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ARTICLE

Comparison of snag densities among regeneration treatments in mixed pine–hardwood forests

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Abstract: Standing dead trees (snags) are an important component of forest ecosystems, providing foraging, nesting, and roosting substrate for a variety of vertebrates. We examined the effects of four forest regeneration treatments on residual snag density and compared those with densities found in unharvested, naturally regenerated forests (controls) during the second, fourth, and sixth year after timber harvest in mixed pine–hardwood forests of Arkansas and Oklahoma. Regeneration treatments were clearcut with snag creation, shelterwood, single-tree selection, and group selection. Density of large snags (≥25.0 cm DBH) differed only during the sixth year after harvest, with shelterwoods having a lower density of large snags (1.0 snags/ha) than the control or group selection stands (4.0 and 4.2 snags/ha, respectively). Density of small snags (10.0–24.9 cm DBH) mirrored residual basal area, with controls and group-selection stands having the greatest snag densities. Creation of snags in clearcuts by injection with herbicides caused initial snag density in these areas to be greater than other treatments, but density in clearcuts declined sharply by 6 years after harvest. In the absence of snag creation, treatments such as shelterwoods that remove most trees may have snag densities below that required to address some management objectives without additional snag creation.

Résumé : Les arbres morts sur pied (chicots) sont une composante importante des écosystèmes forestiers car ils servent de source de nourriture et de lieu de nidification et de repos pour de nombreux vertébrés. Nous avons étudié les effets de quatre traitements de régénération forestière sur la densité résiduelle de chicots et comparé ces résultats à la densité de forêts régénérées naturellement et non exploitées (témoins) au cours des deuxième, quatrième et sixième années après la coupe de forêts mixtes de pins et de feuillus de l'Arkansas et de l'Oklahoma. Les traitements de régénération incluaient : une coupe à blanc avec création de chicots, une coupe progressive d'ensemencement, une coupe de jardinage par pied d'arbre et une coupe de jardinage par groupe. La densité de gros chicots (diamètre à hauteur de poitrine – DHP ≥ 25,0 cm) a été différente seulement pendant la sixième année après la coupe au cours de laquelle les coupes progressives contenaient une plus faible densité de gros chicots (1,0 chicot/ha) que les témoins et les coupes de jardinage par groupe (respectivement 4,0 et 4,2 chicots/ha). La densité de petits chicots (DHP = 10,0–24,9 cm) était proportionnelle à la surface terrière résiduelle, c'est-à-dire que les plus fortes densités étaient associées aux témoins et aux coupes de jardinage par groupe. La création de chicots dans les coupes à blanc par injection d'herbicides a initialement produit une plus grande densité de chicots que les autres traitements, mais elle avait fortement diminué 6 ans après la coupe. Sans création additionnelle de chicots, des traitements comme la coupe progressive, qui prélève la plupart des arbres, peuvent engendrer une densité de chicots sous le seuil visé par certains objectifs d'aménagement. [Traduit par la Rédaction]

Introduction

The importance of snags to vertebrates in forest ecosystems is widely known. Over 85 species of North American birds use snags for foraging or nesting (Scott et al. 1977), and snags provide important roosting habitat for many species of bats, including the endangered Indiana bat (*Myotis sodalis*) (Britzke et al. 2003). Snags retained during forest harvest operations benefit insectivorous birds and other taxa (Stribling et al. 1990). Consequently, forest-management plans often include snag-retention guidelines (Bull et al. 1997). For example, guidelines for some US national forests call for retaining 5–10 snags of a minimum size per hectare (Hutto 2006; Ouachita National Forest 2005). Approximately 8 snags/ha is believed to support 100% of the maximum population density of woodpeckers in forests of the Pacific northwestern US (Thomas et al. 1979) and 100% of primary and secondary avian cavity nesters in the Coastal Plain of the southeastern US (Harlow and Guynn 1983). However, other studies have suggested snag densities of 10 snags/ha or greater (e.g., Bull et al. 1997; Schreiber and deCalesta 1992), and desirable snag densities may differ based on forest community type and successional stage (Hutto 2006). Although the density of snags is considered important, diameter, height, and decay condition of individual snags may also affect the availability of snags for different animal taxa (Thomas et al. 1979). Thus, forest managers often strive to maintain adequate snags during management activities, including harvest, thinning, and timber stand improvements.

Historically, even-aged management, consisting of clear-cutting, site preparation, and planting of seedlings was the dominant method for regenerating pines (*Pinus* spp.) on national forests across the southeastern US. Under clear-cutting systems, retention or creation of snags is often included as part of the prescription based on decades of wildlife research. However, public pressure related to environmental concerns in the 1990's prompted most national forests in the southeastern US to switch to less-intensive regeneration methods, such as shelterwood, seed tree, and single-tree selection that rely on natural regeneration (Baker 1994). In the absence of deliberate snag retention or creation during management activities, natural snag densities under these alternative regeneration methods are not fully understood, especially in areas dominated by naturally

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regenerated forests of mixed shortleaf pine (*Pinus echinata* Mill.) and hardwoods.

Various natural processes and forest-management activities can affect snag abundance and size distribution. In the absence of large-scale mortality events such as ice storms, disease outbreaks, or wildfire, the diameter distribution of snags in the southeastern US may resemble that of live trees in mature forests, with most snags being in the smaller size classes in unthinned stands (McComb and Muller 1983; Shifley et al. 1997; Moorman et al. 1999). However, snags may represent only 5%–14% of the total number of stems (McComb and Muller 1983; Shifley et al. 1997). Consequently, removing a portion of the trees via partial harvesting likely reduces snag density. Mechanical site preparation methods and timber stand improvements, such as midstory removal, may also reduce the number of smaller snags immediately after harvest and in the future. However, disturbance associated with logging, including root disturbance, skidder damage, and damage to residual trees from tree fall, could potentially increase the number of snags.

Numerous studies have examined snag dynamics in other regions of North America, especially the Pacific northwestern US (e.g., Rose et al. 2001). Less information is available on snag dynamics or effects of management on snags in forests of the southeastern US. Research in other regions suggest single-tree selection and thinning reduces the number of snags (McComb and Noble 1980; Graves et al. 2000; Doyon et al. 2005; Wisdom and Bate 2008), although commercial-thinning entries may create snags via unintentional damage to trees during thinning (Homyack et al. 2011). Unthinned mature stands may have substantially greater numbers of snags than partially harvested (seed tree or shelterwood) stands (Doyon et al. 2005; Wisdom and Bate 2008). In northern hardwood forests, 65- to 75-year-old, second-growth, even-aged stands may have a substantially greater density of snags than single-tree selection stands (Goodburn and Lorimer 1998). However, few studies have compared residual snag densities resulting from a variety of regeneration methods (e.g., Homyack et al. 2011). Therefore, we compared snag densities in clearcuts, unharvested controls, and stands under three partial harvest treatments the second, fourth, and sixth years after harvest in the Interior Highlands of Arkansas and Oklahoma. Our goal was to examine differences in snag densities among alternative regeneration methods and to determine whether additional snag creation under these alternatives might be warranted to meet management objectives for various animal taxa.

Materials and methods

Study areas

We conducted the study in the Ouachita Mountains and Arkansas River Valley of west-central Arkansas and east-central Oklahoma, in the Ouachita and Ozark-St. Francis National Forests. The Ouachita Mountains region is dominated by east–west oriented ridges and valleys where elevations range from 152 to 853 m. Throughout the region, mean annual temperature ranged from 14.0 to 16.2 °C (Skiles 1981), mean annual precipitation ranged from 112 to 142 cm, and the growing season was 200–240 days (McNab and Avers 1994).

We selected 20 mature, second-growth, mixed pine–hardwood stands, grouped into four physiographic blocks (5 stands/block) (Baker 1994). Each stand was >70 years old, >14 ha, and located on southerly aspects with slopes generally <20%. Average total basal area (BA) before harvest was 26.0 (±1.0 SE) m^2/ha. Of this, 17.6 (±0.9; range = 13.8–27.5) m^2/ha was pine and 8.4 (±0.6; range = 4.2–11.5) m^2/ha was hardwood. These stands resulted from initial cutting early in the 20th century, and were generally uneven-aged. Stands that met these criteria were randomly selected from those available within four blocks (Baker 1994). As a group, the most abundant tree species within study stands were shortleaf pine, post oak (*Quercus stellata* Wengenh.), white oak (*Quercus alba* L.), sweetgum (*Liquidambar styraciflua* L.), and hickories (*Carya* spp.).

Treatments

Within each of the four physiographic blocks, we randomly assigned one of five treatments to each stand; thus, each treatment was replicated four times in a randomized complete block design. Each block contained four harvest treatments, plus a mature unharvested control. Harvesting was conducted between late May and mid-September of 1993; site preparation occurred the following winter. No intentional snag creation was included in treatments other than clearcuts. The overall goal of harvest was to regenerate shortleaf pine. Treatments were single-tree selection, group selection, shelterwood, clearcut, and unharvested control.

1. Single-tree selection: Some overstory pines and hardwoods were removed uniformly throughout the stand using BDq methods (Baker et al. 1996). Target retained pine BA was 10.3–14.9 m^2/ha and hardwood BA was 1.1–4.6 m^2/ha. Site preparation was performed uniformly throughout the stand, and consisted of felling all hardwoods 5–15 cm DBH with chainsaws.
2. Group selection: All pines and most hardwoods were removed in openings that ranged from 0.04 to 1.9 ha in size; these openings constituted 6%–14% of the stand area. Pines within the matrix surrounding the openings were thinned, but no hardwoods were harvested within the matrix. Within group openings, target overstory hardwood retention was 1.1–2.3 m^2/ha, and all hardwoods 5–15 cm DBH were felled; no site preparation was applied in the surrounding matrix.
3. Shelterwood: From 49 to 99 of the largest pines and hardwoods per hectare were retained uniformly throughout the stand, with BA retention targets of 6.9–9.2 m^2/ha pine and 1.1–3.4 m^2/ha hardwood. All other pines and hardwoods (≥5 cm DBH) were harvested or felled.
4. Modified clearcut: All merchantable pines and hardwoods were harvested except a few scattered hardwood trees (BA target of 0.5–1.1 m^2/ha) retained for wildlife. Site preparation consisted of injecting all nonmerchantable standing trees (except retained wildlife trees, primarily oaks and hickories) with herbicide (Garlon 3A; Dow AgroSciences, Indianapolis, Indiana). Two of the four clear-cut stands were ripped with a bulldozer the following summer (1994); rips were 3 m apart and 15–20 cm deep. Two of the clearcuts were not ripped. Ripped clearcuts were hand planted with shortleaf pine at 2.4-m intervals within the rips and nonripped clearcuts were hand planted on a 2.4 m × 3 m grid.
5. Unharvested control: These stands consisted of mature, closed-canopy, second-growth, pine–hardwood forests >70 years old with little history of management other than fire suppression. One control was inadvertently harvested in 1997 and was replaced by a similar stand. Consequently, snag density for the fourth year after harvest included only three control stands.

All stands contained ephemeral stream drainages that typically flowed only during heavy rain events. Unharvested buffer strips (greenbelts) were established for water-quality protection at 15 m on each side of these drains. The total percentage of each stand retained as greenbelt ranged from 4% to 20% and averaged 10.9% across all 16 harvested stands.

Snag and basal area measurements

In each stand, we established four to nine parallel transects prior to harvest. Transects were 30–95 m apart, ran perpendicular to stand slope, and were 15 m wide. Within these belt transects, we tallied all snags ≥10 cm DBH and ≥1 m tall, based on requirements for most nesting birds and roosting bats (Evans and Conner 1979; Thomas et al. 1979; Perry and Thill 2007). Snags were tallied during early March, 1 year prior to harvest (1992) and in 1995, 1997, and 1999 (2, 4, and 6 years after harvest). Diameter (cm DBH) of all snags encountered within belt transects were measured with a

Table 1. Comparison of mean (±SE) density (no./ha) of snags and mean basal area (BA; m²/ha) of live trees (≥5 cm DBH) prior to treatment in 20 forest stands in the Ouachita Mountains of Oklahoma and Arkansas.

	Control	Group selection	Single-tree selection	Shelterwood	Clearcut	P[a]
Large snag density	1.2±0.4a[b]	4.1±0.5b	3.2±0.6ab	1.6±0.4a	3.2±0.6ab	0.007
Small snag density	16.9±3.9	20.0±4.5	13.9±5.9	7.8±2.9	14.9±4.4	0.425
All snag density	18.1±4.3	24.1±4.4	17.1±6.5	9.5±3.0	18.2±4.7	0.339
Pine BA	19.0±2.9	15.3±0.5	18.2±2.9	18.1±1.9	17.5±1.4	0.867
Hardwood BA	8.9±1.6	9.6±1.8	7.8±1.5	8.1±1.5	7.2±0.8	0.803
Total BA	27.9±4.2	25.0±1.4	26.0±1.5	26.2±2.0	24.8±1.4	0.886

Note: Large snags were ≥25 cm DBH and small snags were 10–24.9 cm DBH. Sample size was four stands per treatment.

[a] Probability based on ANOVA.

[b] Among rows, like letters indicate no significant difference based on Tukey's adjustment to least-squares means.

DBH tape, and height (m) of each snag was measured with a clinometer or telescoping measuring pole. Each snag was classified into one of four decay classes: (1) full height with branches and fine twigs; (2) some major branches remaining, may have lost up to half of the upper bole; (3) no major branches remaining, >2 m tall, with more than half of the upper bole gone; and (4) advanced decay, 1–2 m tall. Total area sampled for snags in each stand ranged from 2.05 to 2.14 ha (mean = 2.10 ± 0.01 ha). Because of the random placement of transects, belt transects sampled 0.05–0.69 ha of greenbelts within each stand. We removed these portions of transects so that only harvested portions of stands were included in comparisons among treatments, resulting in total sample areas in stands ranging from 1.3 to 2.1 ha. In group-selection stands, total sample areas in group openings was 0.19–0.42 ha (mean = 0.29 ± 0.05 ha), with the remainder of the sample area in the surrounding matrix.

Along each transect, 100 points were established at 15-m intervals. We randomly selected 30 of these points where we estimated live-tree BA with a 10-factor English prism, which was converted to metric (m²/ha). Random points that fell in greenbelts were not included in BA estimates. Only trees ≥5.0 cm DBH were included in BA estimates. Basal area of live trees was estimated each year that snag surveys were conducted.

Analyses

For preharvest data (1992), we compared BA estimates of live trees (≥5.0 cm DBH) among future treatments prior to harvest using analysis of variance (ANOVA) in a randomized block design for mixed models (Proc Mixed; Littell et al. 1996). We analyzed pine BA, hardwood BA, and total BA separately. We compared snag densities (pine and hardwood combined) among future treatments for three size classes of snags (large (≥25.0 cm DBH), small (10–24.9 cm DBH), and combined (all snags ≥10 cm DBH)) using similar ANOVAs. All analyses were conducted at $\alpha = 0.05$.

For postharvest data, we compared mean BA of live pine, hardwood, and total (pine and hardwood combined) among the five treatments using a repeated-measure ANOVA and a variance component (VC) estimate for the covariance matrix (Proc Mixed; Littell et al. 1996). We tested for year effects and treatment × year interaction for the three postharvest sampling years in a randomized block design during all postharvest years combined.

We compared postharvest snag densities for three size classes of snags (small, large, and combined) each sample year after harvest using mixed-model ANOVAs in a randomized block design. We did not conduct analysis on snag density for all years combined because we believed that changes each year in snag density due to falling of old snags (and creation of new snags) rendered a combined-year analysis uninformative.

For all analyses, we considered "Block" a random variable and we tested data for normality prior to analyses using Shapiro–Wilk tests (Littell et al. 1996; SAS Institute Inc. 2000). We used Kenwood–Roger degree of freedom adjustments if variances were unequal (Littell et al. 1996) and used Tukey's adjustment to separate least-squares means when ANOVA indicated a significant difference among treatments (SAS Institute Inc. 2000). All variables were normal without transformation except preharvest BA of live pines (which required a $1/x$ transformation) and postharvest density of large snags (which required an $\ln[X + 1]$ transformation).

We compared mean height and mean decay class of snags each year among the five treatments (all diameter classes combined and by four diameter classes: 10–14.9, 15–24.9, 25–34.9, and >35 cm DBH) using similar ANOVAs. Decay-class and snag-height data for each year and size class were normally distributed and did not require transformation. We also compared mean densities of large (≥25.0 cm DBH) and small (10.0–24.9 cm DBH) snags between greenbelts and controls for each year of sampling. Because these data were not normal, we used Wilcoxon scores in a nonparametric analysis. Finally, we conducted simple linear regression between residual BA of live trees (≥5 cm DBH) and total snag density for each year of sampling after harvest, using each stand as the experimental unit. Because snags were intentionally created in clearcuts using herbicide injection, we excluded clearcuts from this analysis.

Results

Prior to harvest, BA of live pines, hardwoods, and combined BA did not differ among future treatments (Table 1). Further, density of small snags (10–24.9 cm DBH) and combined snag density (small and large) did not differ among future treatments (Table 1). However, density of large snags (≥25.0 cm DBH) differed among future treatments, with controls and shelterwoods having a significantly lower density of large snags than group-selection stands prior to harvest.

After harvest, the BA of live trees (pine, hardwoods, and total) differed along a gradient, with unharvested control stands having the greatest hardwood, pine, and total BA, and clearcuts having the least BA (Table 2). For the BA of live trees, year effects and treatment × year interaction were not significant for hardwoods (year: $F_{2,41} = 0.18$, $P = 0.839$; treatment × year: $F_{8,41} = 0.23$, $P = 0.983$), pines (year: $F_{2,41} = 0.87$, $P = 0.425$; treatment × year: $F_{8,41} = 0.09$, $P = 0.999$), or total (year: $F_{2,41} = 0.65$, $P = 0.530$; treatment × year: $F_{8,41} = 0.15$, $P = 0.996$). Pine BA and total BA differed among all treatments except between single-tree selection and group-selection stands. The BA of live hardwoods differed among treatments but was similar in clearcuts and shelterwoods, and similar between shelterwoods and single-tree selection stands (Table 2).

After harvest, clearcuts had the greatest total snag density 2 and 4 years after treatment, although these densities were not significantly different from snag density in controls (Fig. 1). By 4 years after harvest, shelterwood stands had the lowest total density of snags, and density of snags in shelterwoods was only 8% of that in controls the sixth year after harvest. Snags created in clearcuts by herbicide injection were relatively short-lived. In clearcuts, the mean density of all snags 6 years after harvest (20.5 ± 4.3 snags/ha) was only 43% of that found in clearcuts 2 years after harvest (48.0 ± 8.4 snags/ha). Six years after harvest, total snag densities in

Table 2. Postharvest mean (±SE) basal areas (BA; m²/ha) of live trees ≥5.0 cm DBH in 20 forest stands under five silvicultural treatments in the Ouachita Mountains of Arkansas and Oklahoma.

	Control	Group selection	Single-tree selection	Shelterwood	Clearcut	P[a]
Pine BA	19.4±0.9a[b]	11.1±1.2b	12.5±0.7b	7.4±0.5c	0.4±0.1d	0.001
Hardwood BA	9.1±0.6a	6.1±0.6b	3.2±0.6c	2.8±0.3cd	0.9±0.1d	0.001
Total BA	28.5±1.1a	17.2±1.4b	15.8±0.8b	10.2±0.7c	1.3±0.1d	0.001

Note: Year effects and year × treatment interactions were not significant for any group.

[a] Probability based on repeated-measures ANOVA.

[b] Like letters among treatments indicate no significant difference during the three postharvest sample periods (2–6 years after harvest) based on Tukey's adjustment on least-squares means.

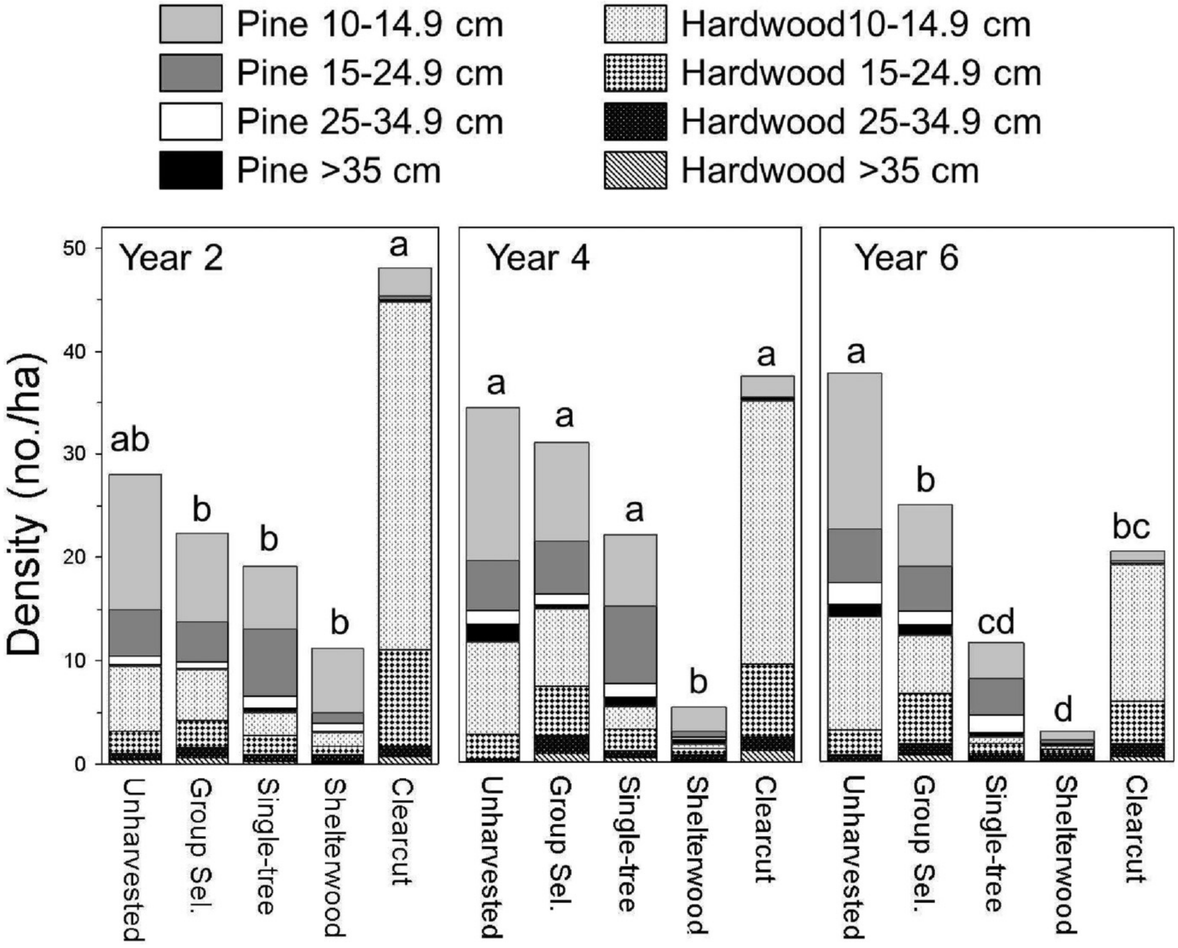


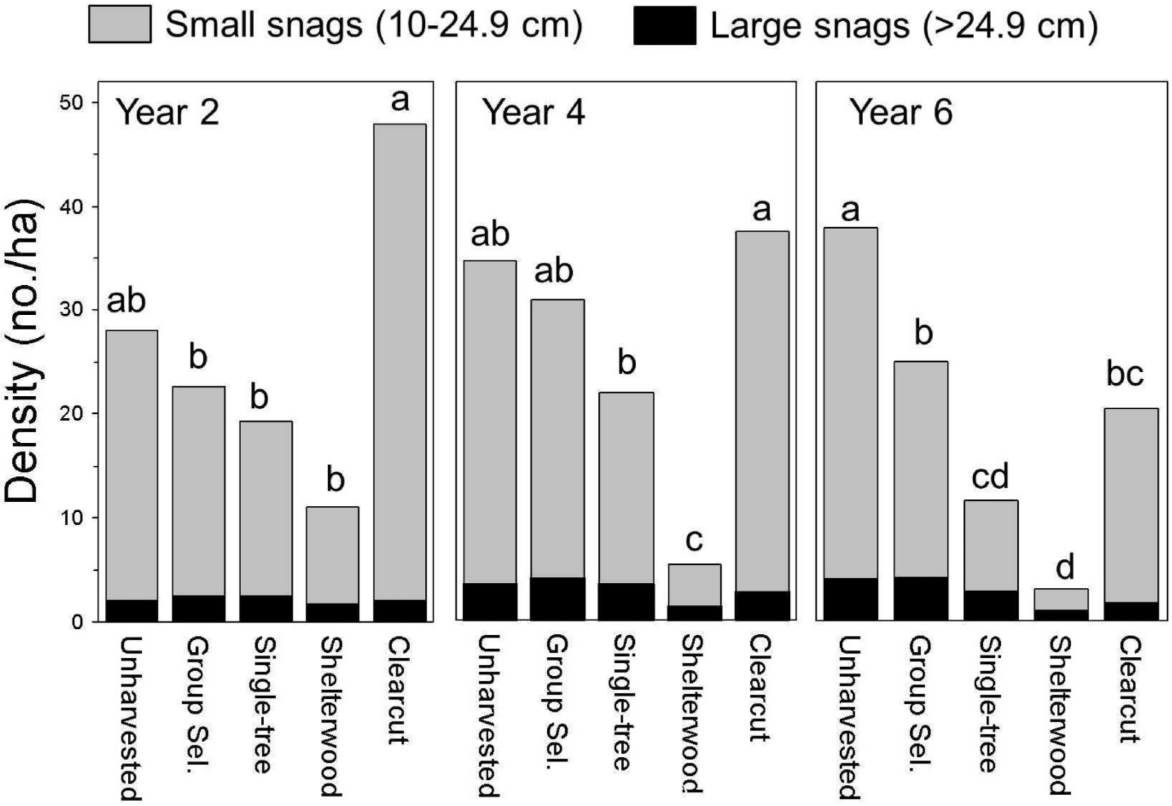
Fig. 1. Mean density of pine and hardwood snags (no./ha) by four size classes in 20 forest stands under five silvicultural treatments 2, 4, and 6 years after harvest (Year 2, Year 4, and Year 6) in the Ouachita Mountains of Arkansas and Oklahoma. Like letters above columns indicate no significant difference in total density among treatments (all size classes combined and pine–hardwood combined) within each of the three sample periods based on ANOVA and Tukey's adjustment to least-squares means.

clearcuts were similar to those in group-selection and single-tree selection stands, and lower than total snag density in the controls. By 6 years after harvest, the density of snags in the controls was significantly greater than in all harvested stands. In clearcuts, ripping reduced snag abundance by an average of 18%. Density (number/ha) of all size classes of snags combined was 53.2 ± 10.4, 41.7 ± 0.5, and 22.0 ± 7.3 (Year 2, Year 4, and Year 6, respectively) in nonripped clearcuts, whereas density in ripped clearcuts was 42.9 ± 16.1, 33.3 ± 9.7, and 18.9 ± 7.4, respectively.

The numbers of small snags (10–24.9 cm DBH) mirrored the pattern of overall snag density, with shelterwoods having the lowest small snag density by year 4 after harvest (Fig. 2). By 6 years after harvest, the density of small snags was greatest in the controls and least in shelterwood stands. No difference existed among treatments in the number of large (≥25.0 cm DBH) snags during year 2 ($F_{4,12} = 0.25$, $P = 0.902$) or year 4 ($F_{4,10.5} = 1.16$, $P = 0.382$) after harvest. However, the density of large snags differed among treatments 6 years after harvest ($F_{4,15} = 4.00$, $P = 0.021$); shelterwood stands had fewer large snags (0.97 ± 0.59 snags/ha) than the controls (4.05 ± 0.26 snags/ha) or the group-selection stands (4.20 ± 0.46). There was no significant difference in small or large snag density (pine and hardwood combined) between greenbelts and unharvested controls any year after harvest.

We found no difference in the mean height of snags among the five treatments for any of the three postharvest sample years. This included snag heights when compared by four snag diameter classes and when all diameter classes were combined. The mean height of snags the second, fourth, and sixth years after treatment

Fig. 2. Mean density (no./ha) of small (10–24.9 cm DBH) and large (>24.9 cm DBH) snags in 20 forest stands under five silvicultural treatments 2, 4, and 6 years after harvest (Year 2, Year 4, and Year 6) in the Ouachita Mountains of Arkansas and Oklahoma. Like letters above columns indicate no significant difference in density of small snags among treatments within each of the three sample periods based on ANOVA and Tukey's adjustment to least-squares means. Density of large snags differed only in Year 6, with shelterwoods having significantly lower snag density than controls or group-selection stands.



in all stands combined was 8.9 ± 0.5, 9.7 ± 0.6, and 9.0 ± 0.6 m, respectively. Similarly, no difference existed in the mean decay class of snags among treatments in any postharvest sample year (by the four diameter classes and all diameter classes combined). The exception was year 6, when the mean snag decay class in the 10–14.9 cm diameter class was 3.1 ± 0.7 in clearcuts, which was significantly more decayed than the snags in controls (2.4 ± 0.1). Among all treatments combined, means for snag decay classes were 2.7 ± 0.1, 2.4 ± 0.1, and 2.7 ± 0.1 for the second, fourth, and sixth years after harvest, respectively.

With clearcuts removed, the density of snags (all sizes combined) was linearly related to live-tree BA after harvest in two out of the three years examined (Fig. 3). Two years and 6 years after harvest, the relationship between BA and residual snag density was significant (Year 2: $F_{1,14} = 7.50$, $P = 0.016$, $r^2 = 0.35$; Year 6: $F_{1,14} = 16.69$, $P = 0.001$, $r^2 = 0.54$), whereas 4 years after harvest, the relationship was not significant ($F_{1,13} = 4.07$, $P = 0.065$, $r^2 = 0.24$). The slope of the relationship was greatest 6 years after harvest ($1.51x$).

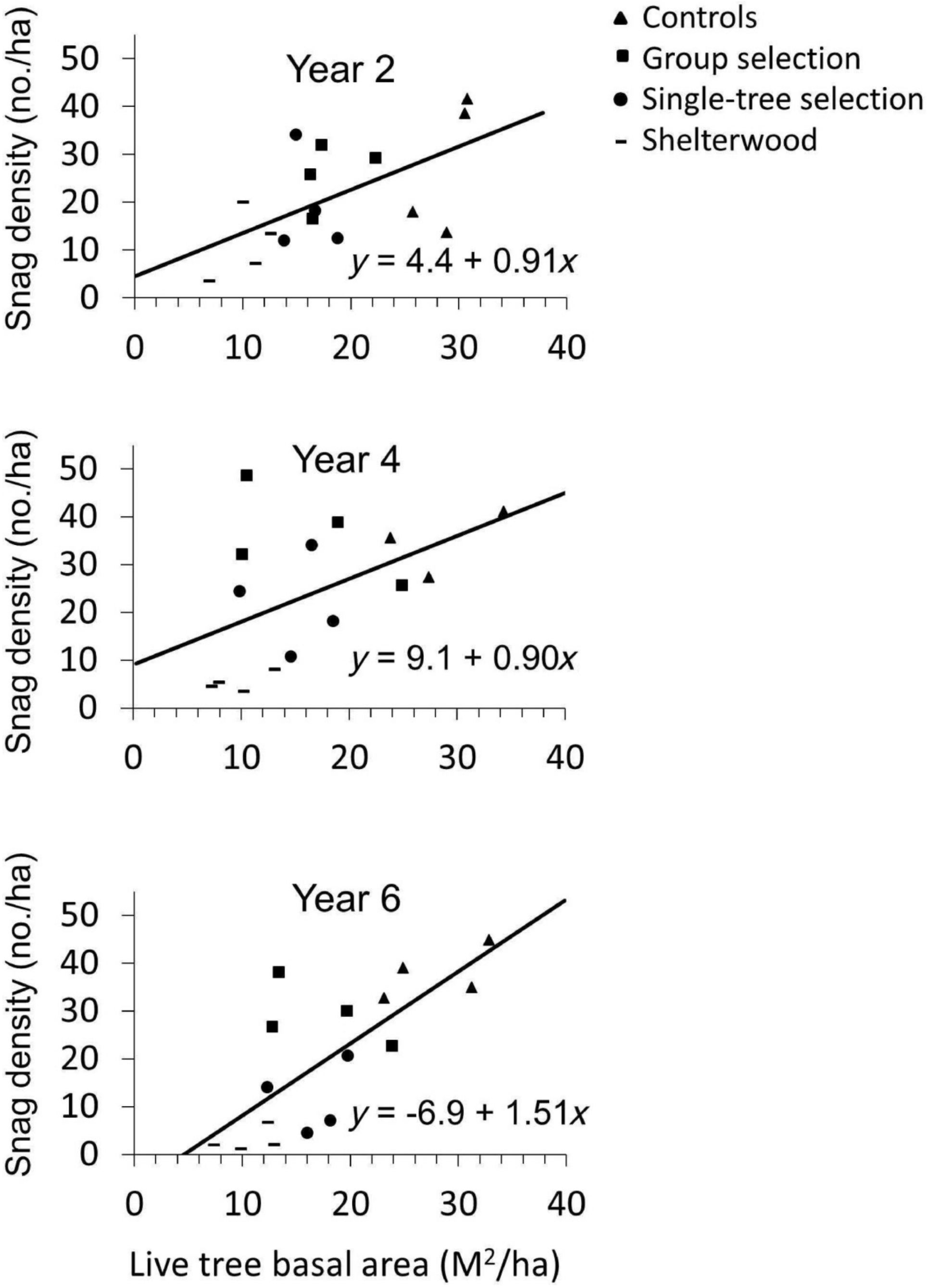
Discussion

With the exception of clearcuts, snag density followed a pattern similar to residual tree density; areas with the most retained trees had the most snags. Initial snag densities in clearcuts were generally greater than other treatments owing to the creation of snags in those areas. Although the average abundance of large snags did not differ between clearcuts and other treatments, 91% (Year 2) to 85% (Year 6) of retained snags in clearcuts were small (<25 cm DBH) hardwoods. Many of these smaller snags were short-lived; by year 6 after harvest, only 41% of these snags were still standing. Studies suggest retaining large snags because they stand for longer periods and meet the needs of nearly all of the snag-utilizing faunal community (Harlow and Guynn 1983; Ganey 1999). These larger snags also provide habitat for large secondary cavity users such as owls, wood ducks, and raccoons.

Large-diameter snags typically stand for longer periods than smaller diameter snags (Dickson et al. 1983; Cain 1996; Harrington 1996; Garber et al. 2005), but snag decay rates may vary based on many factors, including snag size, species, climate, stand density, silviculture system, and cause of death (Garber et al. 2005). Oaks injected with herbicide may deteriorate faster than girdled oaks because the initiation of decay in girdled oaks takes longer (Conner et al. 1983), but injected trees may become available for excavation more quickly than snags created in other ways. Similar to this study, Cain (1996) found only 50% of injected hardwoods <25 cm DBH were still standing after 5 years.

Hardwood snags may persist longer than pine snags (Moorman et al. 1999) and some hardwood species are more durable than others (Harmon 1982; Dickson et al. 1995). Wood decays at different rates in different climates (Harmon 1982), and snags may remain standing for years in the northeastern and western US, whereas snags in humid areas of the southeastern US may be relatively short-lived (Dickson et al. 1983; Moorman et al. 1999). Lower densities of retained live trees may also result in shorter snag duration because of exposure to wind (Schmid et al. 1985). Mechanical site preparation and silvicultural systems that include frequent entries such as single-tree selection may have lower snag abundance due to the actions of machinery and the felling of trees during additional harvests (Garber et al. 2005), and chemical site preparation may retain more snags than mechanical site preps

Fig. 3. Relationship (simple linear regression) between mean density (no./ha) of snags (≥10 cm DBH) and residual basal area (BA; m²/ha) of live trees (≥5 cm DBH) in forest stands under four silvicultural treatments 2, 4, and 6 years after harvest (Year 2, Year 4, and Year 6) in the Ouachita Mountains of Arkansas and Oklahoma. Clearcuts are excluded. Generally, stands with higher BA had greater densities of snags.



(Hanberry et al. 2012). We found ripping in clearcuts reduced overall snag abundance by around 18%. Consequently, snags retained immediately after harvest cannot be expected to stand for more than a few years, and a supply of snags from the crop of live trees is likely reduced over the long term when overall BA in a stand is reduced. However, when regenerated trees in a cohort reach the stem-exclusion phase in stand development, abundant, albeit relatively small, snags will typically be produced (e.g., Peet and Christensen 1987).

The importance of snag height and level of decay for various wildlife species is well-established. For example, relatively tall snags that still retain exfoliating bark are an important habitat component for many bat species in the Ouachita Mountains (Perry and Thill 2007, 2008*b*). We found snag heights and decay classes were generally similar among treatments. Thus, regeneration methods appeared to have little influence on snag height or decay class.

Snags are often defined as >10 cm DBH and >1.8 m tall, based on the minimum size and height used by nesting birds (Thomas et al. 1979). However, depending on the region and type of forest ecosystem, various snag sizes may be considered large, and bird species with wide distributions may show different requirements for snag sizes in different regions (Vaillancourt et al. 2008). Based on the needs of foraging and nesting birds, some authors consider snags greater than 23–30 cm DBH large (Russell et al. 2006; Saab et al. 2007; Vaillancourt et al. 2008), whereas others consider large snags >38 cm DBH (Raphael and White 1984). For example, optimal snag size for excavating and nesting by pileated woodpeckers (*Dryocopus pileatus*) may be >50 cm DBH and the minimum size may be 33 cm (Conner et al. 1975; Evans and Conner 1979). Therefore, snag retention guidelines often focus on retaining these large snags (e.g., >40 cm DBH) (Evans and Conner 1979; Thomas et al. 1979; Hartwig et al. 2004).

Although the density of large snags (>24.9 cm DBH) ranged from 1.0 to 4.2/ha in harvested stands, the density of the largest snag class (≥35 cm DBH) was relatively low across all treatments. The second year after harvest, the number of snags per hectare ≥35 cm was 0.8 ± 0.5 in group-selection stands, 0.8 ± 0.3 in single-tree selection stands, 0.3 ± 0.2 in shelterwoods, and 0.9 ± 0.2 in clearcuts. These densities were below the densities of large snags >36 cm (1.0–6.8 snags/ha) recommended by some authors for species such as red-bellied woodpeckers (*Melanerpes carolinus*) and red-headed woodpeckers (*Melanerpes erythrocephalus*), but were within the density range suggested for pileated woodpeckers (0.1–0.6 snags/ha) (Evans and Conner 1979). However, the density of large snags found in relatively unmanaged, mature controls was below these suggested densities as well (0.7 ± 0.4 snags ≥35 cm DBH/ha). After harvest, the density of live trees ≥38 cm ranged from 19.9 trees/ha in shelterwoods to 40.9 trees/ha in group-selection stands. Thus, trees of this size likely were not a limiting factor and creating more of these larger snags was possible. It should be noted that snag guidelines for the Southeast, including density and size, have been generalized from data obtained in midwestern and northern forests, and the appropriateness of these guidelines for southern, pine-dominated forests is unclear (Blanc and Walters 2009).

Although Evans and Conner (1979) suggested snags <10 cm DBH were of little value for feeding and nesting birds, other fauna such as bats may readily use these smaller snags for roosting. For example, most snags used by northern long-eared bats (*Myotis septentrionalis*) and big brown bats (*Eptesicus fuscus*) in Arkansas were <25 cm DBH (Perry and Thill 2007, 2008*b*), and male evening bats (*Nycticeius humeralis*) roosted more in snags 5–10 cm DBH than any other snag size class (Perry and Thill 2008*a*). Because small snags were abundant in some partially harvested stands (group-selection and single-tree selection), these snags may provide plentiful habitat for many species. Consequently, the importance of small snags to forest ecosystems should not be overlooked, and small snags should be retained when possible.

In single-tree selection and shelterwood stands, the density of small snags was reduced partially because of site preparation treatments, which called for felling hardwoods <15 cm DBH. This reduction in midstory trees reduced the available crop for future snag recruitment. Consequently, girdling or injecting some of these smaller trees, instead of felling, would provide small snags for wildlife species initially after harvest, at least in the short term. However, it is unknown if these smaller snags would persist long with additional treatments such as burning.

Snag densities in greenbelts were similar to those in unharvested control stands, which had significantly greater snag densities than all other treatments by year 6 after harvest. These greenbelts comprised 4%–20% of the area within each stand. Thus, retention of these greenbelts in harvested stands provided areas of relatively high snag density imbedded within harvested areas of lower snag abundance.

To maintain faunal diversity, snag management should take into account snag size (including height), decay class, density, and distribution of snags in forest stands. Because of the territoriality of nesting birds, some previous recommendations suggest retaining large (>40 cm DBH) equally spaced snags at a density of around 4–10 snags/ha (Bull et al. 1997). In the Pacific Northwest, other studies suggest retaining snags in clumps for the bird community (Raphael and White 1984; Walter and McGuire 2005). Unlike territorial birds, female maternity colonies of bats are communal social networks, and they typically roost in areas of clustered snags (Willis and Brigham 2004; Perry and Thill 2007). Furthermore, solitary male and nonreproductive female bats may readily use small (<10 cm DBH) snags. During harvest treatments, retaining clusters of larger snags, along with abundant small snags, would likely increase habitat suitability for bats and birds, whereas also retaining relatively evenly distributed large snags would enhance the habitat for some birds. Because bats rarely use snags in young clearcuts in the southeastern US for roosting (Perry et al. 2007), management of snags in clearcuts might focus on birds, whereas in partial harvest treatments that bats readily use for roosting (Perry et al. 2007), snag distribution might include both bat- and bird-targeted snag distributions.

Management recommendations

Killing some small trees as opposed to felling during midstory removal and site preparation would ensure a short-term abundance of smaller snags within stands under partial harvest treatments. Methods such as seed tree or shelterwood cuts that remove substantial numbers of trees may result in snag densities below the thresholds for some management objectives without additional snag creation. Consequently, snag creation similar to that practiced in clearcuts may be warranted when conducting seed tree and shelterwood harvest cuts if higher snag densities are desired. Furthermore, if larger snags (>35 cm DBH) are in short supply, additional large snag creation could be included in harvest prescriptions.

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