Forest Ecosystems 13 (2025) 100305

Contents lists available at ScienceDirect

Forest Ecosystems

journal homepage: www.keaipublishing.com/cn/journals/forest-ecosystems

Growth dynamics of longleaf pine during conversion to uneven-aged stands

Ashton Shell[a], Ajay Sharma[b,*], John L. Willis[c], John Tracy[d], Adam Polinko[e], Santosh Ojha[f], Jason Vogel[g]

[a] West Florida Research and Education Center, University of Florida, Milton, FL, 32571, USA
[b] College of Forestry, Wildlife and Environment, Auburn University, Auburn, AL, 36849, USA
[c] USDA Forest Service, Southern Research Station, Auburn, AL, 36849, USA
[d] School of Renewable Natural Resources, Louisiana State University, Baton Rouge, LA, 70803, USA
[e] Department of Forestry, Mississippi State University, Mississippi State, MS, 39762, USA
[f] Department of Biological and Environmental Sciences, Alabama A&M University, Normal, AL, 35762, USA
[g] School of Forest, Fisheries, and Geomatics Sciences, University of Florida, Gainesville, FL, 32611, USA

A R T I C L E I N F O

Keywords:
Uneven-aged silviculture
Multi-aged stands
Stand conversion
Group openings
Hurricane disturbance
Southern pine
Pinus palustris Mill.

A B S T R A C T

A growing recognition that uneven-aged silviculture can offer multiple benefits to forested ecosystems has encouraged some landowners in the southern region of the United States to convert even-aged pine stands into multi-aged stands. For shade-intolerant pines of the southern United States, however, few studies have examined residual tree growth following silvicultural treatments that convert even-aged stands to multi-aged stands. Understanding the growth response of residual trees to different kinds of stand conversion treatments is critical to stand development and sustainability, as trees must be recruited into larger size classes during the conversion process to develop the desired stand structure and maintain productivity. In this study, we utilized a replicated, long-term silvicultural experimental trial in the southeastern United States to assess the effects of two cutting treatments (dispersed "single tree cutting" that created small canopy gaps and the "patch cutting" that created 0.1–0.8 ha patch openings) and an uncut control on the 14-year growth (~cutting cycle length) of residual longleaf pine (*Pinus palustris* Mill.) trees. We found that tree growth, measured as mean basal area increment (BAI), was significantly higher following patch cutting (mean BAI of 16.97 cm^2) compared to both the single tree cutting (13.33 cm^2) and the uncut control (12.68 cm^2) ($p < 0.001$). In patch cutting, the size of the patch opening, the location of trees surrounding the patch opening, and the position of the tree canopy all had a significant effect on BAI. Trees surrounding patch openings of 0.4 ha exhibited greater growth, with a mean BAI of 19.24 cm^2, compared to those surrounding 0.1 and 0.8 ha patch openings, which had mean BAI values of 15.89 and 15.71 cm^2, respectively ($p < 0.001$). The position of a tree around the patch opening also influenced tree growth, as residual trees more to the North, South, and East sides exhibited significantly higher mean BAI than trees on the West side of the patch openings ($p < 0.001$). However, distance from the patch opening border did not significantly affect the mean BAI ($p = 0.522$). In all treatments, dominant and co-dominant trees exhibited higher BAI than intermediate and overtopped trees, indicating that tree canopy position significantly influenced tree growth ($p < 0.001$). Understanding how residual trees grow after these silvicultural treatments is crucial for thoroughly assessing their efficacy with longleaf pine. This study's findings will enhance our understanding of stand dynamics during stand conversion and help land managers anticipate the growth of longleaf pine into larger size categories after single tree and patch cuttings.

1. Introduction

The longleaf pine (*Pinus palustris* Mill.) ecosystem is one of the most diverse ecosystems in North America and dominated the southeastern United States during the pre-European settlement era when it occupied an estimated 37 million ha (Connor et al., 2014). The historical range once covered by longleaf pine forests now only partially remains due to extensive logging, land conversion, and the deliberate prevention of fires during the 1900s (Frost, 1993), making it one of the most threatened ecosystems in the United States (Frost, 2006). Restoring the structure,

* Corresponding author. College of Forestry, Wildlife and Environment, Auburn University, Auburn, AL, 36849, USA.
E-mail address: sharma@auburn.edu (A. Sharma).

Peer review under the responsibility of Editorial Office of Forest Ecosystems.

https://doi.org/10.1016/j.fecs.2025.100305
Received 24 September 2024; Received in revised form 11 December 2024; Accepted 4 February 2025

function, and biodiversity of these forests is currently a major land management goal (Palik et al., 2002; Brockway and Outcalt, 2000, 2015), and conversion of even-aged longleaf pine to support uneven-aged silviculture is considered one of the most effective strategies to restore multifunctionality in these forests (Guldin, 2006; Brockway and Outcalt, 2015, 2017; Sharma et al., 2016).

Consistent with these ideas, forest management and land use policies are increasingly trending toward management for a broadened set of objectives, including economic, ecological, as well as socio-cultural benefits (Cubbage et al., 2007; Diaci et al., 2011; Bradford and D'Amato, 2012). In this context, a shift toward uneven-aged management, which maintains forest stands as naturally sustaining and continuous cover stands with complex structures (Nyland, 2016), has gained relevance. As opposed to even-aged stands, uneven-aged stands are considered ecologically more efficient for maximizing multiple benefits (Tahvonen et al., 2010; Guldin, 2006; O'Hara, 2014; Sharma et al., 2016). In addition, they are perceived as recreationally and aesthetically favorable by the public (Bradley and Kearney, 2007; Gundersen and Frivold, 2008; Paudyal et al., 2018), are resilient to damages caused by disturbances such as snow or tropical storms (Holling, 1973; Brang, 2001; Hanewinkel et al., 2014; Sharma et al., 2021; Polinko et al., 2022), provide enhanced biodiversity and other ecosystem services (Pukkala, 2016; Joelsson et al., 2017; Nolet et al., 2018), and are economically competitive with even-aged management in certain situations (Tahvonen, 2009; Susaeta et al., 2021, 2022). However, implementing uneven-aged silvicultural systems is more complex compared to even-aged systems (Brockway et al., 2006; O'Hara, 2014; Nyland, 2016). Additionally, uneven-aged systems have been less thoroughly investigated in the southeastern United States, as in parts of Europe, where pine-centric silvicultural research in the last 70 years has focused mainly on systems suitable to even-aged stands to maximize timber production (Fox et al., 2007). Consequently, only a few silvicultural trials have explored uneven-aged methods for pine stands in the region (Guldin and Farrar, 2002; Brockway and Outcalt, 2017; Sharma et al., 2019; Frazier et al., 2021; Shell et al., 2022). Further, we lack examples of successful methods for transitioning even-aged southern pine stands into a multi-aged condition appropriate for future uneven-aged silvicultural treatments.

When conversion treatments are implemented into even-aged stands, they periodically remove trees, creating openings in the canopy by taking individual trees that create small openings or removing groups of trees that develop larger openings (Nyland, 2003; Shell et al., 2022). Successful conversions have typically involved partial cuttings that resemble heavy thinning and periodic patch cutting (Leak, 1999; Nyland, 2003, 2016). For these treatments to be successful, it is necessary to establish new cohorts of trees with multiple age classes and maintain satisfactory levels of tree growth (Nyland, 2003; Kelty et al., 2003). To ensure stand sustainability, these conversion treatments must also establish adequate regeneration for a new age class at each entry, recruiting new trees into the smaller size classes and growing the remainder to larger sizes during each cutting cycle, which can all be driven by the opening sizes created (Hanewinkel and Pretzsch, 2000; Kelty et al., 2003; Nyland, 2003). While some studies have examined short-term regeneration and understory responses to non-traditional cutting strategies in longleaf pine forests (Brockway and Outcalt, 1998; Gagnon et al., 2004; Kirkman and Mitchell, 2006; Mitchell et al., 2011; Brockway and Outcalt, 2017), questions remain about how such treatments influence growth of the residual longleaf trees that help maintain productivity of stand and affect the recruitment and intermixing of age classes over a longer period (Messerer et al., 2020).

Individual tree growth between two successive cuttings (e.g., ~14–15 years for a 15-year cutting cycle in longleaf pine) is affected by several factors. These factors include the spatial arrangement of residual trees (i.e., dispersed singly or by groups), factors related to the size of openings or gaps, or canopy position and location of trees around the gap edges (Jones and Thomas, 2004; York et al., 2004; Fortin et al., 2008; Gray et al., 2012; Stan and Daniels, 2014; Shell et al., 2022). For example, cutting patches of different sizes might result in higher growth of trees around the edges compared to the effects of single tree openings (Palik et al., 2003; Shell et al., 2022). Depending on the opening size, shape, and location, a complex heterogeneous stand environment might result in differing tree growth responses (Gray and Spies, 1997; McGuire et al., 2001; Frazier et al., 2021; Shell et al., 2022). It is plausible that residual trees may respond favorably to an increase in opening size, particularly in central and northern positions in gaps, as these locations usually have higher light levels than southern positions (Sharma et al., 2019). If valid, longleaf pine, a shade-intolerant, may grow faster near the northern positions of gaps and along the edges of larger openings. However, attributes related to individual trees, such as tree size and tree canopy position, also affect tree growth responses to cutting treatments and should be accounted for (Nyland, 2016; Shell et al., 2022).

While research on longleaf pine tree growth in uneven-aged stands is limited, Shell et al. (2022) evaluated slash pine (*Pinus elliottii* Engelm, another southern pine species) growth responses to initial stand conversion cutting treatments in dense plantations in hydric flatwoods sites of Florida, USA. In this study, factors related to cutting methods, tree canopy position, harvest opening size, and distance of tree from group opening border significantly affected tree growth in slash pine. Longleaf pine, like slash pine, is shade intolerant and possibly may exhibit a similar response as slash pine in similar situations. Alternatively, different site conditions, stand age, site disturbances, or modifications to harvest treatments may produce different tree responses in longleaf pine or slash pine.

Several other studies have investigated the impacts of group or patch cuttings on other species. For example, in a Douglas fir (*Pseudotsuga menziesii*) forest (Gray et al., 2012) and in western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and Pacific silver fir (*Abies amabilis*)-dominated forests (Stan and Daniels, 2014), trees on the southern side of gaps displayed higher growth than trees on the northern side. In contrast, York et al. (2004) observed no relationship between tree growth and tree position around the gaps. However, these studies consistently showed that as a gap's distance increases, tree growth declines (York et al., 2004; Gray et al., 2012; Stan and Daniels, 2014). Nevertheless, the species investigated in these studies were highly shade-tolerant or moderately shade-tolerant. Longleaf pine, an intolerant species, may respond differently to similar cutting practices.

In this study, we examined and quantified the residual longleaf pine tree response to single tree and patch cuttings as a strategy to actively convert an even-aged stand to an uneven-aged stand. Our specific questions were: (1) How do single tree cuttings and patch cuttings affect individual tree growth during the initial step in converting even-aged longleaf pine to multi-aged stands? (2) Does tree growth depend on the tree's canopy position? and (3) Is tree growth affected by (a) patch opening size, (b) tree's distance from patch opening border, and (c) tree's position around the patch opening? Based on our previous study in slash pine (Shell et al., 2022) and the shade-intolerant nature of longleaf pine, we expected to observe (1) greater tree growth among treated stands than in uncut controls and greater growth in patch cutting treatment compared to single tree cutting treatment, (2) greater tree growth in larger patch opening size and lower growth with increasing distance of tree from patch opening border, (3) greater growth among trees on the northern sides of patch openings, and (4) greater growth in dominant and co-dominant trees. We utilized an existing silvicultural experimental trial in southern Alabama, USA, and based on dendrochronological measurements, we estimated individual tree growth after single tree and patch cuttings over 14 years.

2. Materials and methods

2.1. Study area description

The study site, Escambia Experimental Forest (EEF), is a typical mesic upland longleaf pine forest type located centrally in the southeastern outer coastal plains in southern Alabama (31° N, 87° W) (Fig. 1). The climate is temperate, with a 200-day growing season and abundant annual precipitation averaging 1,557 mm, with more than half occurring in the growing season. Monthly temperature ranges from 16 °C to 31 °C between April and October and 5 °C–20 °C from November to March. The site elevation is around 75 m above sea level on undulating terrain. Surface slopes range from gently (<5%) to moderately inclined (10%–15%) and are derived from unconsolidated marine sediments. Predominant soils developed from these parent materials include Troup (Grossarenic Paleudult), Lucy (Arenic Paleudult), Wagram (Arenic Paleudult), Benndale (Typic Paledudult) and Dothan (Plinthic Paleudult) series. These soils are deep and well-drained, with a loamy and sandy composition. They have low levels of organic matter and nutrients, and their water-holding capacity ranges from low to moderate.

The canopy of the forest stands on this site is dominated by second-growth longleaf pine, which naturally established following an earlier period of logging from 1900 to 1919. The understory includes grasses such as little bluestem (*Schizachyrium scoparium*), woody shrubs such as inkberry (*Ilex glabra*), and many other herbaceous species (Connor et al., 2014). This site is representative of many millions of hectares of mesic forest sites throughout the southeastern United States that were once inhabited by longleaf pine.

2.2. Description of experimental design and cutting treatments

We utilized the existing "Comparative Analysis of Reproduction Techniques (CART) for Sustainable Management of Longleaf Pine Ecosystems" experimental trial established at Escambia Experimental Forest (Bohn et al., 2015). The CART study was installed in 2004 as an operational-scale silvicultural effort to evaluate different cutting methods applied to convert mature second-growth even-aged longleaf pine stands to uneven-aged stand conditions. The experiment was set up using a randomized complete block design, with three treatments repeated three times: single tree cutting, patch cutting, and an uncut control (Fig. 2, Table 1). It may be noted here that the original CART installation also had a shelterwood cutting treatment, which was applied using a seedcut that reduced the basal area to 6.9 m^2·ha^{-1} in 2004 when the harvest treatment was implemented. However, these shelterwood plots were completely destroyed by Hurricane Ivan less than two months after the harvest and had to be excluded from the study. The three replications constituted three blocks that addressed the initial variation in overstory structure. The treatment plots were large enough to be considered operational-scale applications (300 m × 300 m or 9 ha per plot, 81 ha for the study). Within every treatment plot, 36 steel poles were set up with a 50 m × 50 m spacing to create an internal grid network. Using the grid poles as geographical reference points, five subplots were then positioned within each treatment plot. The subplots measured 20 m × 50 m and were aligned in a north-south direction. These subplots were the main areas used for data collection.

Prior to harvest treatments in 2004, the basal area was 17.7 ± 3.0 m^2·ha^{-1} (mean ± standard deviation) in control, 18.5 ± 4.3 m^2·ha^{-1} in the single tree, and 18.3 ± 2.4 m^2·ha^{-1} in the patch cutting treatment plots (Table 1). The single tree cutting treatment removed dispersed individual trees of all size classes relatively evenly throughout the plots following the "Proportional-B" prototype selection method (Brockway et al., 2014) and reduced basal area from 18.5 ± 4.3 m^2·ha^{-1} to a target of 11.5 m^2·ha^{-1}. Patch cutting treatment removed groups of trees in defined areas following the "Proportional-B" prototype selection method (Brockway et al., 2014), creating three patch openings in each plot (approximately 0.1, 0.4, and 0.8 ha in area) and thinning the matrix to reduce the overall plot basal area to 11.5 m^2·ha^{-1}. The proportional-B method, which is designed specifically for longleaf pine, apportions the target residual basal area into a stand structure consistent with a ratio of 1:2:3 for small (<15 cm), medium (15–30 cm), and large (>30 cm) dbh size classes, respectively. In our study, this method apportioned the target of 11.5 m^2·ha^{-1} into approximately 1.9 m^2·ha^{-1} for small (<15 cm), 3.8 m^2·ha^{-1} for medium (15–30 cm), and 5.8 m^2·ha^{-1} for large (>30 cm) dbh size-class groups. More details of the tree marking implementation following the Proportional-B prototype selection method can be found in Brockway et al. (2014). The harvests were conducted in July–August of 2004. The control plots were left uncut. Although both single tree cutting and patch cutting treatments created comparable stand-level basal areas after the harvests in July–August 2004, Hurricane Ivan the next month (on September 16, 2004) impacted the study stands further reducing the basal areas to an average of 6.33 ± 1.29 m^2·ha^{-1} in single tree cutting, 10.6 ± 1.0 m^2·ha^{-1} in patch cutting, and 15.2 ± 1.6 m^2·ha^{-1} in uncut control plots in 2005, respectively (Table 1). Notably, the single tree cutting treatment plots were disproportionally hit by the hurricane, resulting in the death of many large trees and greater loss of

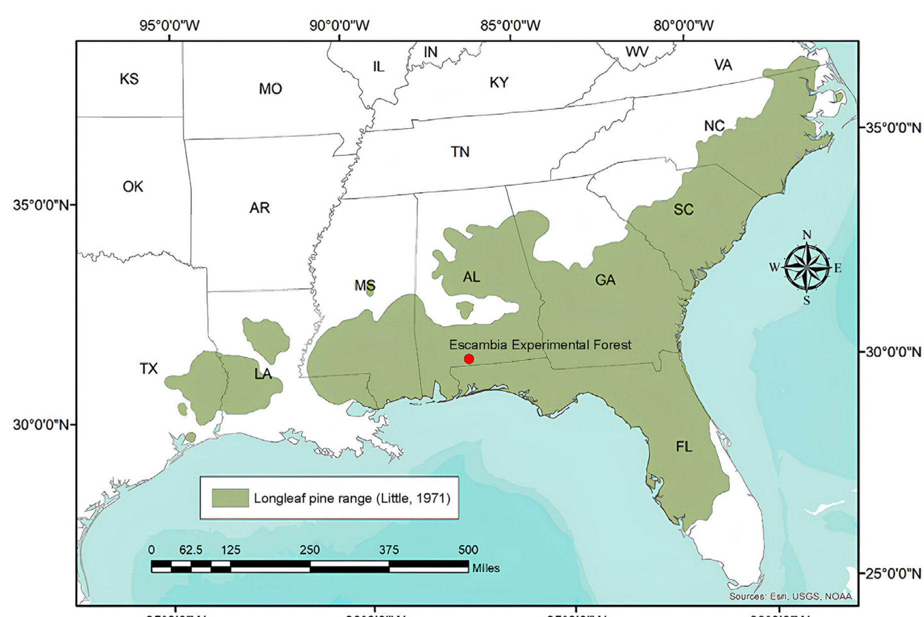

Fig. 1. The study site (Escambia Experimental Forest) located within the longleaf pine's historical range.

Fig. 2. An example of each of the three harvest treatment plots, viz., single tree cutting, patch cutting, and control, as seen in 2006. The cuttings were completed in July–August 2004.

Table 1
Basal area (Mean ± stdev) of single tree and patch cuttings and uncut control plots of longleaf pine. Pre-treatment measurements were conducted in 2003, and cutting treatments were implemented from July to August 2004. Hurricane Ivan occurred on September 16, 2004, and post-hurricane measurements were conducted in 2005.

Replication (Block)	Treatment	Pre-treatment basal area ($m^2 \cdot ha^{-1}$)	Post-treatment basal area ($m^2 \cdot ha^{-1}$)	Post-Hurricane Ivan basal area ($m^2 \cdot ha^{-1}$)
1	Single tree cutting	18.1	11.5	4.7
2	Single tree cutting	23.0	11.5	7.1
3	Single tree cutting	14.4	11.5	7.2
Mean ± stdev		18.5 ± 4.3	11.5 ± 0	6.33 ± 1.29
1	Patch cutting	17.4	11.5	9.4
2	Patch cutting	21.0	11.5	11.3
3	Patch cutting	16.4	11.5	11.1
Mean ± stdev		18.3 ± 2.4	11.0 ± 0	10.6 ± 1.0
1	Uncut control	18.0	18.0	14.0
2	Uncut control	14.5	14.5	14.7
3	Uncut control	20.5	20.5	16.9
Mean ± stdev		17.7 ± 3.0	17.7 ± 3.0	15.2 ± 1.6

basal area compared to patch cutting and control plots.

As part of the longleaf pine management plan, all the treatment plots, including the control, were burned every two years. Periodic fire is key to sustaining this fire-dependent ecosystem. It helps create a suitable mineral seedbed for seed germination, reduces competition from fire-susceptible species, enhances understory species diversity, and promotes overall ecosystem health (Jose et al., 2007) while having no adverse effects on the survival or productivity of mature trees (Willis et al., 2021).

2.3. Data collection and processing

We collected tree increment cores from residual trees from each treatment plot in 2019–2020, approximately 14 years after the cutting treatments. For both the control and single tree cutting treatments, we randomly sampled trees from each of the five subplots, totaling 15 in each treatment plot (replicate) and 45 for each of these treatments. We cored these trees at breast height (1.37 m) on the East side of the trees (Speer, 2010). Coring all trees uniformly on one side (East) was done to minimize any confounding effects the direction might have on tree radial growth distribution. The patch cutting treatment involved extracting cores around the borders of the patch opening, following the methods described by Shell et al. (2022) and York et al. (2004). Cores were collected from five trees in each cardinal direction (North, South, East, and West). The cores were obtained at breast height and perpendicular to the patch opening border. For instance, cores from trees on the North and South borders of the patch opening were taken from the East side of the tree (facing West), while cores from trees on the East and West borders of the patch opening were taken from the South side of the tree (facing North). Selection of trees for coring in each cardinal direction was based on their distance to the patch opening border, starting with the tree closest to the edge. To choose the next four trees, we moved 5, 10, 15, and 20 m from the border and selected the trees within those distances with the farthest distance of no more than 30 m from the border (Fig. 3). At some distances, the hurricane damage had led to no existing mature trees, resulting in smaller sample size for those distances. Additionally, we discarded the low-quality cores with indistinguishable rings from the pool, leaving an unbalanced sample size of 44 cores in control, 38 in single tree cutting, and 154 for the patch cutting treatments (Table 2). The totals for the distance of tree from the patch openings' border, tree

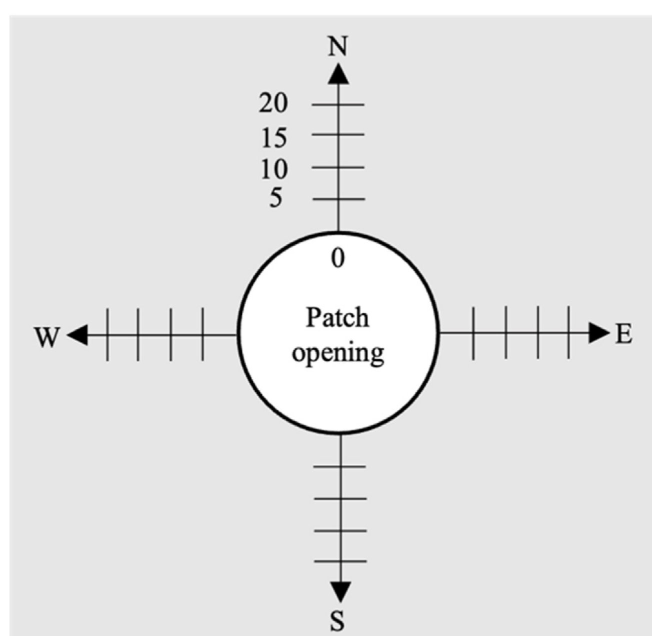

Fig. 3. Sampling scheme around the patch opening in each direction, with one tree on the border and others nearest to 5, 10, 15, and 20 m from the opening.

canopy position, and position of tree around the patch opening for each patch size are provided in Table 3.

Additional tree data collected was diameter at breast height, position around the patch opening (i.e., distance of tree from the patch opening border in each cardinal direction), and canopy position. We used the tree canopy position criteria from Nyland (2016), where dominant trees have crowns extending above the canopy and receiving direct light across the upper branches' top and sides. Co-dominant trees have crowns within the main canopy and receive direct light across the top of the upper branches. Intermediate trees have crowns that partially extend into the lower part of the main canopy and receive direct light only at a limited area at the top of the tree. Overtopped trees have crowns below the main canopy and receive no direct sunlight. The values for the distance of the tree from the patch opening border were categorized into five classes (0–5, 5–10, 10–15, 15–20, and 20–30 m).

After collection, the cores were left to air-dry at room temperature before being sanded with 80-grit and 120-grit sandpaper, as outlined by Speer (2010). Subsequently, the cores were scanned using an Epson Perfection V800 Photo® Scanner, and the acquired images were analyzed with the WinDendro® software developed by Regent Instruments Inc. Each individual core image underwent a visual examination to confirm the presence of each ring indication. Furthermore, crossdating of the cores was performed in the WinDendro® program to ensure the accuracy of the year for each ring, employing the skeleton plotting method described by Cropper (1979). Within the WinDendro® program, the skeleton plotting method uses a graphic of ring widths in the function of the year, which can simultaneously display master chronologies and ring widths of the sample under analysis and correlate them to identify any error.

After crossdating was completed, the basal area increment (BAI) for each year was computed based on the ring width, denoted as w, and the radius length, denoted as R. The BAI for a specific year, t, was determined using an equation that calculates the difference in area between two circles (Shell et al., 2022; Visser et al., 2023).

$$\mathrm{BAI}_t = \pi\left(R_t^2 - R_{t-1}^2\right)w$$

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

From the annual BAI values, we computed the mean BAI for each tree over the 14-year period from 2005 to 2018. This estimate was used as a measure of tree growth (Burkhart et al., 2018).

2.4. Data analyses

We conducted an analysis of variance (ANOVA) to test the effects of cutting treatment (single tree cutting, patch cutting, and uncut control), tree canopy position (i.e., dominant, co-dominant, intermediate, and overtopped), and the interaction between cutting treatment and tree canopy position on the tree mean BAI. In the patch cutting treatment, we conducted an ANOVA to examine the impact of patch opening size (0.1, 0.4, and 0.8 ha), tree position around the opening (North, South, East, and West), distance of the tree from patch opening border (0–5, 5–10, 10–15, 15–20 m, and >20 m), tree canopy position, and the interaction between these factors on tree mean BAI. In cases where we observed significant results, we carried out Tukey HSD tests to identify notable differences among the means. Treatments were considered to be significantly different at $\alpha = 0.05$. All data were analyzed using R version 4.1.3.

Table 2
Number of tree core samples used in the study to evaluate the three cutting treatments and the tree canopy position classes. Note that the single tree cutting treatment had only 31 (~82% of all) dominant or codominant trees compared to 143 (93%) in patch cutting treatment.

Cutting treatment	Total	Tree canopy position			
		Dominant	Co-dominant	Intermediate	Overtopped
Uncut control	44	17	18	7	2
Single tree	38	15	16	3	4
Patch	154	85	58	9	2

3. Results

3.1. Effects of cutting treatment and tree canopy position on tree growth

In general, the mean BAI was significantly higher in the patch cutting (16.97 cm^2) compared to both the single tree cutting (13.33 cm^2) and the uncut control (12.68 cm^2) ($p < 0.001$). Also significant was the interaction between tree canopy position and cutting treatment ($p < 0001$). The dominant and co-dominant trees in the patch cutting treatment had a significantly higher mean BAI (17.66 and 16.98 cm^2, respectively) than the dominant and co-dominant trees in the single tree cutting (14.32 and 12.76 cm^2, respectively) and uncut control (13.68 and 14.01 cm^2, respectively) treatments (Fig. 4). The intermediate trees in the patch cutting and single tree cutting treatments had a significantly higher mean BAI (12.17 and 13.60 cm^2, respectively) than those in the uncut control (8.07 cm^2) (Fig. 4). There were no significant differences in mean BAI of overtopped trees between treatments.

3.2. Effects of patch characteristics on tree growth

The interactions between patch opening size and canopy position, patch opening size and position around patch opening (direction), patch opening size and distance from the patch opening border, tree canopy position and tree distance from patch opening border, and position around patch opening (direction) and distance from the patch opening border were all significant, all having a p-value <0.001. Within the patch cutting treatment, patch opening size, tree canopy position, and tree position around the patch opening, all had significant effects on mean BAI, all having $p < 0.001$ (Table 4). The effect of the distance of the tree from the patch opening border on mean BAI was not statistically significant ($p = 0.522$). Residual trees located around the 0.4 ha patch opening had significantly higher mean BAI (19.24 cm^2) compared to 0.1 and 0.8 ha patch opening (15.89 and 15.71 cm^2, respectively) (Table 4).

Trees oriented on the North and East sides of the patch opening had significantly higher mean BAI (17.67 and 17.76 cm^2, respectively) than trees on the West side (15.70 cm^2) (Table 4).

3.2.1. Effects of patch opening size and tree canopy position

Generally, the trees in upper canopy positions showed higher growth rates than those in lower canopy positions in most patch sizes. Notably, the average BAI of the dominant trees surrounding the 0.4 ha patch opening was significantly higher (BAI = 20.91 cm^2) than those around the 0.1 and 0.8 ha patch openings (BAI values of 15.67 and 15.96 cm^2, respectively) (Fig. 5). No significant differences existed between the mean BAI of treatments for any other canopy positions between the treatments (Fig. 5).

3.2.2. Effects of patch opening size and tree position

No significant difference was found in mean BAI for different directions in the 0.1 ha patch opening (Fig. 5). Yet, trees oriented around the North, South, and East sides of the 0.4 ha patch openings showed significantly higher mean BAI (21.07, 19.21, and 20.18 cm^2, respectively) than trees on the West side (16.49 cm^2) (Fig. 5). For the 0.8 ha patch openings, trees located on the East side had a significantly higher mean BAI (18.64 cm^2) than trees on the South and West sides (14.00 and 14.18 cm^2, respectively) (Fig. 5). There was no significant difference in mean BAI between the trees on the North, South, and West sides in the 0.8 ha patch opening (Fig. 5).

3.2.3. Effects of patch opening size and tree distance from patch opening border

The mean BAI was significantly affected by the distance of trees from

Table 3
Number of tree cores used for evaluating the patch cutting treatment considering the variables of patch opening size, tree canopy position, tree position around the patch opening, and distance of tree from the patch opening border.

	Canopy position				Position around the patch opening				Patch opening size (ha)		
	Dominant	Co-dominant	Intermediate	Suppressed	North	South	East	West	0.1	0.4	0.8
Distance from patch opening border (m)											
0–5	24	19	3	0	12	12	9	13	16	14	16
5–10	18	14	1	1	10	6	9	9	17	13	4
10–15	13	11	2	1	9	6	8	4	7	10	10
15–20	19	10	2	0	5	18	8	8	11	8	12
20–30	11	4	1	0	4	3	4	5	3	7	6
Canopy position											
Dominant					22	16	24	23	33	31	21
Codominant					16	18	11	13	21	15	22
Intermediate					1	3	2	3	0	4	5
Overtopped					1	0	1	0	0	2	0
Position around patch opening											
North									14	13	13
South									14	13	10
East									14	13	11
West									12	13	14

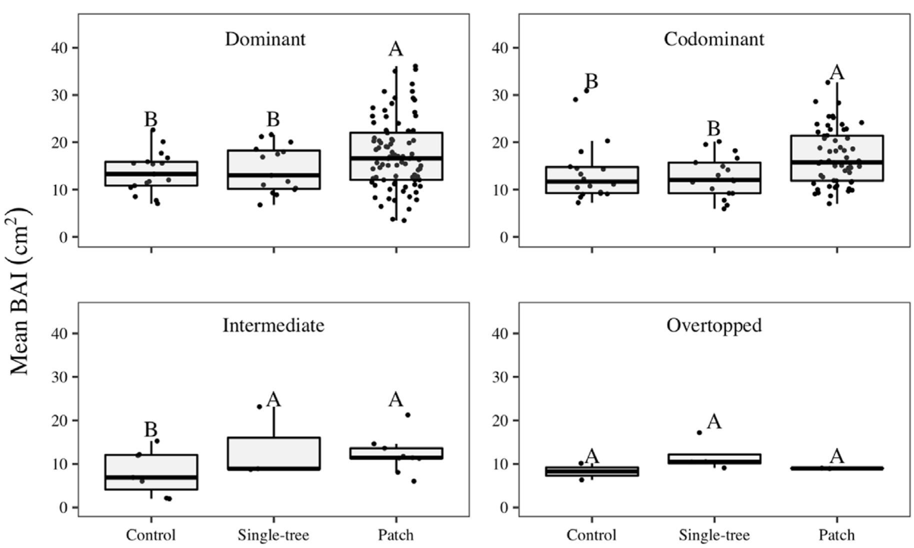

Fig. 4. Mean basal area increment (BAI) for tree canopy position in control, single tree and patch cutting treatments. ANOVA and Tukey-Kramer tests were conducted at a significance level of $\alpha = 0.05$. Any values sharing the same letter are not considered significantly different.

the patch opening border, but this effect was only observed in the 0.1 ha patches. Trees located 20–30 m from the border exhibited a higher mean BAI (19.24 cm^2) compared to trees positioned 5–10 and 10–15 m from the patch opening border, which had mean BAI values of 15.24 and 13.02 cm^2, respectively (Fig. 5).

3.2.4. Effects of tree canopy position and distance from patch opening border

Within a distance of 0–5 m from the border of the patch opening, the mean BAI of dominant and co-dominant trees was significantly higher (17.71 and 17.23 cm^2, respectively), compared to the mean BAI of intermediate trees (10.43 cm^2) (Fig. 5). At 5–10 m from the border of the patch opening, dominant, co-dominant, and intermediate trees showed a significantly higher mean BAI (18.16, 15.39, and 21.25 cm^2, respectively) than overtopped trees (9.06 cm^2) (Fig. 5). At 10–15 m, dominant and co-dominant trees had significantly higher mean BAI (15.52 and 18.33 cm^2, respectively) than overtopped trees (8.92 cm^2) (Fig. 5). At 15–20 m, dominant and co-dominant trees showed significantly higher mean BAI (18.65 and 15.26 cm^2, respectively) than intermediate trees (10.35 cm^2) (Fig. 5). Between 20 and 30 m, co-dominant trees exhibited a significantly higher average BAI (21.93 cm^2) than dominant trees, which had an average BAI of 17.50 cm^2 (Fig. 5).

3.2.5. Effects of tree position and distance from patch opening border

Tree position had a variable response to distance from the patch opening border. For trees on the North side, the mean BAI did not show a significant difference between the distance categories (Fig. 5). However, significant differences in BAI were found in other directions. For example, trees on the southern side of the patch opening exhibited a significantly greater mean BAI (17.68 cm^2) when located 0–5 m from the patch opening border compared to trees situated 10–15 m away from the border (12.23 cm^2) (Fig. 5). Also, trees at 20–30 m from the South side of a patch opening exhibited a significantly higher mean BAI (24.42 cm^2) than the other distances (Fig. 5). Trees located on the East and West sides of the patch opening at different distances showed variable responses (Fig. 5).

4. Discussion

4.1. Effects of cutting treatment

Our study aimed to assess the development of residual trees after implementing single tree and patch cutting treatments in mature, second-growth longleaf pine stands, intending to transition them to multi-aged

Table 4
Basal area increment (BAI) estimates (mean ± SE) of residual trees in the patch cutting treatment plots for each patch opening size, distance of tree from the border of patch openings, tree canopy position, and position of tree around the patch opening (cardinal direction). ANOVA and Tukey-Kramer tests were conducted at a significance level of $\alpha = 0.05$. Any values sharing the same letter are not considered significantly different.

Attribute	Class	BAI (cm^2)	*F*-stat	*p*-value
Patch opening size (ha)	0.1[a]	15.89 ± 0.31	43.999	<0.001
	0.4[b]	19.24 ± 0.39		
	0.8[a]	15.71 ± 0.34		
Distance from patch opening border (m)	0–5[a]	17.04 ± 0.36	0.804	0.522
	5–10[a]	16.84 ± 0.50		
	10–15[a]	16.20 ± 0.47		
	15–20[a]	17.02 ± 0.44		
	20–30[a]	18.22 ± 0.61		
Canopy position	Dominant[a]	17.66 ± 0.30	20.76	<0.001
	Codominant[a]	16.98 ± 0.30		
	Intermediate[b]	12.17 ± 0.47		
	Overtopped[b]	8.99 ± 0.77		
Position around patch opening	North[a]	17.67 ± 0.39	6.246	<0.001
	South[ab]	16.74 ± 0.40		
	East[a]	17.76 ± 0.41		
	West[b]	15.70 ± 0.44		

stand conditions. Patch cutting in mature even-aged longleaf pine stands resulted in higher 14-year growth of residual trees compared to single tree cutting treatment and uncut control plots, and trees occupying dominant and co-dominant canopy positions showed superior growth responses to cutting treatments. Contrary to our expectations, the single tree cutting did not result in significantly higher tree growth than in the uncut control treatment. The lower tree growth in single tree selection cutting is likely due to the disproportionally more severe damage caused to single tree cutting treatment plots by Hurricane Ivan, which caused excessive damage to even the surviving trees, adversely affecting the post-hurricane growth for several years. The post-hurricane single tree cutting plots also had a similar proportion of dominant and co-dominant trees comparable to control plots but lower than those in patch cutting plots (see Table 2). Since the intermediate and overtopped trees did not show as high a growth response as the dominant or codominant trees following the cutting treatments, this also could have contributed to overall lower tree growth in single tree cutting plots. Notably, because of the unequal sample size in the patch cutting treatment of our study, most of the sampled trees were located on or near the border of the patch openings (more than 50% of trees existed within 10 m of the patch opening border and 70% within 15 m) and many of them occupied dominant and co-dominant canopy positions (Table 3). Since mature longleaf pine trees can have lateral roots extending to more than 15 m from their stems (Stone and Kalisz, 1991), the patch openings likely provided a competition-free, resource-rich soil environment to these border trees, resulting in increased growth. The border trees around openings also receive high light levels (Sharma et al., 2012, 2019), further boosting growth for shade-intolerant species. Within both cutting treatments, tree canopy position was an influential factor. The dominant and co-dominant trees exhibited greater growth than the intermediate and overtopped trees. Within the patch-cutting treatment, the size of the patch opening, the distance of the tree from the opening border, and the tree's position in relation to the patch opening all had varying effects on tree responses. Overall, just like thinning (release) treatments that maintain or stimulate the growth of residual trees (Farrar, 1986; Bédard and Majcen, 2003; Plauborg, 2004; Harrington, 2011; Gonzalez-Benecke et al., 2012), the cutting treatments also stimulated tree growth. The results of our study show that residual longleaf pine trees aged 60–80 responded positively to being released, indicating the possibility of achieving growth while transitioning from even-aged longleaf pine stands to multi-aged conditions through patch cutting.

4.2. Factors influencing tree growth within the patch cutting treatment

Several microenvironmental variables are affected by gap creation, including light availability, soil moisture, nutrients, and soil temperature (O'Hara, 2014). Further, opening size, shape, and orientation affect the distribution of resources within and around the patches, which interact to influence residual tree response (O'Hara, 2014). In longleaf pine, belowground fine root biomass distribution and aboveground fine fuel distribution and light availability are also affected by gap characteristics (Brockway and Outcalt, 1998, 2017; Gagnon et al., 2004). In our study, these microenvironmental dynamics in patch cutting plots likely influenced our observed tree growth bordering the patch openings. Additionally, trees on the northern side of gaps in the sites located in the northern hemisphere typically receive greater light than those on the southern side, which could explain the relevance of tree position around the patch openings, as observed in our study (Sharma et al., 2019). With other species, Stan and Daniels (2014) and Gray et al. (2012) noted that tree growth was higher on the south side of gaps in mixed stands of Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Pacific silver fir (*Abies amabilis*). Yet, Pedersen and Howard (2004) and York et al. (2004) found no relationship between tree position around gaps and growth. Several studies suggest that the distance of trees from gaps also influences growth following gap cuttings (York et al., 2004; Gray et al., 2012; Stan and Daniels, 2014). While we did not notice any substantial impact of the distance from the patch opening border on tree growth, the patch opening size did have a significant effect. Trees around 0.4 ha patch opening had the highest tree growth in our study, suggesting that the patch size could be crucial in developing patch cutting silvicultural prescriptions for converting even-aged to uneven-aged structure in mature longleaf pine stands. In a study in Florida, Gagnon et al. (2004) found that longleaf pine regeneration density increased as group size increased following group cutting treatments. We also observed (data not collected) greater size but variable density of longleaf pine sapling cohorts in 0.8 ha patches in our study that regenerated and developed over 14 years following the cutting treatments. This increase in regeneration and its growth with group or patch size possibly results in increasing competition between the residual trees and the new cohort of seedlings and saplings over time as the regeneration develops into larger size classes. This could be one reason the trees oriented near 0.8 ha gaps in our study displayed lower growth than those oriented around 0.4 ha. Also, our observations in the treatment stands found the 0.1 ha patches did not have much regeneration response, possibly because 0.1 ha is not large enough to provide an adequate increase in resource availability for shade-intolerant longleaf pine. 0.4 ha patches appeared to have a moderate level of regeneration. It is also possible that the hurricane-caused disturbances in residual stand structure could have confounded the effects of patch size on residual tree growth. These possibilities could explain why we observed higher tree growth in trees around 0.4 ha gaps. For successful stand conversion, an effective method would lead to adequate natural regeneration (new age cohort) and high residual tree growth. Additional studies would be needed to establish the optimal size for patch cutting for stand conversion in longleaf pine.

In another similar study on slash pine (*Pinus elliottii* Engelm), we found broadly similar tree growth responses where group cutting treatments resulted in significantly higher tree growth compared to uncut control (Shell et al., 2022). In this same study, additional shelterwood cutting treatment resulted in even higher tree growth than group cutting in slash pine. In our longleaf pine study, shelterwood cutting treatment was eliminated at the experiment's outset due to the complete destruction of these plots by Hurricane Ivan. The slash pine sites were never impacted by any hurricane during the study and represented a different site condition than our longleaf study site. Our two studies (this one in longleaf pine and the one by Shell et al. (2022) in slash pine) suggest that silviculture and natural disturbance interactions may influence tree growth responses and stand dynamics in a complex manner in southern pines.

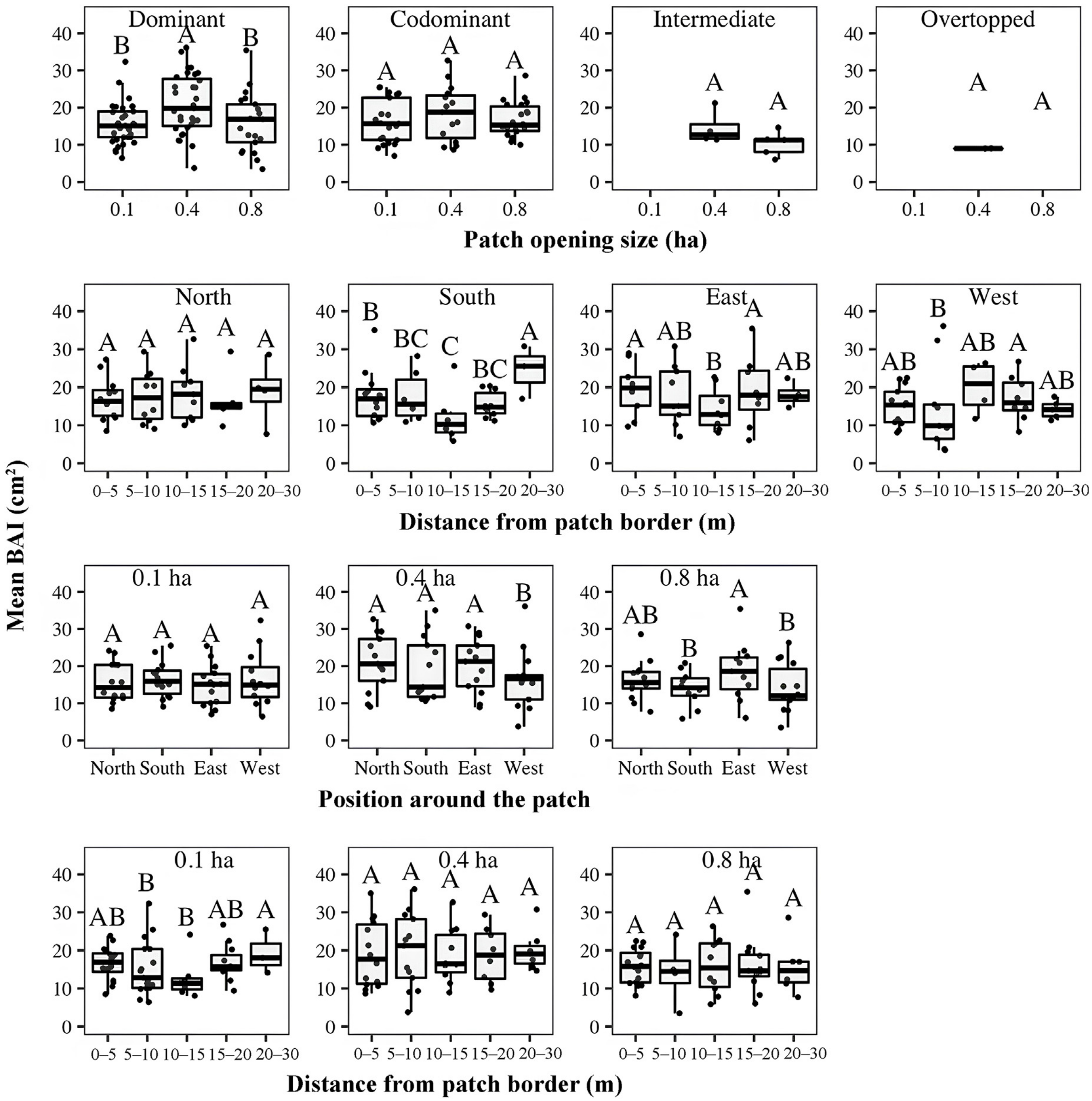

Fig. 5. Mean basal area increment (BAI) of longleaf pine based on tree canopy position, distance of tree from patch opening border, tree position around patch opening, and size of patch opening in the patch cutting treatment. ANOVA and Tukey-Kramer tests were conducted at a significance level of $\alpha = 0.05$. Any values sharing the same letter are not considered significantly different.

4.3. Management implications

The findings of our study contribute to enhancing our comprehension of stand dynamics in even-aged stands under conversion to multi-aged stand conditions, which may help forest managers forecast the growth of longleaf pine into larger size classes when treated by cutting single trees or openings of varying sizes. Our study showed that mature 60 to 80-year-old longleaf pine trees in second-growth, even-aged stands respond positively when released by patch cuttings, implying that uneven-aged silviculture (or stand conversion) could be initiated even in mature longleaf pine stands and gains in tree growth could be realized while achieving the goal of naturally regenerating, structurally diverse, continuous cover longleaf pine stands.

Single tree cutting treatment plots were vulnerable to storm damage; such damages may negate any gain in tree growth that otherwise may accrue due to release caused by cutting treatments. In the absence of a hurricane, single tree cutting may have also resulted in increased tree growth. Previous studies in longleaf pine forests have reported successful natural regeneration and improvement in native understory species diversity after cutting treatments similar to our study (Brockway and Outcalt, 1998, 2015, 2017; Gagnon et al., 2004). Together with those studies, our study provides further evidence that longleaf pine may respond positively to single tree or patch cuttings to initiate stand conversion to a multi-aged condition.

4.4. Conclusions

Our study demonstrated that the residual longleaf pine growth responded positively over 14 years after patch cutting for converting stands to a multi-aged stand condition. The best growth of residual trees occurred around 0.4 ha patch openings. Additionally, dominant and codominant trees grew faster than intermediate or overtopped trees. The optimal patch size for improving the growth of residual longleaf pine was found to be 0.4 ha, but further research is necessary to understand the impact of patch opening size on regeneration responses before suggesting the most suitable patch opening size for converting even-aged longleaf pine stands to uneven-aged stands to managers.

CRediT authorship contribution statement

Ashton Shell: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Ajay Sharma:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **John L. Willis:** Writing – review & editing. **John L. Tracy:** Writing – review & editing. **Adam Polinko:** Writing – review & editing. **Santosh Ojha:** Writing – review & editing. **Jason Vogel:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to check grammar and rephrase some sentences. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Funding

The USDA NIFA McIntire Stennis project #1014653 and the University of Florida Institute of Food and Agricultural Sciences funded the research presented in this publication.

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.

Acknowledgments

We express our gratitude to Dr. Dale Brockway and the staff at Escambia Experimental Forest for the installation and maintenance of the long-term experimental trial. We acknowledge Justin McKeithen and Barbara Cory for their assistance with the fieldwork.

References

Bédard, S., Majcen, Z., 2003. Growth following single-tree selection cutting in Québec northern hardwoods. For. Chron. 79, 898–905. https://doi.org/10.5558/tfc79898-5.

Bohn, K., Chancy, C., Brockway, D., 2015. Structure and regrowth of longleaf pine forests following uneven-aged silviculture and hurricane disturbance at the Escambia Experimental Forest. In: Holley, A.G., Connor, K.F., Haywood, J.D. (Eds.), Proceedings of the 17th Biennial Southern Silvicultural Research Conference. E–Gen. Tech. Rep. SRS–203. US Department of Agriculture, Forest Service, Asheville, NC, pp. 372–373.

Bradford, J.B., D'Amato, A.W., 2012. Recognizing trade-offs in multi-objective land management. Front. Ecol. Environ. 10, 210–216. https://doi.org/10.1890/110031.

Bradley, G.A., Kearney, A.R., 2007. Public and professional responses to the visual effects of timber harvesting: different ways of seeing. West. J. Appl. For. 22 (1), 42–54.

Brang, P., 2001. Resistance and elasticity: promising concepts for the management of protection forests in the European Alps. For. Ecol. Manag. 145, 107–119.

Brockway, D.G., Loewenstein, E.F., Outcalt, K.W., 2014. Proportional basal area method for implementing selection silviculture systems in longleaf pine forests. Can. J. For. Res. 44 (8), 977–985.

Brockway, D.G., Outcalt, K.W., 2017. Influence of reproduction cutting methods on structure, growth and regeneration of longleaf pine forests in flatwoods and uplands. For. Ecol. Manag. 389, 249–259. https://doi.org/10.1016/j.foreco.2017.01.002.

Brockway, D.G., Outcalt, K.W., 2015. Influence of selection systems and shelterwood methods on understory plant communities of longleaf pine forests in flatwoods and uplands. For. Ecol. Manag. 357, 138–150. https://doi.org/10.1016/j.foreco.2015.08.020.

Brockway, D.G., Outcalt, K.W., Boyer, W.D., 2006. Longleaf pine regeneration ecology and methods. In: Jose, S., Jokela, E.J., Miller, D.L. (Eds.), The Longleaf Pine Ecosystem: Ecology, Silviculture, and Restoration. Springer Series on Environmental Management. Springer, New York, NY, pp. 95–133. https://doi.org/10.1007/978-0-387-30687-2_4.

Brockway, D.G., Outcalt, K.W., 2000. Restoring longleaf pine wiregrass ecosystems: hexazinone application enhances effects of prescribed fire. For. Ecol. Manag. 137 (1–3), 121–138.

Brockway, D.G., Outcalt, K.W., 1998. Gap-phase regeneration in longleaf pine wiregrass ecosystems. For. Ecol. Manag. 106, 125–139. https://doi.org/10.1016/S0378-1127(97)00308-3.

Burkhart, H.E., Avery, T.E., Bullock, B.P., 2018. Forest Measurements. Waveland Press, USA.

Connor, K.F., Brockway, D.G., Boyer, W.D., 2014. Restoring a legacy: longleaf pine research at the forest service Escambia experimental forest. In: Hayes, D.C., Stout, S.L., Crawford, R.H., Hoover, A.P. (Eds.), USDA Forest Service Experimental Forests and Ranges: Research for the Long Term. Springer, New York, NY, pp. 85–101. https://doi.org/10.1007/978-1-4614-1818-4_4.

Cropper, J.P., 1979. Tree-ring skeleton plotting by computer. Tree-Ring Bull. 39, 47–54.

Cubbage, F., Harou, P., Sills, E., 2007. Policy instruments to enhance multi-functional forest management. For. Pol. Econ. 9 (7), 833–851.

Diaci, J., Kerr, G., O'Hara, K., 2011. Twenty-first century forestry: integrating ecologically based, uneven-aged silviculture with increased demands on forests. Forestry 84, 463–465. https://doi.org/10.1093/forestry/cpr053.

Farrar, R.M., 1986. Volume and Growth Predictions for Thinned Even-Aged Natural Longleaf Pine Stands in the East Gulf Area. US Department of Agriculture, Forest Service, Southern Forest Experiment Station.

Fortin, M.F., Bédard, S.B., DeBlois, J.D., Meunier, S.M., 2008. Accounting for error correlations in diameter increment modelling: a case study applied to northern hardwood stands in Quebec, Canada. Can. J. For. Res. 38, 2274–2286. https://doi.org/10.1139/X08-063.

Fox, T.R., Jokela, E.J., Allen, H.L., 2007. The development of pine plantation silviculture in the southern United States. J. For. 105 (7), 337–347.

Frazier, J.E., Sharma, A., Johnson, D.J., Andreu, M.G., Bohn, K.K., 2021. Group selection silviculture for converting pine plantations to uneven-aged stands. For. Ecol. Manag. 481, 118729.

Frost, C., 2006. History and future of the longleaf pine ecosystem. In: Jose, S., Jokela, E.J., Miller, D.L. (Eds.), The Longleaf Pine Ecosystem: Ecology, Silviculture, and Restoration. Springer Series on Environmental Management. Springer, New York, NY, pp. 9–48. https://doi.org/10.1007/978-0-387-30687-2_2.

Frost, C.C., 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. Proceedings of the Tall Timbers Fire Ecology Conference. No. 18, Tallahassee, FL.

Gagnon, J.L., Jokela, E.J., Moser, W.K., Huber, D.A., 2004. Characteristics of gaps and natural regeneration in mature longleaf pine flatwoods ecosystems. For. Ecol. Manag. 187, 373–380. https://doi.org/10.1016/j.foreco.2003.07.002.

Gonzalez-Benecke, C.A., Gezan, S.A., Leduc, D.J., Martin, T.A., Cropper, W.P., Samuelson, L.J., 2012. Modeling survival, yield, volume partitioning and their response to thinning for longleaf pine plantations. Forests 3, 1104–1132. https://doi.org/10.3390/f3041104.

Gray, A.N., Spies, T.A., Pabst, R.J., 2012. Canopy gaps affect long-term patterns of tree growth and mortality in mature and old-growth forests in the Pacific Northwest. For. Ecol. Manag. 281, 111–120. https://doi.org/10.1016/j.foreco.2012.06.035.

Gray, A.N., Spies, T.A., 1997. Microsite controls tree seedling establishment in conifer forest canopy gaps. Ecology 78 (8), 2458–2473.

Guldin, J.M., 2006. Uneven-aged silviculture of longleaf pine. In: Jose, S., Jokela, E.J., Miller, D.L. (Eds.), The Longleaf Pine Ecosystem: Ecology, Silviculture, and Restoration. Springer Series on Environmental Management. Springer, New York, NY, pp. 217–249. https://doi.org/10.1007/978-0-387-30687-2_7.

Guldin, J.M., Farrar, R.M., 2002. The plantation conversion demonstration at the crossett experimental forest–implications for converting stands from even-aged to uneven-aged structure. Gen. Tech. Rep. SRS-48,. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Gundersen, V.S., Frivold, L.H., 2008. Public preferences for forest structures: a review of quantitative surveys from Finland, Norway and Sweden. Urban For. Urban Green. 7 (4), 241–258.

Hanewinkel, M., Kuhn, T., Bugmann, H., Lanz, A., Brang, P., 2014. Vulnerability of uneven-aged forests to storm damage. Forestry 87 (4), 525–534.

Hanewinkel, M., Pretzsch, H., 2000. Modelling the conversion from even-aged to uneven-aged stands of Norway spruce (*Picea abies* L. Karst.) with a distance-dependent growth simulator. For. Ecol. Manag. 134 (1–3), 55–70.

Harrington, T., 2011. Overstory and understory relationships in longleaf pine plantations 14 years after thinning and woody control. Can. J. For. Res. 41, 2301–2314. https://doi.org/10.1139/x11-140.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Systemat. 4 (1), 1–23.

Jones, T.A., Thomas, S.C., 2004. The time course of diameter increment responses to selection harvests in Acer saccharum. Can. J. For. Res. 34, 1525–1533. https://doi.org/10.1139/x04-034.

Joelsson, K., Hjältén, J., Work, T., Gibb, H., Roberge, J.M., Löfroth, T., 2017. Uneven-aged silviculture can reduce negative effects of forest management on beetles. For. Ecol. Manag. 391, 436–445.

Jose, S., Jokela, E.J., Miller, D.L., 2007. The Longleaf Pine Ecosystem. Springer, New York.

Kelty, M.J., Kittredge Jr, D.B., Kyker–Snowman, T., Leighton, A.D., 2003. The conversion of even-aged stands to uneven-aged structure in southern New England. North. J. Appl. For. 20 (3), 109–116.

Kirkman, L.K., Mitchell, R.J., 2006. Conservation management of Pinus palustris ecosystems from a landscape perspective. Appl. Veg. Sci. 9, 67–74. https://doi.org/10.1111/j.1654-109X.2006.tb00656.x.

Leak, W.B., 1999. Stand structure in evenaged northern hardwoods: development and silvicultural implications. North. J. Appl. For. 16 (2), 115–119.

McGuire, J.P., Mitchell, R.J., Moser, E.B., Pecot, S.D., Gjerstad, D.H., Hedman, C.W., 2001. Gaps in a gappy forest: plant resources, longleaf pine regeneration, and understory response to tree removal in longleaf pine savannas. Can. J. For. Res. 31 (5), 765–778.

Messerer, K., Kacprowski, T., Kolo, H., Baumbach, J., Knoke, T., 2020. Importance of considering the growth response after partial harvesting and economic risk of discounted net revenues when optimizing uneven-aged forest management. Can. J. For. Res. 50, 487–499. https://doi.org/10.1139/cjfr-2018-0546.

Mitchell, R.J., Hiers, J.K., O'Brien, J.J., Jack, S.B., Engstrom, R.T., 2011. Silviculture that sustains: the nexus between silviculture, frequent prescribed fire, and conservation of biodiversity in longleaf pine forests of the southeastern United States. Can. J. For. Res. 36, 2724–2736. https://doi.org/10.1139/x06-100.

Nolet, P., Kneeshaw, D., Messier, C., Béland, M., 2018. Comparing the effects of even- and uneven-aged silviculture on ecological diversity and processes: a review. Ecol. Evol. 8, 1217–1226. https://doi.org/10.1002/ece3.3737.

Nyland, R.D., 2016. Silviculture: Concepts and Applications. Waveland Press, USA.

Nyland, R.D., 2003. Even-to uneven-aged: the challenges of conversion. For. Ecol. Manag. 172 (2–3), 291–300.

O'Hara, K.L., 2014. Multiaged Silviculture: Managing Complex Forest Stand Structures. Oxford University Press, UK.

Palik, B., Mitchell, R.J., Pecot, S., Battaglia, M., Pu, M., 2003. Spatial distribution of overstory retention influences resources and growth of longleaf pine seedlings. Ecol. Appl. 13, 674–686. https://doi.org/10.1890/1051-0761(2003)013[0674:SDOORI]2.0.CO;2.

Palik, B.J., Mitchell, R.J., Hiers, J.K., 2002. Modeling silviculture after natural disturbance to sustain biodiversity in the longleaf pine (*Pinus palustris*) ecosystem: balancing complexity and implementation. For. Ecol. Manag. 155, 347–356. https://doi.org/10.1016/S0378-1127(01)00571-0.

Paudyal, R., Stein, T.V., Ober, H.K., Swisher, M.E., Jokela, E.J., Adams, D.C., 2018. Recreationists' perceptions of scenic beauty and satisfaction at a public forest managed for endangered wildlife. Forests 9, 241. https://doi.org/10.3390/f9050241.

Pedersen, B.S., Howard, J.L., 2004. The influence of canopy gaps on overstory tree and forest growth rates in a mature mixed-age, mixed-species forest. Forest Ecol. Manag. 196 (2–3), 351–366.

Plauborg, K.U., 2004. Analysis of radial growth responses to changes in stand density for four tree species. For. Ecol. Manag. 188, 65–75. https://doi.org/10.1016/j.foreco.2003.07.022.

Polinko, A.D., Willis, J.L., Sharma, A., Guldin, J.M., 2022. Stand-level structural characteristics dictate hurricane resistance and resilience more than silvicultural regime in longleaf pine woodlands. Forest Ecol. Manag. 526, 120585.

Pukkala, T., 2016. Which Type of Forest Management Provides Most Ecosystem Services? Forest Ecosyst, 3, 9. https://doi.org/10.1186/s40663-016-0068-5.

Sharma, A., Bohn, K.K., Jose, S., Dwivedi, P., 2016. Even-aged vs. uneven-aged silviculture: implications for multifunctional management of southern pine ecosystems. Forests 7 (4), 86.

Sharma, A., Bohn, K.K., McKeithen, J., Singh, A., 2019. Effects of conversion harvests on light regimes in a southern pine ecosystem in transition from intensively managed plantations to uneven-aged stands. For. Ecol. Manag. 432, 140–149.

Sharma, A., Jose, S., Bohn, K.K., Andreu, M.G., 2012. Effects of reproduction methods and overstory species composition on understory light availability in longleaf pine–slash pine ecosystems. For. Ecol. Manag. 284, 23–33.

Sharma, A., Ojha, S.K., Dimov, L.D., Vogel, J.G., Nowak, J., 2021. Long-term effects of catastrophic wind on southern US coastal forests: lessons from a major hurricane. PLoS One 16 (1), e0243362.

Shell, A.B., Sharma, A., Vogel, J.G., Willis, J.L., 2022. Converting plantations to uneven-aged stands: effects of harvest type, group opening size, orientation, and canopy position on residual tree development. Trees Forests People 10, 100342.

Speer, J.H., 2010. Fundamentals of Tree-Ring Research. University of Arizona Press, USA.

Stan, A.B., Daniels, L.D., 2014. Growth releases across a natural canopy gap-forest gradient in old-growth forests. For. Ecol. Manag. 313, 98–103. https://doi.org/10.1016/j.foreco.2013.11.004.

Stone, E.L., Kalisz, P.J., 1991. On the maximum extent of tree roots. For. Ecol. Manag. 46, 59–102. https://doi.org/10.1016/0378-1127(91)90245-Q.

Susaeta, A., Klizentyte, K., Sharma, A., Adams, D.C., 2021. Can uneven-aged management improve the economic performance of longleaf pine? Can. J. For. Res. https://doi.org/10.1139/cjfr-2020-0437.

Susaeta, A., Sharma, A., Klizentyte, K., Adams, D.C., 2022. Economic analysis of uneven-aged forest management in the southeastern United States. Can. J. For. Res. 53 (1), 38–47.

Tahvonen, O., 2009. Optimal choice between even-and uneven-aged forestry. Nat. Resour. Model. 22 (2), 289–321.

Tahvonen, O., Pukkala, T., Laiho, O., Lähde, E., Niinimäki, S., 2010. Optimal management of uneven-aged Norway spruce stands. For. Ecol. Manag. 260 (1), 106–115.

Visser, H., van der Maaten-Theunissen, M., van der Maaten, E., 2023. Bai bias–An evaluation of uncertainties in calculating basal area increments from cores. Dendrochronologia 78, 126066.

Willis, J.L., Sharma, A., Kush, J.S., 2021. Seasonality of biennial burning has no adverse effects on mature longleaf pine survival or productivity. Front. Forest. Glob. Change 4, 684087.

York, R.A., Heald, R.C., Battles, J.J., York, J.D., 2004. Group selection management in conifer forests: relationships between opening size and tree growth. Can. J. For. Res. 34, 630–641. https://doi.org/10.1139/x03-222.