

Long-term effects of group opening size and site preparation method on gap-cohort development in a temperate mixedwood forest

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ABSTRACT

Management aimed at regenerating softwoods and hardwoods in the same stand (i.e., a mixedwood) has some appeal in the pine-hardwood forests of the southern United States. We revisited a group selection experiment installed in 1991 to evaluate the influence of gap size and site preparation treatments on a pine-hardwood stand in Louisiana, USA. Experimental treatments included a factorial combination of three group opening sizes (0.1, 0.25, 0.4 ha) and three methods of site preparation (chemical, mechanical, untreated) in the harvest gaps. Specifically, we tested two hypotheses: 1) regeneration of shade-intolerant tree species increased with gap size and the addition of site preparation and 2) if this site preparation decreased the regeneration of species that are more tolerant of shade and reliant on advance reproduction. In 2016, the density and basal area of the shade-intolerant loblolly pine (*Pinus taeda*), shortleaf pine (*Pinus echinata*), and sweetgum (*Liquidambar styraciflua*) increased with increasing gap size ($P < 0.05$), supporting our first hypothesis. Compared to untreated gaps, white oak (*Quercus* section *Quercus*), red oak (*Quercus* section *Lobate*), and red maple (*Acer rubrum*) abundances were significantly reduced in gaps treated with chemical or mechanical site preparation, supporting our second hypothesis. Based on these results, it appears possible to secure adequate pine regeneration with a relatively wide range of early gap-treatment option in similar pine-hardwood forest types. However, pines dominated nearly all gaps (regardless of treatment), so much so that many no longer qualify as mixedwood. This outcome suggests that managers interested in group selection for mixedwoods in this part of the coastal plain should consider creating larger gaps (≥ 0.25 ha) in areas with preferred hardwood advance reproduction, while limiting within-gap site preparation to help protect it.

1. Introduction

A “mixedwood” stand consists of hardwood (angiosperms) and softwood (gymnosperms) species in which neither group contributes > 70%–80% of the composition (Helms, 1998; Cavard et al., 2011; Kabrick et al., 2017). Such mixed-species forests offer a range of benefits to both natural systems and society not possible in monocultures (Gamfeldt et al., 2013; Willis et al., 2019). For example, in addition to generating commercial timber harvests for multiple markets (Pretzsch et al., 2017), mixedwoods can provide a wider array of habitat elements and food resources needed to support diverse wildlife populations (Hunter, 1999; Girard et al., 2004) and a range of other ecosystems services (e.g., Gamfeldt et al., 2013; Felipe-Lucia et al., 2018). Mixedwood tree communities also usually consist of species with differing morphological, physiological, and life history attributes (e.g., functional diversity), which tend to enhance forest resilience against catastrophic pest and pathogen outbreaks (Laughlin et al., 2017; Messier et al., 2019). Hence, mixedwood management leading to more resilient forests may help address future climate change and disturbances, particularly disease-causing biota (Jactel and Brockerhoff,

2007; Griess and Knoke, 2011).

A variety of management treatments can produce mixedwood stands (Perry and Waldrop, 1995; Rantis and Johnson, 1998). When properly applied to the right conditions, even-aged systems emphasizing high timber yields (such as clearcuts or seed tree harvests) are certainly capable of generating mixedwood stands. However, even-aged systems may also produce undesirable stand outcomes—including a lack of tree age diversity—resulting in structural homogeneity that does not meet the management objectives for some landowners (Silvennoinen et al., 2001; Saunders and Wagner, 2008; Puettmann et al., 2015). For these landowners, gap-based silviculture (such as group shelterwood and selection systems) that maintains forest cover and increase structural and compositional complexity in mature forest habitats may be preferred (Silvennoinen et al., 2001; Puettmann et al., 2015).

Globally, gap-based silviculture has been found to be an effective and desirable strategy for sustaining mixedwoods (e.g., Lieffers and Beck, 1994; Orois and Soalleiro, 2002; Saunders and Wagner, 2008). Aspects of many of the mixedwood forests on the coastal plains of the southern United States (U.S.), which are combinations of shade-

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intolerant pines (*Pinus* spp.) and an often diverse assemblage of variably shade-tolerant hardwoods (Eyre, 1980), are likewise favorable for gap-based management. For instance, small-scale disturbances that create single to multiple tree-fall gaps in the upper canopy are common natural drivers of forest turnover in southern mixedwood forests (Rantis and Johnson, 1998). These small canopy openings tend to release shade-tolerant species from overtopping competition, while larger openings often provide shade-intolerant species reliant on post-disturbance establishment (such as sweetgum (*Liquidambar styraciflua*) and the southern pines) an advantage during early cohort development (Murphy et al., 1993; Hoffman et al., 2018). However, larger natural gaps also release advance reproduction of species more tolerant of shade, such as red maple (*Acer rubrum*) and the oaks (*Quercus* spp.), which generally have a growth advantage in the partially shaded portions of these openings in these forest systems (Murphy et al., 1993).

Silvicultural research into the optimal gap size to produce mixed southern pine-hardwoods is limited and largely based on early gap-phase regeneration, with mixed results and unclear answers. For example, Cain and Shelton (2001) concluded that pine and hardwood sapling densities were unaffected by gap size (range of 0.1–1 ha) three years post-group selection cutting, but pine seedling stocking was greater in small gaps (0.1 ha). Other studies found larger gaps (> 0.1 ha) with more sunlight and soil disturbance contained significantly greater abundance of shade-intolerant species (McGuire et al., 2001; Olson and Bragg, 2018). Because canopy disturbance alone may not be sufficient to produce desired regeneration outcomes (especially for non-sprouting species who germinate after gaps are formed), site preparation may improve the odds in southern pine-hardwood stands (Harcombe et al., 2002; Weber et al., 2014; Trammell et al., 2017). Both mechanical and chemical site preparation methods are generally effective for both conifers and hardwoods in the southern U.S., with tree performance improvements typical after site preparation (Perry and Waldrop, 1995; Harrington and Edwards, 1998; Fox et al., 2007). In theory, site preparation within group openings, either before or after gap creation, may allow pine seedlings to become established before hardwoods (Perry and Waldrop, 1995; Cain and Shelton, 2001). However, site preparation is usually cost-limited to even-aged management in this region, so data on its long-term effectiveness in group openings are scarce.

These results suggest that combining group selection and site preparation may have potential to produce mixed pine-hardwood stands in the southern U.S. as well as comparable stand types in other regions. However, there is little information on this combination's effectiveness beyond the first few growing seasons (Cavard et al., 2011; Olson and Bragg, 2018). To help address this knowledge gap, we revisited an older experiment (Cain and Shelton, 2001) that evaluated group selection silviculture treatments in naturally regenerated mixed pine-hardwood forests of the West Gulf Coastal Plain (WGCP). The main objective of our research was to determine the long-term effects of gap treatments (both gap size and method of site preparation) on compositional and structural development of regeneration cohorts. Specifically, we tested two hypotheses related to harvest gap size and within-gap site preparation: 1) the regeneration of shade-intolerant tree species, particularly the pine species and sweetgum, increased with gap size and the addition of site preparation and 2) if this site preparation decreased the regeneration of species that are more tolerant of shade and reliant on advance reproduction, particularly red maple and the oaks. Since pine-hardwood management was a main focus of the original experiment, we also evaluated if the treatments resulted in regeneration cohorts that met the criterion of a mixedwood (defined here as 26–75% conifer) twenty-five years after they were installed.

2. Methods and materials

2.1. Original study

The study site is a 48-ha, second-growth pine-hardwood stand on the Winn District of the Kisatchie National Forest in Grant Parish, LA (31.765 N, –92.546 E). This fairly productive West Gulf Coastal Plain (WGCP) site has an elevation of approximately 38 m above sea level, with gently rolling (2–12% slopes), moderately well-drained soils (primarily Cadeville very fine sandy loams, with minor components of Mayhew and Metcalf series sandy loams) and a loblolly pine (*P. taeda*) site index of about 27 m (base age of 50 years) (NRCS, 2017). Common tree species in the study area currently include loblolly and shortleaf (*P. echinata*) pines, blackgum (*Nyssa sylvatica*), hickories (*Carya* spp.), red maple (*A. rubrum*), sweetgum, and numerous oaks, including cherry-bark (*Quercus pagoda*), post (*Quercus stellata*), southern red (*Quercus falcata*), water (*Quercus nigra*), white (*Quercus alba*), and willow (*Quercus phellos*).

The original experiment (Cain and Shelton 2001) employed a randomized complete block design with three replications of a 3x3 factorial treatment combination with the gap as the experimental unit, yielding 27 experimental units (gaps). The blocks were approximately 16 ha and based on proximity to an intermittent drainage. Each block consisted of nine group openings of three sizes: three 0.1-ha (small) gaps, three 0.25-ha (medium) gaps, and three 0.4-ha (large) gaps. These respective opening sizes were selected to create gaps with diameters of approximately 1.2, 2.0 and 2.5 times the typical height (~32 m) of the dominant pines on the gap edge, which were expected to admit enough light for regenerating pine. Gaps were separated by at least 30 m of mature forest. In October 1991, all merchantable pines and hardwoods were removed to create the harvest gaps. A thinning of only pine sawtimber was conducted in the area between the gaps (i.e., no hardwoods or pine pulpwood were removed) to a residual pine basal area of 17.4 m² ha⁻¹. Oaks were the dominant hardwood species in the area between the gaps, accounting for approximately two-thirds of hardwood basal area.

The initial investigators were concerned that sprouting hardwoods and brush competition may overwhelm the seed-origin pines, thereby inhibiting the ability of group selection to support mixedwood development. Hence, mechanical and chemical site preparation techniques were employed to see which may work best on the study area (Cain and Shelton, 2001). In the southern U.S., mechanical site preparation treatments include a variety of methods used to expose bare mineral soil and improve seedbed for pines, remove physical impediments to regeneration, and check herbaceous and woody plant growth, while chemical site preparation treatments can either eliminate competition from undesirable species or improve desired species performance by adding nutrients to a site. For the original study, method of site preparation (chemical, mechanical, none) was randomly assigned to gap locations in each block (i.e., each gap receiving a single site preparation treatment throughout the entire gap). In July 1993, chemical site preparation consisting of foliar spot application of glyphosate, using backpack sprayers on non-pine competitors, was applied. Mechanical site preparation began in September 1993, and included chainsaw-felling hardwoods > 7.6 cm dbh and bulldozing any smaller hardwoods.

Note that to further ensure acceptable pine regeneration in harvest gaps, site preparation had been delayed until an adequate seed crop was detected (previous work had indicated that 100,000 sound seeds ha⁻¹ were needed for loblolly and shortleaf pines to adequately regenerate (Cain and Shelton, 1996)). Pine seed production was monitored from October through February for three years (1991, 1992, 1993) using 0.08 m² seed traps. While pine seed crops in 1991 and 1992 were limited, the 1993 seed crop was estimated to average 1,250,000 seeds ha⁻¹, triggering site preparation.

There have been no additional silvicultural actions on the study,

Table 1

Mean size of group openings by gap size category on the Kisatchie National Forest. Gaps measured used as expanded gaps in 2016. Height values represent mean heights of pine border trees. Variance is in standard deviation.

Gap size	Area (ha)	Dia. (m)	Height (m)	Gap D:H
Small	0.13 ± 0.01	41.9 ± 2.0	32.3 ± 2.1	1.3 ± 0.1
Medium	0.28 ± 0.02	62.4 ± 1.6	32.4 ± 1.8	1.9 ± 0.1
Large	0.46 ± 0.04	79.3 ± 3.0	32.9 ± 2.4	2.5 ± 0.2

including prescribed burning, since site preparation treatments were implemented. However, there have been localized outbreaks of the southern pine beetle (*Dendroctonus frontalis*) near a few harvest gaps, some dating back to the beginning of the study.

2.2. Current study design

The present study was initiated in 2016, twenty-five years after the gaps were created and 23 years after site preparation (Mohler, 2019). Group openings were georeferenced as expanded gaps (Runkle, 1982) by recording coordinates at the boles of border trees along gap perimeters (see Table 1 for gap size estimates). Within-gap sampling was divided by tree size. Species and dbh (measured with diameter tape to the nearest 0.1 cm) were recorded for all trees ≥ 8.9 cm dbh rooted within the perimeters of expanded gaps. Trees 1.3–8.8 cm dbh were sampled using five circular plots sized to survey equal proportions across the three original gap sizes (3.6 m, 5.7 m, and 7.2 m for small, medium, and large gaps, respectively), with one placed at gap center and the others located in four cardinal directions approximately half-way to the gap edge (9.7 m, 15.2 m, and 21.3 m for small, medium, and large gaps, respectively). Nine 0.1-ha circular plots were installed in the mature stand surrounding the study site to describe the untreated matrix (i.e., experimental control) for comparison with the gap cohorts. The same small tree (those < 8.9 cm DBH) sub-plot layout was used in the small gaps. The matrix plots were positioned far enough from group openings to avoid edge effects from the study gaps and the effect of thinning between the gaps by applying buffers to the gap polygons in ArcMap and only considered areas outside of the study area perimeter. In addition, areas with stump sprouts and other evidence of cutting (i.e., skid trails) were avoided when placing matrix plots to ensure these plots were not in areas affected by the 1991 thinning.

2.3. Analytical procedures

Data were compiled into species groups prior to analysis. Small trees (1.3–8.8 cm dbh) were placed into the following taxonomic groups: white oaks (section *Quercus*), red oaks (section *Lobate*), pines, sweetgum, red maple, blackgum, and other. Large trees (≥ 8.9 cm dbh) were placed into the following groups: white oaks, red oaks, pines, sweetgum, red maple, and other species (blackgum was not included as a separate species category because of insufficient sample size). Density (trees ha⁻¹) served as the response variables for the small tree groups, and density and basal area (m² ha⁻¹) were the response variables for the large tree groups. Importance value (IV, in terms of percent) was derived based on the relative basal area (RBA) and relative density (RD) of pine. RBA and RD were calculated by averaging the pines' basal area and density within each gap and dividing them by the summed averages of the total basal area and density of all species, respectively. Pine IV was calculated as an indicator of mixedwood composition due to the fact that pines were the only softwood species present; therefore, the proportion of pine IV would indicate the softwood/hardwood composition. For example, we defined a plot as mixedwood if pine IV ranged between 26 and 75%, with those with 25% or less being hardwood-dominated and those > 75% as pine-dominated.

A mixed ANOVA procedure tested for effects of gap size and site

preparation methods on the response variables (density, basal area) of tree regeneration 25 years after gap creation for a randomized complete block design using PROC MIXED in SAS 9.4. Tukey's 1-df test was used to test for block-treatment interactions, the Shapiro-Wilk test was used to test for normality, and Levene's test was used to check equality of variances. Normality of large other species and small blackgum densities were improved by square-root transformation. Tukey-Kramer's test was used to detect significant differences among means. Statistical significance was determined at $P < 0.05$.

3. Results

3.1. Size class distribution

The diameter distributions based on trees greater than a 1.3-cm dbh displayed a reverse-J shape in all of the gap treatments, with the larger diameter classes clearly dominated by pine and sweetgum (Fig. 1). As gap size increased, total density (trees ha⁻¹) across dbh classes tended to increase (more noticeably going from small to large gaps), suggesting that increased gap size enhanced recruitment of stems into the larger size classes. The small tree classes are dominated by the other species category, with notable amounts of sweetgum and red maple. Although the oaks are a minor component in most gap cohorts, the large, untreated gaps contained a considerable red oak group component across large tree dbh classes (196 trees ha⁻¹) and an even larger amount of white oak group regeneration in the small tree category (277 trees ha⁻¹; Fig. 1C). Compared to gap cohorts, hardwoods made up a bigger proportion of each size class in the matrix, while pines were more apparent in the larger diameter classes and noticeably absent from smaller diameter classes (91 trees and 5 trees ha⁻¹). The oak component was greater in each size class when compared to the gap distributions. White oaks were more abundant than red oaks (136 and 64 trees ha⁻¹, respectively) in most size classes in the matrix and accounted for larger proportions in the intermediate diameter classes compared to the gaps.

3.2. Influence of gap size on tree density and basal area

The ANOVA model testing the treatment effects on the densities of the large tree class found gap size to be a significant treatment factor for pines and sweetgum ($P < 0.05$; Table 2). Mean separation for pine detected over twice the density in the large and medium gaps compared to the small gaps (771 ± 96 (mean ± standard error) and 704 ± 69 vs. 348 ± 54 trees ha⁻¹, respectively), and sweetgum mean separation indicated two-times greater density in the large gaps compared to the small gaps (141 ± 17 vs. 69 ± 17 trees ha⁻¹, respectively; Fig. 2A).

Gap size was a significant treatment factor ($P < 0.05$) in the ANOVA model for large pines, sweetgum, and other species basal area. Mean separation detected pines had significantly greater basal area in the large and medium gaps when compared to the small gaps (17.3 ± 1.4 and 14.1 ± 1.4 vs. 5.1 ± 0.8 m² ha⁻¹, respectively; Fig. 2B). Sweetgum had greater basal area in the large gaps than the small gaps (1.7 ± 0.2 vs. 0.8 ± 0.2 m² ha⁻¹, respectively). Basal area of the other species group was significantly greater in the small gaps compared to the medium (0.8 ± 0.2 vs. 0.2 ± 0.1 m² ha⁻¹).

3.3. Tree density and basal area as a function of site preparation

Site preparation was a significant treatment factor in ANOVA models for stem densities and basal areas of large white oaks, red oaks, red maple, and others (Table 2). The white oak groups' mean density in the large tree class was significantly greater in the untreated gaps vs. the mechanical gaps (25 ± 5 vs. 5 ± 2 trees ha⁻¹, respectively), and red oaks and red maple mean densities were significantly greater in the untreated gaps compared to the chemical and mechanical gaps (59 ± 9 vs. 25 ± 10 and 20 ± 8 trees ha⁻¹ for red oaks; and 22 ± 5 vs. 2 ± 2 and 5 ± 3 trees ha⁻¹ for red maple, respectively;

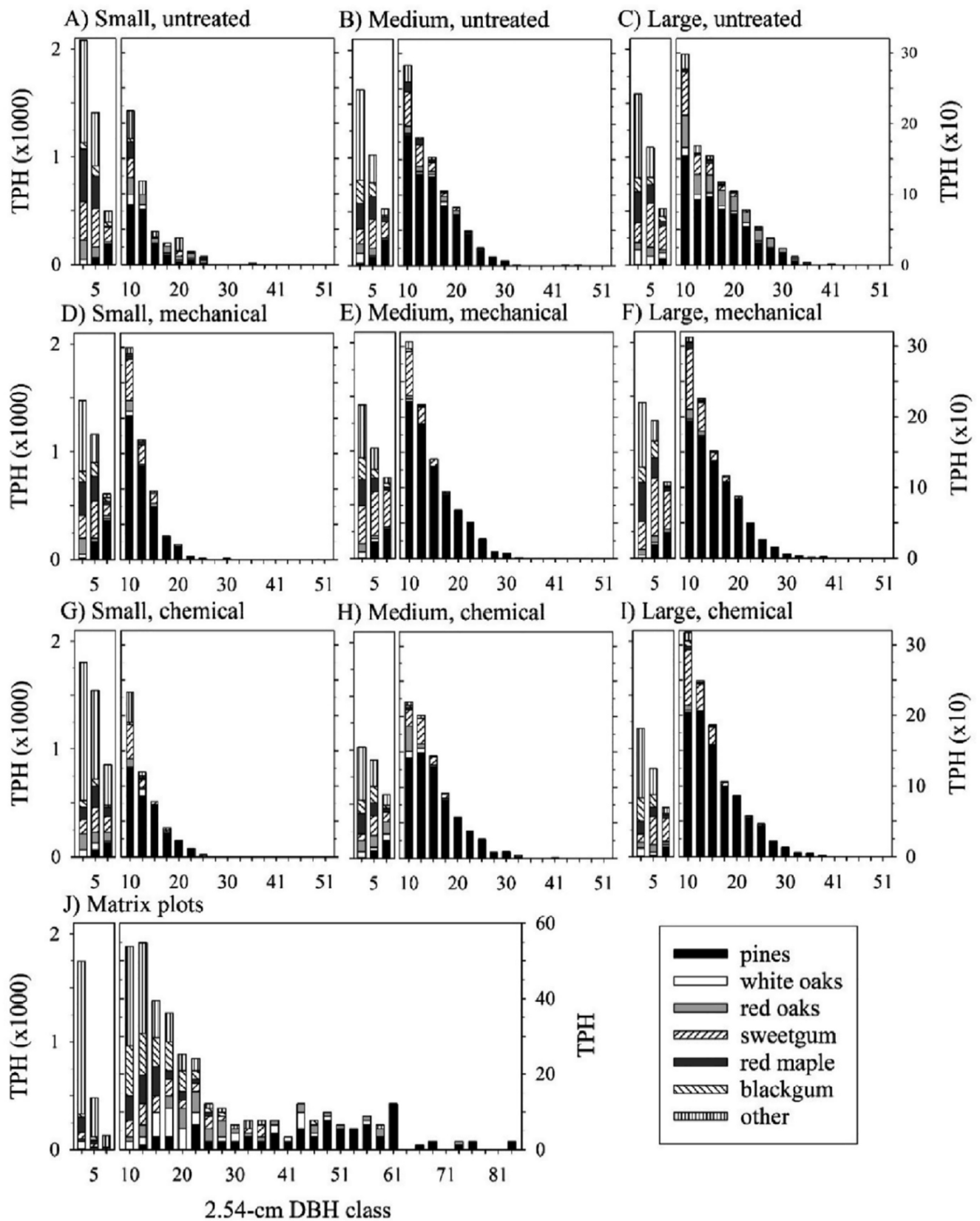


Fig. 1. Diameter distributions by species groups for the nine, gap size-site preparation combinations (A-I) and the matrix plots (J). The left y-axes are scaled for the small-tree class and the right y-axes are scaled for the large-tree class.

Table 2

P-values from ANOVA models testing effects of gap size (G), site preparation (P), and their interaction (G*P) on density and basal area of main species groups in the large tree class (≥ 8.9 cm dbh). Significant P-values ($P < 0.05$) are italicized.

Species groups	Density			Basal area		
	G	P	G*P	G	P	G*P
pin	< 0.001	0.114	0.523	< 0.0001	0.554	0.640
white oaks	0.995	0.007	0.240	0.772	0.005	0.217
red oaks	0.873	0.001	0.053	0.224	< 0.0001	0.095
sweetgum	0.028	0.506	0.796	0.021	0.961	0.843
red maple	0.532	0.002	0.157	0.346	< 0.001	0.365
other	0.110	0.008	0.359	0.020	0.017	0.699

Fig. 3A). Mean separation for other found greater density in the untreated gaps compared to the chemical gaps (52 ± 10 vs. 30 ± 10 trees ha^{-1} , respectively). Mean basal area was significantly greater in untreated gaps than the mechanical and chemical gaps (Fig. 3B) for white oak (0.57 ± 0.09 , 0.14 ± 0.21 , and 0.07 ± 0.07 $\text{m}^2 \text{ha}^{-1}$, respectively), red oak (1.26 ± 0.23 , 0.18 ± 0.09 , and 0.18 ± 0.11 $\text{m}^2 \text{ha}^{-1}$), red maple (0.37 ± 0.09 , 0.05 ± 0.02 , and 0.05 ± 0.02 $\text{m}^2 \text{ha}^{-1}$), and other species (0.78 ± 0.18 , 0.3 ± 0.09 , and 0.37 ± 0.11 $\text{m}^2 \text{ha}^{-1}$). For the small tree class, site preparation was a significant factor in the ANOVA model for white oaks, pines, and sweetgum densities ($P < 0.05$; Table 3). Pines and sweetgum densities were significantly greater in the mechanical gaps than the chemical

gaps (2253 ± 388 trees ha^{-1} vs. 911 ± 230 trees ha^{-1} for pine, and 4861 ± 650 trees ha^{-1} vs. 2327 ± 511 trees ha^{-1} for sweetgum; Fig. 4).

3.4. Interaction of gap size and site preparation on small white oaks

The interaction between gap size and site preparation was significant in the model for small white oak density (Fig. 5). The difference was found among the large gaps, where estimated means were significantly greater in the untreated gaps compared to the mechanical gaps (1386 ± 232 trees ha^{-1} vs. 269 ± 109 trees ha^{-1} , respectively). There were no significant interactions between gap size and site preparation for the pines, red oaks, sweetgum, red maple, blackgum, or other species groups in the small tree class and no significant interactions for any species groups in the large tree group.

3.5. Mixedwood status of gap cohorts

Twelve of the gap cohorts (44%) met the definition of mixedwood composition 25 years after gap creation, while 15 (56%) gaps were pine dominated and none were dominated by hardwoods (Fig. 6). The IV of pines was $> 50\%$ in all but one gap, a small gap without site preparation (27%). When pine IV was averaged by gap treatment combination, a mixedwood composition was observed in small-untreated, small-chemical, and large-untreated treatments, while the remaining six combinations were softwood dominated, including all three medium-gaps combinations and all three mechanically treated gaps.

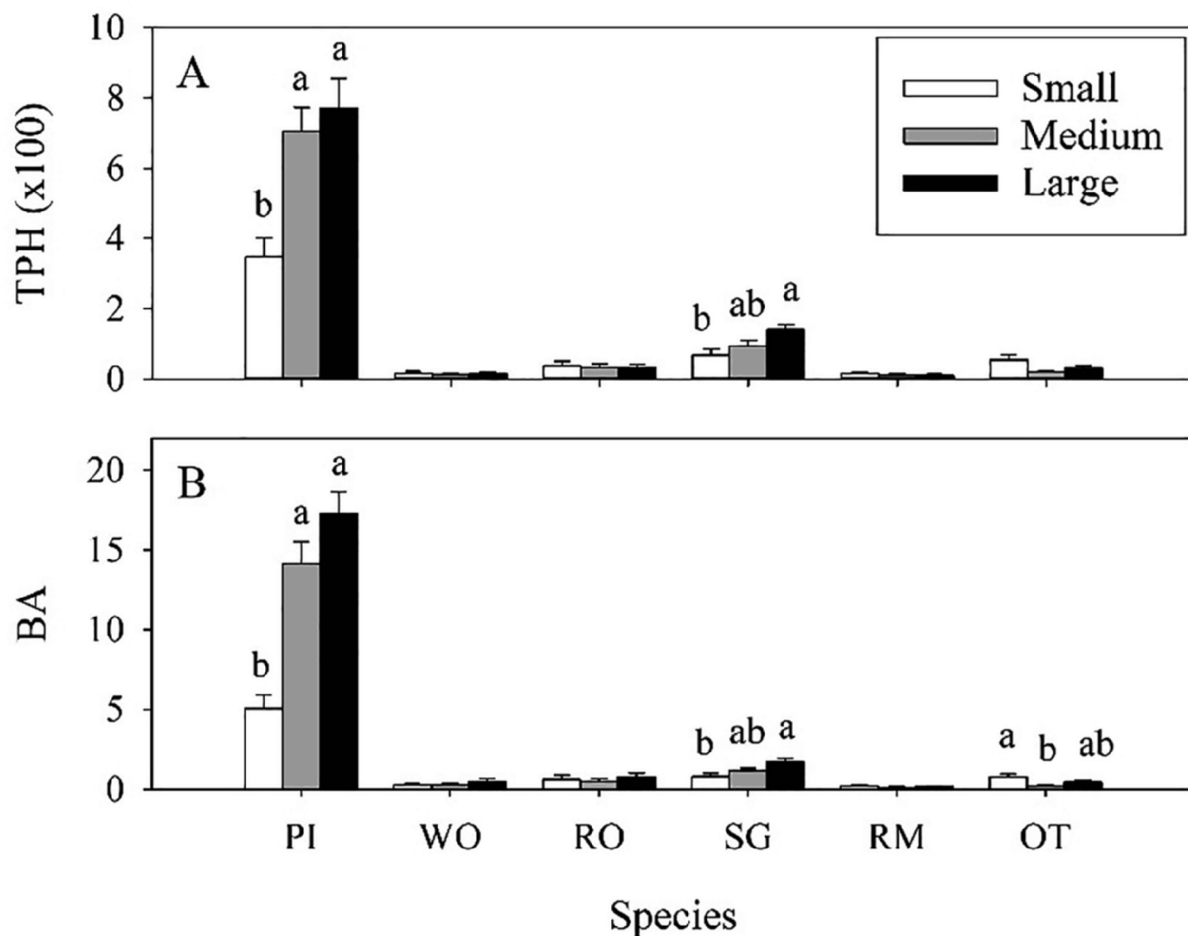


Fig. 2. Mean densities (A; trees ha^{-1}) and basal areas (B; $\text{m}^2 \text{ha}^{-1}$) of species in the large-tree class (≥ 8.9 cm dbh) averaged by gap size treatment. Species codes are: PI = pine, WO = white oak, RO = red oak, SG = sweetgum, RM = red maple, and OT = other. Mean separation results shown for significant main effects only ($P < 0.05$). Means within species with the same letter are not significantly different. Error bars represent one standard error.

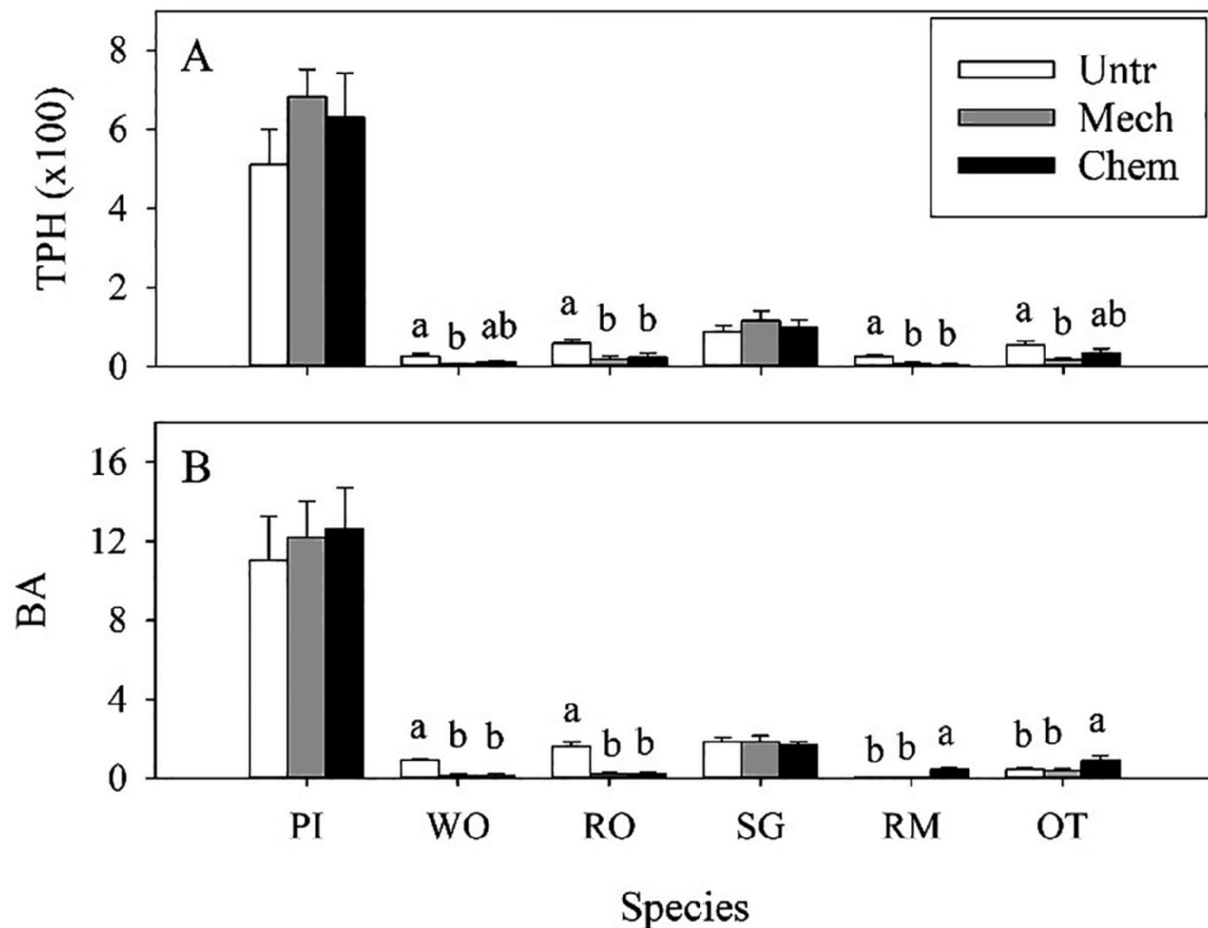


Fig. 3. Mean densities (A; trees ha⁻¹) and basal areas (B; m² ha⁻¹) of species in the large-tree class (≥ 8.9 cm dbh) averaged by site preparation treatment. Species codes are: PI = pine, WO = white oak, RO = red oak, SG = sweetgum, RM = red maple, and OT = other. Mean separation results shown for significant main effects only ($P < 0.05$). Means within species with the same letter are not significantly different. Error bars represent one standard error.

Table 3

P-values from ANOVA models testing effects of gap size (G), site preparation (P), and their interaction (G*P) on density of main species in the small-tree class (1.3–8.8 cm dbh). Significant P-values ($P < 0.05$) are italicized.

Species groups	Density		
	G	P	G*P
Pines	0.084	<i>0.027</i>	0.717
white oaks	0.135	<i>0.005</i>	<i>0.019</i>
red oaks	0.171	0.079	0.613
Sweetgum	0.476	<i>0.022</i>	0.414
red maple	0.498	0.211	0.891
Blackgum	0.124	0.851	0.919
Other	0.896	0.608	0.256

4. Discussion

This study supported our first hypothesis that increasing gap size and addition of site preparation enhanced the regeneration of shade-intolerant pine species and sweetgum. This effect was most evident for the large tree class in relation to gap size. After 25 years, the medium and large gaps contained twice the pine density and basal area of that found in the small gaps. Although not as dominant as the pines, sweetgum density and basal area increased with increasing gap size and this species accounted for a sizeable portion of the large tree abundance in medium and large gaps. These are not surprising results, given that the shade-intolerant loblolly and shortleaf pines and sweetgum were

promoted by increasing the intensity of harvest gap disturbance in this WGCP pine-hardwood forest. In the case of sweetgum, the larger group openings likely stimulated the development of sprouts from lateral roots, which can constitute a major regeneration source for this species (Kormanik, 1990). Others have documented similar results, as the larger gaps received more direct sunlight which favored establishment and recruitment of the shade-intolerant species (Rantis and Johnson, 1998; Cain and Shelton, 2001; Harcombe et al., 2002; Prévost and Raymond, 2012; Weber et al., 2014; Holmström et al., 2016; Trammell et al., 2017).

In addition to greater light availability, the large and medium gaps also experienced heavier harvest-related disturbance, such as soil scarification that exposed bare mineral soil and enhanced seedbed conditions. Early results from the original study found that though pine seed supply was lower in large gaps, particularly the amount reaching gap center, the heavier disturbance promoted greater pine seedling establishment for the amount of seed that was present (Cain and Shelton, 2001). The removal of physical litter impediments and herbaceous vegetation likely provided the light-seeded pine roots easier access, and sweetgum roots less competition, to mineral soil substrates and belowground resources (McDonald and Fiddler, 1991). However, pine and, to a lesser extent, sweetgum continue to dominate the large tree class years after site preparation regardless of treatment; a significant result considering site preparation was delayed for three years to coincide with a good pine seed crop (Cain and Shelton, 2001). The main pine species of these gap cohorts is loblolly pine, a species capable of prolific natural regeneration (Baker and Langdon, 1990).

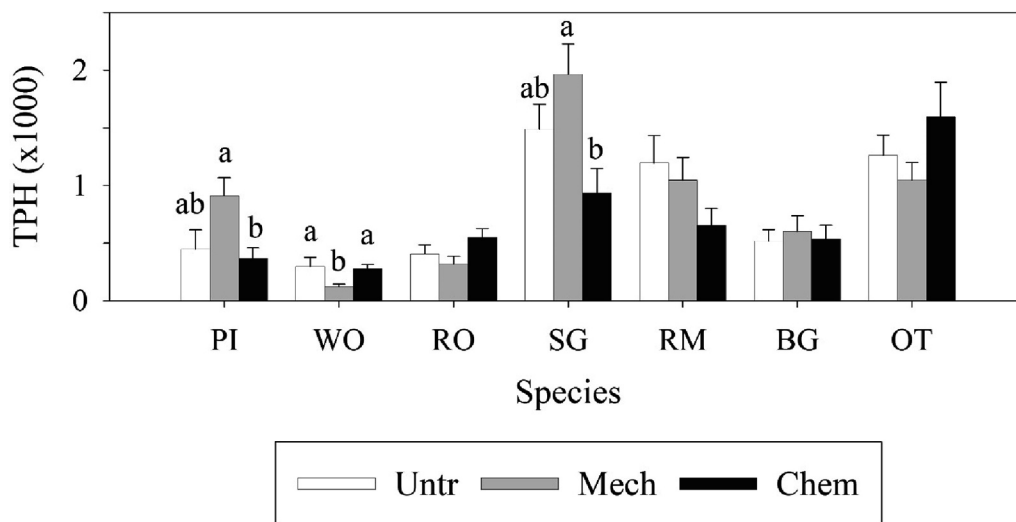


Fig. 4. Mean densities of species in the small tree class (1.3–8.8 cm dbh) averaged by site preparation treatment. Species group codes are: PI = pines, WO = white oaks, RO = red oaks, SG = sweetgum, RM = red maple, BG = blackgum, and OT = other. Mean separation results shown for significant main effects only ($P < 0.05$). Means within species groups with the same letter are not significantly different. Error bars represent one standard error.

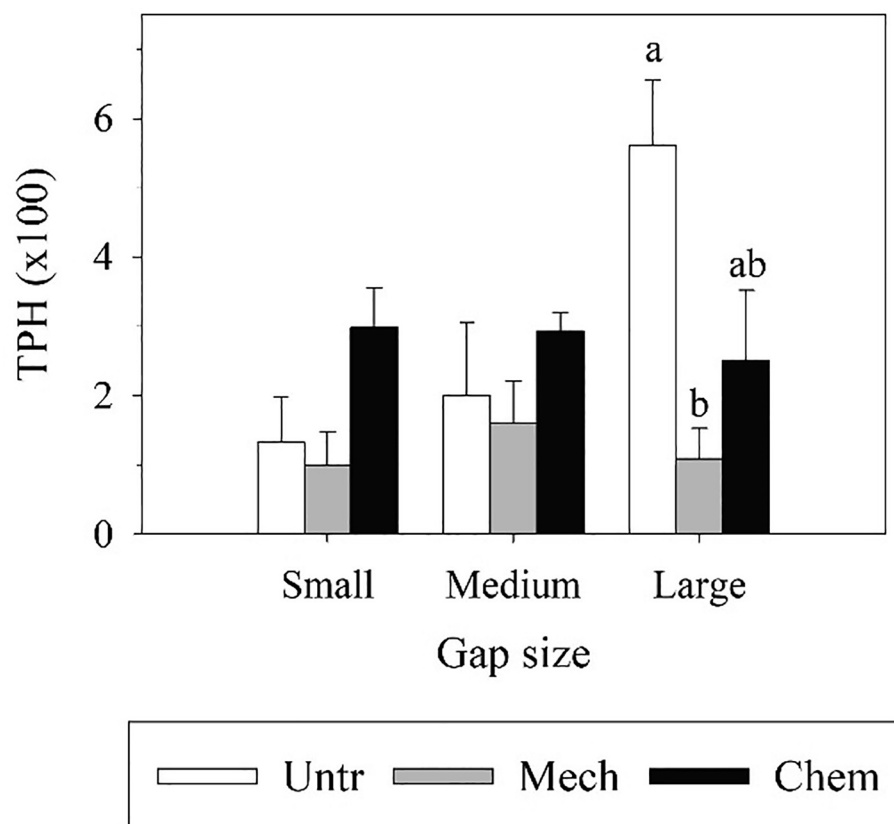


Fig. 5. Mean densities of white oak in the small tree class (1.3–8.8 cm dbh) averaged site preparation treatment within each gap size treatment. Mean separation results shown for significant interaction effect detected in the large-gap treatment only ($P < 0.05$). Means within gap size with the same letter are not significantly different. Error bars represent one standard error.

Consistent with our second hypothesis, site preparation treatments had more of an effect on the abundance of shade-tolerant hardwood species than gap size. In gaps treated with either mechanical or chemical site preparation, the densities and basal areas of oaks and red maple were significantly lower when compared to untreated gaps. Because oak and maple advance reproduction often develops in closed forests of eastern North America (Dey, 2014), it is likely that site preparation treatments in this study negatively influenced advance reproduction and enhanced pine regeneration success (e.g., Harrington and Edwards, 1998; Waldrop, 1997; Cain and Shelton, 2001). Similar response to site preparation has been noted in other group selection experiments. For example, scarification of group openings in northern hardwood stands reduced the density of shade-tolerant species advance

reproduction while simultaneously benefiting a light-seeded, mid-tolerant species (Reuling et al., 2019).

Although hardwood control may be critical to pine regeneration success under group selection (Perry and Waldrop, 1995), the efficacy of any mixedwood management regime hinges on its ability to recruit both softwood and hardwood species in the same stand. Of the hardwood species associated with pine-hardwood forests of the eastern U.S., the oaks are arguably the most important (Dey, 2014). The results of our study suggest that oaks may have benefited most from creating larger gaps without site preparation, especially our red oak species group. For example, the diameter distributions of large gaps without site preparation show a trend of a greater red oak component in the large diameter classes when compared to the other treatment

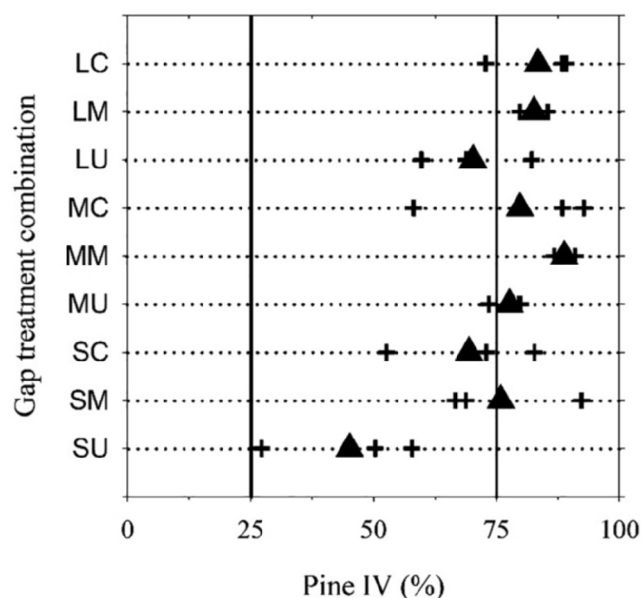


Fig. 6. Pine IV of individual gaps (plus) and treatment-averaged pine IVs (triangle) for each of the nine, gap size-site preparation treatment combinations. The first letter of the treatment code indicates gap size treatment (S = small, M = medium and L = large) and the second is site preparation (U = untreated, M = mechanical, and C = chemical). Mixedwood composition is defined here as pine IV ranging from 26 to 75%, which is represented above by thick vertical lines.

combinations. Under more open canopy conditions, red oaks are capable of growth rates that enable them to compete successfully with many other hardwood species (Hibbs, 1983; Clatterbuck and Hodges, 1988; Waskiewicz et al., 2013; Vickers et al., 2014). As an example, Barden (1981) found red oaks were capable of capturing growing space in multiple-tree gaps when compared to more shade-tolerant species. Red oak saplings exhibited faster height growth than white oak saplings where overstory density was low ($< 5 \text{ m}^2 \text{ ha}^{-1}$) in managed hardwood stands (Vickers et al., 2014).

Since the original experiment was installed to inform group selection systems for managing southern pine-hardwood stands, it is also important to consider compositional status of gap cohorts, particularly the relative abundance of pine and hardwood species. Nearly all gap cohorts had a dominant pine component 25 years after gap creation and 23 years after site preparation. In fact, pine IV, a measure of pine's relative abundance, was $> 50\%$ in all but one of the gaps inventoried in this study. According to our criterion of a mixedwood (26–75% pine IV), nearly half of the gap cohorts were mixedwoods, while the remainder were pine dominated ($> 75\%$ pine IV). A salient feature of gap cohorts was their reverse-J shaped diameter distribution with pines dominating the largest size classes and hardwoods comprising a greater share of smaller classes. Assuming that individuals in these gaps are largely part of the same age cohort (age data not available), the distributions suggest gap cohorts could be best described as even-aged, stratified mixtures. This pattern emerges from interspecific differences in growth and shade tolerance with slower-growing, shade-tolerant species capable of surviving beneath faster-growing, shade-intolerant species, which leads to canopy stratification (Oliver and Larson 1996). This also suggests gap cohort development followed the initial floristics composition model of secondary succession (Egler, 1954), as both early- and late-successional species regenerated after gap creation. Furthermore, the variability in gap sizes and within-gap disturbances appear to have initiated a range of secondary successional trajectories at the gap-scale in this WGCP forest. Regenerating an ecologically diverse mixture of tree species with group selection may be a viable strategy for enhancing the resilience and adaptive capacity of WGCP forest

ecosystems.

Our results not only confirm conclusions from earlier reporting on this study that gap harvesting can successfully regenerate southern pine species and site preparation methods can effectively check hardwood growth and competition (Cain and Shelton, 2001), but that the effects of these treatments were still evident in the third decade of this experiment. Although this study provided a longer-term perspective on the gap-scale development of southern pine-hardwood forests, future research should consider impacts of successive regeneration cuttings and gap-cohort tending at multiple scales (gap to stand) to fully evaluate group selection silvicultural systems in these mixedwoods.

5. Management implications

Silvicultural intervention can be important in the maintenance of mixedwoods (Weber et al., 2014; Trammell et al., 2017). To this end, uneven-aged management may appeal to some landowners interested in a consistent, sustained sawtimber yield at each harvest entry for a continuous flow of income (Guldin and Baker, 1988). In the WGCP, regenerating pine-dominated cohorts in larger gaps, could offer the landowner the option to commercially thin the faster-growing pole-sized pine. This targeting of pine would provide an opportunity to economically manipulate gap cohorts to achieve a more desired residual stand composition, including a more balanced mixedwood. Although the feasibility of this treatment depends on timber markets, gap thinning could be timed with the creation of new group openings and the concurrent harvest of sawlogs to offset treatments in younger cohorts that may yield less commercial value.

Group selection involves more than just decisions about appropriate gap size and method of site preparation, but also should be implemented with inherent sub-stand variability and desired species' regeneration ecology in mind. In southern forests managed for mixedwood composition, creating group openings in locations where desirable advance reproduction is present (e.g., oak) and mature overstory pine species are in close proximity have been recommended to meet natural regeneration objectives (Trammell et al., 2017). Given the results of this study (treatments favored pines) and Olson and Bragg (2018) (lack of site prep favored hardwoods), it is probably best to consider natural regeneration in group openings of the WGCP as especially vulnerable to competitive interactions and to adopt an adaptive management approach that monitors gap cohort development to help ensure a desired regeneration outcome.

For instance, it appears possible to secure adequate pine regeneration with a relatively wide range of early gap-treatment option (i.e., gap size and site preparation) in similar pine-hardwood forest types. Indeed, others have documented loblolly pine's ability to regenerate under a wide range of silvicultural treatments (e.g., Wahlenberg, 1960; Schultz, 1997). However, a smaller study (Shelton, 1998) of gap size in south-east Arkansas testing the same size range (but not site preparation approaches) indicated that long-term pine regeneration success is not assured under group selection. Early in this study, initial pine seedling density and stocking appeared sufficient to ensure long-term pine dominance in all gaps regardless of opening size (Shelton, 1998), but twenty-four years after their creation, nearly all gaps contained relatively poor pine stocking likely due to aggressive, unchecked competition from hardwoods, shrubs, and woody vines (Olson and Bragg, 2018).

With these results in mind, when managing for mixedwoods in the WGCP using group selection it may be beneficial to regenerate a substantial pine component at early stages of cohort development. Not only would this approach ensure a pine component, but it would also allow shade-tolerant hardwoods to develop beneath the pine, and, therefore, work with the natural dynamic of these mixedwood systems. Low pine stocking in the third decade, as seen in the companion study in Arkansas (Shelton, 1998), could make it difficult to shift gap cohorts to a mixedwood composition later, since the window of opportunity to

regenerate shade-intolerant pine closes after crown closure. However, under a group selection system, not all openings need to regenerate pine for this system to be successful. This system may still maintain a mixedwood stand if pine dominance is maintained in a portion of the group openings.

CRedit authorship contribution statement

Colby Mohler: Writing - original draft, Writing - review & editing, Data curation. **Mohammad Bataineh:** Methodology, Writing - review & editing. **Don C. Bragg:** Methodology, Writing - review & editing. **Robert Ficklin:** Writing - review & editing. **Matthew Pelkki:** Writing - review & editing. **Matthew Olson:** Conceptualization, Methodology, Supervision, 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.

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