concentric circles around the plot center within each 0.08-ha plot. In the treatment units designated for natural reproduction, ten natural pin oak seedlings within the 0.08-ha plots were selected and marked with numbered tags. Natural pin oak seedlings that were 1-year-old, as evidenced by presence of an attached acorn to the base of the stem, were selected.

Each of the four stock types was treated with competition control treatments: 1) midstory removal ("midstory") and 2) midstory removal combined with understory removal ("midstory + understory"). In the midstory treatment, 1 ml of imazapyr herbicide was applied into hacks (one hack per each 7.5 cm of diameter) made in the tree bole of all non-oaks in the midstory with diameter at breast height (dbh) that were > 1 cm but < 11.4 cm in February 2003. Following the first growing season, treated trees that had not died were retreated with herbicide. The understory treatment was a foliar application of triclopyr with a Solo® backpack sprayer to all woody and herbaceous vegetation within 1 m from each tagged pin oak seedling in June 2003. Tagged pin oak seedlings were shielded during herbicide application to minimize injury caused by exposure to the herbicide.

2.3. Overstory harvests

In 2010, three overstory harvest treatments were added to the experimental design to release pin oak advance reproduction. Within each pool (Mingo or Duck Creek), each of the three study blocks were randomly assigned one of the treatments (Fig. 1), resulting in two replicates of each overstory harvest treatments:

1) Single-tree selection: this treatment reduced the basal area of canopy dominant and co-dominant trees (generally trees ≥ 30 cm dbh) by about 10 to 15 %. The residual basal area was approximately 23 to 25 m^2/ha, checked frequently with a prism during marking. No set diameter limit or diameter guiding curve was used, but some of the larger trees (>102 cm dbh) were retained to biological maturity and other large trees judged not likely to survive to the next 15-year cutting cycle entry were removed. The harvest was intended to create single-tree gaps to release existing clumps of large oak advance reproduction. All cavity trees were left to provide habitats for wildlife species.

2) Selection cut: this treatment combined single-tree selection and small group openings to reduce the basal area by 50 % by removing trees > 15 cm dbh. The residual basal area following the entry was 14 m^2/ha, checked frequently with a prism during marking. No set diameter limit or diameter guiding curve was used, but again, the desire was to carry some trees to biological maturity by retaining the larger trees (>102 cm dbh) and removing large trees judged to not survive to the next 15-year cutting cycle entry. This first entry was a basal area reduction by removal of: 1) large or poor-quality trees that would either die before next entry or add little value to the stand, 2) a single tree or small group of trees that released existing clumps of advanced oak reproduction or small oak trees, and 3) enough trees to meet the residual target by considering factors such as tree species, crown condition and tree form. Small groups were occasionally used where there were large groups of desirable oak advance reproduction. All cavity trees were retained.
3) Shelterwood with reserves: this treatment retained 30 to 40 % of the residual overstory basal area. The largest oaks were retained in the overwood and all other non-oaks were harvested or slashed. The trees retained in order of preference were pin oak, willow oak, and cherrybark oak. Generally, residual trees were of good form, had full spreading crowns, and appeared to be healthy. Moreover, most cavity trees were retained. It is expected that during subsequent years, many of the reserve trees would decline and die as they surpass their biological maturity, providing snag and cavity trees to the future stand. Surviving trees will provide a biological legacy to the future stand.

2.4. Additional competition control

In 2010, an additional midstory competition control treatment was applied after the overstory harvest in the two experimental units within each block where the direct seeding had originally been applied at the beginning of the experiment (Fig. 1). The purpose of this treatment was to test the effects of a late release of pin oak reproduction by controlling competing woody vegetation (e.g., red maple and green ash). All non-oak stems > 60 cm tall or larger within the 0.08-ha overstory vegetation plot were treated with a basal bark application with triclopyr herbicide (25 % solution) mixed with oil (75 % solution). Since the direct seeding had been a failure (Motsinger et al. 2010), this additional competition control treatment was applied to investigate its effects on the density of natural reproduction of oaks and other hardwood species.

2.5. Data collection

The initial basal diameters and heights of tagged individual seedlings of each stock type (natural, bareroot, and RPM®) were recorded in April 2003, when planting occurred. All surviving seedlings were re-measured following the first (2003), second (2004), and third (2005) growing seasons (Motsinger et al., 2010). Prior to implementing the overstory harvests, the tagged seedlings were re-inventoried in 2010, and subsequently in 2012 and 2017. In 2017, data were collected on natural reproduction in the 0.08-ha circular plot established at the center of each experimental unit during the original study. The species and dbh of each midstory woody stem (3.8 cm ≤ dbh < 11.4 cm) were recorded. In addition, species and dbh of all trees between 1.37 m tall and 3.8 cm dbh were measured in five 0.004-ha subplots, and species and height of all trees < 1.37 m tall measured in five 0.0004-ha subplots (Fig. 1B).

2.6. Statistical analyses

2.6.1. Tagged artificial reproduction

Survival was very low for the original direct seeded acorns and tagged natural reproduction, and thus these stock types were not included in this analysis. The effects of overstory harvest, competition control treatment (midstory, midstory + understory), year, and their interactions on survival, size, and growth of bareroot and RPM® stock types (Objective 1) were tested with repeated measures split-plot analysis of variance (ANOVA) using MIXED procedure of SAS (version 9.3; SAS Institute, Inc., Cary, NC). Overstory harvest was the whole-plot factor, and the split-plot factor was a factorial that combined two levels of competition control treatment (midstory, midstory + understory) and two levels of stock type (bareroot and RPM®). We used overstory harvest, competition control treatment, year of measurement, and their interactions as fixed effects and the random effects included block, and block × overstory harvest interaction. Annual growth of the oaks was calculated as the difference in height or basal diameter between sampling years, divided by number of years. All pairwise comparisons were evaluated with Tukey's honestly significant difference adjustment.

We tested the effect of initial size of bareroot and RPM® pin oak advance reproduction on the likelihood of survival for each growing season that data were collected using logistic regression (Objective 2). We used a generalized linear mixed model with a binomial distribution, a logit link function, and random intercepts that used experimental unit, and experimental unit nested within block as subjects, using GLIMMIX procedure of SAS.

2.6.2. Natural reproduction

For Objective 3, we were interested in evaluating the effects of the study treatments (midstory and understory competition control and subsequent overstory harvest) on the development of natural reproduction. We grouped natural reproduction into nine species groups based on abundance and management objectives, including white oak species, red oak species, green ash, red maple, persimmon, flowering dogwood (*Cornus florida* L.), hickory species, sweetgum, and "others". The white oak group included overcup oak, and the red oak group included pin oak, willow oak, and cherrybark oak. The hickory group included bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch), and "others" group included possum haw (*Ilex decidua* Walt.), honey locust (*Gleditsia triacanthos* L.), button bush (*Cephalanthus occidentalis* L.), American elm, slippery elm (*Ulmus rubra* Muhl.), winged elm (*Ulmus alata* Michx.), pumpkin ash (*Fraxinus profunda* (Bush) Bush), boxelder (*Acer negundo* L.), blackgum (*Nyssa sylvatica* Marsh.), sugarberry (*Celtis laevigata* Willd.), hawthorn (*Crataegus monogyna* Jacq.), baldcypress, black willow (*Salix nigra* Marsh.), hackberry (*Celtis occidentalis* L.), and sassafras (*Sassafras albidum* (Nutt.) Nees). The abundance of stems in each species group was summarized for seedlings (trees < 1.37 m tall), small saplings (trees > 1.37 m height and < 3.8 cm dbh) and large saplings (trees 3.8 cm to 11.4 cm dbh).

For this analysis, we grouped the original experimental units into three treatment levels that varied in the type and timing of releases: 1) the untreated control; 2) the original midstory removal with and without understory release, applied in 2003, referred to hereafter as "midstory removal"; and 3) the additional release applied in 2010, referred to hereafter as "midstory removal + late release". Of the original nine experimental units within each block, the untreated control was applied to one experimental unit, the midstory removal + late release treatment was applied to two experimental units, and the other six experimental units each received the early midstory removal treatment. These three treatment designations (midstory removal, midstory removal + late release, and untreated control) will hereafter be referred to as "competition control timing".

We tested the effects of overstory harvest, competition control timing, species group, year, and their interactions on the density of natural reproduction with repeated measures split-plot analysis of variance (ANOVA) using MIXED procedure of SAS (version 9.3; SAS Institute, Inc., Cary, NC). Overstory harvest was used as the whole-plot factor, competition control timing as the split-plot factor, and species group as the split-split-plot factor. Overstory harvest, competition control timing, species group, year of measurement, and their interactions were the fixed effects and the random effects included block, block ×

overstory harvest, and block × overstory harvest × competition control timing interactions. Since the density data included zeros, we added a constant of 1 to each density value and log-transformed to normalize the data (i.e., log (density + 1)). For significant treatment effects (α = 0.05), the differences among individual means were estimated using Tukey's honestly significance difference.

3. Results

3.1. Survival of artificial pin oak reproduction

There was a significant interaction between competition control treatment (midstory, midstory + understory) and sampling year on survival of pin oak reproduction (p = 0.01; Fig. 2). Survival following each of the first three growing seasons was greater in the midstory treatment relative to midstory + understory treatment. However, this effect diminished through time, and the competition control treatment was not significant at years 8, 10, and 15. Survival in both competition control treatments exceeded 60 % after year 3 but dropped to 40 % or less after year 15. Overstory harvest (p = 0.75), stock type (p = 0.27), and competition control treatment (p = 0.43) showed no effects on the survival of pin oak reproduction. No other interactions were significant (Supplementary Table S1).

The importance of the stem diameter at planting for subsequent survival differed between bareroot seedlings and the RPM® seedlings. The probability of survival of bareroot pin oak plantings increased with increasing initial diameter following year 8, with the strength of the relationship then increasing through time (Fig. 3; Supplementary Table S2). The survival probabilities of bareroot seedlings with initial diameter > 1.4 cm exceeded 0.60, and these seedlings were at least 3 times more likely to survive than those that had initial diameters of < 0.8 cm following year 15. For RPM® seedlings, survival increased with planting size at years 8 and 10, but this relationship was no longer significant at year 15. At year 15, all RPM® seedlings, regardless of size, showed survival probabilities<0.50, with an overall mean survival probability of 0.31.

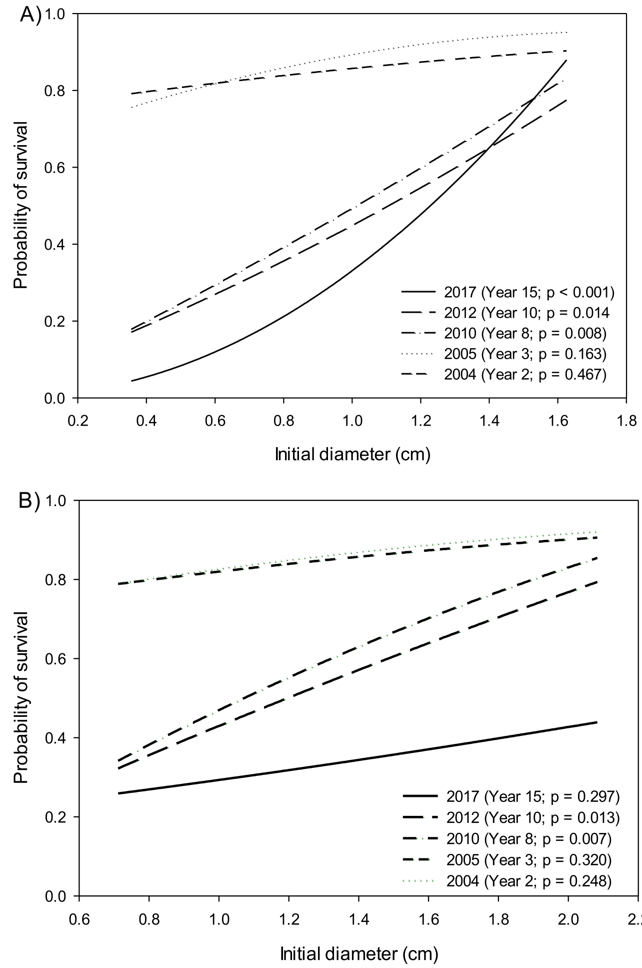

Fig. 3. Probability of bareroot (A) and RPM® (B) pin oak survival at the end of each year in relation to initial diameter.

3.2. Size and growth of artificial pin oak reproduction

The interaction between overstory harvest and year was statistically significant for height (p = 0.04) and diameter (p = 0.03) (Fig. 4A and C). There were no significant differences in the height or diameter of the planted pin oak seedlings among the overstory harvest treatments until 15 years after planting. The selection cut and shelterwood treatments resulted in similar heights, both of which were greater than height in the single-tree selection. The diameters in selection cut and shelterwood were also similar but only selection cut showed an increase when compared to the single-tree selection. There was, however, no significant interaction between the overstory harvest treatment and sampling year on height growth (p = 0.25) and diameter growth (p = 0.08) (Fig. 4B, D).

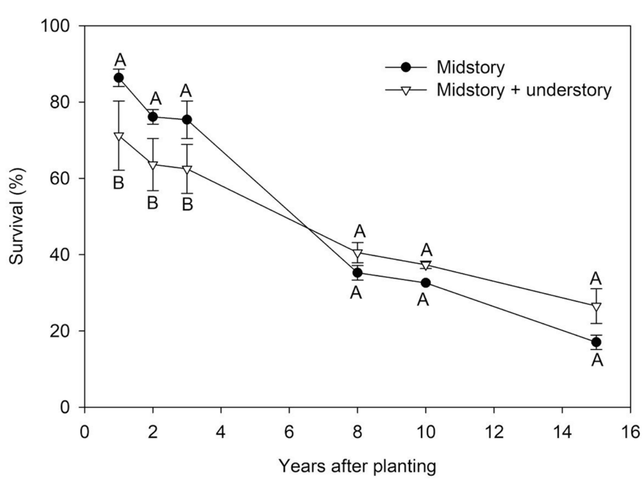

Fig. 2. Percentage survival (mean ± 1 SE) of bareroot and RPM® pin oak reproduction by treatment at the end of each growing season. Treatments included midstory removal (midstory), and midstory plus understory removal (midstory + understory). Different letters within a given time period indicate significant differences between the two levels of treatments (p < 0.05). Differences among years within each treatment were not shown to reduce complexity and increase readability.

There was a significant effect of stock type on height (p = 0.04), diameter (p = 0.05), height growth (p = 0.02), and diameter growth (p = 0.01) (Supplementary Tables S3 and S4). Across the study years, the size and growth of RPM® container stock were greater than the bareroot stock (Fig. 5). The competition control treatments (midstory, midstory + understory) had no effect on height (p = 0.89), diameter (p = 0.95), height growth (p = 0.65), and diameter growth (p = 0.64) of pin oak advance reproduction. No other interactions were significant (Supplementary Tables S3 and S4).

3.3. Density of natural reproduction

For seedlings (trees < 1.37 m tall), there was a significant interaction effect of species group and year on the density of seedlings (p < 0.01) (Fig. 6), and no other interactions were significant (Supplementary Table S5). The red oak group was the most abundant species group in

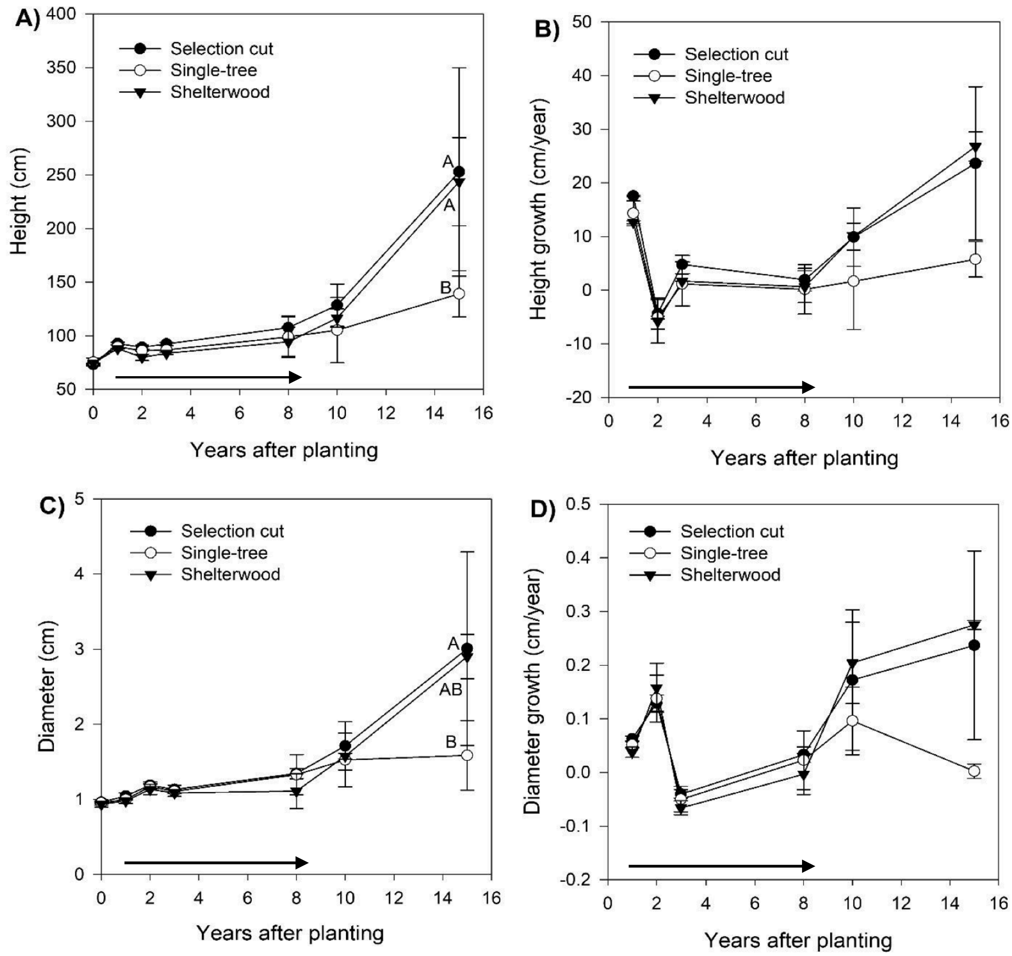

Fig. 4. Height (mean ± 1 SE) (A), height growth (B), diameter (C), and diameter growth (D) of pin oak bareroot and RPM® reproduction. Different letters within a given time period indicate significant differences among the three levels of treatments ($p < 0.05$). Differences among years within each treatment were not shown to reduce complexity and increase readability. The horizontal arrow along the x-axis indicates when the harvest took place.

2010 and 2012, and red maple was the only competitor species that was not different from the red oak group. By 2017, all the species groups had declined in density, but the red oak group had greater abundance than all the other species groups. There was a significant effect of competition control timing on the density of seedlings ($p < 0.01$; Supplementary Table S5) (Fig. 7). The densities of seedlings in the midstory removal and midstory removal + late release treatments were greater than the untreated control. However, there was no difference between the densities of midstory removal and midstory removal + late release treatments.

The interaction effect of overstory harvest and species group on the density of small saplings (trees > 1.37 m tall and < 3.8 cm dbh) was statistically significant ($p = 0.02$; Supplementary Table S6) (Fig. 8). The density of red maple was greater than the other species groups in all the overstory harvest treatments. Except for red maple and green ash, the density of small red oak saplings in the shelterwood treatment was greater than all the other species groups. The interaction between overstory harvest and competition control timing affected the density of small saplings ($p = 0.04$; Supplementary Table S6) (Fig. 9). The densities of small saplings in the midstory removal, and midstory removal + late release treatments were greater than the untreated control in both the shelterwood and selection cut, but there were no differences among the competition control timing treatments in the single-tree selection. We found no differences in density of small saplings among the overstory harvest treatments within midstory removal. Within midstory removal + late release, the densities of small saplings were similar in both shelterwood and selection cut, but only those in shelterwood were greater than single-tree selection. Similarly, within the untreated control, the densities of small saplings were similar in both shelterwood and selection cut, but single-tree selection was greater than the selection cut.

There was a significant three-way interaction among competition control timing, species group, and year on the density of large saplings (≥3.8 cm dbh but < 11.4 cm) ($p < 0.01$; Supplementary Table S7) (Table 2). There were substantial quantities of most competitor hardwood species in the untreated control treatments in 2010 and 2012 but these sharply declined in 2017. The midstory removal, and midstory removal + late release treatments appeared to be effective in reducing the quantities of most species groups. Red maple, green ash, persimmon, sweetgum, and the category “other species” in these treatments were lower than in the untreated control treatments in 2010 and 2012. However, some of these species groups, especially red maple, resurfaced in greater quantities in 2017 than existed in the untreated control treatments in 2010 and 2012. The competition control timing did not have any effect on the oaks. Both the red oak and white oak tree densities were not different among the untreated control, midstory removal, and midstory removal + late release treatments in all years. Red maple and sweetgum appeared to be the most prolific competitor hardwood species in the long term, but the midstory removal + late release treatment reduced both, since in 2017, their densities reduced in the midstory removal + late release compared to the midstory removal treatment.

There was a three-way significant interaction effect of overstory harvest, species group, and year on the density of large saplings ($p < 0.01$; Supplementary Table S7) (Table 3). Shelterwood treatment

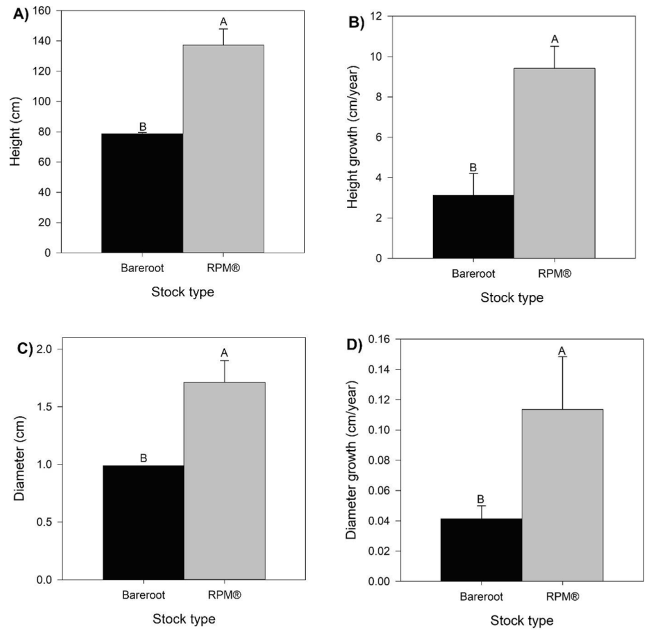

Fig. 5. Height (mean ± 1 SE) (A), height growth (B), diameter (C), and diameter growth (D) by stock type of pin oak reproduction. Different letters between bareroot and RPM® stock types indicate significant differences ($p < 0.05$).

increased the density of large white oak saplings compared to the single-tree selection and selection cut treatments in 2017. The density of red oak on the other hand was not affected by any of the overstory harvest treatments in all years. Although the shelterwood increased the density of white oak in 2017, it also resulted in proliferation of red maples. In 2017, red maple was the most dominant species group, being greater in density than the other species groups within the overstory treatments that received the most cut (i.e, selection cut and shelterwood).

4. Discussion

Our study tested a sequence of release events applied to different forest canopy layers, with interest in regenerating oak in bottomland forests. Previous studies have demonstrated enhanced development of

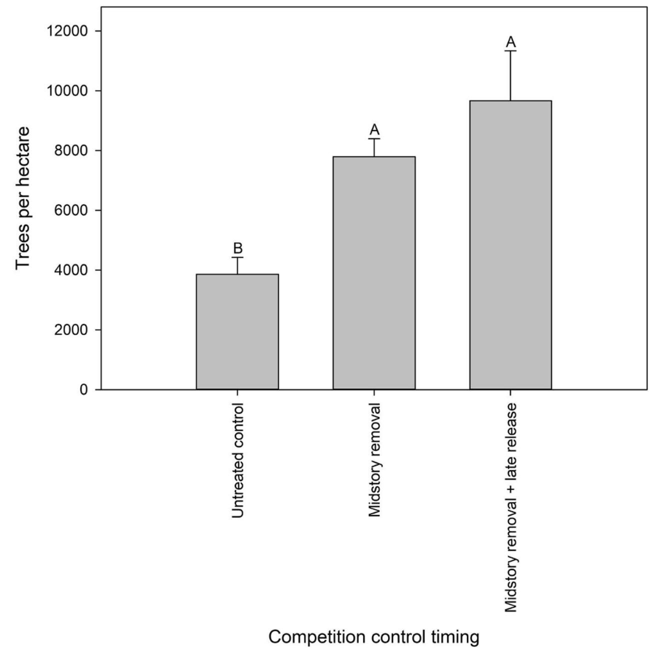

Fig. 7. Competition control timing effects on density of seedlings (trees < 1.37 m tall). Different letters indicate significant differences among competition control timing treatments ($p < 0.05$).

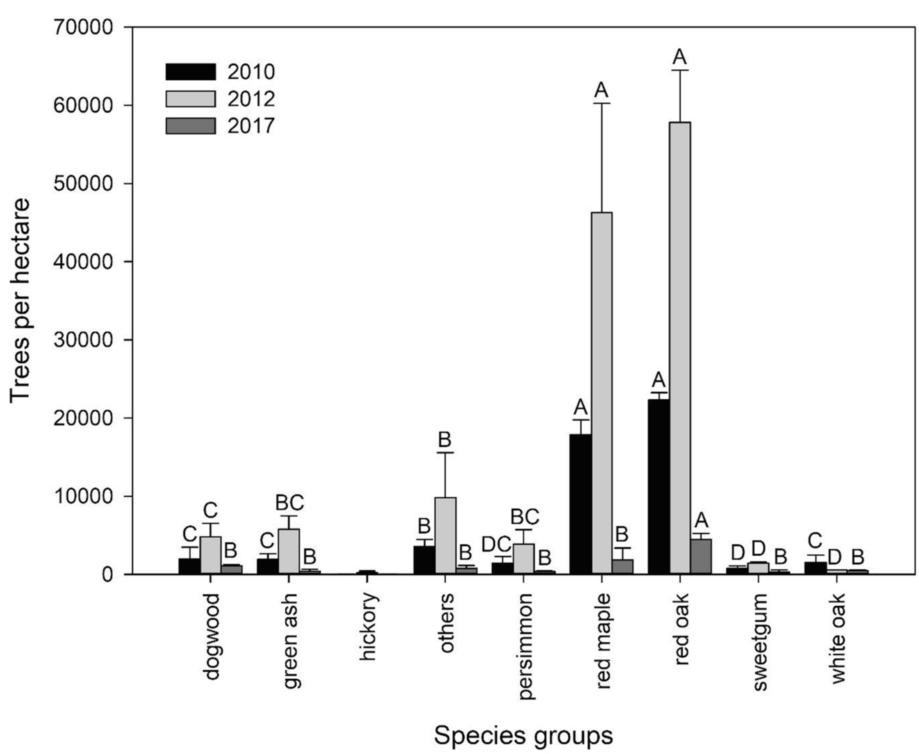

Fig. 6. Density of seedlings (trees < 1.37 m tall) by species groups through time. Different letters within a given year indicate significant differences among the species groups ($p < 0.05$).

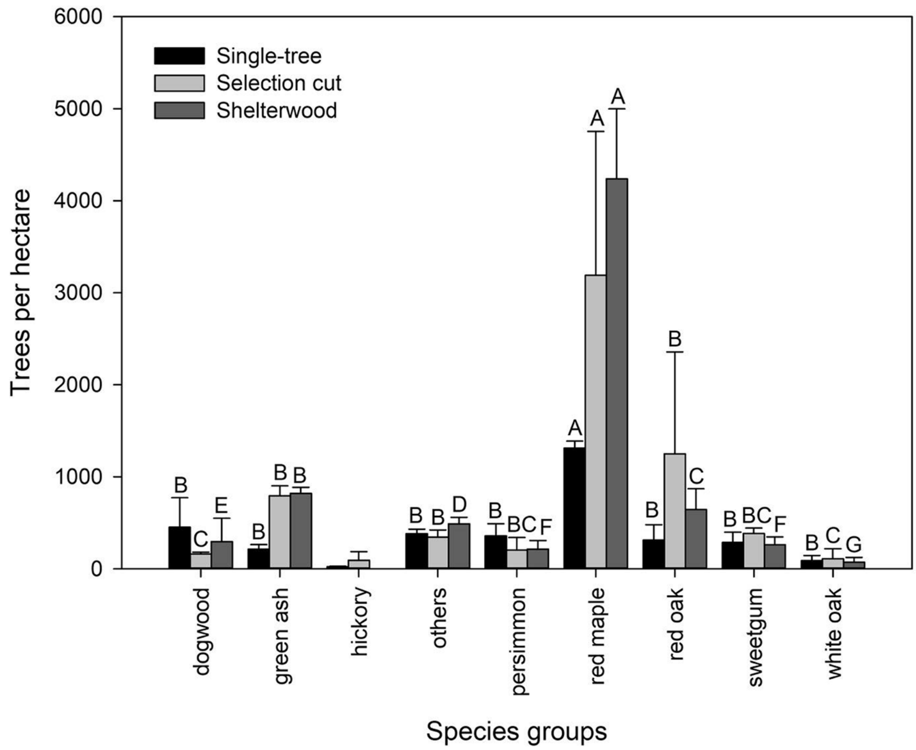

Fig. 8. Density of small saplings (trees > 1.37 m height and < 3.8 cm dbh) by species groups within each overstory harvest treatments. Different letters within an overstory harvest treatment indicate significant differences among the species groups ($p < 0.05$).

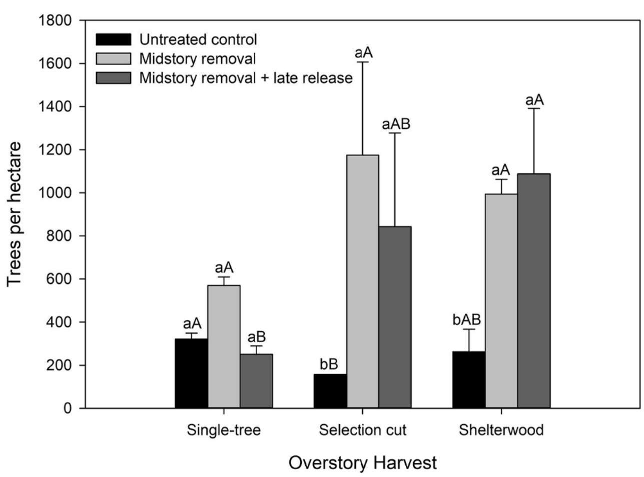

Fig. 9. Graphical representation of interaction effects of overstory harvest and competition control timing on density of small saplings (trees > 1.37 m height and < 3.8 cm dbh). Different uppercase letters indicate significant differences among overstory harvest treatments within a given competition control timing treatment. Different lowercase letters indicate significant differences among competition control timing treatments within a given overstory harvest treatment.

oak advance reproduction following midstory and overstory release (Lockhart et al., 2000; Lhotka and Loewenstein, 2009; Miller et al., 2017; Frank et al., 2018). In productive sites, multiple release events may be necessary to generate sustained growth of oak. Our study evaluated the effect of midstory and understory competition control and a subsequent overstory release on underplanted and naturally regenerated oak advance reproduction.

Results from our study indicated that characteristics of planting stock may result in some long-term differences in survival. We found that bareroot seedling survival increased with initial planting size. This has also been reported with other plantings, including shortleaf pine (*Pinus echinata* Mill.) (Kabrick et al., 2015, 2011), longleaf pine (*Pinus palustris* Mill.) (South et al., 2005), and nuttall oak (Gardiner et al., 2009). Larger seedling sizes generally tend to have more balanced root to shoot ratio that lessen transplant shock and increase seedling survival. This relationship was found in intermediate years but did not persist for RPM® seedlings. We assume that the RPM® seedlings had well-developed and intact root system that promoted early survival and growth irrespective of initial planting size. Across the seedling populations, we found no difference in mean survival between the two stock types, yet the bareroot seedlings that were big at the start appeared to have much better survival than the RPM® seedlings by the fifteenth year after planting. This is in contradiction with other studies that have reported better survival for RPM® container stock over bareroot stock (Dey et al., 2004; Wilson et al., 2007; Walter et al., 2013). Our results thus suggest that survival of RPM® seedlings is not different than that of bareroot stock over the long-term. The RPM® container stock that survived, however, grew larger than the bareroot stock.

Our results suggested no benefit to survival or growth from understory competition control applied during the first few years following planting, regardless of pin oak seedling stock. Similarly, Gardiner and Yeiser (2006) found no effect on survival and growth of cherrybark oak four years after controlling Japanese honeysuckle (*Lonicera japonica* Thunberg) with metsulfuron-methyl herbicide. Controlling herbaceous competition with glyphosate herbicide reduced survival and growth of underplanted oaks following the first growing season in bottomland forests in Texas (Oliver et al., 2019). Contrary to our findings, other studies have reported increased survival and growth of oaks following understory competition control (Ezell and Hodges, 2001; Ezell et al., 2007; Woeste et al., 2005; Self et al., 2014). In our study, we suspect that inadvertent overspray or off-target drift from the triclopyr herbicide applied to the competing non-oaks may have reduced the survival of bareroot and RPM® pin oak reproduction in the first few years after application. Also, it is likely that some herbicide residue from the target

Table 2
Natural reproduction per hectare by competition control treatment for each species group through time for large saplings (trees ≥ 3.8 cm dbh but < 11.4 cm) sampled in 0.08-ha plot. Differences within columns are indicated with lowercase letters and differences within rows are indicated with uppercase letters ($p < 0.05$).

Treatment	Dogwood	Green ash	Hickory	Others	Persimmon	Red maple	Red oak	Sweetgum	White oak	p-value
Trees per hectare in 2010										
Untreated control	1.0 E	13.5 D a	1.0 E	113.5 A a	16.8 D a	77.7B a	2.7 A	53.5C a	3.5 E	<0.01
Midstory removal	1.1B	2.1B b	1.4B	11.7 A b	1.6B b	12.0 A b	2.8B	6.1 AB b	2.3B	<0.01
Midstory removal + late release	1.8B	1.8B b	1.8B	8.5 A b	1.4B b	2.7B c	1.4B	7.7B b	2.3B	0.01
p-value	0.90	<0.01	0.90	<0.01	<0.01	<0.01	0.86	<0.01	0.93	
Trees per hectare in 2012										
Untreated control	1.0 D	14.3C a	1.0 D	83.1 A a	13.1C a	69.8 A a	2.7 D	62.7B a	2.7 D	<0.01
Midstory removal	1.1B	2.2B b	1.4B	12.5 A b	1.5B b	10.5 A b	2.1B	5.7 AB b	1.8B	<0.01
Midstory removal + late release	1.0	1.8b	1.8	4.3b	1.0b	1.8c	1.8	1.8b	1.8	0.34
p-value	1.00	<0.01	0.82	<0.01	<0.01	<0.01	0.93	<0.01	0.65	
Trees per hectare in 2017										
Untreated control	1.0	1.0b	1.0	4.3	1.0	7.7c	1.0	4.3c	1.0	0.69
Midstory removal	3.4 D	33.4C a	7.7 D	11.0CD	7.2 D	141.5 A a	10.5 D	43.9B a	7.2 D	<0.01
Midstory removal + late release	1.0C	17.7B a	1.0C	7.7B	1.0C	124.3 A b	1.0C	11.0B b	7.7B	<0.01
p-value	0.75	0.01	0.53	0.36	0.22	<0.01	0.23	<0.01	0.09	

Table 3
Natural reproduction per hectare by harvest treatment for each species group through time for large saplings (trees ≥ 3.8 cm dbh but < 11.4 cm) sampled in 0.08-ha plot. Differences within columns are indicated with lowercase letters and differences within rows are indicated with uppercase letters ($p < 0.05$).

Treatment	Dogwood	Green ash	Hickory	Others	Persimmon	Red maple	Red oak	Sweetgum	White oak	p-value
Trees per hectare in 2010										
Single-tree	1.8B	3.5B	1.0B	26.8 A	4.6B	31.8 A	4.8B	24.5 A	1.6B	<0.01
Selection cut	1.0C	5.6B	2.1 BC	40.3 A	11.1B	33.8 A	1.0C	13.6B	4.8 BC	<0.01
Shelterwood	1.1C	8.4B	1.1C	66.6 A	4.1 BC	26.7B	1.1C	29.2B	1.7C	<0.01
p-value	0.90	0.27	0.79	0.44	0.93	0.36	0.16	0.40	0.40	
Trees per hectare in 2012										
Single-tree	1.0C	3.6C	1.0C	26.0 A	4.6 BC	29.8 A	4.6 BC	22.5 AB	1.8C	<0.01
Selection cut	1.0C	4.1C	2.1C	14.1 A	7.0 BC	13.2 A	1.0C	4.7C	3.3C	<0.01
Shelterwood	1.1C	8.1B	1.1C	58.4 A	2.8C	22.5B	1.0C	24.1B	1.1C	<0.01
p-value	1.00	0.35	0.69	0.26	0.53	0.06	0.08	0.45	0.37	
Trees per hectare in 2017										
Single-tree	1.0	7.7b	2.0	4.3b	4.3	28.6b	7.7	15.3b	4.3b	0.06
Selection cut	2.0B	11.5B b	6.7B	5.3B b	2.4B	41.0 A b	2.4B	18.1 A b	1.0B b	<0.01
Shelterwood	2.4CD	32.9B a	1.0 D	13.4B a	2.4CD	203.9 A a	2.4 DC	25.8B a	10.5 BC a	<0.01
p-value	0.93	<0.01	0.72	<0.01	0.94	<0.01	0.95	<0.01	0.01	

vegetation may have had contact with leaves of the oak seedlings. Broadcast application of triclopyr herbicide prior to planting may have been more effective in controlling the understory competition and prevented damage to oak seedlings in this study.

The midstory removal treatments used in our study did not increase the abundance of natural oak advance reproduction. Midstory removal is often used to enhance the establishment and development of oak reproduction by increasing understory light levels and directly removing competitors. Compared to the untreated control, the midstory removal increased the density of seedlings and small saplings, regardless of species. While the release treatments did not disproportionately favor oak species, we found that red oaks were among the most abundant seedlings in each measurement year. However, the midstory removal treatments failed to increase the density of large oak saplings, suggesting that oak seedlings are not recruiting into larger size classes. Instead, the release treatments resulted in the dominance of red maple in the large sapling size class at the end of the study period. We were not able to test the effects of midstory removal on planted pin oaks.

We found that the intensity of the overstory removal affected the size of artificially regenerated pin oak, with the greatest pin oak size in the shelterwoods. Our findings are consistent with other studies that have reported increased height and diameter of oak reproduction under shelterwood treatment (Loftis, 1990; Brose, 2011; Miller et al., 2017; Frank et al., 2018; Hackworth et al., 2020). The larger seedling sizes in the shelterwood stands can be attributed to increased light levels that translated into increased photosynthetic rates. Shelterwood harvest can provide 35 to 50 % of full sunlight to promote the development of oak advance reproduction and improve the chances of maintaining an oak component in a stand when more than 50 % of the basal area is removed (Gottschalk, 1994; Dey and Parker, 1997; Dey et al., 2007).

The release provided by the shelterwood harvest also affected other species, potentially increasing competitive pressure on pin oak reproduction. In particular, the abundance of red maple increased with the shelterwood treatment. Other studies have reported similar findings of increased density of red maple and other competing vegetation following shelterwood treatment (Gottschalk, 1994; Hackworth et al., 2020). The selection cut increased the growth of planted oaks, just like the shelterwood, but released fewer red maple saplings. Moderate light levels produced by the selection cut releases oaks without releasing many red maples. This suggests that multiple intermediate removals such as those targeting the midstory followed later by those removing some of the overstory favor the development and recruitment of oak by releasing fewer competitors. Additional control of oak competitors, particularly red maple, may be warranted to ensure oak recruitment.

5. Conclusion

The results from this study indicate that the survival of bareroot pin oak seedlings increased with increasing initial basal diameter, and survival exceeded 60 % following the fifteenth growing season when the initial basal diameter was > 1.4 cm. The survival of RPM® pin oak seedlings on the other hand, did not show any clear pattern of dependence on size at the time of planting. We speculated that the RPM® seedlings had well-developed root system that promoted early survival and growth irrespective of initial planting size. We found no difference in stock type for survival fifteen years after planting, but bareroot seedlings with big initial basal diameter appeared to have better survival than the RPM® seedlings. Thus, we recommend planting big bareroot oak seedlings to ensure better survival in the long-term. We found no benefit of understory release on survival or growth of oak advance reproduction. Natural oak advance reproduction was unaffected by late midstory release probably due to influx of oak competitors following treatment application that restricted their establishment and development. While the shelterwood harvest increased the growth of planted pin oaks, its likelihood for oak regeneration success depends on sufficient size and numbers of oak advance reproduction prior to overstory harvest. We found that the shelterwood treatment also resulted in abundant natural reproduction of oak competitors. Thus, a lighter overstory harvest such as that in our selection cut may provide better balance between increasing the growth of oak advance reproduction while also suppressing the development of competitors.

CRediT authorship contribution statement

Isaac Hayford: Methodology, Formal analysis, Writing – original draft. **Benjamin O. Knapp:** Methodology, Formal analysis, Writing – review & editing, Supervision. **John M. Kabrick:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Funding for this project was provided by the Missouri Department of Conservation and the USDA Forest Service. We thank Nicholas Krekeler, Jonathan Motsinger, Daniel Dey, Michael Anderson, David Wissehr, Keith Cordell, Dawn Henderson, Megan Buchanan, Mark Pelton, Ross Glenn, Joe Garvey, Brad Pendley, Ben Mense, Jason Lewis, Texas Nall, Billy Bryant, and Seph DeRuiter, and many others who set up the project or supported the work through time.

References

Allen, J.A., Keeland, B.D., Stanturf, J.A., Clewell, A.F., Kennedy, H.E., Jr., 2001. A guide to bottomland hardwood restoration. USDA Forest Service General Technical Report SRS-40, Southern Research Station, Asheville, NC, pp. 132.

Belli, K.L., Hart, C.P., Hodges, J.D., Stanturf, J.A., 1999. Assessment of the regeneration potential of red oaks and ash on minor bottoms of Mississippi. South. J. Appl. For. 23, 133–138. https://doi.org/10.1093/sjaf/23.3.133.

Brose, P.H., 2008. Root development of acorn-origin oak seedlings in shelterwood stands on the Appalachian Plateau of northern Pennsylvania: 4-year results. For. Ecol. Manage. 255, 3374–3381. https://doi.org/10.1016/j.foreco.2008.02.021.

Brose, P.H., 2011. A comparison of the effects of different shelterwood harvest methods on the survival and growth of acorn-origin oak seedlings. Can. J. For. Res. 41, 2359–2374. https://doi.org/10.1139/X11-143.

Clatterbuck, W.K., Meadows, J.S., 1993. Regenerating oaks in the bottomlands. In proceedings, oak regeneration: serious problems, practical recommendations. USDA Forest Service General Technical Report SE-84, Southern Research Station, Asheville, NC, pp. 184-195.

Dey, D.C., Kabrick, J., Gold, M.A., 2003. Tree establishment in floodplain agroforestry practices. In proceedings of the 8th North American agroforestry conference. Association for Temperate Agroforestry, Corvallis, OR, pp. 102–115.

Dey, D.C., Lovelace, W., Kabrick, J.M., Gold, M.A., 2004. Production and early field performance of RPM® seedlings in Missouri floodplains. Proceedings of the 6th walnut council research symposium. USDA Forest Service General Technical Report NC-243, North Central Research Station, St. Paul, MN, pp. 59–65.

Dey, D.C., Miller, G.W., Kabrick, J.M., 2007. Sustaining northern red oak forests: managing oak from regeneration to canopy dominance in mature stands. USDA Forest Service General Technical Report PNW-733, Pacific Northwest Research Station, Portland, OR, pp. 91-105.

Dey, D.C., Jacobs, D., McNabb, K., Miller, G., Baldwin, V., Foster, G., 2008. Artificial regeneration of major oak (*Quercus*) species in the eastern United States - a review of the literature. For. Sci. 54, 77–106. https://doi.org/10.1093/forestscience/54.1.77.

Dey, D.C., Parker, W.C., 1997. Overstory density affects field performance of underplanted red oak (*Quercus rubra* L.) in Ontario. North. J. Appl. For. 14 (3), 120–125.

Ezell, A.W., Hodges, J.D., 2001. Herbaceous weed control improves survival of planted shumard oak seedlings. In proceedings of the Biennial Southern Silvicultural Research Conference, Knoxville, TN, pp. 273–275.

Ezell, A.W., Yeiser, J.L., Nelson, L.R., 2007. Survival of planted oak seedlings is improved by herbaceous weed control. Weed Technol. 21, 175–178. https://doi.org/10.1614/wt-06-114.1.

Frank, G.S., Rathfon, R.A., Saunders, M.R., 2018. Ten-year response of underplanted northern red oak to silvicultural treatments, herbivore exclusion, and fertilization. Forests 9 (9), 571.

Fredrickson, L.H., Baskett, T.S., Brakhage, G.K., Cravens, V.C., 1977. Evaluating cultivation near duck blinds to reduce lead poisoning hazard. J. Wildl. Manage. 41, 624. https://doi.org/10.2307/3799982.

Gardiner, E.S., Jacobs, D.F., Overton, R.P., Hernandez, G., 2009. Root collar diameter and third-year survival of three bottomland hardwoods planted on former agricultural fields in the lower Mississippi Alluvial Valley. In national proceedings: Forest and Conservation Nursery Associations-2008. Proceedings of RMRS-P-58, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 85-89.

Gardiner, E.S., Yeiser, J.L., 2006. Underplanting cherrybark oak (*Quercus pagoda* Raf.) seedlings on a bottomland site in the southern United States. New For. 32, 105–119. https://doi.org/10.1007/s11056-005-4168-2.

Gottschalk, K.W., 1994. Shade, leaf growth and crown development of *Quercus rubra*, *Quercus velutina*, *Prunus serotina* and *Acer rubrum* seedlings. Tree Physiol. 14 (7), 735–749.

Hackworth, Z.J., Lhotka, J.M., Stringer, J.W., 2020. Midstory removal facilitates growth but reduces competitiveness of oak reproduction prior to and after shelterwood establishment cutting. For. Sci. 66, 371–381. https://doi.org/10.1093/forsci/fxz083.

Hayford, I., Chhin, S., 2020. Influence of climate on oak savanna tree species in the midwestern United States. Int. J. Environ. Clim. Chang. 10, 7–23. https://doi.org/10.9734/ijecc/2020/v10i1030243.

Hodges, J.D., Gardiner, E.S., 1993. Ecology and physiology of oak regeneration. In proceedings, oak regeneration: serious problems, practical recommendations. USDA Forest Service General Technical Report SE-84, Southern Research Station, Asheville, NC, pp. 54-65.

Holladay, C.A., Kwit, C., Collins, B., 2006. Woody regeneration in and around aging southern bottomland hardwood forest gaps: effects of herbivory and gap size. For. Ecol. Manage. 223, 218–225. https://doi.org/10.1016/j.foreco.2005.11.004.

Johnson, R.L., 1984. Direct-seeded cherrybark and shumard oaks battle natural regeneration through 10 years. South. J. Appl. For. 8 (4), 226–230.

Kabrick, J.M., Dey, D.C., Shifley, S.R., Villwock, J.L., 2011. Early survival and growth of planted shortleaf pine seedlings as a function of initial size and overstory stocking. In proceedings of the 17th Central Hardwood Forest Conference, Lexington, KY, USA. USDA Forest Service General Technical Report NRS-P-78, Northern Research Station, Newtown, PA, pp. 277-286.

Kabrick, J.M., Knapp, B.O., Dey, D.C., Larsen, D.R., 2015. Effect of initial seedling size, understory competition, and overstory density on the survival and growth of *Pinus echinata* seedlings underplanted in hardwood forests for restoration. New For. 46, 897–918. https://doi.org/10.1007/s11056-015-9487-3.

Kellison, R.C., Young, M.J., 1997. The bottomland hardwood forest of the southern United States. For. Ecol. Manage. 90, 101–115. https://doi.org/10.1016/S0378-1127(96)03905-9.

Kennedy Jr., H.E., 1993. Artificial regeneration of bottomland oaks. In: In ProceedIngs, Oak Regeneration: Serious Problems, Practical Recommendations. USDA Forest Service General Technical Report SE-84. Southern Research Station, Asheville, NC, pp. 241–249.

Krekeler, N., Kabrick, J., Dey, D., Wallendorf, M., 2006. Comparing natural and artificial methods for establishing pin oak advance reproduction in bottomland forests managed as greentree reservoirs. In: USDA Forest Service General Technical Report SRS-92. Southern Research Station, Ashville, NC, pp. 224–228.

Lhotka, J.M., Loewenstein, E.F., 2009. Effect of midstory removal on understory light availability and the 2-year response of underplanted cherrybark oak seedlings. South. J. Appl. For. 33, 171–177. https://doi.org/10.1093/sjaf/33.4.171.

Lockhart, B.R., Hodges, J.D., Gardiner, E.S., 2000. Response of advance cherrybark oak reproduction to midstory removal and shoot clipping. South. J. Appl. For. 24, 45–50. https://doi.org/10.1093/sjaf/24.1.45.

Löf, M., Castro, J., Engman, M., Leverkus, A.B., Madsen, P., Reque, J.A., Villalobos, A., Gardiner, E.S., 2019. Tamm review: direct seeding to restore oak (*Quercus spp.*) forests and woodlands. For. Ecol. Manage. 448, 474–489. https://doi.org/10.1016/j.foreco.2019.06.032.

Loftis, D.L., 1990. A shelterwood method for regenerating red oak in the southern Appalachians. For. Sci. 36 (4), 917–929.

Lorimer, C.G., 1993. Causes of oak regeneration problem. In proceedings, oak regeneration: serious problems, practical recommendations, symposium. USDA Forest Service General Technical Report SE-84, Southern Research Station, Knoxville, TN, pp. 66-78.

Lorimer, C.G., Chapman, J.W., Lambert, W.D., 1994. Tall understorey vegetation as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. 82 (2), 227–237.

Meadows, J.S., Stanturf, J.A., 1997. Silvicultural systems for southern bottomland hardwood forests. For. Ecol. Manage. 90, 127–140.

Miller, G.W., Brose, P.H., Gottschalk, K.W., 2017. Advanced oak seedling development as influenced by shelterwood treatments, competition control, deer fencing, and prescribed fire. J. For. 115, 179–189. https://doi.org/10.5849/jof.16-002.

Miller, G.W., Kochenderfer, J.N., Gottschalk, K.W., 2004. Effect of pre-harvest shade control and fencing on northern red oak seedling development in the central Appalachians. In proceedings of the upland oak ecology symposium: history, current conditions, and sustainability, USDA Forest Service General Technical Report SRS-73, Southern Research Station, Asheville, NC, pp. 182-189.

Motsinger, J.R., Kabrick, J.M., Dey, D.C., Henderson, D.E., Zenner, E.K., 2010. Effect of midstory and understory removal on the establishment and development of natural and artificial pin oak advance reproduction in bottomland forests. New For. 39, 195–213. https://doi.org/10.1007/s11056-009-9164-5.

Oliver, L.B., Stovall, J.P., Comer, C.E., Williams, H.M., Symmank, M.E., 2019. Weed control and overstory reduction improve survival and growth of underplanted oak and hickory seedlings. Restor. Ecol. 27 (1), 70–81.

Oswalt, C.M., Clatterbuck, W.K., Houston, A.E., 2006. Impacts of deer herbivory and visual grading on the early performance of high-quality oak planting stock in Tennessee, USA. For. Ecol. Manage. 229, 128–135. https://doi.org/10.1016/j.foreco.2006.03.014.

Rives, R.G., Knapp, B.O., Olson, M.G., Weegman, M.D., Muzika, R.M., 2020. Regenerating mixed bottomland hardwood forests in north Missouri: effects of harvest treatment on structure, composition, and growth through 15 years. For. Ecol. Manage. 475, 118371 https://doi.org/10.1016/j.foreco.2020.118371.

Sander, I.L., Johnson, P.S., Watt, R.F., 1976. A guide for evaluating the adequacy of oak advance reproduction. USDA Forest Service General Technical Report NC-23, Northern Research Station, St. Paul, MN, pp. 7.

Self, A., Ezell, A., Rowe, D., 2014. Performance of oak seedlings grown under different Oust® XP regimes. Forests 5, 1331–1340. https://doi.org/10.3390/f5061331.

South, D.B., Harris, S.W., Barnett, J.P., Hainds, M.J., Gjerstad, D.H., 2005. Effect of container type and seedling size on survival and early height growth of *Pinus palustris* seedlings in Alabama, U.S.A. For. Ecol. Manage. 204, 385–398. https://doi.org/10.1016/j.foreco.2004.09.016.

Spetich, M.A., Dey, D.C., Johnson, P.S., Graney, D.L., 2002. Competitive capacity of *Quercus rubra* L. planted in Arkansas' Boston Mountains. For. Sci. 48, 504–517. https://doi.org/10.1093/forestscience/48.3.504.

Vickers, L.A., Fox, T.R., Loftis, D.L., Boucugnani, D.A., 2011. Predicting forest regeneration in the Central Appalachians using the REGEN expert system. J. Sustain. For. 30, 790–822. https://doi.org/10.1080/10549811.2011.577400.

Walter, W.D., Godsey, L.D., Garrett, H.E., Dwyer, J.P., Van Sambeek, J.W., Ellersieck, M. R., 2013. Survival and 14-year growth of black, white, and swamp white oaks established as bareroot and RPM® containerized planting stock. North. J. Appl. For. 30, 43–46. https://doi.org/10.5849/njaf.11-047.

Wilson, E.R., Vitols, K.C., Park, A., 2007. Root characteristics and growth potential of container and bareroot seedlings of red oak (*Quercus rubra* L.) in Ontario. Canada. New For. 34, 163–176. https://doi.org/10.1007/s11056-007-9046-7.

Wittwer, R.F., 1991. Direct seeding of bottomland oaks in Oklahoma. South. J. Appl. For. 15, 17–22.

Woeste, K.E., Seifert, J.R., Selig, M.F., 2005. Evaluation of four herbicide and tillage for weed control on third year growth of tree seedlings. Weed Sci. 53, 331–336. https://doi.org/10.1614/WS-04-120R.