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Basal Injury from Smoldering Fires in Mature *Pinus Ponderosa* Laws.

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Abstract. Fuel accumulations were measured in duff mounds around the bases of 19 mature *Pinus ponderosa* Laws. (ponderosa pine) in a 200-year-old stand in Glacier National Park, Montana. Tree diameter at breast height ranged from 50 to 114 cm (mean = 80 cm). The stand burned at intervals between 13 to 58 years prior to European settlement. This stand had not burned for 69 years. The duff depth 30 cm from the tree bole ranged from 3 to 39 cm (mean = 18 cm). Duff depth increased with tree diameter and decreased with distance from the bole. Duff depth 90 cm from the bole averaged one-half the depth 30 cm from the bole.

Duff consumption and its effect on cambium mortality were quantified following a late summer, low intensity fire. Duff moisture contents on a dry weight basis were: fermentation (20%) and humus (36%). Smoldering combustion consumed 98% of the duff beneath the trees. Two patterns of duff burning were documented: downward spreading and lateral spreading. Temperatures near the root crown were above 300°C for 2 to 4 hours, resulting in mortality of 45% of the cambium samples (n=76) tested at the root crown. The probability of cambium mortality increased with duff depth and tree diameter. However, cambium mortality was lower than expected from analysis of thermal diffusion through bark. Cooling by mass transport through phloem and xylem is suggested as a possible explanation for the low cambium mortality.

Keywords: Fire ecology; Fire effects; Tree mortality; Heat transfer; Glacier National Park, Montana; *Pinus ponderosa*.

Introduction

In the absence of fire, litterfall typically exceeds decomposition in northern Rocky Mountain forests (Behan 1971). When fires occur frequently, fuel loads (mass per unit area) remain light and fires burn out quickly. Fire exclusion, however, has led to the accumulation of fuel in *Pinus ponderosa* Laws. (ponderosa pine) forests (Lunan and Habeck 1973; Habeck and Mutch 1973), creating favorable conditions for bole and root injury even in the most fire-resistant trees (Sackett 1988; Ryan 1990; Swezy and Agee 1991).

Surface fuels beneath large, mature *P. ponderosa* are primarily needles and exfoliated bark plates. These decompose forming an organic duff (fermentation and humus) layer that increases over time. The duff depth increases from the canopy drip line to the bole, with an especially sharp rise near the tree bole forming a mound around the root crown (Figure 1). Duff accumulations near the bole favor extended smoldering following surface fires (Sackett 1988).

Temperatures associated with smoldering combustion in duff (>300 °C) (Hartford and Frandsen in prep.) are considerably greater than the lethal temperature for cambial tissue (ca. 60 °C). Under these conditions, heat transfer theory (Gephardt 1961) suggests cambium injury is predominantly controlled by the duration of heating and bark thickness (Ryan 1982; Peterson and Ryan 1986), and thermophysical properties (Spalt and Reifsnyder 1962; Martin 1963; Reifsnyder et al. 1967). Duration of heating depends on the amount of duff and its burning rate. The burning rate depends on the duff's moisture and mineral content (Frandsen in press). Given that the conditions governing the burning rate do not vary greatly within duff mounds, we would expect the duration of burning to increase as duff accumulates. Because foliar biomass (Brown 1978; Stanek and State 1978) and bole surface area increase with tree diameter, litterfall can be expected to also increase with tree diameter. Longer durations of burning and increased cambium injury should be expected if litterfall leads to deeper duff around trees (Wagener 1961; Vines 1968; Gill 1974; Tunstall et al. 1976).

In contrast, fire resistance increases as bark thickness increases with tree diameter (Brown and Davis 1973, p. 49; Ryan 1982; Harmon 1984; Peterson and Ryan 1986; Ryan et al. 1988; Ryan and Reinhardt 1988). Heat transfer theory (Gephardt 1961; Spalt and Reifsnyder

1962), laboratory studies (Martin 1963; Reifsnyder et al. 1967), and field studies (Hare 1965; Fahnestock and Hare 1964; Vines 1968; Rego and Rigolot 1990) suggest that resistance to lethal cambium temperatures increases as a square of the bark thickness. Because bark thickness increases linearly with tree diameter (cf. Ryan 1982), fire resistance should increase proportionally to the square of the diameter.

The above discussion suggests that two opposing factors determine the susceptibility to cambium injury as tree diameter increases. Fuel accumulation increases the potential for cambial injury while increasing bark thickness reduces it. The relative importance of these factors is unknown. Improved understanding of relationships between fuels and fire injury is needed to aid managers in reintroducing fire into coniferous forests. As part of an effort to improve fire management, an experimental fire was conducted in Glacier National Park. The objectives of this study were to: (1) quantify fuel accumulations in duff mounds surrounding mature *P. ponderosa*, (2) determine temperatures and durations of ground fires in duff mounds, and (3) quantify effects of these fires on basal injuries.

Methods

Study Area Description

The study area is located in Glacier National Park, 33 km south of the Canadian border in northwestern Montana, USA. It is 0.5 km south of Logging Creek and bounded on the south and west by the North Fork Flathead River Road at UTM Zone 11, 707.8, 5397.0 (48° 42' N, 114° 11' W). The area is approximately 35 hectares and gently sloping (2 to 6%) to the southwest. The elevation is approximately 930 m. Soils have developed from well drained glacial till.

The area supports a multistoried, all-aged mixed conifer forest. Mature seral *P. ponderosa* and *Larix occidentalis* Nutt. (western larch) dominate the overstory. These two species comprise only 4% of the trees, but over 60% of the stem basal area on the site. Intermediate and younger trees are *Pseudotsuga menziesii* [Mirb.] Franco (Douglas-fir), a locally recognized hybrid *Picea engelmannii* x *glauca* (spruce), and *P. contorta* var. *latifolia* Engelm. (lodgepole pine). The site is classified as the *Picea/Clintonia uniflora* [Schult.] Kunth (spruce/queencup beadlilly) habitat type (Pfister et al. 1977). For reference, additional site and vegetation information may be found in Lunan and Habeck (1973) (stand # 1), Wakimoto (1984), and Kilgore (1986).

Mature *P. ponderosa* in the stand range from 190 to 240 years old (Lunan and Habeck 1973). The stand last burned in 1914. The mean interval between fires was 25 years between 1655 and 1914 (Barrett 1983; Barrett et al. in press). The stand contains a few trees with either exposed or obvious healed-over fire scars, but most trees show no evidence of previous injury. Dead surface fuels were sparse and discontinuous, and consisted primarily of a litter (O_i) layer derived from conifer needles and herbaceous material. They were underlain by compact fermentation (O_e) and humus (O_a) horizons averaging 5 cm deep, except beneath mature *P. ponderosa* and *L. occidentalis* where it often exceeded 20 cm. Woody fuels occupied 12% of the ground surface and consisted primarily of logs in varying stages of decomposition. A recent *Dendroctonus ponderosae* Hopkins (mountain pine beetle) epidemic killed most of the *P. contorta*. The majority of these were still standing and contributed little to the available fuel. The area was classified as a closed timber-litter fuel type (fuel model 8) for fire behavior purposes (Anderson 1982).

Study Trees

Nineteen mature *P. ponderosa* were sampled for fuel accumulation and observation of ground fire effects on cambium. Trees were located in proximity of vegetation plots established by Kilgore (1986) and selected to be representative of those scattered throughout the stand. None of the trees had visible basal fire scars. Diameter at breast height (137 cm) ranged from 50.3 cm to 114.0 cm (mean = 79.7 cm, std. dev. = 32.3 cm). The prefire average height to the base of the living crown of the sample trees was 13.2 m. This was 3.4 m higher than the average height of foliage scorch on adjacent understory conifers. Three trees received a trace of foliage scorch on the lower branches while the remainder were unscorched. All trees had charred bark at the ground line and minor bark scorching up to 0.1 m on the bole.

Two trees were selected for monitoring temperatures in the soil near the root crown during burning. On tree A (diameter at breast height = 53 cm), measurements were made in a 7 cm deep mound on the southwest side exposed to the afternoon sun. On tree B (diameter = 57 cm), measurements were made in a 17 cm deep mound on the northeast side in the shade. Fuels in the mounds were derived from needle fall and sloughed bark.

Burning Conditions

The area was burned on the afternoon of August 31, 1983. Strip head fires were used to ignite the area. Maximum daytime temperatures reached 30 °C. Minimum relative humidities were 18%. Surface wind speeds were less than 0.9 m s^{-1}. Precipitation during the preceding 60 days was 10.4 cm. This is about 50% above normal (Finklin 1986) but, because of canopy interception, the duff mounds remained relatively dry. Moisture contents were: litter (O_i) 13%, fermentation (O_e) 20%, humus (O_a)36%, and top 2 cm of the mineral soil (A_1) 10%.

The fire was a low to moderate intensity surface fire (flame lengths < 2 m) except when the crown of an occasional understory tree ignited. The height of crown scorch on understory trees averaged 9.8 m (std. dev. = 5.1 m, n = 82, range 0 to 33 m). Seven percent of the total area remained unburned. Fourteen percent was lightly burned, meaning that only the O_i was charred (Ryan and Noste 1985). The remaining 79% was moderately burned, i.e. both O_e and O_a were charred. The fire was classified as a "moderate intensity - moderate ground char (3-M) fire" (*sensu* Ryan and Noste 1985) .

Fuel Accumulation and Duff Consumption

Prior to burning, metal duff-pins (cf. McRae et al. 1979) were inserted into the ground 30, 60, 90, 150, and 210 cm from the base of the trees. Pins were placed in each of the four cardinal directions, flush with the surface of the litter and extending into the mineral soil. Duff depths were measured 1 month after the fire. Preburn duff depth was computed as the distance (± 5 mm) between the head of the duff-pin and the mineral soil. The mean and standard deviation were used to evaluate the change in duff depth with distance from the base of the tree. Additionally, the average prefire duff depth and average depth of duff burned were determined, by aspect, for the 30 cm duff-pin data. Correlation of duff depth by aspect within trees was also evaluated. Analysis of covariance, with tree diameter as a covariate, was used to test the hypotheses that neither prefire duff depth nor depth of duff burned differed by aspect.

Temperature Measurement

Temperatures were measured in the duff and A_1 horizons near the root crown of two mature *P. ponderosa* trees. A narrow trench was excavated to expose a profile of the forest floor horizons. Temperature probes, 0.5 mm diameter chromel-alumel thermocouples ensheathed in 2 mm diameter stainless steel tubes, were inserted horizontally 20 cm into the undisturbed profile positioning the sensing tip within 5 cm of the surface of the bark. Probes were placed in the mounds at different vertical depths in each of the O_i, O_e, O_a, and top 5 cm of the A_1 horizons as determined from the edge of the trench. Thermocouple junctions were located 0.5 cm beyond the end of the tube to minimize potential lateral heat conduction caused by the tube. Soil was placed back in the trench to limit the lateral diffusion of air into the duff profile and to protect the thermocouple extension wires. Data were recorded on a Campbell Scientific CR-5/S250 data logger. Temperatures were recorded at one minute intervals for the first 30 minutes after ignition and at 15-minute intervals thereafter until temperatures returned to near ambient. The temperatures measured are assumed to be representative of those experienced at the bark surface of the 19 sample trees.

Cambium Sampling

Thermocouples were excavated from the soil and ashes one month after the fire. No unburned duff remained. Samples of cambium tissue were removed with an increment borer and tested for presence of peroxidase with a vital stain (Ryan 1983). Samples were taken at the root crown next to the thermocouples and in the four cardinal directions (Fig. 1). Eleven months after the fire cambium viability was tested adjacent to the

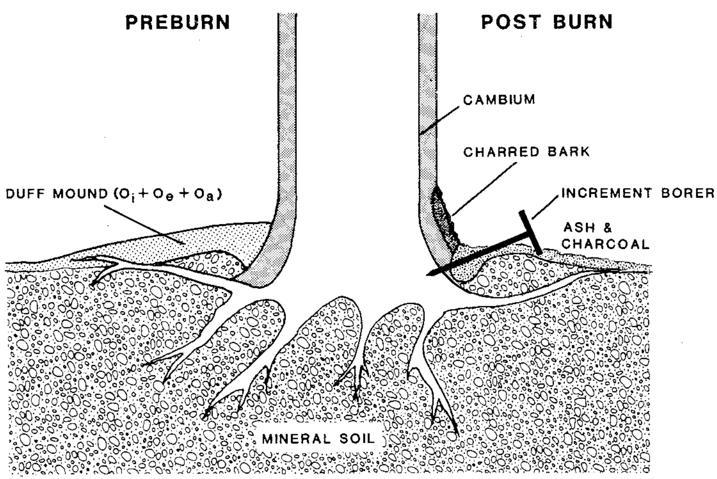

Figure 1. Illustration of the effects of smoldering ground fires on mature *Pinus Ponderosa* in Glacier National Park, Montana.

thermocouple locations and at each of the cardinal directions. At 23 months the cambium was tested 5 cm counterclockwise from the original test locations. The purpose was to determine if previous tests were representative of a larger portion of the circumference and to detect if new cambia were sealing-off the wounds.

Multiple linear regression was used to test hypotheses that the number of dead cambium samples per tree (0 to 4), 11 months after the fire, was not different for average depth of duff consumed per tree, tree diameter, or tree diameter squared. It is questionable if the assumptions of ordinary least squares regression are rigorously satisfied because the number of dead cambium samples could take only one of five ordinal values. Thus, we also used a maximum likelihood estimator procedure (Bishop et al. 1975) to model cambium death. Binary logistic regression (0 = dead, 1 = alive) was used to test the hypothesis that the probability of cambium death did not vary by aspect, tree diameter, diameter squared, or the depth of duff burned. The SAS-CATMOD (SAS 1985) procedure was used to estimate coefficients of the logistic model. Goodness-of-fit of model parameters was evaluated by the Wald (1943) statistic. The likelihood ratio statistic (McCullagh 1986; Pierce and Schafer 1986) and informal graphical techniques (e.g., local mean deviance plots) (Landwehr et al. 1984) were used to evaluate model goodness-of-fit.

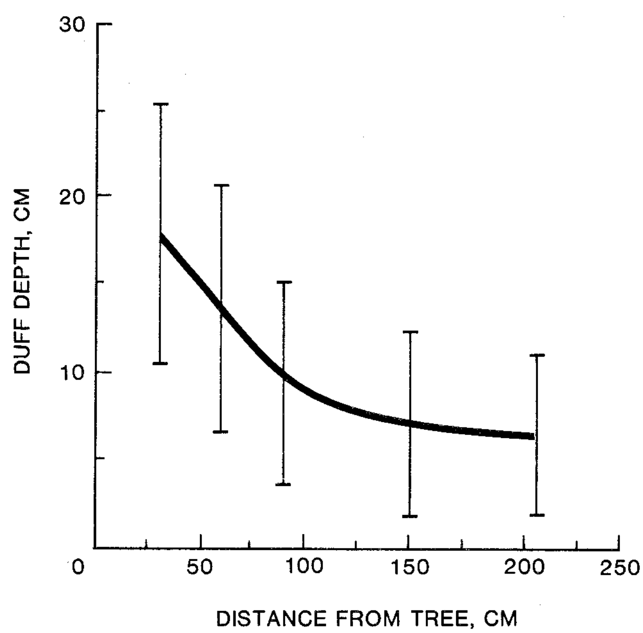

Figure 2. Mean and Standard deviation of duff depth (cm) as a function of the distance (cm) from the base of the tree.

Results and Discussion

Fuel Accumulation and Duff Consumption

Average duff depth decreases from 17.8 to 6.3 cm between 30 and 210 cm from the base of the tree (Fig. 2). The coefficient of variation increases from 42 to 75% over this same distance. The average preburn duff depth varies by aspect. At the 30 cm distance it ranges from 16.0 cm on the west aspect to 19.3 cm on the north (Table 1). The trend for deeper duff at the north and east aspects is not, however, significant ($p_r = 0.37$). Preburn depths are moderately correlated between the north and east aspects ($r = 0.89$) and between the south and west aspects ($r = 0.68$). Correlations between north or east and south or west are much less (ca. 0.15).

The average preburn duff depth (APDD) 30 cm from the base of the tree increases with tree diameter (DBH):

$$\text{APDD (cm)} = 0.29 \text{ DBH (cm)} - 5.28; \quad n = 19;\ SE = 53.0;\ F = 12.8;\ R^2 = 0.43 \tag{1}$$

Although the F ratio is highly significant (p = 0.002) the equation explains only 43% of the variation in duff depth. The intercept is not significant at the 0.05 probability level. Field observation leads us to speculate that a major source of unexplained variation in duff depth results from the random displacement of mineral soil associated with tree diameter expansion at the root crown. Average depths are similar to those reported by Swezy and Agee (1991) for *P. ponderosa* in Oregon.

Litter and duff distributions may be affected by slope and wind. On steep slopes, accumulations are greater on the uphill side of trees. Basal fire scars are also most commonly found on the uphill and lee sides (Arno and Sneck 1977; McBride 1983). The study area is relatively flat and the prevailing wind speed is generally low, so very little difference in depth is expected with aspect. Nevertheless, the trend towards deeper duff on the north and east aspects is consistent with the slope and prevailing wind direction.

Ninety-eight percent of the duff burned around the 19 sampled trees. All but one of the duff-pin sample points burned to charcoal and ash. The one unburned point is on the north aspect and has 20.0 cm of duff. As a result the average depth of duff burned on the north aspect is slightly less (18.2 cm) than the preburn depth shown in Table 1. The depths of burn for the remaining aspects are the same as the pre-burn values in Table 1. Given that most of the duff burned, analysis of covariance also shows that tree diameter is significantly related to depth of burn but aspect is not.

Below about 35% moisture content duff can burn

Table 1. Preburn duff depth (cm) and number of dead cambium samples (NDEAD) by aspect for 19 mature Pinus ponderosa trees in Glacier National Park. Preburn duff depth was measured 30 cm from the tree.

	Duff Depth				
Aspect	Mean	Std. Dev.	Maximum	Minimum	NDEAD
	— — — — — —	— — — cm	— — — — — —	— — — —	— —
North	19.3	8.2	33.0	8.5	8
East	19.1	9.5	39.0	7.5	13
South	16.9	7.0	28.0	3.5	6
West	16.0	7.2	26.0	3.0	7

independently of a surface fire (i.e., the surface fire provides an ignition source but heat from the surface fire is not necessary to sustain smoldering in the duff) (cf., Shearer 1975; Norum 1977; Sandberg 1980; Brown et al. 1985). Duff moisture content was between 20 and 36%. These conditions were favorable for complete duff consumption once the duff mounds were ignited by the surface fire. Given an average bulk density of 0.1 gm cm^{-3}, approximately 1.4 kJ of heat was released for each cubic centimeter of duff consumed (Frandsen 1989). This coupled with slow heat release and good insulating properties of duff contributed to extended high temperatures at the root crowns.

Temperature History

Temperature histories were obtained at six depths within the mounds of two instrumented trees. Histories were selected that illustrate the temperatures achieved in the soil horizons (Figs. 3A and 3B) and that contribute to an understanding of the form of the smoldering combustion front (Figs. 4A and 4B). There were no apparent substantive differences in maximum temperature or duration between the two locations that could be attributed to solar insolation or duff depth.

The initial peak temperature of 700 °C 1 cm below the litter surface (Fig. 3A) suggests that a surface fire initially spread through the O_i horizon of the 7 cm deep mound beneath tree A. Such temperatures are commonly associated with flaming combustion in low intensity fires. The broad peak temperatures of the two deeper thermocouples (450 °C and 325 °C) in the O_e and O_a horizons, respectively, are suggestive of a smoldering ground fire. The sequential occurrence of peak temperatures with increasing depth and time suggests a downward smoldering fire (Fig. 4A). Temperatures were not measured in the A_1 horizon because the duff/mineral soil interface at the thermocouple junction did not coincide

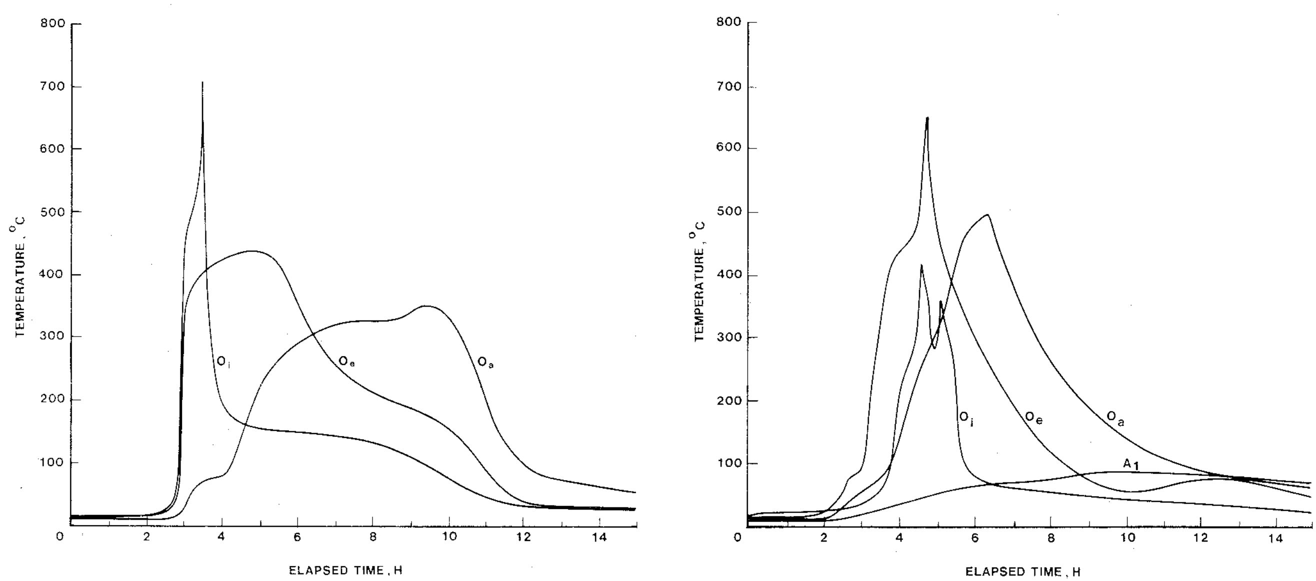

Figure 3. Temperatures associated with burning of duff mounds beneath two mature Pinus ponderosa in Glacier National Park, Montana. Temperature profile A is from a downward spreading ground fire in 7 cm deep duff beneath a 53 cm d.b.h. tree. Temperature profile B is from a lateral spreading ground fire in 17 cm deep duff beneath a 57 cm d.b.h. tree. Where: O_i, O_e, O_a, and A_1 refer to the litter, fermentation, humus, and surface mineral soil horizons, respectively.

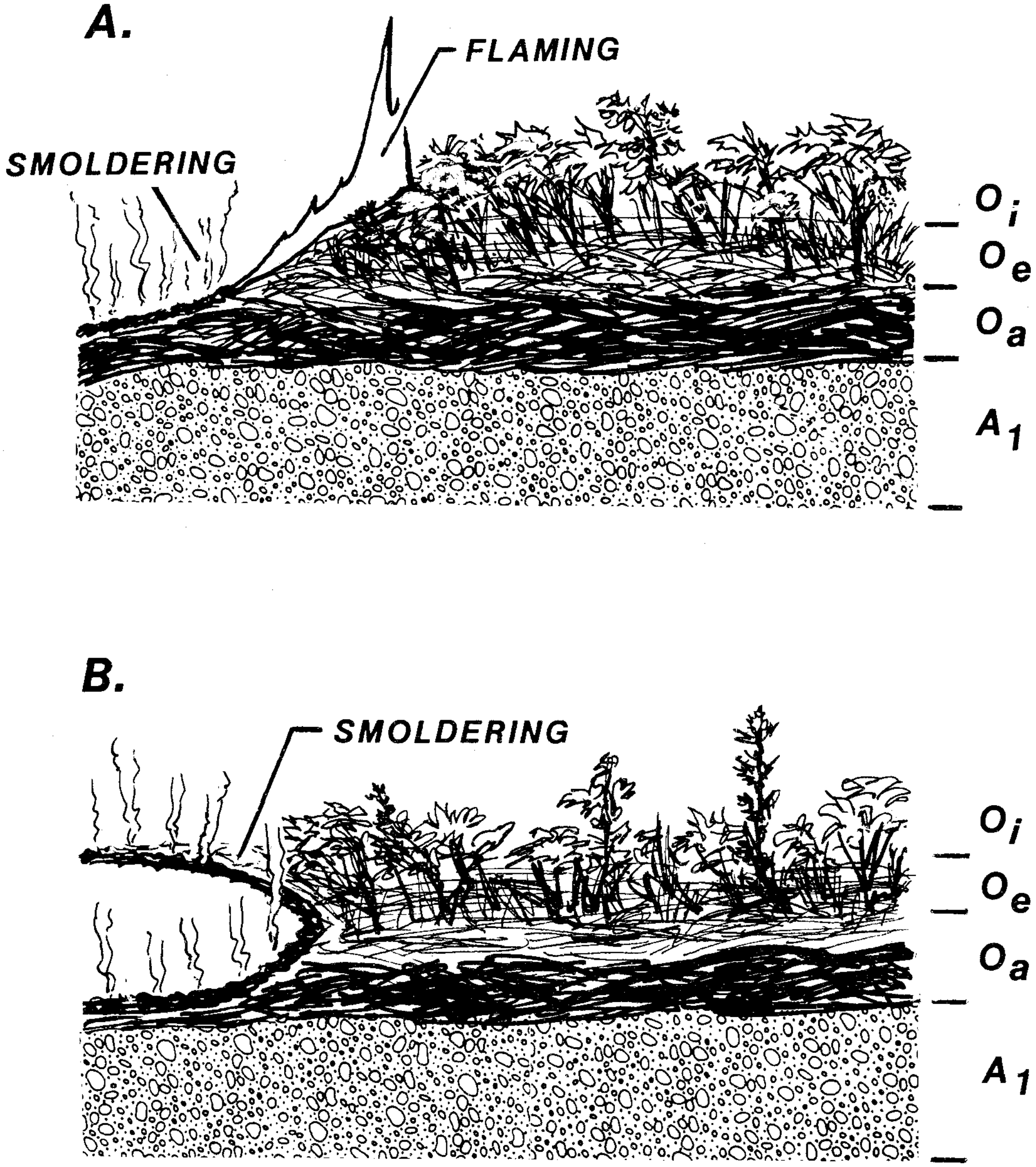

Figure 4. Illustration of downward spreading (A) and lateral spreading (B) ground fires. Where: Oi, Oe, Oa, and A1 refer to the litter, fermentation, humus, and surface mineral soil horizons, respectively.

with the interface in the trench. Vertical irregularities of the interface preclude certainty in placing the thermocouple junction in the desired strata without disturbing the profile thereby affecting its consumption.

At the base of tree B a significant temperature increase occurred at 11 cm in the O_e horizon about 1 hour before it occurred at the 2 cm depth in the O_i horizon (Fig. 3B). This suggests the fire spread laterally as a smoldering wedge below the litter (Fig. 4B). Two centimeters into the A_1 horizon, temperatures never rose above 100 °C but exceeded lethal temperatures (ca. 60 °C) for over 10 hours.

Similar temperatures have been reported for duff burning in mixed conifer stands in California (Agee 1973) and Montana (Ryan 1982; Hartford and Frandsen in prep.). However, point source estimates of duration vary. Agee (1973) found temperatures in excess of 300 °C for up to 2 hours when burning *P. ponderosa* and *Libocedrus decurrens* Torr. (incense cedar) duff. Hartford and Frandsen (in prep.) found temperatures in excess of 300 °C for 12 hours when burning a 6.3 cm deep mixture of *L. occidentalis* and *P. contorta* duff at an 18% moisture content. The durations reported here are intermediate to those reported for mixed conifers but the sample size is small in all cases. Logistical constraints limit one's ability to extensively sample the spatial variation in temperatures and durations during fires. Thus, it is difficult to predict many important fire effects in the absence of theoretically sound, operationally useful models of combustion and heat transfer (cf. Frandsen and Ryan 1986, Frandsen 1989, and Hungerford 1990).

Fire Effects on Cambium

On both instrumented trees, one month after burning, vital staining indicated dead cambium adjacent to the thermocouple positions and at 7 of the 8 cardinal directions. Eleven months after the burn, 9 of 10 cambium samples again tested dead, but one sample tested dead next to a previously live sample and vice versa. Tree A had 4 dead cambium samples at 1 month and 5 dead at 11 months. The tree's foliage appeared visually healthy at 11 months but the tree was dead by the 23rd month. Tree B successfully "pitched-out" *D. ponderosae* beetles and was still alive 6 years after burning.

The burning of duff mounds beneath the 19 trees resulted in lethal heating to 45% of the cambium samples and the subsequent death of 4 trees. The number of dead samples per tree ranges from 0 (n=4) to 4 (n=3) with a median of 2. All trees with fewer than 3 dead cambium samples were alive after 6 years. Three of the 6 trees with 3 or 4 dead cambium samples died within three years of burning. A fourth tree died between the third and sixth years. It seems certain that death resulted from disruption of root system function because the crown and main trunk of the trees were not injured. These results suggest disruption of carbohydrate transport to the roots as the main cause. However, lethal heating of surface roots has been reported for *P. ponderosa* in Oregon (Swezy and Agee 1991) and Arizona (Sackett 1988) and may have contributed to the death of these trees.

Bark of *P. ponderosa* is highly fissured, and resistance to fire injury varies somewhat between plates and fissures. Differential heating and/or variable bark thickness often lead to stringers of dead cambium. But, point samples of cambium vitality provided reasonably good estimates of basal injury. We found better than 90% agreement between samples taken at 1, 11, and 23 months after burning. Mortality of adjacent cambium samples 23 months after burning agreed with cambium mortality at 11 months in all but 6 cases. Four cases in which cambium tested alive at 11 months had adjacent dead cambium at 23 months. The lack of verification on a few points (i.e., differences in cambium mortality at adjacent positions) some months later is not surprising. It illustrates the problem of using point samples to estimate the proportion of the circumference girdled while minimizing destructive sampling.

The number of dead cambium samples per tree (NDEAD) is positively correlated with the average depth of duff burned (ADB). The amount of dead cambium is negatively correlated with tree diameter but only at the 0.11 level. Diameter also is not significant when burn depth is in the model. Results are similar for squared diameter. The best model for predicting the number of dead cambium samples is:

$$\text{NDEAD (0 to 4)} = -0.046 + 0.11\ \text{ADB (cm)}$$
$$n = 19;\ SE = 1.3;\ F = 5.7;\ R^2 = 0.25 \qquad (2)$$

Although the F ratio is significant (p = 0.03) the equation explains only 25% of the variation in the number of dead cambium samples per tree. The intercept is not significant. Equation 2 implies that the probability of cambium mortality for these trees approaches unity as duff consumption approaches 36 cm.

Cambium mortality varies by aspect (Table 1). Probabilities of mortality for north, east, south, and west are 0.42, 0.68, 0.32, and 0.37, respectively. Mortality is significantly greater on the east aspect but differences between the other aspects are not significant. Neither tree diameter nor diameter squared are significant predictors of cambium mortality for these trees. The best logistic model for predicting the probability of cambium mortality includes depth of duff burned and an indicator variable for east aspect:

$$P_m = 1/(1 + \exp(2.89 - 0.14\ \text{DOB} - 1.40\ \text{ASP}))$$

where:
P_m is the probability of mortality (0 to 1)
DOB is the depth of duff burned (cm)
ASP = 1 if east, otherwise ASP = 0
n = 76, likelihood ratio = 84.1 (3)

Although the Wald (1943) statistic indicates the probability of mortality is significantly greater on the east aspect, the likelihood ratio for Eq. 3 is significant only at the 0.18 probability level. This suggests that a combined model for all aspects also fits the data:

$$P_m = 1/(1 + \exp(2.46 - 0.13\ \text{DOB}))$$

where:
P_m is the probability of mortality (0 to 1)
DOB is the depth of duff burned (cm)
n = 76, likelihood ratio = 93.4 (4)

The likelihood ratio statistic for this model is significant (p = 0.03). Equation 4 indicates there is a nearly linear increase in the probability of cambium mortality over our range of duff consumption (Fig. 5). Further, the equation indicates that when more than 19 cm of duff

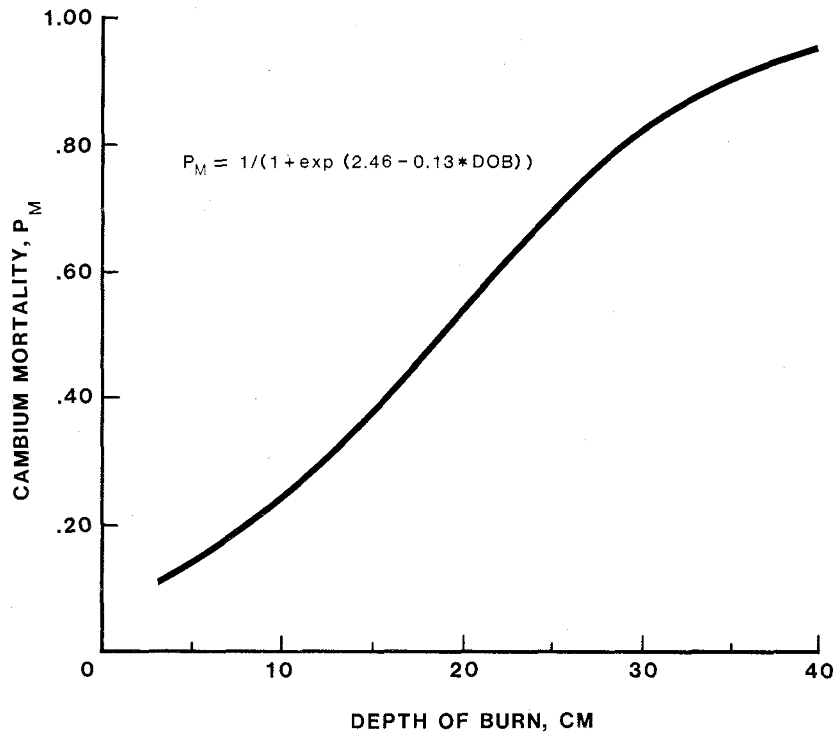

Figure 5. Logistic regression model for predicting the probability of cambium mortality in mature Pinus ponderosa resulting from duff consumption.

burns cambium is more likely dead than alive. Local mean deviance plots (Landwehr et al. 1984) indicate generally good fit of both Eqs. 3 and 4 to the data.

Bark thickness normally increases with tree diameter. Although diameter is not a significant formal statistical predictor of cambial mortality, evidence suggests that mortality is sensitive to tree diameter. First, diameter is the best predictor of duff depth (Eq. 1) which is, in turn, the best predictor of cambial mortality. Second, the sign of the coefficient is negative, which is consistent with an apparent trend for more cambium injury in larger trees. Third, if bark thickness continues to increase with diameter in old-growth trees, then heat transfer theory suggests that diameter should have a strong positive effect on resistance to thermal injury.

Heat-caused cambial injury is not uniform around tree boles (Hare 1965; Gill 1974; Tunstall et al. 1976). Winds were light during the fire but may have affected the rate of duff consumption and the resultant temperatures. The east side of the trees was the lee side where the wind would have the greatest influence on heating and causing injury. The suggested differential heating around the base of the tree is consistent with the increased mortality on the east side of the trees.

On average, bark thickness of western Montana *P. ponderosa* is approximately 0.06 times tree diameter but is somewhat thicker at the base of the tree (Faurot 1977). Our range in tree diameters suggest that bark thickness ranges from about 3 to 8 cm. The following expression shows how the expected cambium temperature depends on the bark thickness and duration of heating (Gephardt 1961, p. 54):

$$T = T_o + (T_i - T_o)\ \mathrm{erf}(x/(2\ (\alpha\tau)^{0.5}))$$

Where:
T is the expected cambium temperature, °C;
T_o is the initial bark surface temperature, 20 °C;
T_i is the fire-elevated bark surface temperature, 300 °C;
α is the bark thermal diffusivity, 0.06 cm^{2}min^{-1};
τ is the duration of burning, min; and
x is the bark thickness, cm; (5)
$\mathrm{erf}(x/(2\ (\alpha\tau)^{0.5}))$ is Gauss' error integral.

The initial and fire-elevated bark surface temperatures are comparable to our temperatures. The thermal diffusivity is a representative value for pine bark (Martin 1963; Reifsnyder et al. 1967). Figure 6 illustrates the expected cambium temperature beneath our expected minimum (3 cm), average (5 cm), and maximum (8 cm) bark thickness. Temperatures above 300 °C existed in the O_e and O_a horizons from 2.5 to 4 hours (Fig. 3). Under these conditions, Figure 6 indicates that cambium should be lethally heated beneath all but the thickest bark. Further, duff consumption also caused some of the bark to be burned away (Fig. 1), thereby reducing insu-

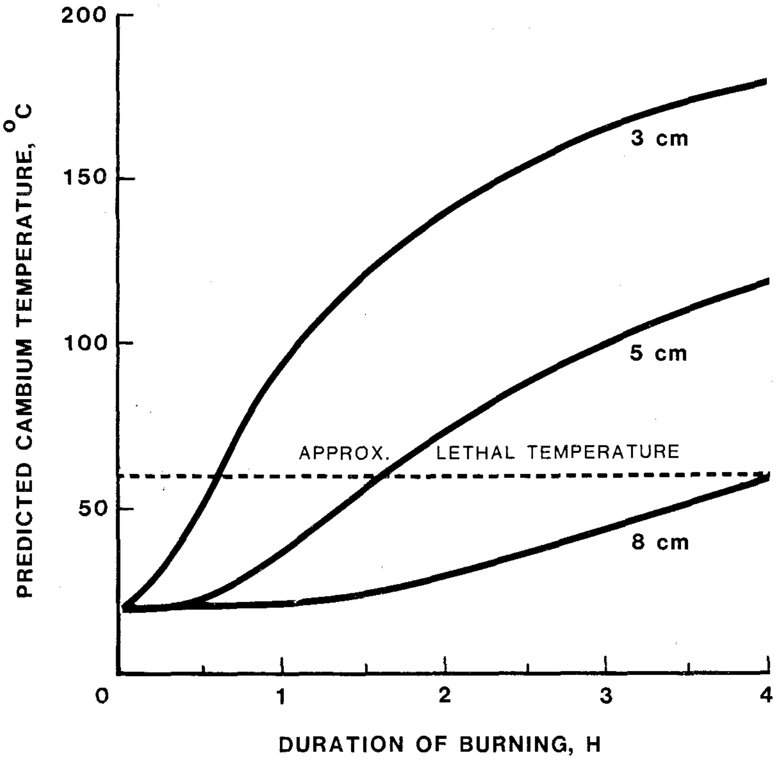

Figure 6. Predicted cambium temperature (°C) vs. duration of burning (min.) for 3, 5, and 8 cm thick bark.

lation thickness and bringing the combustion front closer to the cambium. Heat from burning bark should have penetrated deeply into the bole. Based on the measured temperatures and heat transfer theory cambium mortality could be expected to be higher than the observed 45%.

Variations in heating due to duff properties and variations in heat transfer due to bark properties may partially explain the observed low cambium mortality. Alternatively, heat transfer at the base of tree boles may be more complex than indicated by the simple diffusion equation (eq. 5). For example, there is experimental evidence for internal cooling resulting from mass flow within the xylem and phloem (Vines 1968). Mass flow would be most effective at reducing heat injury when heat is supplied to a narrow band at a relatively slow rate such as in the case of burning duff mounds.

Conclusions

In *P. ponderosa* communities along the North Fork of the Flathead River in Glacier National Park, Barrett (1983; Barrett et al. in press) found that in the 200 years prior to European settlement, fires occurred every 13 to 58 years with a mean fire-free interval of 26 years. Based on the tree ring record, these communities are currently experiencing their longest fire-free period. In the absence of periodic fires, fuels have accumulated around the base of mature *P. ponderosa* trees. When duff mounds are deep and dry, fire can lead to significant cambium injury and tree mortality due to girdling. If high survival of mature pines is a goal of a program to reintroduce fire into these ecosystems, it may be desirable to burn when the O_e and O_a horizons are too moist to sustain a ground fire (Frandsen 1987).

It is common knowledge that fire resistance increases with tree size regardless of species (cf., Ryan et al. 1988; Ryan and Reinhardt 1988). Mature *P. ponderosa* are also considered among the most fire-resistant trees in western North America (Brown and Davis 1973, p. 52). But, the amount of fuel at the base of mature P. ponderosa also increases with tree diameter. Thus the extended heating associated with the combustion of these deeper mounds results in greater cambium mortality in bigger trees. The trend for greater mortality of larger trees is contrary to conventional wisdom and results from previous studies (cf., Lynch 1959; Lindemuth 1962; Wooldridge and Weaver 1965; Wyant et al. 1986; Harrington 1987; Saveland et al. 1990). Future studies on the effects of fire reintroduction need to critically evaluate the trade-off between greater resistance due to size and greater heat potential due to fuel accumulation.

Thermal diffusion through a semi-infinite solid has been used to model heat transfer through bark (Spalt and Reifsnyder 1962; Vines 1968; Ryan 1982; Peterson and

Ryan 1986; Rego and Rigolot 1990). The model, however, has not been validated in a field environment. The model may be appropriate when a significant surface area of the bole is exposed to fire temperatures but it may not provide a fully adequate description of the heating of a narrow band of the circumference by a slow burning ground fire. The lower than expected mortality suggests that the model should be rigorously tested in a variety of fire conditions.

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