Available online at www.sciencedirect.com
SCIENCE DIRECT®
Forest Ecology and Management 221 (2006) 140–146
Forest Ecology and Management
www.elsevier.com/locate/foreco

Ponderosa pine snag densities following multiple fires in the Gila Wilderness, New Mexico

Zachary Alan Holden [a,*], Penelope Morgan [a], Matthew G. Rollins [b], R. Gerald Wright [c]

[a] Department of Forest Resources, University of Idaho, Moscow, ID 83844-1133, USA
[b] Fire Sciences Laboratory, Rocky Mountain Research Station, USDA Forest Service, Missoula, MT 59807, USA
[c] USGS Fish and Wildlife Research Unit, University of Idaho, Moscow, ID 83844-1136, USA

Received 16 February 2005; received in revised form 15 September 2005; accepted 16 September 2005

Abstract

Fires create and consume snags (standing dead trees), an important structural and ecological component of ponderosa pine forests. The effects of repeated fires on snag densities in ponderosa pine forests of the southwestern USA have not been studied. Line intercept sampling was used to estimate snag densities in areas of the Gila Wilderness that had burned one to three times under Wildland Fire Use for Resource Benefit (WFU), a fire management policy implemented since 1974 aimed at restoring natural fire regimes. Twenty randomly located transects were measured in areas burned since 1946; six in once-burned areas, six in twice-burned areas and eight in thrice-burned areas. The mean density $\pm$ standard errors of large (>47.5 cm dbh) snags for areas that burned once, twice and thrice was 7.0 ± 2.7, 4.4 ± 1.1 and 4.1 ± 1.3 snags/ha, respectively. Differences in snag densities between once- and multiple-burned areas were significant (F-test; $p < 0.05$). There was no significant difference in density of large snags between twice- and thrice-burned areas. Proportions of type 1 snags (recently created) were higher in once- and twice-burned areas than in areas that burned three times, likely reflecting high tree mortality and snag recruitment resulting from an initial entry fire. Type 3 snags (charred by previous fire) were more abundant in areas that burned multiple times. The lack of differences in snag densities between areas that burned two and three times suggests that repeated fires leave many snags standing. The increasing proportion of type 3 snags with repeated fires supports this conclusion.

Keywords: Ponderosa pine; Fire; Snag; Southwest

1. Introduction

As a keystone disturbance agent, fire has played a critical role in shaping the structure and function of ponderosa pine (*Pinus ponderosa*) forests (Cooper, 1960; Covington and Moore, 1994a). Historically in the southwestern USA, frequent surface fires carried by grasses and fine fuels maintained open stands of mixed size and age that were ‘‘park-like’’ in appearance, with an understory characterized by dense, tall grasses and forbs (Cooper, 1960; White, 1985). Grazing, road development and an intense campaign of fire suppression all contributed to the exclusion of fire from many ponderosa pine forests. After long periods without fire, many ponderosa pine forests have undergone significant changes, including increased surface fuel loading and much higher densities of trees than were thought to have occurred historically (Covington and Moore, 1994b; Savage, 1991). These changes are particularly well documented in the southwestern USA (Friederici, 2003; Mast et al., 1999; Moore et al., 1999, 2004). The need for ecological restoration of ponderosa pine forests is now widely acknowledged by researchers and managers (Allen et al., 2002; Covington and Moore, 1994a; Weaver, 1951). A major goal of ecological restoration of ponderosa pine ecosystems is restoring fire as a natural ecological process (Society for Ecological Restoration, 1996). Increasing fire frequency will alter forest structure. The implications of repeated fires for snags and the many birds and mammals that use them are unknown.

* Corresponding author. Tel.: +1 208 882 3847.
E-mail address: zack_holden@hotmail.com (Z.A. Holden).

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2005.09.014

In 1974, The Gila National Forest, NM formally implemented one of the first Wildland Fire Use for Resource Benefit (WFU) programs in the nation. Wildland Fire Use fires are those naturally ignited fires which are managed to continue burning to accomplish resource benefits as long as no critical resources are threatened, adequate personnel and resources are available for suppression and an approved fire management plan is in place (USFS, 1996). The goal of the WFU program is to restore natural fire regimes, and ultimately to allow fires to burn with a minimum of human intervention. More than 7000 ha in the Gila–Aldo Leopold Wilderness Complex have now burned three or more times since 1974, 82% of those areas in ponderosa pine and Douglas-fir (*Pseudotsuga menzesii*) potential vegetation types (Rollins, 2000) (Fig. 1). The Gila Wilderness has been touted as a model for restoration of natural fire regimes to forested ecosystems (Boucher et al., 2000). WFU is destined to become the new paradigm in fire management, especially in remote areas (Government Accounting Office, 2002). However, such broad-scale fire management decisions will significantly impact wildlife and other resources, and the potential impacts of ponderosa pine restoration treatments are still being debated (Block et al., 2001; Boucher et al., 2000; Tiedemann et al., 2000).

1.1. Snag management

Fire kills trees, creating new snags and removing existing snags. However, the effects of repeated fires on snag densities have never been measured. Balda (1975) established 4.2 snags/ha as the minimum snag density required to sustain cavity-nesting bird species in southwestern ponderosa pine forests. This number has since been adopted by many land management agencies in guidelines for management of snags (U.S. Department of Agriculture, 1996). Historical snag densities in ponderosa pine forests are very low (0.1 snags/ha) and Ganey's (1999) work in the southwestern USA suggests that Balda's (1975) guidelines may be unrealistically high. Boucher et al. (2000) suggested that current snag densities in ponderosa pine forests in the southwestern USA may be artificially high due to fire exclusion. A fire that follows a long fire-free period may burn intensely, killing many trees through crown damage. Where crowning does not occur, accumulated litter and duff laters can smolder and kill cambial tissue and fine roots, creating snags even where fire intensity was modest (Sackett et al., 1996). However, snag densities are likely to decrease with repeated fires. Prescribed burning in ponderosa pine forests in Arizona

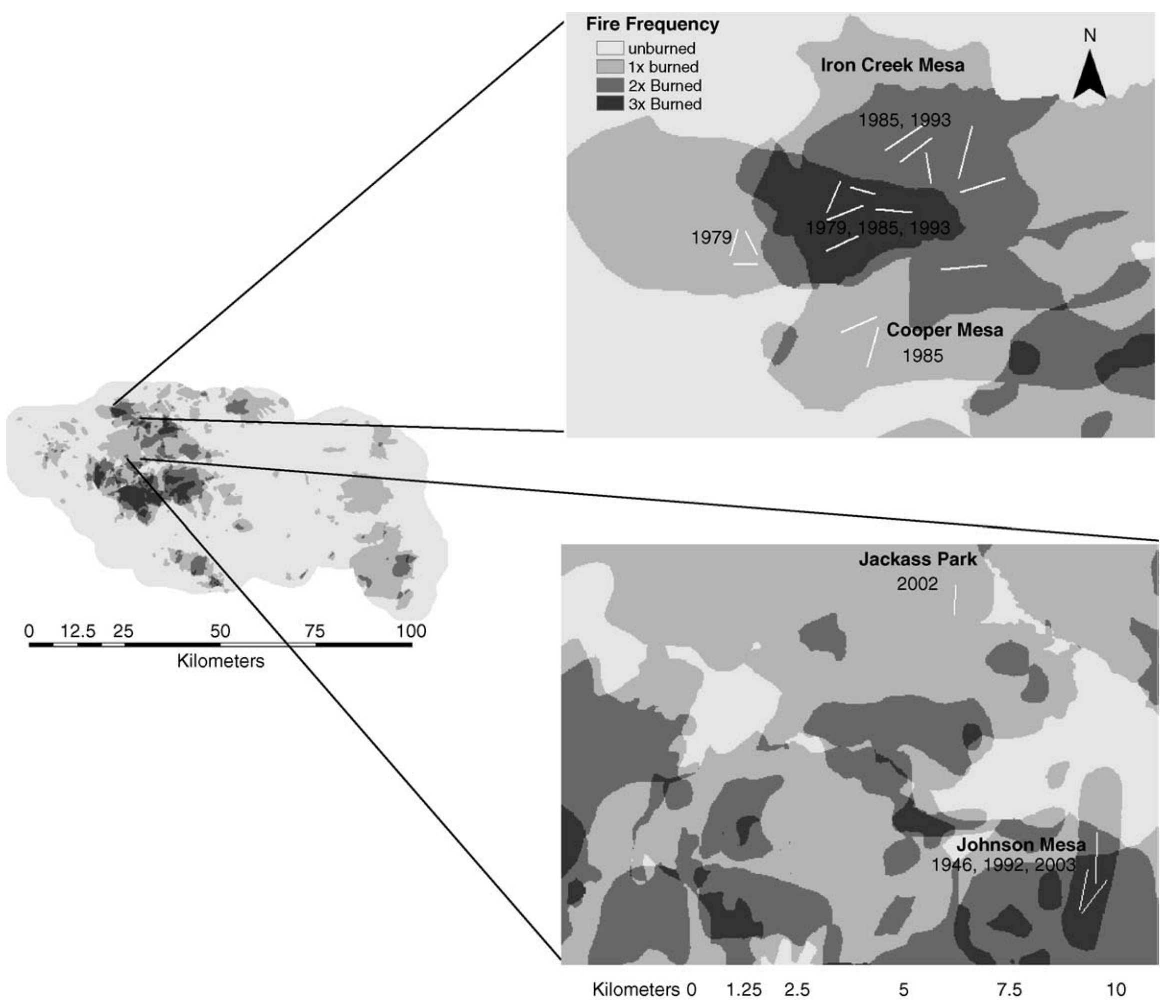

Fig. 1. Study area fire atlas with transect locations (white lines) and fire years in the Gila–Aldo Leopold Wilderness Complex, New Mexico.

decreased snag densities (Gordon, 1996; Horton et al., 1988). Several researchers have observed that continuous understory vegetation and grasses grow near the base of snags and large trees (Boucher et al., 2000; Fulé and Covington, 1995). Understory vegetation and fine fuels may carry fire to the base of snags, which then burn and fall to the ground. According to this model, repeated fires would lead to low snag densities.

The objective of our study was to compare snag densities in ponderosa pine forests of the Gila Wilderness that had burned one to three times since 1946 (the first recorded fire in our study area). We were unable to locate unburned areas large enough to permit snag density sampling and to serve as controls for this natural experiment. We defined snags as all dead ponderosa pine and Douglas-fir trees greater than 47.5 cm dbh and 5 m tall. Other studies have measured snags of all size classes. We measured only large-diameter snags because of their longer retention time and preferred use by cavity-nesting bird species (Bull, 1983; Bull et al., 1997). Based on previous research that measured the removal of snags by prescribed fire (Horton et al., 1988), and observations by fire managers that snags frequently burn and fall during fire events, we hypothesized that snag densities would be significantly higher in areas that had burned only once and would continue to decrease with repeated fires.

2. Methods

2.1. Study area

2.1.1. Gila Wilderness

The 230,800 ha Gila Wilderness lies 70 km north of Silver City, in west central New Mexico. Together with the Aldo Leopold Wilderness Area, it forms the Gila–Aldo Leopold Wilderness Complex (GALWC) (Fig. 1). Encompassing the Gila River and its headwaters, the Mogollon Mountains and the Black range, elevations in the Gila range from 1300 to 3300 m. Volcanic events in the late Cretaceous period formed the parent material of the Gila Wilderness. Annual precipitation varies from 250 to 760 mm at higher elevations, falling as snow in the winter and as rain in the early-summer monsoon storms characteristic of the region. Thunderstorms are common in the summer months, resulting from rapid lifting of moist air from the Gulf of Mexico. These storms are localized, and often produce lightning, leading to favorable fire conditions. Our sample transects were located in the northern part of the Gila Wilderness which is characterized by broad, relatively flat mesa tops dominated by extensive ponderosa pine stands. Historically, low-severity (low tree mortality) surface fires were frequent in this area (3–10 years MFI) (Swetnam, 1983). With grazing and fire suppression, fires were less frequent during the 20th century, although large fires did occur (e.g. in 1946 and 1951) (Rollins et al., 2001).

3. Field sampling and analysis

Snag densities in the Gila Wilderness were estimated in May–August of 2004 using line transect sampling methods (Anderson et al., 1979). We measured the diameter at breast height (dbh) and perpendicular distance to all ponderosa pine and Douglas-fir snags 47.5 cm dbh or greater along each transect. Twenty snag transects were randomly located on mesa tops in the locations described below across approximately 60,000 ha of the northern part of the Gila Wilderness (Fig. 1). Transects were located in areas dominated by ponderosa pine, although Douglas-fir trees occur on more mesic aspects and occurred infrequently in all sample transects. Six transects were located in areas that had burned once, six in areas that had burned twice and eight in areas that burned three times according to fire atlas records. Sampling was stratified using historical fire perimeter records compiled in a digitized fire atlas (Rollins et al., 2001). We attempted to locate transects across the study area on geographically isolated mesa tops with unique fire histories (Fig. 1) in order to avoid pseudoreplication (Hurlbert, 1984). Once-burned areas included Iron Creek Mesa (1979); Cooper Mesa (1993) and Jackass Park (2002). Twice-burned areas were located only on Iron Creek Mesa (1985 and 1993). Thrice-burned areas were located on Iron Creek Mesa (1979, 1985 and 1993) and Johnson Mesa (1946, 1992 and 2003). Because transects in areas that burned twice all occurred within the perimeters of the same two fires, they are technically unreplicated. However, the 1985 and 1993 fires were large (18,000 and 22,000 acres, respectively) and both burned for more than a month. Transects were dispersed across overlapping areas of the two fire perimeters in an effort to encompass variability in fire intensity and behavior during the life of the fires. Detailed pre-fire information is lacking for all areas sampled, and observations of fire behavior are general and not site specific to transect locations. Fire conditions were likely highly variable because these fires burned for many days and nights. We assumed that causes of tree mortality (e.g. lightning strikes and bark beetles) also varied in non-systematic ways across the transects. We believe this assumption is appropriate, given the interspersion of transects and treatments across the study area and the size of sampled areas relative to the fine-scale variation in forest structure.

Transect start points and azimuths were selected randomly within each fire frequency strata. A minimum of 40 snags were measured along each transect and the number of observations collected along each transect varied from 41 to 79. Transect lengths varied from 500 to 1800 m. We discontinued sampling along an individual transect if it approached an area with a different fire frequency, or if the transect reached the edge of a mesa. Snags were grouped into three categories, following methods described by Boucher et al. (2000). Type 1 snags appeared to have been dead for less than 6 year and retained needles and/or small branches. Type 2 snags had probably been dead for more than 6 years and had lost all twigs and small branches. Type 3 snags were charred snags that had clearly experienced a recent fire (extensive visible char around circumference of the bole) but remained standing. All type 3 snags appeared to have been dead for at least 6 years.

Snag densities were estimated using the program DISTANCE (Laake et al., 1996). Uniform, half normal and hazard rate models for detection distances of each transect were compared. Best fitting models of snag detection were selected by comparing Akiake Information Criterion (AIC) values between the different models. Statistical differences in snag densities between areas with different fire frequencies were assessed for normality and compared using analysis of variance procedures in the program R, an open source statistical environment (R Development Core Team, 2003).

Fire atlases are valuable records of landscape fire frequency (Rollins et al., 2001) but are prone to inaccuracy because they often exclude small fires and include unburned areas within the fire perimeter (Morgan et al., 2001). This may have affected the accuracy of our sampling and contributed to variation in our results. In the Iron Creek Mesa area of the Gila Wilderness, sample transects were sometimes located near the boundary of two intersecting fire perimeters. To evaluate our the accuracy of fire atlas perimeters with which we stratified our sampling, we used Landsat Thematic Mapper (TM) images to map burned area perimeters of two fires sampled in the Gila Wilderness (Holden, 2005; Holden et al., 2005). Correspondence between the atlas-derived and imagery-derived fire perimeters was high, especially at the eastern and western edges that defined critical boundaries between fire treatments (one to three times burned areas), generally confirming our sampling stratification for overlapping areas of the 1985 and 1993 fire perimeters (Fig. 2). Because Landsat TM data was unavailable for early fires, we were unable to confirm the fire frequencies for sample transect locations for the older fire perimeters (1946 and 1979) within which we sampled.

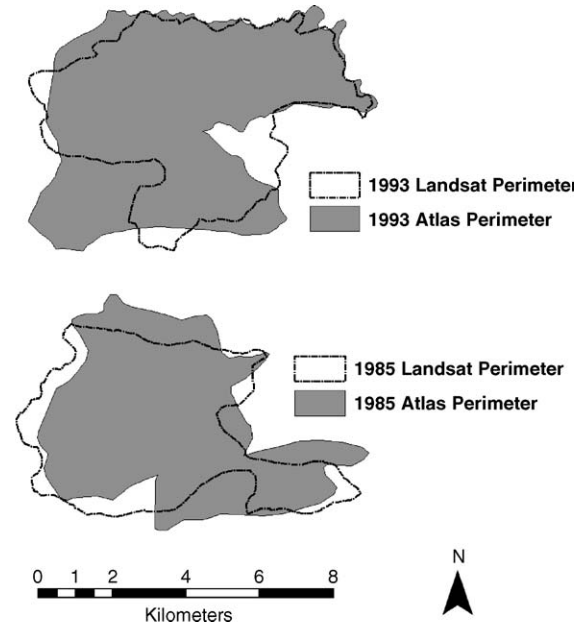

Fig. 2. Correspondence between fire perimeters derived from satellite imagery (clear outline) and fire atlas perimeters (gray) for two fires sampled on Iron Creek Mesa.

4. Results

Mean snag densities in areas that burned one to three times were 7.0 ± 2.7, 4.4 ± 1.6 and 4.1 ± 1.7 snags/ha, respectively (Tables 1 and 2). Snag densities were significantly lower in areas that had experienced two or three fires since 1946 compared to areas that burned only once in that time (Table 2) ($p < 0.05$). Snag densities did not differ significantly between areas that burned two and three times. Areas burned multiple times had significantly higher proportions of type 3 snags than areas burned only once ($p < 0.001$). Type 3 snags (standing snags charred by a previous fire) were two to four times more abundant in twice and thrice-burned areas than areas that burned only once. Differences in the number of type 2 snags between fire treatments were small but statistically significant ($p < 0.01$). Type 1 snags occurred more frequently in once- and twice-burned areas than in areas that burned three times ($p < 0.001$).

Table 1
Locations and estimates of snag density with 95% confidence interval for sample transects within the Gila Wilderness study area

Transect	Location	Density (snag/ha)	95% CI	Fire year	Fire frequency
1	Iron Creek Mesa	8.8	6.1–12.7	1979	1× Burned
2	Cooper Mesa	4.5	3.3–6.5	1985	1× Burned
3	Cooper Mesa	7.9	5.4–11.5	1985	1× Burned
4	Jackass Park	6.0	4.2–8.6	2002	1× Burned
5	Iron Creek Mesa	6.2	4.3–8.9	1979	1× Burned
6	Iron Creek Mesa	8.3	5.1–10.5	1979	1× Burned
7	Iron Creek Mesa	4.4	3.0–6.4	1985, 1993	2× Burned
8	Iron Creek Mesa	4.8	3.5–6.8	1985, 1993	2× Burned
9	Iron Creek Mesa	2.9	1.9–4.2	1985, 1993	2× Burned
10	Iron Creek Mesa	5.3	3.7–7.6	1985, 1993	2× Burned
11	Iron Creek Mesa	4.7	3.4–6.6	1985, 1993	2× Burned
12	Iron Creek Mesa	4.3	3.0–6.0	1985, 1993	2× Burned
13	Iron Creek Mesa	7.3	4.7–11.2	1979, 1985, 1993	3× Burned
14	Iron Creek Mesa	4.8	3.4–6.8	1979, 1985, 1993	3× Burned
15	Iron Creek Mesa	4.4	3.0–6.4	1979, 1985, 1993	3× Burned
16	Iron Creek Mesa	3.8	2.8–5.1	1979, 1985, 1993	3× Burned
17	Iron Creek Mesa	4.2	2.9–6.1	1979, 1985, 1993	3× Burned
18	Johnson Mesa	3.6	2.2–3.9	1946, 1992, 2003	3× Burned
19	Johnson Mesa	2.9	2.0–6.6	1946, 1992, 2003	3× Burned
20	Johnson Mesa	1.9	1.2–2.7	1946, 1992, 2003	3× Burned

Table 2
Mean snag densities (snags/ha) with 95% confidence intervals and proportion of each snag type for transects burned one, two or three times

Fire occurrence	1× Burn	2× Burn	3× Burn
Mean	7.0 a	4.4 b	4.1 b
95% CI	4.25–9.65	2.8–5.0	3.1–5.9
Type 3 snags (%)	3	9	18
Type 2 snags (%)	78	72	76
Type 1 snags (%)	19	19	6

Different letters (a and b) next to means indicate significant differences at $\alpha = 0.05$ (F-test).

5. Discussion

As expected, snag densities in areas that burned multiple times were significantly lower than in areas that burned only once. An initial fire after long periods of fire exclusion is likely to cause high tree mortality and hence snag recruitment if there is an excessive accumulation of fuel, including litter and duff that burns around the tree's base. Severe fires can kill fine tree roots near the surface of the soil (Swezy and Agee, 1991), alter microbial and mycorrhizal dynamics at the soil surface (Grogan et al., 2000), and cause cambial heating sufficient to kill trees directly (Harrington, 1996; Ryan, 1988; Sackett et al., 1996). With surface fuel loading reduced after the first fire, a second fire should kill fewer trees, but could fell many of the snags created by the first fire if enough wood at the snag's base is consumed, or if some of the snags are rotten at the base. Subsequent fires could continue to fell remaining snags without killing many additional large live trees.

We were surprised by the lack of differences in snag densities between areas that burned two and three times. We expected snag density reduction to continue with repeated fires. Several scenarios could explain the lack of apparent differences between areas that burned two and three times. One possibility is that with multiple fires, fire-caused snag recruitment and snag reduction reach equilibrium, such that new snags created by a fire are roughly equal to the number of snags felled. Alternatively, repeated fires might contribute to snag resilience to future fires, by removing or altering the quality and or quantity of debris around the snags' base. The condition of the wood at a snag's base will influence the probability of the snag being felled by the fire (Harrington, personal communication). Snags that develop rotten bases are likely to fall from any contact with flame or embers, while snags with a solid base will be more resilient to fire. The snags that remain standing after two fires might be less susceptible to felling by a subsequent fire.

However, we did not record specific information about the condition of individual snags, or their condition prior to and following each fire. Therefore, we cannot be certain that each snag was recruited as a result of fire, or that our assignment of snag type was correct, and we can only speculate as to the reason for lack of differences in snag densities between twice- and thrice-burned areas.

Snag quality as well as quantity determines whether snags are used by cavity-dependent bird species (Bull et al., 1997). Causes of tree mortality may influence suitability of snags for use by wildlife (Shea et al., 2002). We did not carefully evaluate the condition of individual snags (e.g. decay characteristics, presence of insects or cavity-dependent bird species). However, large types 1 and 2 snags are likely to provide the conditions (e.g. wood density, level of decay) preferred by cavity-nesting species (Bull et al., 1997; Farris et al., 2002). Relative decay rates of types 2 and 3 snags are unknown. It is possible that once charred, decay rates of type 3 snags will decrease, increasing their longevity. However, charring could result in significant hardening of a snag, making it less suitable for use by bird species. Previous studies indicate that cavity-nesting birds prefer snags with some degree of decay as nesting or feeding sites (Harris, 1983). Wakkinen (1992) also found that snags with a relatively large number of intact limbs, indicating a recent death, received significantly more use by cavity-nesting birds than trees with reduced numbers of limbs (i.e., snags that have been dead longer). Several studies support the idea that newer snags or partially dead snags (as opposed to 100% dead) are the most important foraging substrates. Cunningham et al. (1980) noted that birds that used snags as a feeding substrate frequently selected those which were recently dead (1–5 years) and had a high percentage of bark cover. They suggested that this is the result of invasion by insect larvae following tree death. Insect larvae peak in numbers at about 2 years after tree death and decline thereafter.

Because we only sampled snags >47.5 cm dbh, we cannot directly compare these results with those from other studies. However, Boucher et al. (2000) reported snag densities (>30 cm) ranging from 1.7 to more than 80 snags/ha in areas that varied widely in past management and fire histories. Horton et al. (1988) reported pre-fire snag densities of 12.9 snags/ha (all size classes) in ponderosa pine forests of Arizona in which fire had been absent for many decades. Ganey (1999) reported snag densities ranging from 0 to 45 snags/ha (all size classes) in ponderosa pine forests across six National Forests in Arizona. These studies highlight the broad range of stand conditions and stand densities that exist in the southwestern USA.

6. Implications for snag management

Results from our study suggest that many large ponderosa pine snags in the Gila Wilderness are retained on the landscape, even after exposure to repeated fires. Snag densities remained within the range recommended by Balda (1975) even after experiencing two or three wildland fires. To our knowledge, this is the first study to quantify the effects of broad-scale, repeated fire treatments on snag densities. These results have important implications for ecological restoration and management of fire in ponderosa pine forests in the southwestern USA and elsewhere. A major challenge to restoring natural fire regimes will be to alter stand structure characteristics and surface fuel loads sufficiently to promote surface fires while minimizing severe stand-replacing events. Repeated fires will be needed to achieve and maintain ecological restoration or fuel management objectives. The abundance of large snags following repeated fires in this unlogged wilderness area without any prior mechanical treatments (e.g. thinning or removal of litter and duff from the base of snags) suggests that restoration treatments that include fire can be applied while still retaining snags. Our results also support previous research suggesting fire-caused mortality of large trees may be high after a long fire-free interval. This initial pulse of snag recruitment is a likely cause of the relatively high snag densities following repeated fires. Retention of large diameter trees is also a major concern in implementing restoration treatments in ponderosa pine forests. Retention of snags may be lower with repeated burning elsewhere, especially if there are fewer large trees to begin with because of logging or past disturbance. Given the importance of snags to wildlife, efforts to reduce net snag loss during repeated fires is prudent. Management for snag recruitment and retention will have to be balanced with the need for minimizing mortality of large trees.

7. Conclusions

Snags and downed logs play an important ecological role in forest dynamics. Pervasive alterations of fire regimes across many forested regions of the USA have altered these dynamics. These changes are most pronounced in areas that experienced historically frequent surface fires, where relatively brief disruption of historical fire regimes can lead to significant departures in vegetation from historical conditions. Ponderosa pine forests are perhaps the best-known and most extensively studied examples of such areas. Fire is now frequently used as a management tool to manage fuels and to restore and maintain structural and ecological conditions in many areas. However, questions still remain about the effects of repeated fires on stand structure and snag densities. Our results suggest that repeated fire treatments leave many large-diameter snags standing. Both recruitment of new snags and retention of snags of a variety of stages of decay will be important to cavity-nesting birds. To the extent that restoration burning promotes growth and survival of large-diameter trees, such burning will promote a supply of large-diameter snags.

References

Allen, C.D., Savage, M., Falk, D.A., Suckling, K.F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M., Klingel, J., 2002. Ecological restoration of Southwestern ponderosa pine ecosystems: a broad perspective. Ecol. Appl. 12, 1418–1433.

Anderson, D.R., Laake, J.L., Crain, B.R., Burnham, K.P., 1979. Guidelines for line transect sampling of biological populations. J. Wildlife Manage. 43, 70–78.

Balda, R.P., 1975. The relationship of secondary cavity nesters and snag densities in western coniferous forests. Forest Wildlife Habitat Technical Bulletin 1, U.S. Department of Agriculture, Forest Service, Southwestern Region, Albuquerque, NM.

Block, W.M., Franklin, J.B., Ward, J.P., Ganey, J.L., White, G.C., 2001. Design and implementation of monitoring studies to evaluate the success of ecological restoration on wildlife. Restor. Ecol. 9, 293–303.

Boucher, P.F., Block, W.M., Benavidez, G.V., Wiebe, L.E., 2000. Implementing the expanded prescribed fire program on the Gila National Forest, New Mexico: implications for snag management. In: Moser, K.W., Moser, C.F. (Eds.), Fire and Forest Ecology: Innovative Silviculture and Vegetation Management, vol. 21. Tall Timbers Research Station, Tallahassee, FL, pp. 104–113.

Bull, E., 1983. Longevity of snags and their use by woodpeckers. In: Snag Habitat Management Symposium, RM-GTR-99. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Flagstaff, Arizona, pp. 64–67.

Bull, E.L., Parks, C.G., Torgersen, T.R., 1997. Trees and Logs Important to Wildlife in the Interior Columbia River Basin. United States Department of Agriculture Forest Service General Technical Report, PNW-GTR-391, pp. 21–34.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecol. Monogr. 30, 129–164.

Covington, W.W., Moore, M.M., 1994a. Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. In: Sampson, R.N., Adamn, D.L. (Eds.), Assessing Forest Ecosystem Health in the Inland West. The Hawthorn Press, pp. 153–181.

Covington, W.W., Moore, M.M., 1994b. Southwestern ponderosa forest structure: changes since Euro-American settlement. J. Forestry 92, 39–47.

Farris, K.L., Garton, E.O., Heglund, P.J., Zack, S., Shea, P.J., 2002. Woodpecker foraging and the successional decay of ponderosa pine. Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests, vol. PSW-GTR-181. In: Laudenslayer, W.F.J., Shea, P.J., Valentine, B.E., Weatherspoon, P.C., Lisle, T.E. (Eds.), USDA Forest Service General Technical Report, PSW-GTR-181, pp. 237–246.

Friederici, P., 2003. Ecological Restoration of Southwestern Ponderosa Pine Forests. Island Press.

Fulé, P.Z., Covington, W.W., 1995. Changes in fire regimes and forest structure of un-harvested Petran and Madrean pine forests. Biodiversity and Management of the Madrean Archipelago: The Sky Islands of the Southwestern United States and Northwestern Mexico. In: Debano, L.F., Ffolliet, P.F., Ortega-Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B. (Eds.), USDA Forest Service General Technical Report. GTR-RM-264, pp. 408–415.

Ganey, J.L., 1999. Snag density and composition of snag populations on two National Forests in northern Arizona. Forest Ecol. Manage. 117, 169–178.

GAO, 2002. Wildland Fire Management: improved planning will help agencies better identify fire fighting preparedness needs, vol. 2004. http://www.gao.gov/new.items/d02158.pdf.

Gordon, J.V., 1996. Effects of prescribed fire on snags and logs in northern Arizona ponderosa pine forests. M.S. Thesis. Northern Arizona University, Flagstaff.

Grogan, P., Baar, J., Bruns, T.D., 2000. Below-ground ectomycorrhizal community structure in a recently burned bishop pine forest. J. Ecol. 88, 1051–1062.

Harrington, M.G., 1996. Fall rates of prescribed fire-killed ponderosa pine. USDA Forest Service Research Paper, INT-RP-489.

Harris, R.D., 1983. Decay characteristics of pileated woodpecker nest trees. Symposium Proceedings, Snag Habitat Management, vol. RM-99. In: Davis, G.A., Ockenfels, R.A. (Eds.), USDA Forest Service Technical Report, pp. 125–126.

Holden, Z.A., 2005. Thirty years of wildland fire use: effects of multiple fires on stand structure in two southwestern wilderness areas. M.S. University of Idaho, Moscow.

Holden, Z.A., Smith, A.M.S., Morgan, P., Rollins, M., Gessler, P., 2005. Evaluation of novel thermally enhanced spectral indices for mapping fire perimeters and comparison of landsat-derived perimeters with fire atlas data. Int. J. Remote Sens. 26, 4801–4808.

Horton, S.P., Mannan, R.W., 1988. Effects of prescribed fire on snags and cavity-nesting birds in southeastern Arizona pine forests. Wildlife Soc. Bull. 16, 37–44.

Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr. 54, 187–211.

Laake, J.L., Buckland, S.T., Anderson, D.R., Burnham, K.P., 1996. DISTANCE User's Guide Version 2.2 Colorado Cooperative Fish Wildlife Research Unit, Colorado State University, Fort Collins.

Mast, J.N., Fulé, P.Z., Moore, M.M., Covington, W.W., Waltz, A.E., 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecol. Appl. 9, 228–239.

Moore, M.M., Covington, W.W., Fulé, P.Z., 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecol. Appl. 9, 1266–1277.

Moore, M.M., Huffman, D.W., Fulé, P.Z., Covington, W.W., Crouse, J.E., 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. Forest Sci. 50, 162–176.

Morgan, P., Hardy, C.C., Swetnam, T.W., Rollins, M., Long, D.G., 2001. Mapping fire regimes across time and space: understanding coarse and fire-scale fine patterns. Int. J. Wildland Fire 10, 329–342.

Rollins, M.G., 2000. Twentieth century fire patterns in the Gila/Aldo Leopold Wilderness Areas, New Mexico and the Selway-Bitterroot Wilderness Area, Idaho/Montana. Dissertation, The University of Arizona, Tucson, Arizona.

Rollins, M.G., Swetnam, T.W., Morgan, P., 2001. Evaluating a century of fire patterns in two rocky mountain wilderness areas using digital fire atlases. Can. J. Forest Res. 31, 2107–2123.

Ryan, K.C., 1988. Modeling long-term fire-caused mortality of Douglas-fir. Forest Sci. 34, 190–199.

Sackett, S.S., Haase, S.M., Harrington, M.G., 1996. Lessons learned from fire use for restoring southwestern ponderosa pine ecosystems. Conference on Adaptive Ecosystem Restoration and Management: Restoration of Cordilleran Coniferous Landscapes of North America, USDA Forest Service Gen. Tech. Report RM-GTR-278, pp. 54–61.

Savage, M., 1991. Structural dynamics of southwestern pine forest under chronic human influence. Ann. Assoc. Am. Geogr. 81, 271–289.

Shea, P.J., Laudenslayer, W.F., Ferrell, G., Borys, R., 2002. Girdled versus Bark Beetle-created ponderosa pine snags: utilization by cavity-dependent species and differences in decay rate and insect diversity. Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests. In: Laudenslayer, W.F.J., Shea, P.J., Valentine, B.E., Weatherspoon, P.C., Lisle, T.E. (Eds.), USDA Forest Service General Technical Report. PSW-GTR-181.

Swetnam, T.W., 1983. Fire history of the Gila wilderness, New Mexico. Masters Thesis. University of Arizona, Tucson.

Swezy, M.D., Agee, J.K., 1991. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Can. J. Forest Res. 21, 626–634.

Team, R.D.C., 2003. R: A language and environment for statistical computing. R Foundation for Statistical Computing, http://www.R-project.org.

Tiedemann, A.R., Klemmedson, J.O., Bull, E.L., 2000. Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk? Forest Ecol. Manage. 127, 1–18.

U.S. Department of Agriculture, Forest Service, 1996. Record of decision for amendments of forest plans: Arizona and New Mexico. U.S. Department of Agriculture, Forest Service, Southwestern Region, Albuquerque, NM.

USFS, 1996. Federal Wildland Fire Policy, vol. 2004. (electronic source) http://www.fs.fed.us/fire/fireuse/index.html.

Wakkinen, D., 1992. Snag site characteristics and their associated use by avian wildlife in ponderosa pine forests. M.S. Thesis. University of Idaho, Moscow.

Weaver, H., 1951. fire as an ecological factor in the southwestern ponderosa pine forests. J. Forestry 49, 93–98.

White, A.S., 1985. Presettlement regeneration patterns in a Southwestern ponderosa pine stand. Ecology 66, 589–594.