Effectiveness of Litter Removal to Prevent Cambial Kill-Caused Mortality in Northern Arizona Ponderosa Pine

James F. Fowler, Carolyn Hull Sieg, and Linda L. Wadleigh

Abstract: Removal of deep litter and duff from the base of mature southwestern ponderosa pine (*Pinus ponderosa* Laws.) is commonly recommended to reduce mortality after prescribed burns, but experimental studies that quantify the effectiveness of such practices in reducing mortality are lacking. After a pilot study on each of four sites in northern Arizona, we monitored 15–16 sets of 8 matched trees on areas designated to be burned and adjacent not-burned sites and randomly assigned one of four litter and duff removal (to mineral soil) treatments: (1) rake to a distance of 23 cm from the bole, (2) leaf blow to a distance of 23 cm, (3) rake to a distance of 1 m, and (4) no litter or duff disturbance or removal. By 3 years postburn, no trees had died because of any of the treatments, but litter and duff removal prevented most cambial kill. However, 17% of the burned, no removal trees had some cambial kill. Litter and duff removal to 23 cm was as effective in preventing cambial kill and bole char as removal to 1 m, and there was no difference between removal by raking versus leaf blower removal. These results suggest that litter and duff removal is not needed to prevent ponderosa pine mortality after fall prescribed burns, but removal to 23 cm is adequate to prevent spots of cambial kill or moderate bark char. FOR. SCI. 56(2):166–171.

Keywords: raking, cambial kill, bark char, postfire mortality, prescribed fire

CONCERNS ABOUT AN INCREASE in mortality of old-growth ponderosa pine (*Pinus ponderosa* Laws.) after prescribed fire have been noted by several researchers (Swezy and Agee 1991, Sackett et al. 1996, Sackett and Haase 1998, Kaufmann and Covington 2001, Fulé et al. 2007), although Peterson et al. (1994) observed that "very few larger trees were killed" postfire in one study. Many investigators have suggested that increased burning intensity and duration at the root crown due to the accumulation of litter and duff resulting from fire exclusion may be the causal factor (Thomas and Agee 1986, Harrington and Sackett 1990, Ryan and Frandsen 1991, Swezy and Agee 1991, Sackett and Haase 1998, Kaufmann and Covington 2001), although drought stress (Kolb et al. 2001, Fulé et al. 2002, Agee 2003) and stand density (Kaufmann and Covington 2001, Agee 2003) may also affect old-growth ponderosa pine postfire mortality.

Recommendations to lessen mortality of old-growth ponderosa pine trees often center on removing litter and duff from the base of trees before prescribed burning as first suggested by Thomas and Agee (1986). These litter/duff removal efforts are intended to compensate for decades of fire suppression and to reduce mortality caused by cambial kill after prescribed fire by reduction of both active burning and smoldering combustion next to the lower bole. This treatment is now widely recommended (Taylor 1996, Covington et al. 1997, Moore et al. 1999, Friederici 2003, Salmants et al. 2003, Kolb et al. 2007) and occasionally applied (Fulé et al. 2001, 2002, Jerman et al. 2004).

Despite the common perception that these efforts will enhance survival of old-growth trees, there are few published findings that address whether this practice does, in fact, lead to higher survival of mature ponderosa pine trees after prescribed fire. Several publications have cited Sackett et al. (1996) as providing evidence that raking litter/duff away from the base of the tree reduced mortality in old-growth ponderosa pine after prescribed fire; however, that publication does not recommend nor did the authors use raking or other litter/duff removal treatments. Two ponderosa pine studies (Swezy and Agee 1991, Fulé et al. 2002) have reported on the limited effectiveness of raking treatments, and no studies have examined the direct mortality effects of raking alone. The latter may be important because raking often occurs a few months before the actual burn, or, in some cases, many months before if burn prescription conditions do not materialize until the next burn season. Further, these litter/duff removal efforts are very labor-intensive and thus expensive, and there is no consensus on techniques to remove the litter and duff.

Two concurrent recent studies were specifically designed to answer the mortality and raking effectiveness question (Fowler et al. 2007, Hood 2007). Hood (2007) tested two raking distances around large ponderosa and Jeffrey pines (*Pinus jeffreyi* Grev. & Balf.) in northern California. Our

James F. Fowler, Ecologist, US Forest Service, Rocky Mountain Research Station, 2500 S. Pine Knoll Dr., Flagstaff, AZ 86001—Phone: (928) 556-2172; Fax: (928) 556-2130; jffowler@fs.fed.us. Carolyn Hull Sieg, Research Plant Ecologist, US Forest Service, Rocky Mountain Research Station, 2500 S. Pine Knoll Dr., Flagstaff, AZ, 86001—csieg@fs.fed.us. Linda L. Wadleigh, Region 3 Fire Ecologist, US Forest Service, 1824 S. Thompson, Flagstaff, AZ, 86001—lwadleigh@fs.fed.us.

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study used two removal techniques and two removal distances, and we controlled for many of the confounding factors that could contribute to mortality of old-growth ponderosa pine at 3 years postfire. The specific objective of this research was to evaluate the effectiveness of litter/duff removal in preventing mortality via cambial kill for large ponderosa pine trees after prescribed fire in northern Arizona.

Methods

A pilot study was implemented at the Kachina Rx on the Coconino National Forest in fall 2004 followed by the main study at four sites in fall 2005: Bald Mesa Rx and the Skunk Canyon Rx on the Coconino National Forest; and Scott Rx and the Road Hollow Rx on the Kaibab National Forest (Figure 1). Sites were chosen to represent the deepest litter/duff available in four regions of northern Arizona. All sites were strongly dominated by ponderosa pine, and the prescribed burns were low-intensity underburns designed to reduce fuel loads and raise crown base heights. This is the predominant type of prescribed burn used in northern Arizona and for which litter/duff removal is often prescribed. The pilot study site had volcanic basalts as the soil parent material, whereas the four main study sites had limestone-derived soils.

We used eight different forest floor fuel treatments on each site with 15 ponderosa pines (≥46 cm dbh) per treatment. The litter/duff removal techniques were rake to a distance of 23 cm from the bole, rake to a distance of 1 m, blow to a distance of 23 cm (with leaf blower), and no removal. These four techniques were applied on both the burned and not-burned prescribed fire treatments. However, in the pilot study, we were not able to get the 23-cm leaf blower treatment applied before the scheduled prescribed fire, so we effectively had 30 "no removal" trees on both burned and not-burned treatments in 2004. At Road Hollow in 2005, 8 experimental trees within the burned unit did not get fire at the base. A total of 608 trees were used in the treatment part of this study. The effectiveness of these treatments was measured by testing for live cambium during stem tip elongation in the first growing season after the fire and checking live/dead tree status for 3 years after the prescribed fire.

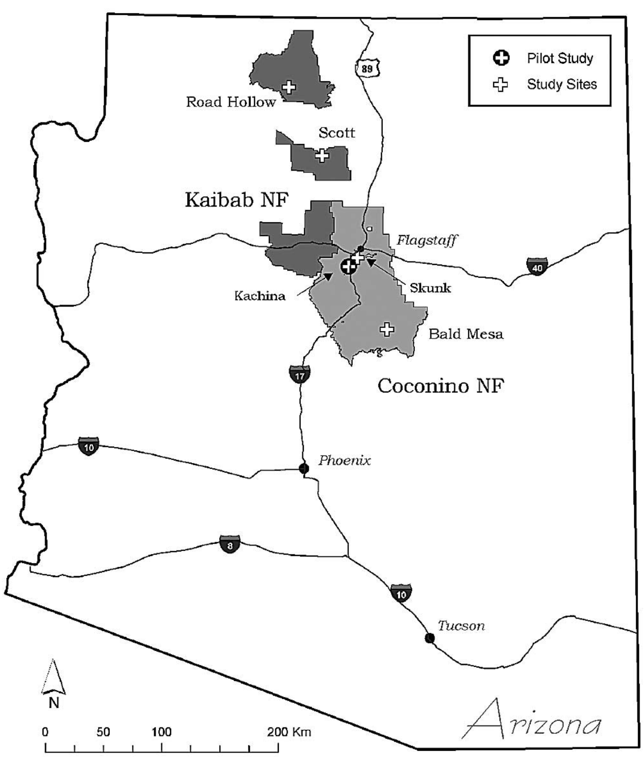

Figure 1. Study area map showing Kaibab and Coconino National Forest boundaries and location of five prescribed burns. The pilot study site was burned in fall 2004 and the other study sites were burned in fall 2005.

At each site, each tree meeting the selection criteria was tagged with a unique number. Selection criteria targeted large healthy trees, with deep litter/duff and no large woody fuels embedded within the litter/duff layers near the lower bole cambium. Specific criteria were the following: trees ≥46 cm dbh; litter/duff depth at least 13 cm within 23 cm of the bole; no woody fuel >8 cm diameter within the potential litter/duff removal radius (1 m); and trees in good vigor, i.e., no obvious evidence of bark beetles, dwarf mistletoe, past fire damage, or broken top.

The experimental design was structured with sites as randomized blocks and used three metrics: cambial kill, bole char (Ryan and Noste 1985), and tree mortality. Within each site (block), 15–16 sets of 8 matched trees (split plots) were selected with treatments randomly assigned to four trees of each set within both the burned and not-burned treatments; thus, the tree was the experimental unit. Sets of trees were matched by dbh, mean litter depth, and volume of woody fuels >8-cm diameter within a 3-m radius of the tree bole in that order of priority. The remaining trees that met the selection criteria but were not chosen for the treatment experiment were designated "extra" trees for postfire mortality and cambial kill analysis.

Pretreatment tree measurements were dbh, height, live crown ratio, crown base height, slope, aspect, lightning scar size (fire scar trees were not chosen), mechanical scar size, bark (yellow or black), top (flat or pointed), dwarf mistletoe rating, and volume of logs and stumps within a 3-m radius of the bole. Log and stump volume was calculated using average diameter and length within a 3-m radius of the bole. The forest floor depth profile on the experimental trees was measured along four transects starting with the azimuth of the major canopy asymmetry and then rotating 90° for each of the remaining three. The major tree asymmetry is defined as the azimuth of the longest live branch or the azimuth of a leaning bole, whichever leads to the most asymmetric distribution of litter. Total litter and duff depths were measured at the base of the tree and then at 30-cm intervals to the dripline. These litter depth measurements were taken by carefully inserting a blunt-ended metal ruler through the forest floor profile with the intent of minimizing disturbance of the litter profile yet adequately characterizing the pretreatment total litter/duff depth.

Litter and duff were removed down to mineral soil using the three different treatments within 30 days of the prescribed burn treatments. Removed litter was scattered evenly under the same tree to avoid creating a mound of

Table 1. **Means ± SD for pretreatment measurements of trees selected for prescribed fire and litter/duff removal treatments in 2005**

Variable	Rake 23 cm	Rake 1 m	Blow 23 cm	No removal
n	122	122	122	122
Dbh (cm)	66 ± 11	66 ± 11	66 ± 11	66 ± 11
Crown base height (m)	6.4 ± 4.0	6.1 ± 3.6	6.3 ± 3.8	6.1 ± 4.2
Tree height (m)	27.8 ± 5.0	27.6 ± 5.0	27.3 ± 5.7	27.6 ± 5.1
Live crown ratio	63 ± 16	65 ± 14	65 ± 16	65 ± 15
Bole litter depth (cm)	11 ± 3	11 ± 3	10 ± 3	11 ± 3
Litter depth under canopy (cm)	7 ± 2	7 ± 2	6 ± 2	7 ± 2
Bole maximum litter depth (cm)	18 ± 5	18 ± 5	17 ± 5	18 ± 5

n = number of trees. Bole litter depths were within 23 cm of the bole with a mean of five measurements representing each tree.

fuel. Litter and duff were left undisturbed on the no removal trees.

Postfire measurements were started within 60 days of each prescribed fire. Litter/duff depth profiles were remeasured along with the following postfire damage variables: ground char class (unburned, light, moderate, and deep) (Ryan and Noste 1985), bole char (none, superficial, moderate, and deep) (Ryan 1982), crown scorch volume (Peterson 1985), and live/dead tree status. The proportion of the surface area covered by each ground char class was visually estimated using cover classes (Daubenmire 1959) in 20 cm × 50 cm quadrats spaced at 30-cm intervals along the litter/duff depth profiles. Midpoints of these cover classes were used to calculate the percentage of each ground char class for each sample point. A ground char value for each sample point was then calculated by a weighted average of light char (1×), moderate char (2×), and deep char (3×).

During stem tip elongation in the first growing season postfire, the width of cambial kill at the rootcollar was measured by visual examination of cambial condition from increment borer samples beginning at the center of a patch of moderate bole char (if present) from the 2005 prescribed fires, and, if dead cambium was found, sampling continued at 5-cm intervals in both directions parallel to the soil surface until live cambium was encountered. We separated cambial kill into two types based on location of the dead cambium: aboveground (bark char cambial kill) and just below the soil surface (vertical-bark-flake consumption cambial kill). The latter term refers to loose, sloughed-off, vertical bark plates trapped between functional bark and the soil. At years 1, 2, and 3 after the fire, each tree was assessed as dead or alive using the presence or absence of green needles as the criterion. Trees killed by lightning and western pine beetle (*Dendroctonus brevicomis* LeConte) were omitted from the analysis.

Statistical analysis was performed using version 9.1 of the SAS system for Windows 2000 (SAS/STAT, 2002–2003). Statistical significance was determined by $P \leq 0.05$. Table analysis was performed in PROC FREQ. The statistical associations were described using the Pearson χ^2 goodness-of-fit test to detect the presence of an association (Loether and McTavish 1976).

Results

Treatment Trees

Average tree size for the large ponderosa pines selected for the prescribed burn and mechanical litter removal treatments was 66-cm dbh and 27.6-m tall with a mean forest floor depth under the canopy of 7 cm and mean depth within 23 cm of the bole of 11 cm. These treatment trees also had at least one pocket of deeper litter/duff next to the bole as shown by a mean maximum litter/duff depth of 18 cm. The four sites had similar mean forest floor depths under the canopy of burn treatment trees: Bald Mesa Rx = 6.23 cm, Skunk Canyon Rx = 7.96 cm, Scott Rx = 6.45 cm, and Road Hollow Rx = 6.34 cm. Forest floor depths for the extra burned trees were similar to the pretreatment depths of the experimental trees, but some individual trees had quite deep maximum depths: Bald Mesa Rx had 10 trees in the 20- to 27-cm depth range; Skunk Canyon Rx had 28 trees in the 20- to 51-cm depth range; Scott Rx had 20 trees in the 20- to 36-cm range; and Road Hollow Rx had 10 trees in the 20- to 25-cm depth range. Pretreatment measurements were similar among the four litter/duff removal treatment groups (Table 1). The prescribed fires consumed 69% (5 cm) of undercanopy depth with an average of <10% crown scorch by volume (Table 2). Ground char was light, 0.8 on a 0–3 scale, and 2–3% of the burned trees had some cambial kill.

Table 2. **Means ± SD for postfire measurements of trees selected for prescribed fire and litter removal treatments in northern Arizona**

Variable	Rake 23 cm	Rake 1 m	Blow 23 cm	No removal
n	61	61	61	61
Canopy litter consumed (cm)	7 ± 2	5 ± 2	4 ± 2	4 ± 2
Ground char	1.0 ± 0.3	0.4 ± 0.2	0.9 ± 0.3	1.1 ± 0.3
Crown scorch volume (%)	4 ± 9 (*n* = 46)	10 ± 18 (*n* = 47)	4 ± 9 (*n* = 47)	9 ± 19 (*n* = 48)

n = number of trees. Ground char has a possible rating of 0–3. For percent crown scorch volume, means are given for trees with that type of fire damage present followed by number of trees with crown scorch in parentheses.

Tree Mortality

The pilot study site, Kachina Rx, was burned in October 2004, and the main study sites, Bald Mesa Rx, Scott Rx, Skunk Canyon Rx, and Road Hollow Rx, were burned in October 2005. At 3 years after prescribed fire, no fire-related mortality has occurred on the burned treatments, and only lightning strike and bark beetle mortality has occurred on the not-burned treatments. In addition, no mortality has occurred in the 189 extra burned trees that met our criteria, even though some litter/duff depths were quite deep.

Cambial Kill

Although no trees were killed by prescribed fire in this study, 17% of the no removal trees had areas of dead cambium the first postfire growing season (Table 3). Table analysis indicates that the presence or absence of cambial kill is significantly associated with removal treatment ($\chi^2 = 31.3274$, $P < 0.0001$, $n = 236$) with no removal-cambial kill present contributing most of the χ^2 value (cell $\chi^2 = 22.5$). None of the litter/duff removal treatment trees had cambial kill as a result of the prescribed fires (Table 3).

Next we analyzed cambial kill for all 386 burned trees in the data set, i.e., both the treatment trees and the extra trees on the four burned sites that were not selected for the litter/duff removal experiment but which met the screening criteria. For these trees, we grouped the three litter/duff removal treatments into one treatment category. The presence of both bark char cambial kill and vertical-bark-flake cambial kill was statistically associated with/without litter/duff removal ($\chi^2 = 21.8197$, $P < 0.0001$ and $\chi^2 = 16.8443$, $P < 0.0001$ respectively, $n = 386$) (Table 4) where the no removal trees had all of the observed cambial kill. Vertical-bark-flake consumption cambial kill occurred in the loose, vertical bark plates that were trapped between the functional bark at the root crown of some trees and the soil. If consumed by smoldering fire, these vertical bark flakes and fine duff left a narrow collar of gray ash and was an indication of possible dead cambium. Only four trees had both bark char cambial kill and vertical-bark-flake consumption cambial kill.

The litter/duff removal treatments also prevented most moderate bole char ($\chi^2 = 44.3646$, $P < 0.0001$, $n = 236$) with the bole char present-no removal cell contributing most of the total χ^2 value ($\chi^2 = 28.038$) (Table 5). Although most no removal trees had superficial bole char, only 34% of them had moderate bole char with a median width of 29 cm ($n = 20$). There was no significant difference in moderate bole char between litter/duff removal techniques (rake 23 cm versus blow 23 cm, $\chi^2 = 2.6692$, $P = 0.1023$) or removal distance (rake 23 cm versus rake 1 m, $\chi^2 = 2.7381$, $P = 0.0980$).

Table 3. Number of trees with cambial kill in the burned plots for each of the four litter/duff removal treatments in the main experimental study

Litter/duff removal treatments	Cambial kill absent	Cambial kill present
	.....(no. trees (cell χ^2))	.....
Rake 1 m	59 (0.1106)	0 (2.5000)
Rake 23 cm	60 (0.1125)	0 (2.5424)
Blow 23 cm	58 (0.1087)	0 (2.4576)
No removal	49 (0.9956)	10 (22.500)

Statistical association between treatments and cambial kill presence/absence was significant ($\chi^2 = 31.3274$, $P < 0.0001$, $n = 236$). Contribution of each cell to total χ^2 is shown in parentheses.

Table 4. Number of trees with and without bark char cambial kill and vertical-bark-flake consumption cambial kill by litter/duff removal treatment: the three removal treatments were combined

Cambial kill type	No removal	With treatment
	.... (no. trees (cell χ^2))	....
Bark char cambial kill		
Absent	181 (0.6130)	182 (0.6871)
Present	23: $x = 15$ cm (9.6750)	0 (10.845)
Vertical-bark-flake consumption cambial kill		
Absent	186 (0.3704)	182 (0.4151)
Present	18: $x = 25$ cm (7.5718)	0 (8.4887)

Mean width of cambial kill in cm is shown when present. Statistical association of bark char cambial kill and vertical-bark-flake consumption cambial kill presence/absence with treatment was significant ($\chi^2 = 21.8197$, $P < 0.0001$ and $\chi^2 = 16.8443$, $P < 0.0001$, respectively, $n = 386$). Contribution of each cell to total χ^2 is shown in parentheses.

Table 5. Number of trees with moderate bole char by four litter/duff removal treatments

Litter/duff removal treatment	Bole char absent	Bole char present
	.......(no. trees (cell χ^2))	....
Rake 1 m	59 (0.8048)	0 (6.5000)
Rake 23 cm	55 (0.0486)	5 (0.3922)
Blow 23 cm	57 (0.5629)	1 (4.5463)
No removal	39 (3.4714)	20 (28.038)

The statistical association of moderate bole char with treatment was significant ($\chi^2 = 44.3646$, $P < 0.0001$, $n = 236$). Contribution of each cell to total χ^2 is shown in parentheses.

Discussion

Previous studies that included raking effectiveness (Swezy and Agee 1991, Fulé et al. 2002, Perrakis and Agee 2006) have been limited in scope, and none provided evidence that raking the forest floor from the base of old-growth ponderosa pine before prescribed fire prevents or reduces mortality. Swezy and Agee (1991) raked the litter layer away from three of six burn trees, and one, low-vigor, raked, and burned tree died 4 years later as a result of a western pine beetle attack. None of the unraked burn trees died. Perrakis and Agee (2006) applied similar treatments to four large (>20-cm dbh) ponderosa pine trees before prescribed fire, but they provided no mortality results. Fulé et al. (2002) raked the forest floor away from the base of all old-growth ponderosa pine trees on two small prescribed fire sites near Mount Trumbull in Northwest Arizona, but that treatment did not prevent mortality because 67% of the ponderosa pine >50-cm dbh died along with 19% of the 5- to 50-cm dbh trees. This mortality was hypothesized to be due to thin lava soils and possible drought stress because similar restoration treatments on nearby sites (Fulé et al.

2001) had good results and did not indicate increased mortality after prescribed fire for old-growth ponderosa pine. None of these studies were specifically designed to study raking effectiveness.

A northern California study concurrent with ours (Hood 2007) was also specifically designed to answer the question of raking effectiveness in preventing mortality in large ponderosa pine after prescribed fire. Although their experimental design and tree selection criteria were different than ours, sample size, forest floor removal to mineral soil, and results were remarkably similar. At 3 years after prescribed fire, we had no fire-related mortality and Hood (2007) reported only two trees dead due to prescribed fire. Both of those dead trees, one raked and the other unraked, had old catface firescars that ignited and caused the center of the tree to burn out (Hood 2007). We screened out trees with catface firescars. Both studies also showed that raking reduced cambial kill and that raking alone, without fire, does not cause tree death. The long-term effects on the tree bole of the cambial kill patches we measured are unknown and perhaps need further investigation.

Only 2 of 386 burned trees had cambial kill on a large portion of their circumference (≈75%), apparently due to consumption of vertical bark flakes and duff. Litter/duff depths for these two trees (23 and 30 cm) were above Sackett's (1988) range of 5- to 20-cm-deep layers that "could create intense heat" around large, fire-exclusion ponderosa pines. Yet, the trees were not killed because the fire, probably smoldering combustion, did not completely girdle the trees. Work on duff moisture before prescribed burns by Varner et al. (2007) may provide a plausible explanation: dry duff moisture burns (62% volumetric in the humus layer) led to 20% mortality in long-leaf pine (*Pinus palustris* Mill.), whereas moist (103%) and wet (124%) duff moisture burns consumed less duff depth and had mortality similar to that of the unburned plots. Hood's (2007) experimental results suggest a sustained smoldering threshold of 65–85% gravimetric moisture content for ponderosa pine duff. We hypothesize that once duff is ignited on a single tree, combustion may continue until a higher moisture threshold is encountered, perhaps on the shady side of the bole, which stops combustion even though more duff fuel is available. Litter/duff removal would prevent most cambial kill and possible tree girdling with burning under dry duff moisture conditions. A more pragmatic solution would be to use duff moisture thresholds in the burn prescription (Varner et al. 2007).

Because we had no mortality at 3 years after prescribed fire and because there was limited cambial kill with no complete tree girdling, it seems that litter/duff removal may not significantly affect mortality after prescribed fire in old-growth ponderosa pine in northern Arizona. Our sites were representative of the deeper end of current ponderosa pine forest floor depths in northern Arizona, so fuels managers may expect similar results on most fuels-reduction, fall prescribed fires used in northern Arizona forests. Litter/duff removal may, however, be an effective technique to prevent cambial kill during prescribed fires. Discussion of our results and the results of Hood's (2007) study with fuels managers and other forest scientists in northern Arizona has led to the suggestion that raking efforts be limited to trees >46 cm dbh to prevent cambial kill or to protect high fire-risk trees: that is, those with rotten catface firescars, pitch seams, or large nearby stumps or those growing in droughty microsites.

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