Forest Ecology and Management 533 (2023) 120864

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Prescribed fire and thinning influence snag density and size in the southern Appalachian Mountains

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ABSTRACT

Snags, or standing dead trees, are an important structural component of forest ecosystems. Many animals, including endangered species, depend on snags for foraging, protection, or raising young. Climate change, habitat loss, and modification of natural disturbance regimes contribute to changes in the availability and characteristics of snags in forests. Therefore, understanding what natural and artificial processes promote snags with the characteristics necessary for wildlife is a significant conservation concern. We examined how low-severity prescribed fire affected the density and characteristics of snags at 80 sites in the Talladega National Forest, Alabama. We sampled sites within 4 prescribed fire intervals, including 1–3 (previously thinned 4–23 years ago), > 3–8, > 8–12, and > 12 years. At each site, we measured snags across transects on 3 different slope positions, including the ridge, mid-slope, and valley, to account for slope-influenced fire behavior and stressors. The average diameter of snags increased in stands with the shortest prescribed fire interval, but snag height, decay class, and percentage of bark remaining were similar across all fire intervals. Snag density was lowest in the shortest fire interval due to fewer small- and medium-sized hardwood snags. A higher density of large snags was found in the shortest fire interval compared to the longest fire interval. Ridges had a greater density of snags compared to mid-slope and valley positions due to more small- and medium-sized pine snags. Although thinning followed by frequent, low-severity prescribed fire reduces snag density, the increase in density of large-diameter snags provides high-quality habitat for snag-dependent birds and bats. More intense fire and other stressors on ridges likely promote higher densities of snags. Our research indicates forest managers can use prescribed fire and thinning to accomplish multiple management goals while continuing to produce valuable snags for wildlife.

1. Introduction

Snags, or standing dead trees, are an important component of forest ecosystems that provide habitat for a wide variety of animals (Guyer and Bailey, 1993; Perry, 2012). Many forest bird species use snags for nesting and foraging (Hagar et al., 1996; Land et al., 1989), and some bat species roost under exfoliating bark (i.e., loose, peeling bark) or in cavities of snags (Arnett and Hayes, 2009; Rabe et al.,1998). Despite their value for wildlife, historically, snags have been felled due to their potential hazards and lack of economic value as timber (Shea et al., 2002; Show and Kotok, 1924). Many natural forests have been converted into heavily managed timber plantations that typically contain a lower density of snags than unmanaged forests (McComb et al., 1986). In addition, land conversion, wildfire suppression, and climate change have significantly impacted forest cover and disturbance regimes, leading to widespread changes in forest structure, including snag recruitment and abundance (Arthur et al., 2021).

National forests in the United States frequently set target densities for snags to increase the potential habitat for snag-dependent wildlife (Morrison et al., 1986; USDA Forest Service, 2004). Although snag density is often the focus of management actions, wildlife species vary greatly in their habitat requirements, including diameter, height, degree of decay, and presence of branches and bark. Many birds and bats select large snags that provide more substrate for cavity excavation, foraging, and roosting (Mannan et al., 1980). However, some species are more flexible in their snag habitat requirements or use smaller-diameter snags (Vaillancourt et al., 2008).

Snags are naturally created when live trees are killed by disturbances such as fire, drought, weather events (e.g., wind, lightning, ice storms, etc.), insect infestations, and disease (Morrison and Raphael, 1993; Spies et al., 1988). The longevity of snags is determined by decay and fall rates which can vary considerably depending on the snag size, species-specific characteristics, and climate (Conner and Saenz, 2005; Keen, 1955). Forest management practices such as logging and prescribed fire can also influence snag recruitment and abundance and, as a result, the wildlife that depend on snags.

While numerous studies have examined snag density and dynamics in the U.S., relatively few have focused on the southeastern region

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https://doi.org/10.1016/j.foreco.2023.120864
Received 31 August 2022; Received in revised form 6 February 2023; Accepted 8 February 2023

(hereafter, the Southeast; Perry and Thill, 2013). Frequent, low-intensity fires ignited by lightning and Native Americans maintained the open-canopy pine woodlands that covered much of the region before European colonization. The onset of industrial logging in the 1890s, coupled with fire suppression, led to the widespread mesophication of southeastern forests resulting in closed canopies dominated by shade-tolerant tree species (Fowler and Konopik, 2007; Nowacki and Abrams, 2008). Prescribed fire was reintroduced to many southeastern public lands in the 1980s and is now widespread. Prescribed fire is used in the Southeast to recreate historic fire disturbance regimes (Guyette et al., 2010; Simberloff, 1993), reduce fuel loading, improve game habitat, promote the regeneration of fire-adapted oaks, and restore open canopy longleaf pine (*Pinus palustris*), shortleaf pine (*P. echinata*), and oak-hickory forests (Stewart et al., 2015; Van Lear et al., 2005; Van Lear and Waldrop, 1989).

Many publicly owned forests in the Southeast focus on habitat management for the federally threatened red-cockaded woodpecker (*Leuconotopicus borealis*; RCW) and associated species dependent on open-canopy pine forests requiring frequent, low-intensity fires (USFWS, 2003). The Southeast is also within the ranges of 45 species of birds and 9 species of bats which use snags at some point in their life histories (Hamel, 1992; Perry, 2012). Many of these snag-using birds and bats are experiencing significant population declines in the Southeast, with the Indiana bat (*Myotis sodalis*), northern long-eared bat (*Myotis septentrionalis*), and Florida bonneted bat (*Eumops floridanus*) federally listed as endangered (USFWS, 2022). Understanding how current management efforts affect snag characteristics and densities is important to effectively restoring habitat for these declining species.

Prescribed fire creates and destroys snags, but there is typically a short-term pulse in snag creation within the first years after reintroducing fire to a stand that has not been managed for ≥ 50 years (Greenberg et al., 2007). During this time, tree mortality exceeds the number of snags consumed by the fire, causing a net increase in snag number and density (Harrod et al., 2009). Mortality from prescribed fire can be delayed for years when a wound or fire scar results in water stress and allows heart rot fungi an opening for infection (Littke and Gara, 1986; Rundel, 1973). Despite these processes, snag density typically declines many years after a fire (Morrison and Raphael, 1993).

The fire interval, or length of time between prescribed fire events, may also affect snag abundance and recruitment (Lloyd et al., 2012). Longer fire intervals can create a build-up of litter, causing a more intense fire that results in greater tree mortality (Sah et al., 2006). Shorter fire intervals usually result in lower fire intensity, causing less tree mortality for fire-dependent species (Graham et al., 1999; Sah et al., 2006). Slope position can also interact with prescribed fire to influence the density and characteristics of snags because of differences in fire behavior, soil moisture, and weather effects (Beaty and Taylor, 2001; de Toledo et al., 2012). Due to preheating and the dry conditions on ridges, prescribed fires can become more intense on ridge tops than on other slope positions (Estes et al., 2017), leading to greater tree mortality. Ridges and steep slopes can also experience more severe weather effects that can create or fell snags (Clinton and Baker, 2000; Lafon, 2006).

In many regions, including the Southeast, forest thinning is often used in conjunction with prescribed fire to restore open-canopy conditions. Thinning can reduce the number of snags in managed stands while interrupting natural recruitment processes (Cline et al., 1980), possibly due to intentional felling and increased wind exposure (Harrod et al., 2009; Mitchell, 1995; Morrison et al., 1986). Forest thinning can also cause an increase in short-term snag recruitment because trees left behind may be damaged by the process, resulting in future mortality (Walter and Maguire, 2004). Understanding how thinning and prescribed fire create or destroy snags and develop snag characteristics favorable for wildlife are needed to assist forest managers in meeting desired management goals.

This study aimed to determine how common forest management techniques in the Southeast affect snags. Specifically, we evaluated how prescribed fire intervals and thinning interact with slope position to influence snag density and characteristics in the Talladega National Forest, Alabama. Based on fire scar analysis and historic witness tree surveys from land surveys, the pre-European settlement forests in this region were dominated by fire-dependent pines (longleaf and shortleaf pine) and oaks with a mean fire interval of 3.2 years (Guyette et al., 2010; Shankman and Wills, 1995; Stambaugh et al., 2017). Fire suppression began in 1937 with acquisition by the US Forest Service (USFS), leading to the loss of open-canopy pine forests (Noss et al., 1995). Beginning in 1995 the Talladega National Forest (TNF) has used prescribed fire during the late winter to spring (January–June), with the greatest efforts in March and April. Current forest practices include intensive management for open-canopy pine forests (mechanical thinning followed by repeated prescribed fire every 1–3 years), as well as less intensive management with no thinning and longer fire intervals (>3–8, > 8–12, and > 12 years).

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the Talladega and Shoal Creek Ranger Districts of the Talladega National Forest (TNF), covering 171,643 ha over Calhoun, Cherokee, Clay, Cleburne, and Talladega Counties in Alabama. Average temperatures range from −2–10.5 °C in winter to 18.3–31.6 °C in summer (Griffith et al., 2001). Elevation in the region ranges from 152 to 734 m above sea level with hills, plateaus, and linear ridges. The TNF overlaps the Piedmont and Ridge and Valley ecoregions and is characterized by an oak-hickory-pine forest community with shallow, excessively drained soils (Carter and Cobb, 2012; Griffith et al., 2001). Pine and pine/hardwood forests are prevalent along ridges and hills, grading into a hardwood/pine mixed forest further downslope (Womack and Carter, 2011). Ridge tops are typically dominated by longleaf pine, shortleaf pine, loblolly pine (*P. taeda*), and Virginia pine (*P. virginiana*) (Womack and Carter, 2011). These pine species mix with hardwoods downslope, the most common species being oak (*Quercus* spp.), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sourwood (*Oxydendrum arboreum*), sweetgum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), and hickory (*Carya* spp.) (Carter and Cobb, 2012; Hill, 1998). The understory of stands managed with frequent prescribed fire (1–3 and > 3–8-year fire intervals) are dominated by herbaceous plants, while stands experiencing less fire (>8–12 and > 12-year fire intervals) are characterized by a thick shrub layer, heavier leaf litter layers and regenerating hardwoods (Womack and Carter, 2011). The area also contains 2 wilderness areas, Cheaha and Dugger, established in 1983 and 1999, respectively. Since their establishment, neither wilderness area has been subjected to management with prescribed fire or logging. Limited wildfire activity has occurred in wilderness areas.

The current USFS goal is to apply prescribed fire to burn ≥ 18,000 ha/year to restore the natural fire regime, promote fire-dependent species, and reduce hazardous fuels (USDA Forest Service, 2009). Forest stands vary by prescribed fire interval, ranging from no recent history of fire to a prescribed fire event occurring every 1–3 years (Fig. 1). As of 2019, the TNF contains 4,500 ha within the 1–3-year fire interval, 35,700 ha within the > 3–8-year fire interval, 10,900 ha within the > 8–12-year fire interval, and 13,300 ha within the > 12-year fire interval. The prescribed fires on TNF predominately cause < 5 % mortality of the upper canopy, a fire severity level that is defined as “no fire effects” under the Interagency Fire Regime Condition Class Guidebook (Barrett et al., 2010). Some stands have also been managed with mechanical timber removal techniques, the most common being mechanical thinning (4,450 ha), a process in which certain tree species (usually hardwoods and young pines) are removed to achieve a basal area between 9 and 16 m^2/ha (USDA Forest Service, 2009). The USFS does not allow for the intentional felling of snags unless they pose a hazard, such as along

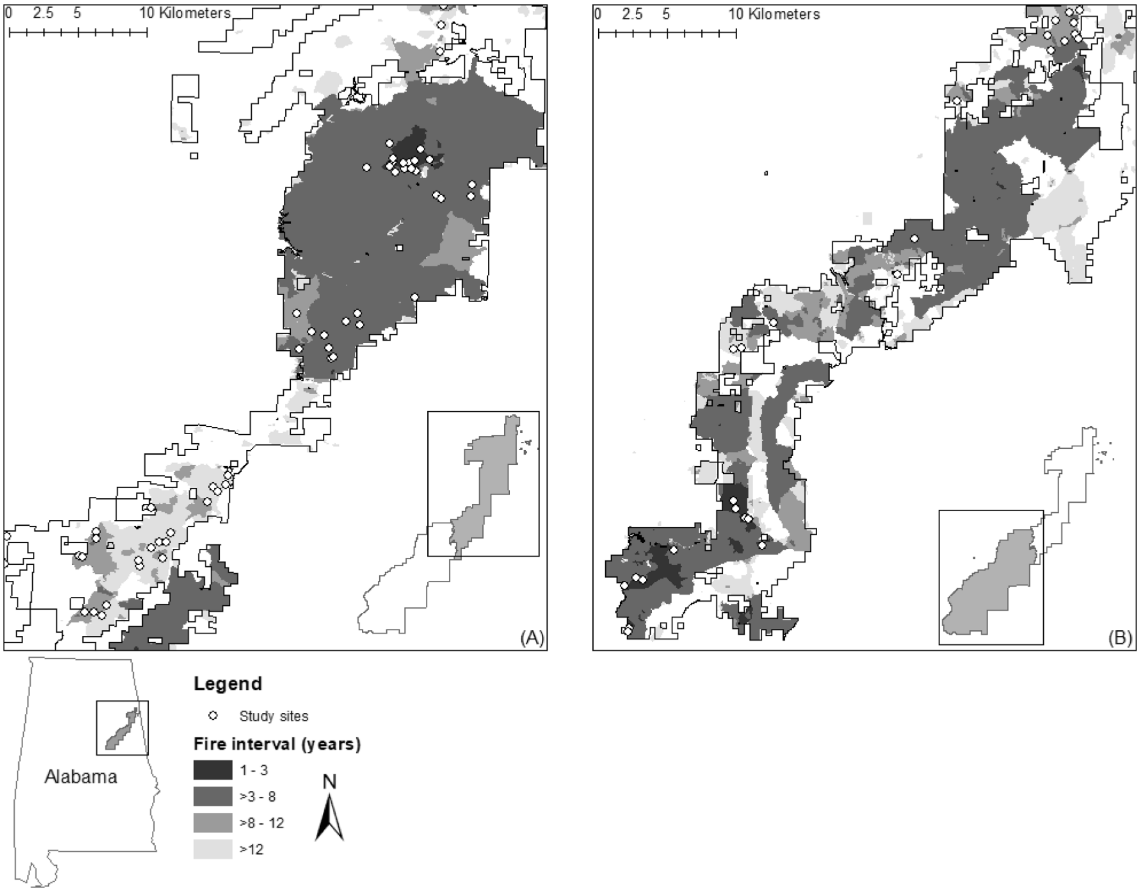

Fig. 1. Snag transect sites (n = 80) across fire intervals in the Shoal Creek (A) and Talladega (B) Ranger Districts of the Talladega National Forest, Alabama.

roads (USDA Forest Service, 2004).

2.2. Study design

From April–November 2018, we counted and evaluated the characteristics of snags at 80 sites across the TNF to assess the effects of fire intervals and slope positions. At each site, 3 belt transects were sampled to account for slope-influenced fire intensity within the stand, one at each slope position, including the ridge top, mid-slope, and valley (Mueller-Dombois and Ellenberg, 1974; Perry et al., 2016). Valley positions were defined as close to the bottom of the slope without passing into the streamside management zones or areas not thinned at slope bottoms. The starting point of the belt transect at each slope position was randomly selected, with the transect running parallel to the terrain and not crossing into other management zones or roads. Each of the 3 belt transects at a site were 33.33 m long by 20 m wide and spaced ≥ 30 m apart along the slope. As a result, the 3 belt transects per site cumulatively extended for 100 m and encompassed 0.2 ha (Anderson and Pospahala, 1970; Arevalo, 2002). We divided the TNF into 4 management categories (20 sites in each category): prescribed fires occurring at 1–3, > 3–8, > 8–12, and > 12-year fire intervals (Stober et al., 2020). The stands experiencing less frequent fire (>3-year fire interval) did not have any mechanical thinning since the establishment of the fire regime. However, the stands in the 1–3-year fire interval represented the most intensive restoration efforts of open-canopy forests for RCW habitat and had been mechanically thinned 4–23 years before our study (mean ± *SE* = 16.7 ± 1.6 years). Thinning likely impacted the number and size distribution of snags we observed in the 1–3-year fire interval stands by changing the live tree distribution from which snags are recruited (Moorman et al., 1999; Perry and Thill, 2013). However, given the length of time since thinning and local climate conditions that promote rapid decay (Harmon, 1982; Moorman et al., 1999), on most of our sites, any snags created during the harvest would have fallen prior to our study. Thus, the snags we observed during our survey were created through a combination of prescribed fire and natural processes. To ensure the stands closely represented the long-term effects of these management techniques, the most frequently burned stands (in the 1–3 and > 3–8-year fire intervals) must have experienced a minimum number of burns: ≥ 7 prescribed fires (mean = 9 fires) in the 1–3-year fire interval and ≥ 4 (mean = 5.8 fires) in the > 3–8-year fire interval. The stands in the > 8–12 (all experienced 2 past fires) and > 12-year fire intervals (all experienced 1 past fire) could not have had a fire event in the past 5 years to avoid measuring the immediate impact of the fire on tree mortality. Sites were randomly selected within fire intervals but had to be ≥ 200 m apart to avoid spatial correlation. Sites also were not allowed < 20 m from a road to avoid biases from the safety actions of USFS during prescribed fires (i.e., intentional snag felling or raking litter from around snags along boundaries to prevent fire from escaping burn units).

At each site, we visually searched for snags within the bounds of the belt transects at the 3 slope positions. Snags were defined as any standing dead tree ≥ 2 m in height and having no visible green leaves during the growing season when this study was conducted. We recorded species type (pine or hardwood based on bark characteristics), diameter at breast height (DBH), and height for each snag > 10 cm DBH. The height of the snag was measured using a laser rangefinder (Forestry Pro, Nikon Corporation, Tokyo, Japan). Each snag location was mapped using a handheld global positioning system (GPS) unit (eTrex10, Garmin International Inc., Olathe, Kansas) and marked with a numbered tag. Additional data collected on the snag included the decay class (Cline et al., 1980; i.e., 1–2 hard snag, 3–5 soft snag, with 5 as the most decayed) and percentage of bark remaining (i.e., visual estimate of the percentage remaining on the bole).

2.3. Data analysis

Densities of snags (all snags and subsets containing pine only, hardwood only, small (<20 cm DBH), medium (≥20 cm and < 40 cm DBH), and large snags (≥40 cm DBH)) were compared across fire intervals and slope positions using two-way analysis of variance (ANOVA) tests. Interaction terms between fire interval and slope position were included in the initial two-way ANOVAs but were all removed because of non-significance ($P > 0.05$). We examined the inclusion of a random effect for the site in the analyses to account for the hierarchical study design. However, the random effect had very small estimated variances in all mixed-effect ANOVA models (variances < 0.001) and was dropped from analyses (Bolker et al. 2009). For any of the significant main effects ($P < 0.05$) in ANOVAs, we used Tukey's Honest Significant Difference (HSD) tests to evaluate pairwise differences among groupings. Tukey's HSD test reduces the type I error rate during multiple pair-wise comparisons. Because snags were frequently not present at all slope positions at a site, snag characteristics (DBH, height, decay class, and percent bark remaining) were averaged for all measured snags on the belt transect across the 3 slope positions at each site. One-way ANOVAs followed by Tukey's HSD tests were performed to compare snag characteristics among fire intervals (2 sites with no snags from the 1–3-year fire interval were removed from analyses). All statistical tests were performed in R 4.2.2.

3. Results

Across the 80 sites, we recorded a total of 264 snags, including 15 % in the 1–3-year fire interval, 28 % in the > 3–8 fire interval, 26 % in the > 8–12 fire interval, and 31 % in the > 12-year fire interval. Hardwoods accounted for 56 % and pine 44 % of all snags. The size distribution of snags included 46 % small, 40 % medium, and 14 % large snags.

3.1. Snag characteristics

The DBH of snags differed among fire intervals ($F_{3,74} = 6.6$, $P < 0.001$), but snag height ($F_{3,74} = 0.09$, $P = 0.96$), decay class ($F_{3,74} = 0.78$, $P = 0.51$), and the average percentage of bark remaining ($F_{3,74} = 0.80$, $P = 0.50$) were similar across fire intervals. Snags in the 1–3-year interval were, on average, 7 cm DBH larger than in the > 3–8, > 8–12, and > 12-year fire intervals (Table 1).

3.2. Snag density

Fire interval ($F_{5,234} = 5.26$, $P = 0.0016$) and slope position ($F_{5,234} = 9.98$, $P < 0.001$) both had a significant effect on the overall density of snags (Fig. 2). The overall density of snags was, on average, about 50 % lower in the 1–3-year fire interval than in the > 3–8 and > 12-year fire intervals. Ridge snag density averaged 36 % greater than mid-slope (Tukey's HSD Test, $P = 0.004$) and 48 % greater than valley positions (Tukey's HSD Test, $P < 0.001$). The mid-slope and valley positions did not differ in snag density (Tukey's HSD Test, $P = 0.56$).

Table 1
Average (±*SE*) snag characteristics measured on belt transect sites (n = 78) in 4 prescribed fire intervals across the Talladega National Forest, Alabama. Subscripts denote statistical differences between fire intervals of $P < 0.05$ from a Tukey's HSD test.

Measurement	1–3 year	> 3–8 year	> 8–12 year	> 12-year
DBH (cm)	31.9 ± 2.8^{A}	25.4 ± 1.4^{B}	21.5 ± 1.3^{B}	23.9 ± 1.0^{B}
Height (m)	10.0 ± 1.1	9.9 ± 0.8	9.6 ± 0.6	9.5 ± 0.7
Decay class (1–5)	2.8 ± 0.3	2.7 ± 0.2	2.3 ± 0.2	2.6 ± 0.2
% bark remaining	59 ± 8	61 ± 6	68 ± 6	70 ± 5

The density of hardwood snags was affected by the fire interval ($F_{5,234} = 6.78$; $P < 0.001$) but not by the slope position ($F_{5,234} = 0.09$, $P = 0.91$). The 1–3-year fire interval averaged 64–75 % fewer hardwood snags/ha than the other fire intervals (Fig. 2). Fire interval did not influence the density of pine snags ($F_{5,234} = 0.41$, $P = 0.75$), while slope position did have a significant effect ($F_{5,234} = 17.19$, $P < 0.001$; Fig. 2). Pine snag density averaged 2 to 4 times higher on ridges than any other slope position (Tukey's HSD Test, $P < 0.05$). Mid-slope and valley positions did not differ significantly in pine snag density (Tukey's HSD Test, $P > 0.05$).

The density of small snags (DBH < 20 cm) differed by fire interval ($F_{5,234} = 4.21$, $P = 0.006$) and slope position ($F_{5,234} = 3.89$, $P = 0.02$). The density of small snags averaged over 60 % lower in the 1–3-year fire interval than in the other 3 fire intervals (Fig. 2). Small snag density averaged 44 % lower in the valley and 30 % lower on the mid-slope compared to ridges (Tukey's HSD Test, $P < 0.05$), but mid-slope and valley did not differ significantly from each other (Tukey's HSD Test, $P > 0.05$). The density of medium snags (DBH ≥ 20 cm and < 40 cm) differed by fire interval ($F_{5,234} = 6.94$, $P < 0.001$) and slope position ($F_{5,234} = 9.18$, $P < 0.001$). The density of medium snags averaged 77 % lower in the 1–3-year fire interval than in the > 12-year fire interval (Fig. 2). Medium snag density averaged 1.8–2.8 times greater on ridges than any other slope position (Tukey's HSD Test, $P < 0.05$). Mid-slope and valley positions did not differ significantly (Tukey's HSD Test, $P > 0.05$). The density of large snags (DBH ≥ 40 cm) was affected by fire interval ($F_{5,234} = 2.73$, $P = 0.044$) but not by slope position ($F_{5,234} = 0.58$, $P = 0.56$). The density of larger snags averaged 73 % lower in the > 12-year fire interval than in the 1–3-year fire interval (Fig. 2).

4. Discussion

We observed no major differences in snag density and characteristics between intermediate to longer prescribed fire intervals of > 3–8, > 8–12, and > 12 year, suggesting that snag dynamics were similar across these management treatments. While the density of snags decreased within the shortest fire interval (1–3 year), this pattern was driven by the loss of small- and medium-sized hardwood snags, which are often considered less valuable to snag-dependent wildlife. Conversely, the largest snags, which are typically retained longer (Garber et al., 2005) and support a wider array of snag-dependent animals (Ganey, 1999), were found in greater density in the 1–3-year fire interval and lower density in the > 12-year fire interval. Our results support that frequent, low-severity prescribed fire facilitates creation of high-quality large snags in restored open-canopy pine forests of the Southeast. In contrast, moderate to longer prescribed fire intervals lead to a lower density of large snags but more small- and medium-sized snags.

The lower snag density in the 1–3-year fire interval compared to the longer fire intervals was likely influenced by the increase in burn frequency and the removal of small- to medium-size trees during thinning (Hammond et al., 2016; Perry and Thill, 2013; Zarnoch et al., 2014.). The diameter size distribution of snags usually correlates closely with that of live trees in a stand, and reducing trees through harvesting will also reduce snag density (Moorman et al., 1999; Perry and Thill, 2013). In addition, repeated burning tends to hinder the recruitment of young trees and decrease the number of small trees because their thinner bark results in greater mortality (Hutchinson et al., 2005; Perry et al., 2017). In our study, 1–3-year fire interval stands had been thinned 4–23 years previously and experienced ≥ 7 prescribed fires, reducing the available live trees and establishment of young trees in the smaller size classes. The longer fire intervals did not experience thinning and had fewer burns, likely supporting a greater pool of small trees for snag recruitment as well as more fire-intolerant species that could have contributed to a pulse of smaller snags post-fire (Perry et al., 2017).

Despite a lower density of smaller snags, there was an increase in large snags (≥40 cm DBH) in the 1–3-year fire interval. While smaller trees are more susceptible to mortality from prescribed fire, larger trees

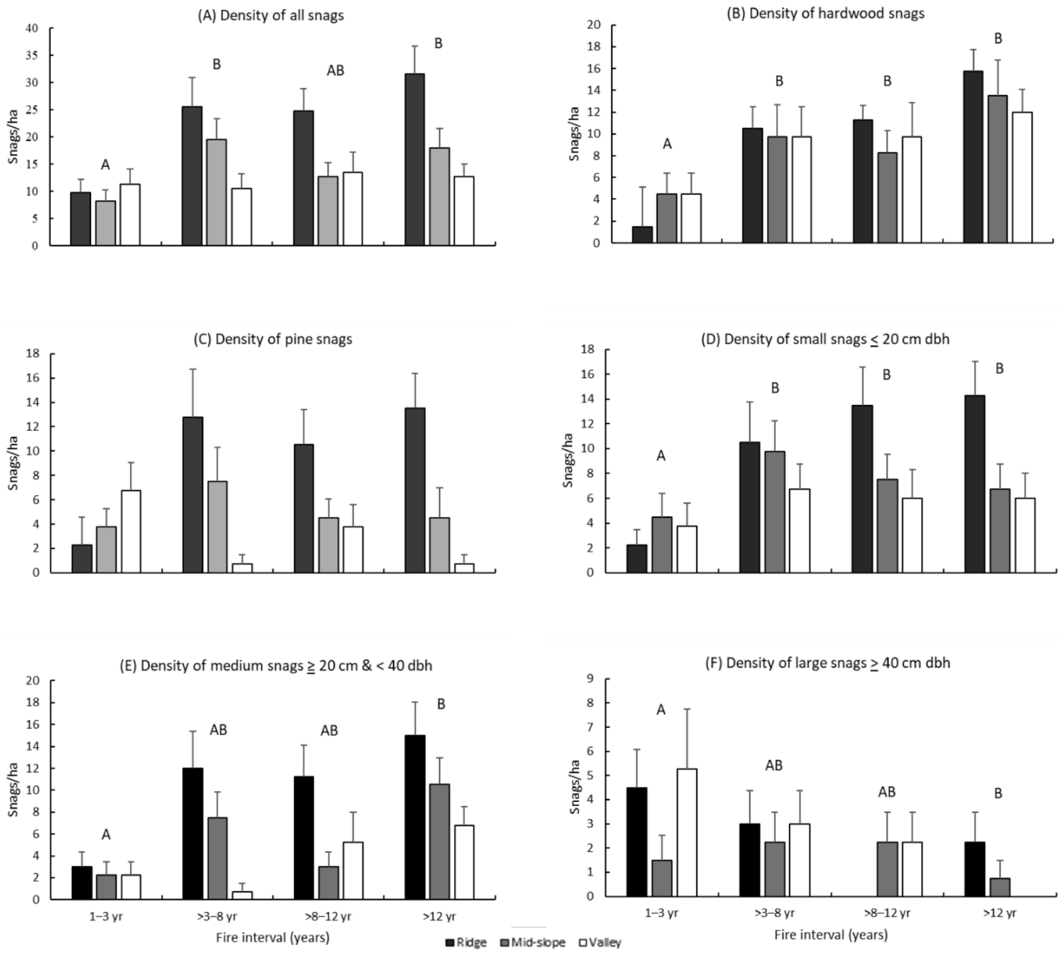

Fig. 2. Average snag density per hectare (+*SE*) across prescribed fire intervals and slope position on 80 transects in the Talladega National Forest, Alabama. Categories shown include the density of all snags (A), density of hardwood snags (B), density of pine snags (C), density of small snags (<20 cm DBH; D), density of medium snags (≥20 cm and < 40 cm DBH; E), density of large snags (≥40 cm DBH; F). Different letters above bars represent statistically significant differences ($P < 0.05$) between fire intervals in Tukey's HSD tests.

can also be damaged or killed (Hammond et al., 2016). As fire becomes more frequent, there is also a higher probability of the stand experiencing a more intense burn (Perry et al., 2017). In addition, fire intensity is likely greater in the 1–3-year interval stands because of more flammable pine-dominated fuel and the open canopies creating dryer and warmer conditions. The longer fire interval stands had more mesic hardwood litter and canopy cover, limiting fire intensity and reducing tree mortality (Kreye et al., 2013). While fire-tolerant trees such as longleaf and shortleaf pine are prevalent in the 1–3-year fire interval on TNF, many stands contain loblolly pines which are less fire tolerant and shorter-lived, possibly contributing to large snag recruitment (Zarnoch et al., 2014).

Ridges in TNF are likely to produce more pine snags than any other slope position due to the xeric and rocky conditions that favor live pines on ridges in the Southeast (Perry and Thill, 2008). Ridges experiencing hotter, more intense prescribed fires than other slope positions may contribute to greater tree mortality rates (Estes et al., 2017). Ridges can also experience more severe weather effects that can create or fell snags (Clinton and Baker, 2000; Lafon, 2006). The decline in snags on the mid-slope and valley positions may have resulted from lower tree mortality and accelerated decay and fall rate related to high soil moisture content, steepness, and transition to more mesic fuel and overstory conditions (Beaty and Taylor, 2001; de Toledo et al., 2012).

Snag height, decay class, and percentage of bark remaining were similar between all fire intervals suggesting that prescribed fire does not greatly influence these snag characteristics. These characteristics are driven by individual characteristics of tree species, weathering, and decay of the snags rather than fire as a primary mechanism (Lloyd et al., 2012). The larger DBH of snags on the shortest fire interval was probably a result of lower density of smaller snags and greater density of large snags. Larger snags are generally considered more valuable for birds and bats as they offer more substrate for nesting, roosting, and foraging (Mannan et al., 1980). Although, some bats in the Southeast, such as the northern long-eared bat, roost mostly in smaller snags (Perry and Thill, 2007). Large snags also stay standing longer than small snags extending their benefits for wildlife (Garber et al., 2005). Prescribed fire can benefit bats by improving insect populations and diversity and reducing mid-story density which causes an increase in solar exposure around snags, aiding in thermoregulation and the development of offspring (Carter et al., 2002; Silvis et al., 2016). Pine snags, in general, are selected more often by bats than hardwood snags (Perry and Thill, 2008). Pine snags are much more likely to have exfoliating bark with large spaces underneath to house large bat colonies (Perry and Thill, 2008). We observed no impact of prescribed fire interval on the density of pine snags, though other studies have found that prescribed fire generally increases pine snag density, which would benefit snag-roosting bats (Estes et al., 2017; Perry and Thill, 2008; Wimberly and Reilly, 2007).

5. Management implications

Creating sufficient snag densities of different sizes and characteristics for a wide range of snag-using wildlife is a challenge facing many forest managers, complicated by the need to manage for recreation, safety, timber, habitat restoration, and endangered species. Results from our study indicate the mosaic of fire management across TNF creates a diverse array of snag density and characteristics. These findings support forest managers' use of prescribed fire to accomplish multiple management goals while creating snags for wildlife.

The federally listed endangered Indiana bat and northern long-eared bat have been found to roost more often in stands with fire management on TNF. However, it is unclear if this is due to the improved snag quality, foraging opportunities, or both (Torrey, 2018). Previous studies have shown that food and roost availability are the two main factors that strongly influence bat distribution (Kunz and Lumsden, 2003). A benefit of fire may be due to the reduction in mid-story density which can aid in echolocation with some bat species (Perry and Thill, 2008). Snag-roosting bats are also more susceptible to prescribed fire's adverse effects due to snags' combustibility and bats' slowed response time during torpor (Carter et al., 2002). However, the benefits of recruiting high-quality snags and foraging habitat for bats likely outweigh the hazards associated with the effect of smoke and heat on roosting bats, especially if burning is done outside of the maternity season (April–August) or growing season (Carter et al., 2002). Additional measures can be taken to protect roosting bats by raking around snags or using fire retardants, as with RCW nest trees, although these methods may be impractical on larger scales (USFWS, 2003).

Further research is needed on the effects of prescribed fire and thinning on snag dynamics, specifically regarding fire season and other fire severities that were not included in this study and can affect tree mortality. In addition, a better understanding of snag longevity, fall rates, and creation is needed to model long-term snag dynamics in managed forests. The mosaic of stand treatments and fire return intervals on the TNF creates a diverse standing inventory of snag across the landscape to support the needs of a wide variety of snag-dependent wildlife. Long-term studies that track trends in retention, recruitment, and species characteristics would be useful to understand how management interacts with these disturbance pulses fully.

Employing methods that produce greater densities of high-quality snags can reduce cost and labor investments by forest management organizations. Protecting every suitable wildlife snag from loss by forestry management practices is infeasible (Hammond et al., 2016), but thinning followed by repeated prescribed fire in frequent fire intervals can create large, high-quality snags for wildlife. In addition, these management practices develop open canopy conditions and herbaceous understories that create higher-quality foraging conditions for many bird and bat species (Hagar et al., 1996; Perry and Thill, 2008). The use of these techniques can improve snag-using wildlife habitat while restoring natural disturbances and accomplishing a variety of management goals.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

We thank Joseph Hendricks and Gregory Payne for their expertise and assistance. Funding was provided by the U.S. Forest Service, the Department of Biology at the University of West Georgia, the Dr. Thomas A. Hart Scholarship, and the Friends of the Talladega National Forest.

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