Effect of Prescribed Burning on Mortality of Presettlement Ponderosa Pines in Grand Canyon National Park

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Abstract—Ponderosa pine (*Pinus ponderosa*) trees established before Euro-American settlement are becoming rare on the landscape. Prescribed fire is the prime tool used to restore ponderosa pine ecosystems, but can cause high mortality in presettlement ponderosa pines. This study uses retrospective techniques to estimate mortality from prescribed burns within Grand Canyon National Park (GCNP). Live and recently dead presettlement ponderosa pines were sampled in four prescribed burns and three adjacent unburned areas. Presettlement ponderosa pine mortality (not including areas of crownfire) was higher than that of control sites in all four burns, although control areas showed elevated mortality rates compared to presettlement times. The highest mortality (23 percent) was found on a prescribed natural fire converted to a wildfire, the second highest (17 percent) on a site with extremely heavy mistletoe, the lowest (10 percent) on a spring burn. Bole scorch height and bole char severity were higher on dead trees than live trees, and may be useful in predicting postfire mortality. GCNP management objectives for overstory mortality are probably being met, but these guidelines do not account for the possibility of mortality delayed more than 5 years.

Introduction

Prescribed fire has become the primary tool in attempting to reverse the degradation of fire-adapted ecosystems due to past fire exclusion and other management activities. However, some researchers have raised doubts about reintroducing fire without otherwise treating the area (Bonnicksen and Stone 1985; Covington and others 1997; Fiedler and others 1996; Sackett and Haase 1998). Of special concern are high mortality rates in presettlement-aged, "old-growth" trees (hereafter presettlement trees). These trees harbor centuries of genetic diversity, provide important wildlife habitat (Thomas 1979), and are an important aesthetic feature (Brown and Daniel 1984). Past logging has dramatically reduced the presettlement ponderosa pine population over the landscape, and surviving trees are more susceptible to pathogens, drought, and injury because of increased stress due to competition from high densities of postsettlement trees (Covington and others 1994; Feeney and others 1998; Sackett and others 1996; Mast and others 1999). Because they would take longer to replace than any other living feature of the ecosystem (200–400 years), preserving a healthy population of these trees should be an important long-term management objective (Moore and others 1999; Mast and others 1999).

Some studies focusing on prescribed fire effects on presettlement pines have found substantial mortality (20–40 percent), some of which can be delayed for a decade or more (Sackett and Haase 1998; Swezy and Agee 1991; Thomas and Agee 1986). A major cause of this type of mortality is thought to be the extended smoldering of the thick duff layer that has accumulated around large trees in the absence of fire. Some researchers and managers now recommend raking this duff away from the bases of the presettlement trees before burning (Covington and others 1997; Sackett and Haase 1998; Taylor 1996). Many fire managers regard such intensive preburn mechanical treatment as impractical to apply over large areas (A. Farnsworth, Prescribed Fire Specialist, Coconino National Forest, K. Kerr, Prescribed Fire Manager, Grand Canyon National Park, personal communications). They argue that basal damage can be controlled by adjusting the burn prescription and that the few documented cases of unacceptably high mortality were due to extenuating factors.

Grand Canyon National Park (GCNP) encompasses one of the largest areas of unlogged ponderosa pine forests remaining in the Southwest. Fire managers have been conducting prescribed burns in GCNP since 1971 (GCNP, unpublished data). Over the past few years, fire managers have greatly increased the area treated with prescribed fire (K. Kerr, Prescribed Fire Manager, GCNP, personal communication).

More surveys of postburn mortality are needed to determine if high levels of mortality in presettlement trees are widespread or limited to special circumstances. Because full mortality may take a decade or more to be expressed, conventional fire effects monitoring studies may not provide information in time to be relevant. This study uses retrospective techniques to estimate long-term mortality of presettlement trees on prescribed burn sites within GCNP, and to relate high mortality to site, burn, and/or tree characteristics. The merits and limitations of this type of study and management implications of results are discussed.

Methods

Study Area

This study examined four prescribed burns (and adjacent unburned control areas) in three distinct areas of Grand

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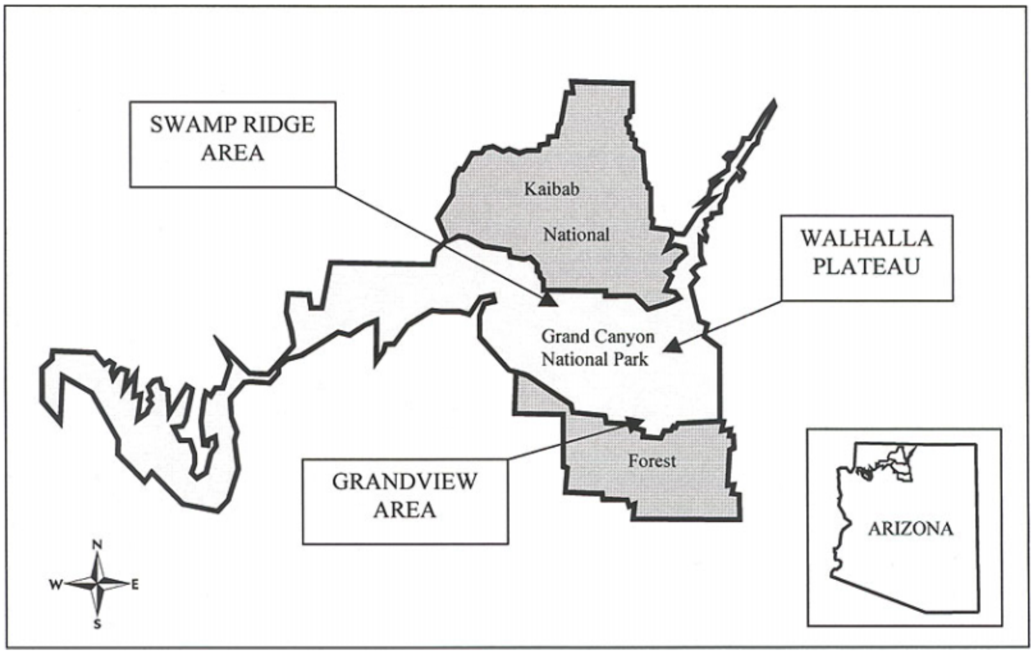

Figure 1—Study areas in Grand Canyon National Park, AZ.

Canyon National Park in Arizona (fig. 1; table 1). Information on the burning conditions and fire behavior during these burns was not available. All sites are within 4 km of the rim of the Grand Canyon and average 2,200 m in elevation. Terrain is dominated by karst topography, mostly level or rolling but deeply dissected by drainages. Most of the soils in this area belong to the Soldier series (Bennett 1974).

Table 1—Prescribed burns sampled in Grand Canyon National Park. All information comes from the Grand Canyon National Park fire history database and prescribed fire program summary reports. Sites are named for the name of the burn or, for controls, the burn unit in which they are found. Sizes are not given for control areas because only portions of these areas were sampled. PNF = prescribed natural fire; MIPF = management-ignited prescribed fire; CTRL = unburned control area.

Site	Type	Size	Ignition date	Sampling date
		ha		
Grandview area:				
Grapevine	MIPF	293	5/95	7/99
Hance	MIPF	267	8/95	7/99
Grandview	CTRL	—	—	7/99
Walhalla Plateau:				
Matthes	PNF	400*	7/95	8/98
Walhalla	CTRL	—	—	8/98
Swamp Ridge area:				
Northwest I/II	MIPF	92	9/92	7/99
Northwest V	CTRL	—	—	7/99

*Area burned before conversion to wildfire.

Average annual precipitation is 57.9 cm on the North Rim and 36.8 cm on the South Rim (GCNP, unpublished data). Precipitation is bimodal, divided between winter snow and late summer rain, with a distinct dry period in May and June.

Although ponderosa pine is the dominant overstory species at all three sites, the associated species differ. At Swamp Ridge, white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*) are present, and Engelmann spruce (*Picea engelmannii*) dominates north facing slopes. White fir and aspen also are present on the south end of the Walhalla Plateau, but are confined to mesic sites—remaining areas are mostly pure ponderosa pine. In the Grandview area, ponderosa pine-Gambel oak (*Quercus gambelii*) forests grade into piñon pine (*Pinus edulis*)-Utah juniper (*Juniperus osteosperma*) woodlands. Big sagebrush (*Artemesia tridentata*) and cliffrose (*Cowania neomexicana*) are common in openings.

The earliest evidence of human presence in this area is 3,000 to 4,000 years old, with further evidence indicating more or less continuous habitation through the present (Altschul and Fairley 1989). The historic fire regime was disrupted by heavy livestock grazing associated with Euro-American settlement (Altschul and Fairley 1989). Fire regime disruption dates are 1879 for the western North Rim and 1887 at Grandview (Fulé and others, in review). Fire regime disruption was found to be less abrupt on the Walhalla Plateau, with mean fire intervals not lengthening significantly until the early 1900s (Wolf and Mast 1998). Active fire suppression began with the designations of the Grand Canyon Forest Reserve in 1893 and Grand Canyon National Park 1919. Livestock were fenced out of GCNP by about 1938 (Fulé and others, in review; Verkamp 1940). Most of GCNP has never been logged.

Field Methods

Burns greater than 40 ha in size and 3–7 years old were selected for this study. A minimum time since fire of 3 years was necessary because trees injured by fire often take several years to die (Sackett and Haase 1996; Wagener 1961). The maximum time of 7 years increased the probability that outer ring dates could be obtained from increment cores for most of the trees that died since the fire. Unburned areas nearby were sampled as controls to determine background mortality rates (in other words, mortality from old age).

Within a selected site, sampling was limited to areas dominated by ponderosa pine and showing no evidence of logging or widespread crown damage from fire. The sites on the Walhalla Plateau were sampled in 1998 and all other sites were sampled in 1999. Minor changes in methods between field seasons are noted. Sites were sampled with belt transects arranged to capture as much spatial variation as possible. Transects were 40 m wide. At least 12 ha in each burn and each control area were surveyed.

Presettlement ponderosa pines judged to have been alive at the time of the burn were tallied in three categories: green trees, snags that torched or were severely scorched in the burn, and recent snags that did not torch. Presettlement trees were identified in the field using characteristics developed by Keen (1943) and modified for use in the Southwest (Covington and Moore 1994; White 1985). Characteristics included bark characteristics (large plates, light color) and crown architecture (large, drooping branches, columnar crown). At each site, several borderline presettlement trees (in other words, trees whose age was questionable) were cored and ring-counted in the field to calibrate these characteristics. Additional borderline trees found on the transects were cored and cross-dated in the lab to evaluate the accuracy of this technique.

Tallied trees were randomly sampled at varying rates (2–20 percent of green trees and 50 or 100 percent of recent snags), depending on relative densities of green trees and snags, to optimize transect length and number of trees sampled. Nominal sampling percentages were held constant for each transect, but actual percentages varied due to the random number generator. The total number of green trees and the total number of recent snags in each transect were recorded.

For each sampled green tree, samples of cambium from four quadrants (uphill, downhill, and both sides at 40 cm above the forest floor) were extracted to determine cambium condition (Ryan 1983). Cambium sampling was initiated in response to ambiguous data from the 1998 season, and therefore was not conducted at Walhalla Plateau sites. Increment cores were taken at 40 cm above the forest floor and through bark plates instead of through furrows (Ryan 1983). Unless the first core taken from a recent snag was completely sound, a second core was taken. The following measurements were made for each cored tree:

- Diameter of the tree or snag at height of core to the nearest cm.
- Condition class according to a tree, snag and log classification system based on that of Thomas and others (1979) and used widely in ponderosa pine forests of the Southwest (Cunningham and others 1980; Fulé and others 1997). Green trees were further classified according to relative health and vigor (Thompson 1940). This system has five vigor classes, which are determined by live crown ratios (LCRs) as follows: AA ("wolf" trees), LCR 70 percent or more; A (full vigor), LCR 55–70 percent; B (good to fair vigor), LCR 35–55 percent; C (fair to poor vigor), LCR 20–25 percent; and D (very poor vigor), LCR less than 20 percent. Recent snags (except those on the Walhalla Plateau sites) were further classified as to needle and fine branch retention as follows: A (retains most needles); B (retains some needles); C (no needles but retains most fine branches); and D (no needles but retains some fine branches). Snags lacking fine branches or having loose bark were assumed to have died before the fire and were not tallied or sampled.
- Obvious damage and tree abnormalities were recorded (for example, dwarf-mistletoe, insect attack, lightning strike, fire scar, fork top, and so forth).

The following measurements were made only on burn sites:

- Bole scorch height (from ground level to the highest point of scorched bark) was measured to the nearest 0.25 m.
- Basal char severity was quantified using the following categories (after Ryan 1983): 0 = no visible charring of bark; 1 = some blackening around base; 2 = bark plate surface uniformly blackened; 3 = some depth of char; 4 = deep char.

Dendrochronology

Cores were mounted, sanded, and crossdated (Stokes and Smiley 1968) using chronologies established for nearby areas (Fulé and others, in review). A systematic subsample of 40 percent of the cores was selected for analysis (all cores from the Walhalla sites were analyzed). Inner ring dates (IRD, just outside the pith) and outer ring dates (ORD, just inside the cambium) and were determined. IRD is an estimate of the year of tree establishment. ORD is an estimate of the year of growth cessation (in other words, imminent death). If crossdating was adequate for more than 100 rings but then became undatable, rings were counted to establish the IRD. For cores in which pith was not included (more than 90 percent of the cores), the IRD was estimated using a pith locator consisting of concentric rings printed on a transparency. IRDs were grouped by 25 year age classes (Mast and others 1999). Undatable cores were classified according to the reason they could not be dated.

Mortality Estimates

Two types of mortality estimates were made: a "field" estimate and a "lab" estimate. The field estimate was made using the tallies of live and recently dead trees on the transects and the visually determined snag decay classes. All trees with green needles were assumed alive, and all snags retaining at least some needles and with tight bark were assumed to have died within the past 5 years (Cunningham and others 1981). Trees that torched in the fire are included in this estimate.

Because this method estimates mortality over approximately the past 5 years, it may slightly underestimate mortality for the 7-year-old NW I/II burn and slightly overestimate mortality for the other (4-year-old) burns. Because condition classes of dead trees and numbers of torched trees were not recorded in the first field season, field estimates using all tallied dead trees (but not including torched trees) are substituted for the Walhalla sites. These numbers overestimate mortality by including many snags that died before the prescribed burn.

"Lab" estimates were based on dendrochronological data. Green trees were assumed alive if the ORD was equal to or 1 year less than the date of sampling. They were assumed dead or dying after the burn if the core showed no growth for 2 years or more before the date of sampling, but were still growing in the year of the burn. It is well established that ponderosa pines showing no basal area growth for 2 years or more have little chance of survival (Rogers and others 1981; Mast and Veblen 1994). Recent snags were assumed to have died after the fire if their ORD was in or after the year of the burn. Snags with earlier ORDs were assumed dead or dying at the time of the burn.

The field estimates are expressed as the percentage of the trees that were alive at the time of the burn but had died by the date of sampling. The lab estimates include some near-future mortality. Neither type of estimate can be directly compared among sites because of the variation in time lags between the burn dates and the sampling dates (3 to 7 years—table 1).

Other Data Analyses

Mean tree diameters were compared between live and dead trees for each site with Bonferroni-corrected approximate two-tailed t-tests for independent samples with unequal variances (corrected p = 0.0071; Ott 1993). Mean bole scorch heights were compared similarly for each burn (corrected p = 0.0125).

Bole char severity distributions for live and dead trees on each burn site (excepting Matthes, which was discarded from this analysis due to inconsistent data collection methods) were analyzed using a Bonferroni-corrected Chi-squared contingency test (corrected p = 0.0167, df = 4; Ott 1993). Vigor class distributions for live and dead trees were also compared with this test, but results were grouped for all sites (p = 0.05, df = 3). Due to the small number of "AA" trees, this category was combined with "A."

Results and Discussion

Sampling

Several issues about the way trees were sampled may influence the conclusions from the data. First, because different proportions of trees were sampled in different transects, some sampled trees represent a greater proportion of the tree population than others do. Second, the crossdating of cores from borderline presettlement trees revealed that most unsampled borderline trees in the Grandview area were in fact of presettlement age. No presettlement trees sampled in 1999 were found to be of postsettlement age. Additionally, few trees tallied in the transects were under 41 cm diameter at 1.37 m, the cutoff for what GCNP fire managers consider overstory trees (K. Kerr, Prescribed Fire Manager, GCNP, personal communication). Presettlement trees smaller than this were almost all highly suppressed members of old-growth clumps. Taken together, these factors suggest that the tree population examined in this study is comparable to the population specified in the GCNP overstory mortality objective. However, the youngest class of presettlement trees (120–150 years old) might be relatively underrepresented, and the highly suppressed presettlement trees relatively overrepresented.

The total number of cores for which an ORD could be determined varied from 31 to 67 per site. The number of cores from green trees varied from 22 to 64. The number of cores from dead trees whose ORD was in or after the year of the fire ranged from 11 to 21 for burned sites and only three to five for unburned control sites. The Grandview sites have smaller numbers of useable cores than the North Rim sites.

For many cores, especially those from dead trees, the ORD could not be determined due to breakage, rot, extreme suppression, or other reasons. These cores are hereafter referred to as "unusable." The proportion of unusable cores from recent snags ranged from 17 percent to 72 percent, and tended to be higher in control areas. Because of the relatively small numbers of dead trees found on these sites, older classes of snags were more likely to be sampled. The number of broken and rotten cores increased along the xeric-mesic gradient between sites (most broken cores were also due to rot). The average proportion of unreadable dead cores is comparable to that reported by Mast and Veblen (1994). The sometimes high proportion of unusable cores may bias lab estimates due to the undersampling of rot-infected trees.

Estimates of Presettlement Tree Mortality

One GCNP fire management objective is to keep overstory mortality, as measured 5 years postburn, below 20 percent over the entire vegetation type in the Park (K. Kerr, Prescribed Fire Manager, GCNP, personal communication). Because the main purpose of this study was to document mortality due to factors other than crown damage, mortality due to widespread crown damage was not documented, although estimates do include trees that torched individually. Therefore, landscape level mortality is higher than numbers reported here.

Field estimates show mortality of presettlement trees in all burned areas is many times greater than in respective controls (table 2). This result supports the idea that noncrown damage from prescribed fires can lead to increased mortality of presettlement trees. The Swamp Ridge area control site estimate may be artificially low due to faster rates of snag decay at this more mesic site. The other control area estimates show mortality rates somewhat lower (0.5–0.75 percent/year) than other studies measuring contemporary background mortality in mature ponderosa pine (1–2 percent/year—Avery and others 1976; Hamilton and Edwards 1976; Mast and others 1999). However, these rates are still much higher than estimates of mortality rates in presettlement times (Mast and others 1999).

The field estimate shows 27 percent mortality on the Hance burn, more than twice that of any other site. This site has very high levels of dwarf-mistletoe infection (70 percent of the trees on transects were infected, compared to 40 percent on the Grandview control area and 20 percent on the Grapevine burn). Infected trees are more likely to torch due to low witches' brooms and have reduced vigor (Harrington

Table 2—Presettlement ponderosa pine mortality estimates. These numbers represent the proportion of trees alive at the time of the prescribed burn that died between the burn date and time of sampling. The field mortality estimate counts all snags retaining needles as dead since the burns. The estimates in parentheses include snags with no needles but most fine branches due to the older age of the NW I/II burn. Because of different data collection methods, the field estimates for Walhalla sites (in italics) include all recent snags retaining needles and/or fine branches. For the lab estimates, a tree is considered dead/dying if its core shows that it has not put on a growth ring for 2 years or more. This estimate can be thought of as including some near-future mortality. All South Rim sites were sampled 4 years postburn. NW sites were sampled 7 years postburn, and WP sites 3 years postburn.

Site	Field estimate	Lab estimate
	- - - - - - - - - - Percent	*- - - - - - - - - - -*
Grandview area:		
Grapevine	10	12
Hance	27	17
Grandview (control)	2	10
Walhalla Plateau:		
Matthes	*13*	23
Walhalla (control)	*3*	5
Swamp Ridge area:		
Northwest I/II	2 (12)	15
Northwest V (control)	1 (2)	5

and Hawksworth 1991) making them more susceptible to other damage. The field estimate for this site may be inflated because of the tendency for witches' brooms to stay alive many years after most of the tree canopy has died (Mathiasen 1996). This could cause many trees that were effectively dead before the prescribed burn to retain needles until the date of sampling.

The Grapevine and Matthes burns show intermediate mortality rates around 10 percent, while the field estimate for the Northwest I/II burn is extremely low (2 percent), even lower than some estimates of background mortality. If snags of condition class C are included, the estimate is 12 percent. True mortality on this site is probably somewhere between these numbers.

The lab estimates, which count trees with cores showing zero growth for 2 years or more as dead or dying, include some near-future mortality. They show background mortality rates roughly comparable to those in other studies (about 1–2 percent/year—Avery and others 1976; Hamilton and Edwards 1976; Mast and others 1999). These numbers translate to the death of approximately 2–7 presettlement pines/ha/decade, depending on the presettlement tree densities at the different sites. The Grandview control site shows a higher mortality rate than the two North Rim control sites, possibly because of higher stress levels of on the former, more xeric site.

The lab estimates show the highest mortality (23 percent) for the Matthes burn, which was a prescribed natural fire that was converted to wildfire status and suppressed due to increasing fire intensity and a lack of resources. The second-highest mortality was found on the dwarf-mistletoe-infested Hance burn. The Grapevine burn, which had the lowest lab mortality estimate (comparable to the rates in control areas) was a spring burn. This suggests that burning in the spring, when forest floor moisture is high, might reduce basal damage. However, spring burning may have other undesirable consequences. For the burns in the Grandview and Swamp Ridge Areas, these lab estimates translate to the death of approximately five presettlement pines/ha. The Matthes burn, occurring in the study area with the highest density of mature pines, had a much higher per-unit-area rate. According to the lab estimate for that burn, approximately 20 presettlement pines/ha died.

If these mortality estimates are accurate, and mortality due to crown damage is not widespread, GCNP management objectives (less than 20 percent overstory mortality 5 years postburn) are probably being met. However, the GCNP management objective does not address the possibility of significant mortality after 5 years. Sackett and Haase (1998), studying presettlement ponderosa pine mortality at the Chimney Spring site in northern Arizona, found that mortality may take more than a decade to be fully expressed. Five years after the initial burns at Chimney Spring, "old-growth" mortality averaged approximately 28 percent in the burned areas. Eighteen years after the burns, the overall old-growth mortality had almost doubled to 50 percent, and old-growth trees were still dying at higher rates than those in the unburned control area were. However, the severe drought in 1996 (the year after most of the sites in this study were burned) probably was a contributing factor in the deaths of many trees. Trees were killed that otherwise may have lingered for years in a weakened state. It is therefore likely that these mortality estimates account for a high proportion of the fire-induced mortality on the burn sites.

Tree, Site, and Burn Characteristics

No statistically significant differences were found in comparisons of diameter or age between live and dead trees on burn sites. Vigor was lower for trees in burned areas than for trees in control areas, but this was not statistically significant, either.

Although not statistically significant, mean bole scorch height (excluding values above 10 m) was higher for dead trees than for live trees for all burns. Basal char severity was higher on recently dead trees on all three burns analyzed. These results support the hypothesis that basal and/or root damage is a contributing factor to postburn mortality. Measures of fire intensity at the bases of trees must be considered in addition to crown scorch when predicting postfire mortality of large trees (Ryan 1983; Regelbrugge and Conard 1993). The failure to identify more significant differences in tree and burn characteristics may be due to the relatively small sample sizes of recent dead trees from some sites.

Conclusions

Estimates show that mortality levels of presettlement ponderosa pines in Grand Canyon National Park are higher in areas treated with prescribed fire compared to unburned areas, even when discounting mortality due to crown damage. Higher mortality is associated with high infection levels of dwarf-mistletoe on one site, and prescribed natural fire that was converted to wildfire on another site. The lowest postburn mortality rate (little higher than control area mortality) occurred on a spring burn, possibly because higher forest floor and soil moisture levels reduced basal damage. Because of the small sample size (four burns), it is not possible to generalize these associations between heightened mortality and other factors. More postburn mortality surveys are needed.

Postburn mortality as measured on these four prescribed burns is probably within management objectives of the GCNP fire program. Because of the 1996 drought, future mortality on these burns is predicted to be relatively low. However, the reduced vigor of trees in the burns in this study, as well as results from other studies, suggest that mortality rates can remain abnormally high long after 5 years postburn in some cases. Methods of predicting future mortality (for example, from annual growth increment data) should be used to supplement studies such as this one.

Mortality estimates based on dendrochronological data in unburned control areas agreed closely with background mortality estimates from other studies. These may be much higher than historical rates, probably because of increased competitive stresses due to higher tree densities in contemporary forests. The 1996 drought might also have elevated the mortality rates in the control areas. The unburned area surveyed on the xeric South Rim shows especially high mortality (more than 2 percent/year). These figures highlight the need to reinvigorate presettlement trees as well as merely protecting them.

This study could not identify tree characteristics associated with increased risk of postfire mortality. Studies measuring tree characteristics both before and after burns are probably better suited than retrospective surveys to gather this type of information. Measures of basal fire intensity were higher on dead trees than live trees in all burns. This agrees with results from other studies and argues that these measures can be important in predicting postburn mortality of mature trees.

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