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Converting plantations to uneven-aged stands: Effects of harvest type, group opening size, orientation, and canopy position on residual tree development☆

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ABSTRACT

Uneven-aged silviculture is becoming increasingly popular as a tool to restore and manage forests for multiple benefits. However, there are few studies that evaluate the growth response of shade intolerant pine species in the southeastern United States to regeneration harvests during stand conversion process. We utilized an existing long-term, operational scale, replicated stand conversion trial in the southeastern United States to evaluate the effects of two initial stand conversion harvest treatments (uniform shelterwood and group cuttings) and an uncut control on the growth of residual slash pine (*Pinus elliottii* Englm.) trees over a 7-year period. In addition, we explored the influence of group opening size, canopy position and distance from group opening border on residual tree growth. Tree growth, measured as basal area increment (BAI), was significantly affected by harvest treatment, canopy position, group opening size, and distance of tree from group opening border. Uniform shelterwood harvest led to significantly higher mean tree BAI (25.04 cm^2) than group cuttings (16.56 cm^2) and uncut control (11.88 cm^2), and group cutting harvest had significantly higher mean BAI than the uncut control ($p < 0.001$). Within the group cutting treatment, 0.1 ha group opening had significantly less mean BAI (13.33 cm^2) than all other group opening sizes (0.2 ha -17.81 cm^2, 0.4 ha - 17.80 cm^2, and 0.8 ha -17.92 cm^2). Residual trees located within 0–5 m from the group opening border had significantly higher mean BAI than trees found further away (5–10 m or 10–15 m) from the group opening border ($p < 0.001$). However, the orientation of trees around the group opening (i.e., North, South, East, and West sides) did not have a significant effect on mean BAI ($p = 0.813$). Overall, canopy position influenced growth significantly, with dominant and codominant trees exhibiting statistically greater growth response than intermediate and suppressed trees ($p < 0.001$). Understanding how residual trees respond to harvests during stand conversion is critical for fully assessing the efficacy of these systems with slash pine. The findings of this study will assist land managers in predicting slash pine ingrowth to larger size classes in uneven-aged systems with varying harvest gap size.

1. Introduction

The objectives of contemporary forest stewardship policies are increasingly broadening to include economic, ecological, and socio-cultural benefits (Cubbage et al., 2007; Diaci et al., 2011; Bradford and D'Amato, 2012). In this context, uneven-aged management, which maintains forests as naturally regenerating, structurally complex, continuous cover stands (Nyland, 2016), has garnered increased attention. When compared to even-aged stands, uneven-aged stands provide multiple benefits from each unit of land (Tahvonen et al., 2010; Guldin, 2006; O'Hara 2014; Sharma et al., 2016), are aesthetically and recreationally favored by the public (Bradley and Kearney, 2007; Gunderson and Frivold, 2008; Paudyal et al., 2018), are more resilient and resistant to damaging disturbances such as snow or wind storms (Holling, 1973; Brang, 2001; Hanewinkel et al., 2014), improve habitat for many endangered and threatened species, as well as provide other environmental services (Pukkala, 2016; Joelsson et al., 2017; Nolet et al., 2018), and can be economically competitive in some market situations

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(Tahvonen, 2009; Susaeta et al., 2021). In the southeastern United States, these considerations have fueled interest in managing and restoring pine ecosystems through uneven-aged silviculture, particularly on public lands where even-aged plantations are being converted to complex, uneven-aged structures (Guldin and Farrar, 2002; Brockway and Outcalt, 2017; Sharma et al., 2019). However, uneven-aged systems are more difficult to implement logistically (Brockway et al., 2006; O'Hara, 2014; Nyland, 2016) and have received less research attention than even-aged systems in the southeastern United States (Brockway et al., 2006; O'Hara, 2014; Nyland, 2016). Over the past 70 years, pine-centric silvicultural research in the southeastern United States largely targeted intensive even-aged systems in a bid to maximize timber production (Fox et al., 2007), leaving forest managers with little silvicultural information to guide their stand conversion projects and effectively practice uneven-aged silviculture.

While a few studies on southern pines have examined how longleaf pine (*Pinus palustris* Mill.), loblolly pine (*P. taeda* L.), and shortleaf pine (*P. echinata* Mill.) respond to uneven-aged silvicultural interventions (Guldin and Farrar, 2002; Guldin, 2011; Brockway and Outcalt, 2015; Bragg 2017; Brockway and Outcalt, 2017), slash pine (*P. elliottii* Englm.) has not been adequately studied. Slash pine is a valuable commercial species that grows on 4.2 million hectares of forest land in the southeastern United States. In Florida, slash pine is the dominant forest species, accounting for 27% of total forest area, far exceeding the current extent of longleaf pine (5.7%) or loblolly pine (6.5%) (Forest Service, 2015). Approximately 70% of this acreage is managed as high-intensity plantations with short rotations of about 30 years (Barnett and Sheffield, 2004), occurring primarily in mesic and wet flatwoods sites (FNAI, 2010; Sharma et al., 2018).

Conversion of plantations to uneven-aged stands is typically accomplished through partial cutting (e.g., group or shelterwood cutting as initial cut) to allow for the natural establishment of multiage cohorts and the eventual application of uneven-aged silvicultural systems (Nyland, 2016; Sharma et al., 2019, 2020). Sustainability of such systems depends largely on obtaining adequate regeneration and being able to recruit trees of smaller size classes to larger sizes throughout each cutting cycle. While Bohn and Sharma (2016) and Frazier et al. (2021) investigated the short-term regeneration and understory responses to conversion harvests in slash pine plantations, the response of residual trees to such harvests is still unknown. As residual trees contribute to future stand productivity and influence recruitment and distribution of distinct size classes and stand structure over time, quantifying their growth is of crucial importance. An effective uneven-aged system should promote regeneration and differentiate cohorts by accelerating the growth of residual trees.

Following a harvest, several factors may influence the growth of individual trees. These factors include harvest intensity and spatial pattern (i.e., uniform or group), individual gap factors such as size, and tree factors such as canopy position or location around gaps (Jones and Thomas, 2004; York et al., 2004; Fortin et al., 2008; Gray et al., 2012; Stan and Daniels, 2014). More intense harvests, for example, may result in greater tree growth than less intense harvests (Dodson et al. 2012; Willis et al. 2018). In a group harvest, characteristics such as group opening size, shape, and location that contribute to a complex heterogeneous stand environment can result in varying tree growth responses (Gray and Spies, 1997; McGuire et al., 2001; Frazier et al., 2021). Harvest gaps may reduce competition for trees at or near the gap borders, potentially increasing their growth compared to trees not near the gap border (Roberts and Harrington 2008; Willis et al. 2018). As a result, it is possible that this effect will increase as the gap size increases. Furthermore, residual trees in northern positions near gaps may respond more strongly because light levels are higher in these locations than in southern positions (Sharma et al., 2019). Consequently, shade intolerant species, such as slash pine, may experience superior growth near the northern borders of gaps. However, individual tree attributes, such as tree size and canopy position, are known to affect tree growth responses to harvest treatments and may modify these responses (Nyland, 2016). Such relationships between harvest type, gap size and orientation, and individual tree growth response for slash pine are not well understood.

To develop this knowledge for slash pine, we conducted this study to examine the response of residual slash pine to stand conversion harvests (uniform shelterwood and group cuttings) in a forest under active conversion from an even-aged to uneven-aged stand. Specific questions included: (1) To what extent does uniform shelterwood and group cuttings for stand conversion affect residual tree growth? (2) Does response at the tree level depend on canopy position? and (3) Within group cuttings, is tree response affected by (a) group opening size, (b) distance from group opening border, and (c) orientation around the group opening? We expected: (1) residual tree growth will increase with harvest intensity, meaning uniform shelterwood cutting will lead to greater tree growth than group cutting, (2) growth will increase with increasing group opening size and decrease with distance to group opening border, (3) trees oriented on the northern sides of group opening will show a higher growth response than other sides of group opening, and (4) dominant and codominant trees to show higher growth response than intermediate or suppressed trees. We used an existing long-term, replicated operational-scale experimental trial in northwest Florida for this study and used dendrochronological methods to estimate individual tree growth over a seven-year period following harvests. The results of this study will contribute to our understanding of stand dynamics and help forest managers and practitioners in predicting the development of slash pine to larger size classes when plantations are converted to uneven-aged stands.

2. Materials and methods

2.1. Site description

The research was conducted in a mature 35-year-old slash pine plantation in Tate's Hell State Forest in northwest Florida, USA (Fig. 1). The climate is humid subtropical, with an average annual rainfall of 1200 mm. The topography is flat, with elevations ranging from 0 to 10 m above sea level. Soil series are primarily Scranton sand, Scranton fine sand, Leon sand, Plummer fine sand, Rutledge fine sand, and Sapelo fine sand, and all are poorly drained (NRCS, 2022). Historically, the diverse site was a mosaic of many diverse communities including wet prairies, pine flatwoods, basin swamps, floodplain swamps, cypress domes (*Taxodium* spp.), and Atlantic white cedar forest (*Chamecyparis thyoides* L.). Typically, the canopy of these flatwoods would have been dominated by longleaf and slash pine, with slash pine dominating on wetter sites. Between 1960 and 1980, the site was converted to pine plantations through large-scale silvicultural operations and hydrological manipulations. Slash pine was planted at a high density (~1800 trees ha^{-1}) and fire was excluded from the site, resulting in an understory dominated by woody shrubs, which include titi (*Cliftonia monophyla* Lam.), swamp titi (*Cyrilla racemiflora* L.), large gallberry (*Ilex coriacea*), inkberry (*Ilex glabra* L.), fetterbush (*Lyonia lucida* Lam.), and saw palmetto (*Serenoa repens* (W. Bartram) Small)).

The Florida Forest Service's current land management goals in the study area are to restore native pine ecosystems on these plantations with a structurally diverse overstory and species rich understory, as well as to integrate public use and recreation (Florida Division of Forestry, 2007). This is being accomplished through partial stand harvesting, using uniform shelterwood and group cutting methods, to encourage natural regeneration and develop forests with uneven-aged stand structures. While uniform shelterwood itself is an even-aged silvicultural method (Nyland, 2016), its first partial cut of an even-aged stand can quickly add another age class to speed up the stand conversion process. The long-term plan for the site is to implement an irregular shelterwood method on this treatment, which initially results in a two-aged forest that develops into an uneven-aged structure over time. The overstory in uniform shelterwood harvest treatment will be retained onsite

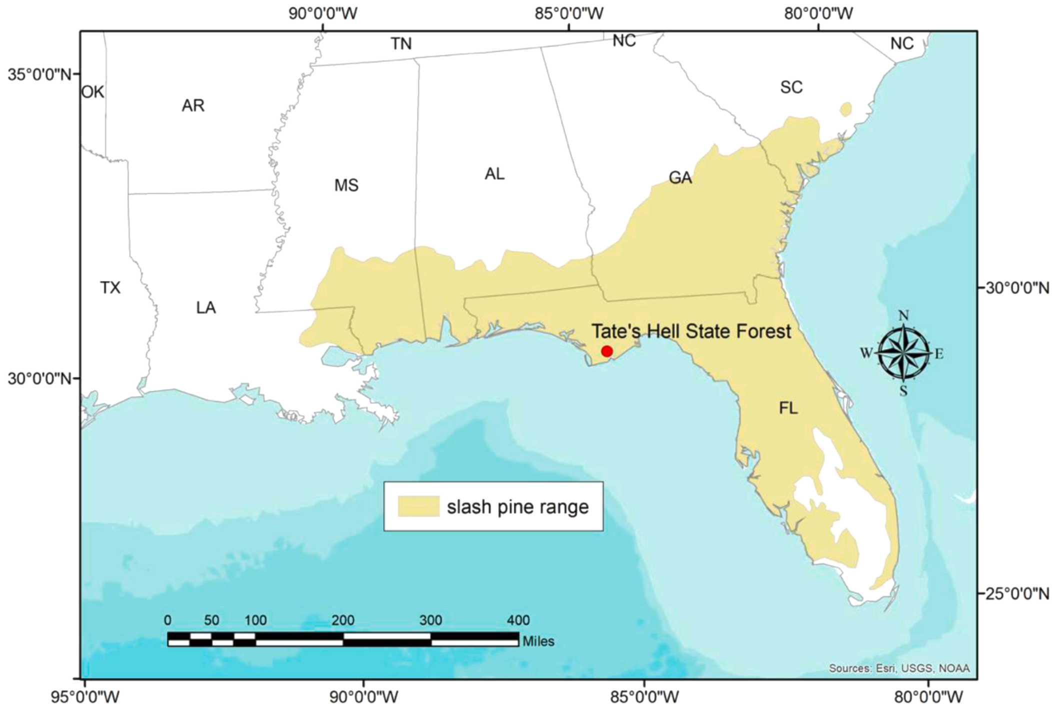

Fig. 1. Location of the study site (Tate's Hell State Forest) in northwest Florida, USA.

throughout and may be partially harvested during next rotations. Additionally, the stands are being prescribed burned at a frequency of every two-to-four years to promote pine regeneration and enhance understory species diversity.

2.2. Experimental treatments and design

We utilized an existing long-term stand conversion silvicultural trial at Tate's Hell State Forest (Sharma et al. 2019). Harvest treatments, including group cuttings and uniform shelterwood treatments representing different harvest intensities (or residual basal areas) and spatial distributions of residual trees, were replicated on three 6.25 ha treatment plots in slash pine plantations beginning in 2011 (Fig. 2). The treatment plots are periodically measured following the sampling methods as described in Sharma et al. (2019) and Bohn and Sharma (2016). This sampling methodology uses five permanent measurement plots (25 m × 25 m), located at random grid points in each treatment plot, for periodic collection of vegetation data. Prior to implementation of harvests, stand conditions were characterized by a stand age of 35 years, basal area of 29 to 33 m^2 ha^{-1}, density of 700 to 850 trees ha^{-1}, and mean tree diameter ranging between 21.4 and 22.3 cm across study sites. Postharvest stand conditions varied depending on the harvest treatment. The group cutting treatment was implemented by intentionally creating circular group openings of sizes approximately 0.1 ha

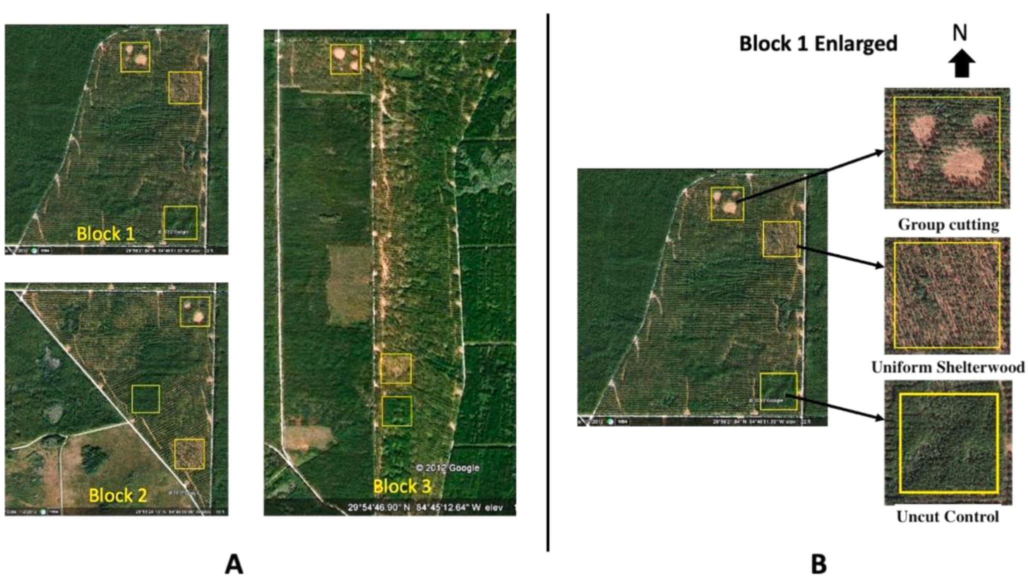

Fig. 2. Slash pine experimental set up in north-west Florida with the two conversion harvest and an uncut control treatments. The study was installed in a randomized complete block design. The treatment plots were operational scale (15.44 ac or 6.25 ha each) and were replicated across three unique, noncontiguous blocks across the forest (A). Block 1 is shown enlarged (B).

(~36 m diameter, approximately one-and-a-half-tree-length diameter), 0.2 ha (~50 m diameter, approximately two-tree-length diameter), 0.4 ha (~71 m diameter, approximately three-tree-length diameter), and 0.8 ha (~101 m diameter, approximately four-tree-length diameter) by cutting all merchantable trees within the group opening boundaries, while thinning (third-row) the rest of the treatment plots. The residual basal area of the stand was approximately 16 m^2 ha^{-1}, independent of group openings. Uniform shelterwood cut was implemented using a seed cut, in which the trees from the lower crown classes were cut first uniformly across the stand, resulting in a residual basal area of approximately 11.5 m^2 ha^{-1}. The residual stand consisted mostly of trees which were the biggest (>20 cm) and best (good crowns, healthy) and were dispersed somewhat uniformly across the stand. Smaller trees of a lower crown class (intermediate) were occasionally retained to maintain a uniform canopy cover across the stand. The uncut, no manipulation treatment served as the experimental control. The stand's basal area of control was approximately 30 m^2 ha^{-1}.

The three treatments (two conversion harvest treatments and an uncut control) were installed in a randomized complete block design. The treatment plots were large enough to be considered operational-scale applications (6.25 ha per treatment plot) and were replicated across three distinct, non-contiguous blocks in the forest. Prescribed fire was applied to the plots in 2015 and 2018 during the dormant season (November-March). These burns were carried out using ground ignition techniques and flanking and backing fires.

2.3. Data collection and processing

Increment cores were taken from residual trees from each treatment plot, approximately 8-to-9 years post-harvest. In both the uniform shelterwood and control treatments, three trees were randomly sampled from each of the five measurement plots, totaling 15 in each treatment plot (replicate) and 45 for each of these treatments. Increment cores were taken on the east side of the tree at breast height (1.37 m) (Speer, 2010). In the group cutting treatment plots, cores were taken from trees around each group opening following the methodology outlined by York et al. (2004), where cores from five trees were taken in each cardinal direction (North, South, East, and West). The cores were taken at breast height and perpendicular to the group opening border; that is, cores from trees on the group opening's North and South borders were taken from the East side of the tree (facing West), and cores from trees on the group opening's East and West borders were taken from the South side of the tree (facing North). Tree selection for coring in each cardinal direction was based on distance to the group opening border and started with the tree closest to the edge. The next four trees were chosen by moving 5, 10, 15 and 20 m from the border and choosing the nearest tree with the farthest distance being no more than 30 m (Fig. 3). A total of 240 cores were collected from 12 group openings, each group opening contributing 20 cores.

Additional tree data recorded included diameter at breast height, orientation around the group opening (cardinal direction of tree location), distance to gap edge, and canopy class occupancy as either dominant (crown extending above the canopy and receiving direct light across the top and all sides of the upper branches), codominant (crown within the main canopy and receiving direct light across the top of the upper branches), intermediate (crown extends partially into the lower part of the main canopy and receives direct light only at a limited area at the top of the tree) or suppressed/overtopped (crown entirely below the main canopy and receiving no direct light), as defined by Nyland (2016). To assess the effect of group openings on residual tree growth surrounding the group openings, residual tree orientation around the group opening and distance from the border of the nearest group opening were measured in the group cutting plots. Distance from the border was classified into five categories (0–5 m, 5–10 m, 10–15 m, 15–20 m, and >20 m). Low quality cores resulting from indistinguishable rings were discarded, creating an unbalanced sampling pool of 39 cores in the

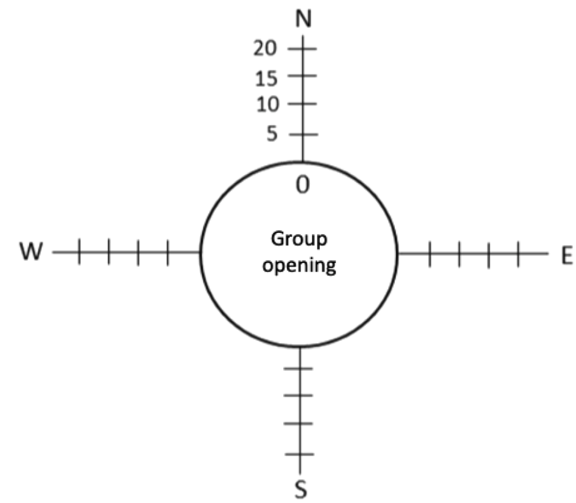

Fig. 3. A schematic diagram of the sampling scheme in the group cutting treatment. In each cardinal direction, the tree on the border of the group opening (0 in the figure) was cored. Then the trees that were nearest 5, 10, 15, 20 m from the group opening in that direction were chosen and cored totaling five trees in each direction and 20 trees in each group opening. A total of 240 cores were obtained from a total of 12 group openings.

control, 32 in the uniform shelterwood, and 211 in the group cutting treatment (Table 1). The total samples remaining for each distance from group opening border, canopy position, and orientation around the group opening for each group opening size are provided in Table 2.

After collection, the cores were air dried at room temperature and then sanded using 120 grit sandpaper (Speer 2010) in preparation for analysis. Each core was scanned using an Epson Perfection V800 Photo® scanner and images and analyzed with the WinDendro® software (Regent Instruments Inc). Each core image was visually analyzed and each ring indication visually confirmed. The cores were also crossdated in the WinDendro® program to verify the correct year for each ring using the skeleton plotting method as outlined by Cropper (1979).

After crossdating was completed, basal area increment (BAI) for each year was calculated from the ring width, w, and radius length, R. BAI at year, t, is calculated from an equation of the difference in area between two circles:

$$BAI_t = n\left(R_t^2 - R_{t-1}^2\right)$$

Where

$$R_{t-1} = R_t - -w_t$$

From the annual BAI values, we calculated mean BAI of individual trees over a period of 7 years (2011–2018). Mean BAI estimates served as the measure of tree growth (Burkhart et al., 2018).

2.4. Data analyses

Analysis of variance (ANOVA) was conducted to test the effects of harvest treatment (uniform shelterwood, group cutting (all group openings), and uncut control), tree canopy position (dominant, codominant, intermediate, and suppressed), and the interaction between harvest treatment and canopy position on mean tree BAI. Within the group cutting treatment, we also conducted an ANOVA to test the effects of gap size (0.1, 0.2, 0.4, and 0.8 ha), distance of tree from group opening border (0–5 m, 5–10 m, 10–15 m, 15–20 m, and >20 m), orientation of tree around the group openings (North, South, East, and West), canopy position, and the interaction between all the variables on mean BAI. Where significant results were found, Tukey HSD test were performed to detect significant differences among means. Treatments were considered significantly different at $\alpha = 0.05$. All data were

Table 1
Number of samples within each tree canopy position class and for each of the three harvest treatments (control, uniform shelterwood, and group cuttings).

Treatment	Total	Canopy Position Dominant	Codominant	Intermediate	Suppressed
Control	39	9	18	10	2
Uniform shelterwood	32	21	10	1	0
Group cutting	211	83	100	21	7

Table 2
Number of tree cores used in the analyses for the group cutting treatment for each combination of variables: group opening size, tree canopy position, orientation around the group opening, and distance from the group opening border.

	Canopy Position				Orientation around the group opening				Group opening size			
	Dominant	Codominant	Intermediate	Suppressed	North	South	East	West	0.1 ha	0.2 ha	0.4 ha	0.8 ha
Distance from group opening border												
0–5 m	31	27	4	2	14	15	14	21	16	16	17	15
5–10 m	21	22	9	2	13	15	14	12	11	18	11	14
10–15 m	13	27	8	3	14	12	13	10	10	12	17	10
15–20 m	16	21	0	0	10	10	12	7	8	11	10	11
>20 m	1	3	0	0	0	4	1	0	2	1	1	0
Canopy Position												
Dominant					19	23	23	16	13	22	23	24
Codominant					24	26	26	31	32	25	28	15
Intermediate					6	6	6	3	1	7	4	9
Suppressed					2	1	0	0	0	4	1	2
Orientation around group opening												
North									9	15	15	12
South									14	14	15	13
East									12	15	13	14
West									12	14	13	11

analyzed using R version 4.1.3.

3. Results

3.1. Effects of harvest treatments and canopy position on BAI

Overall, mean BAI was significantly higher in the uniform shelterwood treatment (25.04 cm^2) than the group cutting averaged over all group opening sizes (16.56 cm^2) and control (11.88 cm^2) treatments, and the group cutting was significantly higher than the control ($p < 0.001$). The interaction between harvest treatment and canopy position was significant with the dominant and codominant trees in the uniform shelterwood treatment having significantly higher mean BAI (26.39 cm^2 and 21.97 cm^2, respectively) than the dominant and

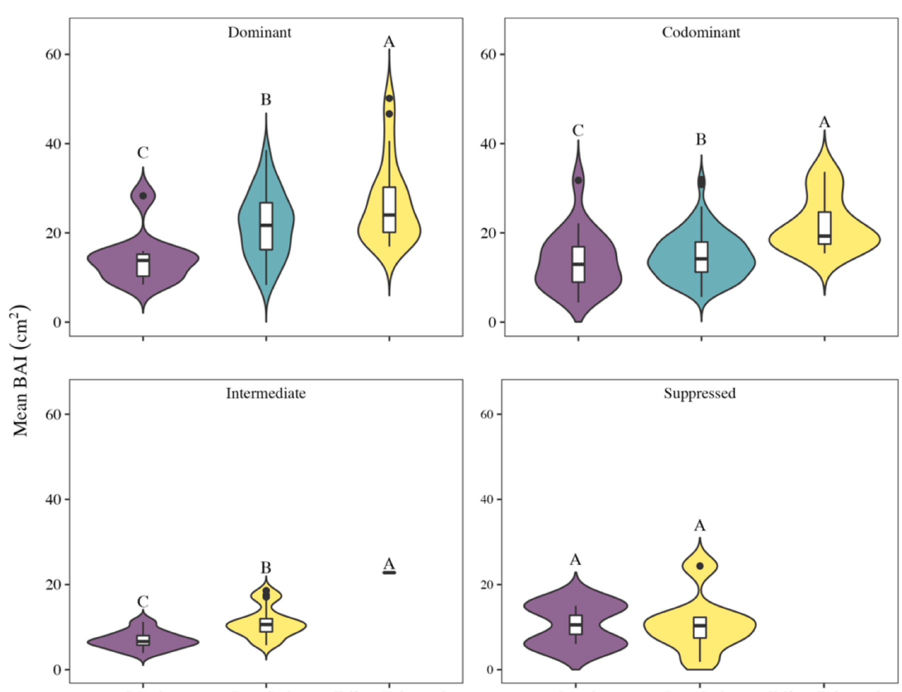

Fig. 4. Distribution of mean basal area increment (BAI) for each tree canopy position in group cutting, uniform shelterwood, and uncut control treatments. Boxplots imbedded within the violin plots show the minimum, first quartile, mean, third quartile, and maximum with the violin plot displaying the distribution with wider areas having more data points. ANOVA and Tukey-Kramer test were applied at α = 0.05. Mean values with the same letter are not significantly different.

codominant trees in the group cutting (21.32 cm^2 and 14.23 cm^2, respectively) and control treatments (14.02 cm^2 and 13.70 cm^2, respectively) (Fig. 4).

3.2. Effects of group opening characteristics on BAI in group cutting treatment

Within the group cutting treatment, the size of group opening, distance from the group opening border, and canopy position all had a significant effect on mean BAI. The 0.1 ha group opening had significantly lower mean BAI than all other three group opening sizes ($p < 0.001$) (Table 3). Trees found within 0-5 m from the group opening border had significantly higher mean BAI than trees found more than five meters from the border of the group opening ($p < 0.001$) (Table 3). Dominant trees had a significantly higher mean BAI than the codominant, intermediate, and suppressed trees, and the codominant trees had significantly higher mean BAI than the intermediate and suppressed trees ($p < 0.001$) (Table 3).

4.2.1. Group opening size and canopy position

The interaction between canopy position and group opening size was significant at $p < 0.001$ (Fig. 5). Dominant trees in the 0.1 ha group opening had a significantly smaller mean BAI (15.60 cm^2) than the dominant trees in the 0.2, 0.4, and 0.8 ha group openings (22.51 cm^2, 20.86 cm^2, and 23.95 cm^2, respectively) (Fig. 5). Codominant trees in the 0.1 ha group opening had a significantly smaller mean BAI (12.48 cm^2) than the codominant trees in the 0.2 ha group opening (15.66 cm^2) (Fig. 5). There were no statistically significant differences between the group opening sizes for intermediate and suppressed trees.

Table 3
Estimates (mean ± SE) of basal area increment (BAI) of trees after harvest in the group cutting treatment for each group opening size, distance from the border of group opening, canopy position and orientation around the group opening (cardinal direction). ANOVA and Tukey-Kramer test were applied at $\alpha = 0.05$. Mean values with the same letter are not significantly different.

Attribute	Class	Mean BAI (cm^2)	F-stat	*p*-value
Group opening size	0.1 ha	13.34 ± 0.43^b	25.535	< 0.001
	0.2 ha	17.81 ± 0.49^a		
	0.4 ha	16.80 ± 0.52^a		
	0.8 ha	17.92 ± 0.57^a		
Distance from group opening border	0-5 m	19.54 ± 0.56^a	24.707	< 0.001
	5-10 m	15.00 ± 0.48^b		
	10-15 m	14.91 ± 0.44^b		
	15-20 m	16.53 ± 0.54^b		
	>20 m	14.12 ± 1.05^b		
Canopy position	Dominant	21.33 ± 0.47^a	104.576	< 0.001
	Codominant	14.24 ± 0.29^b		
	Intermediate	11.05 ± 0.44^c		
	Suppressed	10.85 ± 1.15^c		
Direction	North	16.75 ± 0.54^a	0.317	0.813
	South	16.57 ± 0.50^a		
	East	15.89 ± 0.50^a		
	West	17.04 ± 0.53^a		

4.2.2. Group opening size and orientation

There were no statistically significant differences in mean BAI for each cardinal direction in the 0.1, 0.4, and 0.8 ha groups (Fig. 5). In the 0.2 ha group openings, trees oriented North of the group opening had significantly higher mean BAI (18.71 cm^2) than trees oriented to the East (16.18 cm^2) (Fig. 5).

4.2.3. Group opening size and distance from group opening border

In the 0.1 ha group opening, trees found within 0–5 m from the group opening border had a significantly higher mean BAI (15.91 cm^2) than trees found 5–10 m and 15–20 m from the group opening border (10.36 cm^2 and 11.38 cm^2, respectively) (Fig. 5). In the 0.2 ha group opening, trees found 0-5 m from the group opening border had significantly higher mean BAI (21.31 cm^2) than trees 10-15 m from the group opening border (16.06 cm^2) (Fig. 5). In the 0.4 ha group opening, trees 0–5 m from the group border had significantly higher mean BAI (21.73 cm^2) than trees 5–10 m and 10–15 m from the group opening border (13.65 cm^2 and 14.73 cm^2, respectively) (Fig. 5). There were no statistically significant effects of distance from group opening border on mean BAI in the 0.8 ha group opening (Fig. 5).

4.2.4. Orientation and distance from group opening border

For trees oriented North of group openings, there was no statistically significant difference in mean BAI among distance categories (Fig. 5). For trees oriented on the South, East, and West sides of group openings, trees located 0-5 m form the border had significantly higher mean BAI than trees located 5-10 m, 10-15 m, 15-20 m, and >20 m from the border (Fig. 5).

4. Discussion

4.1. Effects of harvest treatments

We conducted this study to evaluate the growth of residual trees following uniform shelterwood and group cutting treatments applied to a slash pine plantation as a first step to convert it to an uneven-aged stand. When compared to the uncut control plots, both uniform shelterwood and group cuttings accelerated the growth of residual trees over a 7-year period. However, tree growth response varied with the type of harvest (uniform shelterwood or group) and tree canopy position. Furthermore, group opening size and distance from the group opening border influenced residual tree growth within the group cutting treatment. These findings were generally in agreement with our expectations. The response to the harvest treatment is similar to thinning procedures in even-aged slash pine stands, where thinning either preserves growth rates or causes residual trees to be released (Clutter and Jones, 1980; Pienaar et al., 1990). However, contrary to our expectations, we did not find orientation of trees around group openings to significantly affect residual tree growth. Overall, these findings are encouraging because they show that stand conversion to uneven-aged silviculture can be initiated in mature slash pine plantations (35 to 42 years old in our study), with improvements in tree growth still possible while the stand structure is converted to uneven-aged.

Residual slash pine showed higher growth response in the uniform shelterwood harvest treatment than the group cutting harvest, likely because the uniform shelterwood treatment in our experimental trial had a greater reduction in basal area (greater release) than the group cutting treatment. While empirical studies on slash pine tree growth following stand conversion harvests are scarce, other species have been studied extensively. For example, Bedard and Majcen (2003) observed increased tree growth following selection harvests in a sugar maple (*Acer saccharum* Marsh) dominated forest. Bebber et al. (2004) observed increased tree growth in mature residual eastern white pine (*Pinus strobus* L.) following single tree selection harvest. Sugar maple (*Acer*

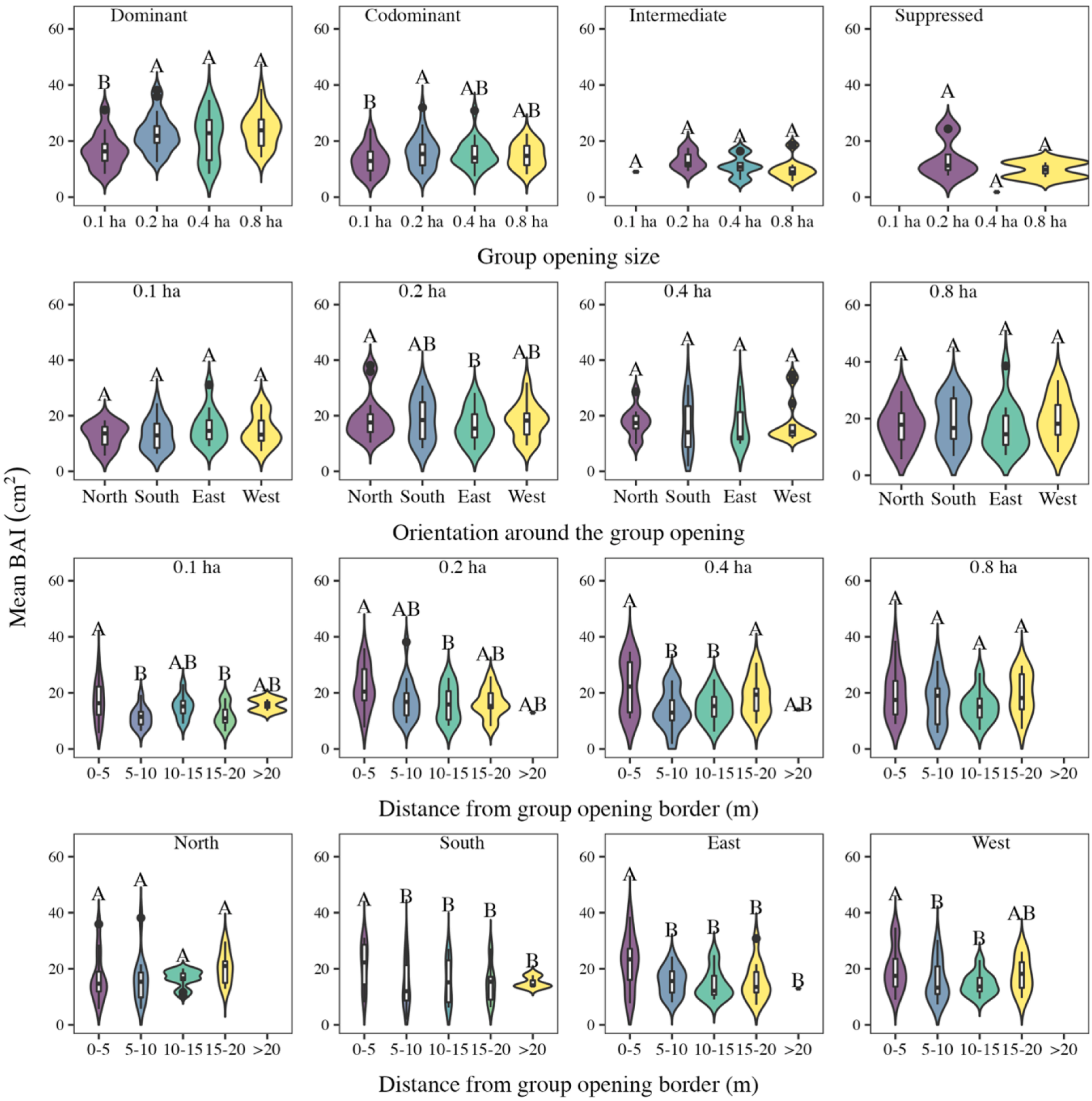

Fig. 5. Distribution of mean basal area increment (BAI) for each group opening size, orientation around the group opening and distance from the group opening border for trees in the group cutting treatment. Boxplots imbedded within the violin plots show the minimum, first quartile, mean, third quartile, and maximum with the violin plot displaying the distribution with wider areas having more data points. ANOVA and Tukey-Kramer test were applied at α = 0.05. Mean values with the same letter are not significantly different.

saccharum Marsh.), American beech (*Fagus grandifolia* Ehrh.) and yellow birch *(Betula alleghaniensis* Britton) responded positively to group selection harvest in another study (Forget et al., 2007).

4.2. Factors influencing growth within group cutting treatment

Microenvironmental variables such as light availability, soil moisture and temperature, and nutrient availability are influenced by gap characteristics such as size, shape, and orientation around the gap (O'Hara, 2014). In our study, slash pine responded positively to group cutting when compared to uncut control, and trees found near group opening borders grew faster than trees further away from gap border. York et al. (2004), Grey et al. (2012), and Stan and Daniels (2014) also found similar tree growth responses in group selection treatments. Trees near gap borders have access to higher light availability, improved soil moisture, and reduced competition, which could lead to increased growth compared to trees away from the border. While we found orientation of tree around group openings to have no effect on tree growth, other studies have found variable results. Grey et al. (2012) observed higher tree growth response in the South side of gaps in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) dominated forest. Similar observations were made Stan and Daniels (2014) for western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and Pacific silver fir (*Abies amabilis* Dougl. ex J. Forbes) dominated forests. Unlike intolerant slash pine, the species examined in these studies were moderate-to-highly tolerant of shade. In contrast and similar to our study, York et al. (2004) and Pederson and Howard (2004) found no relationship between the growth response of trees and tree orientation around the gaps in mixed species forests. However, these studies consistently found that tree growth declined as the distance of tree increased from the gap border.

While orientation around the group opening did not matter, the size of the group opening was a significant factor influencing tree growth. Group openings 0.2 ha and larger exhibited higher tree growth than trees bordering 0.1 ha group openings, suggesting a minimum group opening size of 0.2 ha is needed to release mature slash pine trees. Also, lower amount of light is available in 0.1 ha group openings compared to 0.2 ha or larger openings in slash pine stands (Sharma et al., 2019).

4.3. Management implications

Our study demonstrated that group cuttings and uniform shelterwood harvests led to increased growth of mature slash pine compared to uncut control over the course of a 7-year period during stand conversion. Uniform shelterwood harvests, that led to greater tree growth than group cutting, could be efficient harvest methods as initial steps to stand conversion since realized gains occur in tree growth. However, to be an effective stand conversion treatment, uniform shelterwood method must also lead to satisfactory regeneration to add another age class. Alternatively, when using group cutting for stand conversion, our study suggests that a minimum group opening size of 0.2 ha is needed. In previous studies, it has been demonstrated that slash pine can regenerate in a satisfactory way, adding an age cohort, following group cuttings (Frazier et al., 2021). Group selection management has also been found to be advantageous regarding understory restoration in southern pine flatwoods as it provides higher light availability (Sharma et al., 2012). Our earlier study showed that understory also responded positively to uniform shelterwood and group cuttings in our slash pine treatment plots, where species richness was higher with greater abundance of grasses and forbs (Bohn and Sharma 2016). Furthermore, simulation analyses with slash pine indicate that uneven-aged silviculture creates complex stand structure and promote sustained timber yields and carbon stocks in slash pine (Sharma et al., 2014; Sharma et al., 2016). Combined with this study, these studies support the feasibility of managing slash pine using uneven-aged systems to provide multiple benefits and to develop a new cohort of trees.

5. Conclusions

In southern pines, uneven-aged silviculture is underutilized, and long-term empirical data on its application are rare. There are few experimental trials in southern pines to evaluate these silvicultural systems. While uniform shelterwood harvest can result in increased tree growth during stand conversion, when practicing uneven-aged silviculture using group selection system, our research demonstrates that group openings of at least 0.2 ha are needed to realize increased gain in tree growth in slash pine. Furthermore, dominant and codominant trees will respond to harvests and gap creation more favorably than intermediate and suppressed trees. While group openings of 0.2 ha or more are suitable for residual slash pine growth, more research is needed to determine how gap effects on slash pine regeneration and understory interact with gap size effects on residual trees in order to fully assess gap size for multifunctional long-term feasibility of uneven-aged systems.

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.

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