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Duff mound consumption and cambium injury for centuries-old western larch from prescribed burning in western Montana

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Abstract. Western larch is one of the most fire-adapted conifers in western North America. Its historical perpetuation depended upon regular fire disturbances, which creates open stand conditions and mineral seedbeds. A stand of 200- to 500-year-old larch in western Montana with deep duff mounds resulting from an unusually long 150-year fire-free period was mechanically thinned and prescribed burned to reduce the probability of high intensity wildfire near a community and increase opportunities for larch regeneration. Little documentation is available regarding basal damage to larch from lengthy duff mound burning; therefore this study was established to assess: duff consumption from prescribed burning and resulting cambial damage and tree vitality. Ninety trees averaging 91-cm diameter at breast height were selected, half with duff mounds measured and burned in autumn and half with mounds removed. Duff depths nearest the bole averaged 20 cm and mound consumption approached 100% including large amounts of the basal bark with smouldering combustion lasting 18–24 h. Cambial mortality ranged from 0 to 36% of the basal circumference but no trees had died after 7 years. The cambium mortality was likely due to the spatially infrequent coincident of deep duff and thinner bark. Under similar site and environmental conditions removal of the potential duff consumption injury hazard appears unwarranted.

Additional keywords: bark consumption, bark depth, duff depth, girdling, *Larix occidentalis* (Nutt.), tree mortality.

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Introduction

Western larch (*Larix occidentalis* Nutt.) is a fire-adapted deciduous conifer found exclusively in the inland north-western US and south-western Canada. Its ecological success and perpetuation on warm, moist sites were historically dependent on mixed severity wildfires at moderate return intervals (Barrett *et al.* 1991; Arno and Fischer 1995); on cooler sites, larch are often the lone survivors of less frequent, high intensity fires (Brown and Davis 1973; Barrett *et al.*1991). The favourable fire effects include high mortality of more competitive but fire-sensitive associate species such as lodgepole pine (*Pinus contorta* Dougl.) and creation of open site conditions with mineral soil seedbeds for larch regeneration (Smith and Fischer 1997; Arno *et al.* 2000). Larch characteristics that lead to high resilience to fire injury include thick bark with low resin content, high open crowns, relatively deep root systems and a deciduous nature more tolerant of defoliation (Volland and Dell 1981; Fischer and Bradley 1987; Arno and Fischer 1995; Graham *et al.* 1995; Schmidt and Shearer 1995). Additionally, attacks by bark beetles, such as the Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins), on fire-injured western larch are rare compared with associate species such as lodgepole pine or Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Schmidt *et al.* 1976; Furniss and Carolin 1977).

During the era of successful fire suppression activities beginning in the early 20th century and continuing until the present, stand structures and compositions, as well as forest fuel conditions have changed considerably in forests with historically frequent or moderately frequent fire return intervals, including those with western larch (Habeck 1990; Arno and Brown 1991). These conditions typically involve increased stand densities of shade-tolerant, more fire-susceptible species, a general decrease in shade-intolerant understorey species and increased surface dead woody fuels and forest floor (Arno *et al.* 1997; Morgan *et al.* 1998). Elevated levels of flammable fuels enhance the probability of higher intensity wildfires with more severe fire effects than typically occurred under historical fire regimes with similar fire weather conditions (Barrett *et al.* 1991; Arno *et al.* 2000). These possible fire behaviour and effects consequences are often deemed ecologically and socially undesirable. Therefore, forest managers are conducting restoration–fuel treatments to restore a semblance of historical ecosystem structure and composition and to lessen the level of severe fire exposure to natural resources and human property (Mutch *et al.* 1993; Peterson *et al.* 2005; Ager *et al.* 2010). These treatments often include mechanical thinning to create open stand conditions that lessen crown fire potential and benefit shade-intolerant species, and prescribed fire application to reduce surface fuels and, therefore, surface fire intensity and burn severity from possible wildfires. These burns also produce mineral soil seedbeds to favour all life forms of early successional species including larch (Mutch and Cook 1996; Agee and Skinner 2005).

In addition, uniquely large amounts of dead biomass have accumulated in critical micro-sites throughout many old growth forests during the approximate century of anomalous fire absence (Hood 2010). Naturally cast foliage, branchwood, cones and bark are deposited annually and accumulate at the base of large, old trees over long periods. With recurring fire in the past, these deposits were repeatedly reduced, but with no fire for a century or more and because decomposition lags behind deposition, duff mounding typically occurs (Ryan and Frandsen 1991). The location of this accumulation is significant as it is situated immediately adjacent to the root crowns and bases of trees, separated from the living cambium layer by bark of variable thickness. Additionally, some species on some soil types have shallow roots located closely under this area of high organic deposition (Swezy and Agee 1991; O'Brien *et al.* 2010). When fires do occur, whether intentional or not, the probability is high that much if not all of this basal duff will be consumed and, depending on its depth, it can have a prolonged burning residence time (Hood 2010). This can result in significant heat penetration horizontally towards the cambium or vertically into the mineral soil towards the root system. Tree mortality from burning basal duff has been reported in south-western ponderosa pine (*Pinus ponderosa* C. Lawson) (Sackett *et al.* 1996) and longleaf pine (*Pinus palustris* Mill.) in the south-east (Varner *et al.* 2007), and observed in inland north-west ponderosa pine (Ryan and Frandsen 1991; Perrakis and Agee 2006) and Douglas-fir (Furniss 1965; Amman and Ryan 1991). The duff mound burning process and potential injury has not been documented in stands with western larch. Because the concept of restoration of old growth conditions implies that existing old trees be preserved on a particular site to the extent possible, understanding the potential effects of ecologically sound treatments, such as fire application, is essential (Arno *et al.* 1997). The present study examines the effects of a restoration prescribed burn on duff mound consumption, resulting cambium injury and 7-year post-fire tree mortality in an old growth western larch stand in west central Montana. It offers detailed insights regarding potential effects of fire in fire-excluded ecosystems. The hypothesis presented is that thick basal bark will insulate the larch cambium from expected lengthy duff mound burning.

Methods

Study site

This study was conducted in a stand described previously in Arno *et al.* (1997). They examined 11 uncut stands dominated by old growth ponderosa pine or western larch in western Montana on sites with moderately frequent historical fire, to contrast the change in stand structure and composition between 1900 and the late 1990s. In the early 20th century, stand characteristics at all sites still demonstrated the influence of the last historical fires of the late 19th century; characteristics in the late 20th century demonstrated the response to exceptionally long fire-free periods. The current 30-ha study site, known as Girard Grove, is located ~56 km north-east of Missoula, MT, 3 km west of the town of Seeley Lake, MT, and immediately south of Seeley Lake. Arno *et al.* (1997) classify the area generally as a moist site on flat terrain dominated by an uneven-aged stand of old western larch. From fire scar analysis, they report an average historical fire return interval of 24 years dating from 1671 to 1859. The occurrence of earlier fires in the 1400s and 1500s is implied by cohorts of larch with establishment dates within those time periods. The longest fire-free period during the fire scar record was 42 years but until this study, almost 150 years had passed without another fire.

Fig. 1. Old growth western larch with large basal duff mounds in this western Montana study site.

Between 1900 and 1995, the stand basal area increased from 20 to 52 $m^2 ha^{-1}$ with nearly 75% of this increase occurring from in-growth of Douglas-fir and lodgepole pine (Arno *et al.* 1997). Because these stand conditions were unfavourable for larch perpetuation and had increased the probability of high-intensity wildfire near the recreational community, an ecosystem restoration–fuels treatment plan was implemented. This plan incorporated mechanical thinning in 2002 to reduce stand density and canopy fuel continuity followed by a prescribed burn in 2003 to reduce surface fuels and encourage larch regeneration.

Treatment description

The prescribed burn unit has several hundred large, old western larch with substantially deep duff mounds (Fig. 1). Trees selected for study were within and immediately adjacent to the 1-ha plot used in Arno *et al.* (1997) for stand and fire history reconstruction. The ninety large trees were randomly assigned to one of two treatments, burned and unburned. Duff mounds of burn treatment trees were left intact, were measured and exposed to fire, whereas mounds for unburned treatment trees were dispersed using a power blower leaving ~60 cm of mineral soil around each tree.

Sampling methods

Specific tree attributes measured were diameter at breast height (DBH) at 1.4 m and total height and crown length. Ages were determined for many of the trees by Arno *et al.* (1997) (trees currently were 8 years older), but a large percentage were not datable because of heart rot, common in mature larch.

For quantification of pre-burn duff depths and consumption with minimal disturbance, 30-cm bridge spikes or heavy gage wire were inserted flush with the top of the mound's thin litter layer before burning. Nine spikes per tree were located in three designated, equally spaced directions (south, north-east and north-west) and at three distances from the tree boles (7.6 cm, 30.4 cm and at the mound edge) to capture depth variability within mounds. Duff depths closer than 7.6 cm were not used because of underlying attached bark plates extending into the mound. The mound edge micro-site was where the mound blended into the surrounding forest floor with a mean distance of 70 cm from the tree, ranging from 37 to 121 cm. When burning was complete, the length of the exposed spike above any unburned duff indicated depth of consumption and the length above mineral soil was the total duff depth. The percentage of the total duff depth consumed was then computed.

In addition, because cut trees were skidded out of the unit in full length during the thinning operation, variable amounts of branchwood broke off at the base of the sample trees and accumulated on the duff mounds. Woody fuel loadings on duff mounds were quantified because consumption of these fuels during fires may increase duff consumption due to prolonged heat exposure (Norum 1977; Brown *et al.* 1985). Three woody fuel transects between 2 and 3 m long, depending on mound size, were stretched across the duff mounds in a triangle shape with the tree in the centre and the ends pinned at the mound edge for relocation. Sampling was conducted before and after burning for three standard woody fuel diameter classes, 0–0.6 cm (1-h fuels), 0.6–2.5 cm (10-h fuels) and 2.5–7.6 cm (100-h fuels) as described by Brown (1974). Pre- and post-burn loadings of the 0–7.6-cm woody fuels by size class and resulting consumption were computed for each mound using transect lengths and standard fuel particle characteristics according to Brown (1974). For comparison, surface woody fuels were also sampled before and immediately after burning along 17 systematically established transects through the stand apart from the duff mounds. Woody fuels were sampled in the same size classes as described above; 1-, 10- and 100-h along 2, 2 and 5 m of the transect.

Because moisture conditions strongly influence duff consumption (Brown *et al.* 1985), duff samples were collected from seven mounds during the burning to determine the moisture content of three layers: surface litter, upper duff or fermentation with distinguishable particles and the more decomposed lower duff or humus. Each layer was transported to the laboratory where gravimetric moisture contents were calculated.

The prescribed burn was conducted on 29 September 2003, 2 weeks following 3.1 cm of rain. Air temperatures ranged from 16 to 20°C and relative humidity from 37 to 43%. The south-west winds were light at 2–6 km h^{-1}. The strip head fire ignition technique was used and igniters applied fire near all sample trees to assure the fire spread to the duff mounds. With the litter, upper duff and lower duff moisture contents averaging 13.1, 26.7 and 35.5%, all duff mounds did ignite and smouldered into the next day. When smouldering combustion was complete, the duff spikes were measured and the woody fuel transects were re-measured.

Cambium injury under the burned bark was assessed in June 2004. Increment bores were used to remove samples of remaining bark and cambium to check for vitality; soft, pink tissue indicated live cambium whereas non-pliable, dark brown tissue was dead. Authentication of cambium vitality was periodically verified with a vital stain, orthotoldine (Hare 1965), typically when a visual determination of vitality was not definitive. Sampling was conducted on the bole at a random starting point within the zone that had the most visibly notable bark consumption and highest chance of cambium damage. When dead cambium was located, sampling continued at 2–5-cm intervals until live tissue was found. Then the next patch of dead cambium was sought. In this way a linear length of dead tissue could be recorded for the entire circumference of each tree. After sampling several trees in detail it became apparent that moderately charred bark features indicated the cambium was most certainly alive. In these places bark and cambium did not have to be sampled. With the linear amount of dead tissue measured and summed, the percentage of the circumference killed was computed as an index of extent of injury. The depth of the remaining bark was also measured at each sample point with a bark-depth gage or ruler to obtain a series of bark depths for both living and dead tissue beneath.

An annual examination of vitality of all 90 trees was made for 7 post-burn years looking for mortality or indicators of injury such as thin or discoloured crowns. Three general classes were possible: living-healthy, living-unhealthy and dead.

Data analysis

Detailed statistical analysis was not possible because true replicates of burned and unburned trees could not be established, therefore the project is considered a case study and conclusion may be applicable only for the study site. Following tests to verify homogeneity of variances and data normality unpaired *t*-tests compared pre-burn duff depths between complete and partial consumption micro-sites. Linear regression analyses were conducted to determine if a relationship existed between DBH and duff depths. Linear and non-linear regressions were used to determine if a cause and effect relationship existed between dead cambium amounts and either DBH or duff depth consumed. These analyses along with calculated means and standard deviations were conducted using SAS Enterprise Guide 4.2, 2008 (SAS Institute, Inc., Cary, NC).

Results

Means and standard deviations (s.d.) for tree attributes were similar between the burned and unburned trees, as follows: DBH, 91.7 cm (19.3) and 91.2 cm (19.1); height, 44.2 m (4.6) and 43.9 m (3.7); crown ratio, 0.62 (0.10) and 0.63 (0.10). Mean tree ages approached 400 years and ranged from 207 years for trees near 53-cm DBH to over 500 years for trees >125-cm DBH.

Mean pre-burn duff depths declined spatially from ~20 cm near the tree to 8 cm at the mound edge (Table 1). The deepest duff measured at 7.6 cm from the tree was over 50 cm and nearly 25% of these sample points had depths >25 cm compared with ~10% of sample points at 30.4 cm from the tree. At the mound edge duff depths were quite uniform with 75% of the depths between 5 and 10 cm and only 5% being >13 cm. A general trend of deeper duff for larger trees was noted with a modest, but significant linear relationship between DBH and depth at the 7.6-cm distance:

$$\text{Duff depth} = 4.85 + 0.16\ \text{DBH}\ \left(R^2 = 0.24, P = 0.006\right)$$

The surface fire readily spread through the litter layer on the duff mound, slowly igniting the duff and initiating smouldering combustion lasting for up to 24 h. Significant duff consumption and bark charring was apparent as mounds of white ash encircled all trees (Fig. 2). Nearly 100% of the duff at the 7.6- and 30.4-cm locations on all trees was consumed compared with almost 90% at the edge where 28% of the points had residual duff (Table 1). Pre-burn duff depths at the mound edge where 100% consumption occurred averaged (s.d.) 8.6 cm (1.1) deep compared with 4.8 cm (1.2) where some unburned duff remained, a significant difference ($t = 6.57$, $P < 0.001$).

Fine woody fuel loadings on the duff mound surface varied widely from 0.1 to 1.8 kg m^{-2}, averaging 0.7 kg m^{-2}. These loadings were 40% less than general stand values but percentage consumption approached 90% on the mounds, almost three times that for general stand fuels (Table 2). Even though percentage woody fuel reduction was high on all mounds, the amounts consumed varied widely, from 0.1 to 1.5 kg m^{-2}, a function of pre-burn loadings.

Table 1. Mean pre-burn duff depths (standard deviations) and percentage consumption at three distances from the tree boles
Sample sizes: 45, the number of trees; 135, the number of sample points, three per tree at each distance

	Distance from tree		
	7.6 cm	30.4 cm	Mound edge
Pre-burn duff depth, cm (s.d.) ($n = 45$)	19.8 (6.1)	16.3 (4.1)	7.6 (2.3)
Percentage of mean duff depth consumed ($n = 135$)	99%	99%	87%
Percentage of trees with 100% duff consumed ($n = 45$)	96%	96%	44%
Percentage of points with 100% duff consumed ($n = 135$)	99%	98%	72%

Fig. 2. Completely burned duff mound with significant consumption of basal bark (arrow).

Considerable but unquantified amounts of bark burned in association with near-complete duff burning, forming sizeable concave profiles (Fig. 2). Cambium sampling within this deep-char zone shows a decreasing frequency of trees in the higher dead cambium classes (Fig. 3). Minimal damage (≤10% circumference dead) was found on 78% of the trees and maximum injuries were slightly above 30% of the circumference.

No clear association was found between percentage dead cambium and either DBH or duff depth burned (Fig. 4) as polynomial functions best described the relationships but lacked correlation ($R^2 = 0.095$ for DBH and $R^2 = 0.047$ for duff burned). Trees with no cambium damage ranged from the smallest size classes to the largest and those with duff consumption from lowest to highest. Those with the most damage were in the intermediate size and duff depth burned classes.

A notable pattern emerges when comparing several hundred bark depths with associated cambium vitality (Fig. 5). Only one surviving sample was found beneath bark 0.8 cm or less thick. Somewhat less than one-half of the samples were alive under 1.3 cm of bark, but the percentage nearly doubled at 1.5 cm thick. Beyond this bark depth 90% or greater of the samples survived. No dead tissue was found beneath bark >2.0 cm.

Table 2. Pre-burn loadings and percentage consumption of duff mound woody fuels (n = 45) compared with general stand woody fuels (n = 17)

Fuel size class	Duff mound fuels		General stand fuels	
	Loading (kg m^{-2})	Reduction (%)	Loading (kg m^{-2})	Reduction (%)
1-h	0.1	97	0.1	47
10-h	0.2	89	0.4	34
100-h	0.4	85	0.7	28
Total	0.7	87	1.2	32

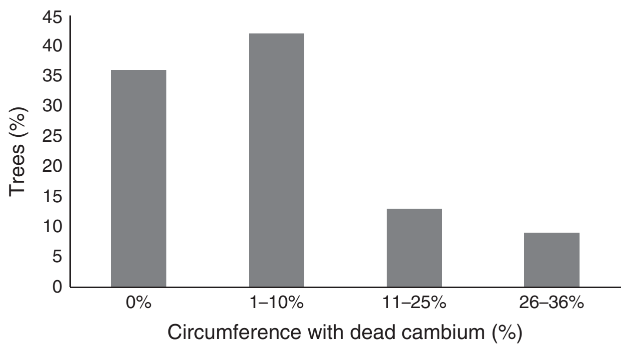

Fig. 3. Percentage of trees ($n = 45$) with specific percentages of circumference having dead cambium.

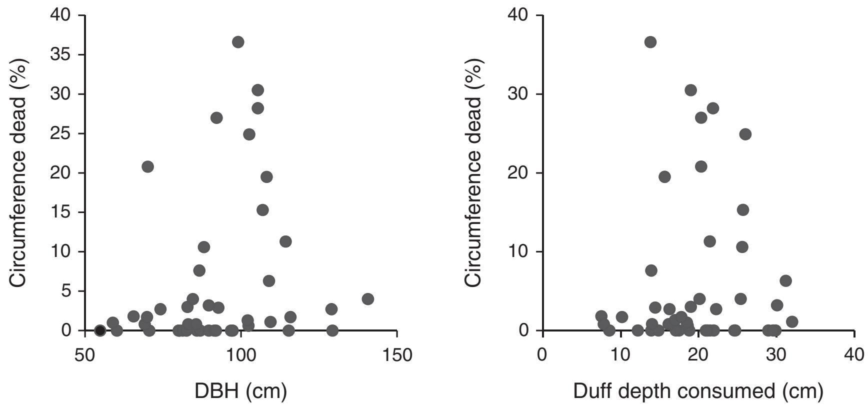

Fig. 4. Percentage circumference dead by diameter at breast height (DBH) (left) and mean duff depth consumed (right) ($n = 45$).

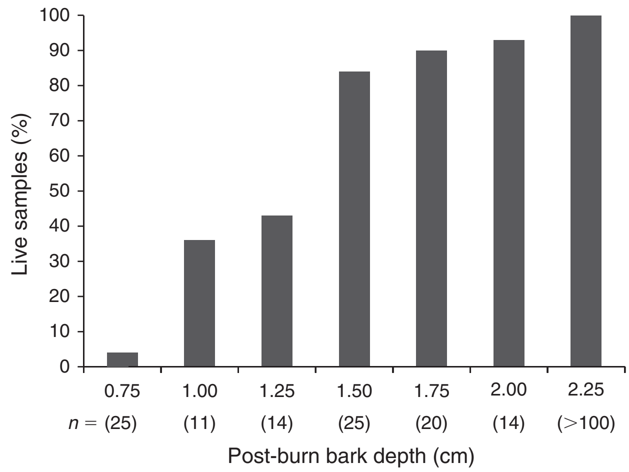

Fig. 5. Percentage of cambium samples alive by residual bark thickness (n, number of samples for each bark thickness).

The visual assessment of tree vitality conducted annually for 7 post-burn years revealed no mortality for burned or unburned trees and no clear crown indicators of tree stress were identified.

Discussion

This project is perhaps the first detailed investigation of the effects of deep duff mound burning in old growth western larch. This stand exceeds the minimum requirements for old growth designation in the Northern Region of the USDA Forest Service of 20 trees ha^{-1}, >53-cm DBH and >170 years old (Green *et al.* 1992). Because areas occupied by this old growth condition provide unique habitat, have greatly declined in vigour in past decades and are currently rare, they are the focus of detailed attention and analysis for forest conservation and restoration (Lesica 1996; Abella *et al.* 2007). Given that relatively frequent fire played a significant role in the development and maintenance of this forest condition historically, prescribed fire is the logical choice in a restoration strategy.

Because of the generally high resistance to fire injury by larch, severe fire effects under prescribed burning conditions are typically not a concern (Arno and Fischer 1995). However, one area of uncertainty with little documentation is possible injury resulting from consumption of uncharacteristically deep duff mounds. Basal wounding from long-smouldering fires has resulted in mortal injury to large trees of other fire-adapted species including ponderosa pine (Ryan and Frandsen 1991; Hood *et al.* 2007; Fowler *et al.* 2010), longleaf pine (Varner *et al.* 2007) and sugar pine (*Pinus lambertiana* Dougl.) (Nesmith *et al.* 2010). Of these studies, only Ryan and Frandsen (1991) reported tree ages or specific fire history, which are indicators of past fire exposure of sample trees and the most recent fire-free period. In this study, the youngest tree – 207 years old – likely experienced one to three historic fire as the last time the area burned was 1859 (Arno *et al.* 1997) and 300–500-year-old trees were probably exposed to seven to nine historic fires. The most recent fire-free period – 144 years – was six times the length of the mean historic fire interval of 24 years and over three times the length of the longest historic interval of fire absence – 42 years. Lack of disturbance typically results in dead biomass accumulation especially in dry micro-sites such as beneath tree crowns where deposition exceeds decomposition (Covington and Moore 1994; Arno *et al.* 1997; Hessburg and Agee 2003; Ritchie *et al.* 2008). Therefore, given the age classes and historic fire intervals, this current fire-free period is truly an anomaly for this stand leading to unprecedented duff mound accumulations and unknown burn effects.

The mean duff mound depth nearest the bole approached 20 cm but amounts >25 cm were common (Table 1). At 30.4 cm from the bole the duff depth mean declined to just over 15 cm. These values are at the high end of reported duff mound depths for other large conifers. Fowler *et al.* (2010) found duff depths of large south-western ponderosa pine averaged 11 cm with mean maximums measuring near 18 cm and Sackett (1988) reported depths up to 20 cm for the same species. Hood *et al.* (2007) measured depths varying from ~4 to 14 cm adjacent to ponderosa and Jeffrey pine (*Pinus jeffreyi* Balf.). Sugar pine duff depths were reported to average 9 cm (Nesmith *et al.* 2010) and Varner *et al.* (2007) observed duff mound depths of 10–13 cm in an old growth longleaf pine stand. Duff mound depths similar to the current study averaged 18 cm in an old growth ponderosa pine stand in Montana with maximums approaching 40 cm (Ryan and Frandsen 1991).

Duff mound consumption within 60 cm of the bole around all trees was nearly complete with a mean moisture content of 35% and a few samples as high as 50% (Table 1). This is consistent with other duff mound burning studies in various pine species (Ryan and Frandsen 1991; Hood *et al.* 2007; Varner *et al.* 2007). In contrast with the thorough consumption of the inner 60 cm of the mounds, 28% of the points at the mound edge had incomplete duff consumption and a corresponding mean pre-burn depth of 4.8 cm, which was significantly less than the 8.6-cm pre-burn depth for points where 100% consumption occurred. It appears that deeper pre-burn duff led to higher overall amounts and percentages of consumption as was also indicated by Sweeney and Biswell (1961) and Harrington (1987). Note that mound edge duff consumption has no influence on stem heating but could affect surface roots (Swezy and Agee 1991; O'Brien *et al.* 2010), which were not studied here.

Lengthy burning of surface woody fuels may increase consumption of duff by drying and igniting duff that otherwise would not likely burn from a short duration surface fire (Norum 1977; Brown *et al.* 1985). In the present study, woody fuel consumed on individual mounds was quite variable (0.1–1.5 kg m^{-2}) and since duff consumption was nearly 100% on all mounds (Table 1) the amount of woody fuel burned evidently had little influence on duff burning under these conditions. In fact, it is conceivable that the thorough duff mound burning led to the near complete (87%) woody fuel consumption (Table 2) because only 32% of fuels not associated with duff mounds were consumed. The conditions of this study do not preclude the possibility that under conditions where self-sustained combustion in duff would not occur, woody fuel burning could contribute to additional duff burning. Hood *et al.* (2007) similarly described almost 90% woody fuel consumption on mounds where duff burning was near 100% and only 57% woody fuel consumption away from mounds.

Cambium injury from conductive heating is dictated by the opposing features of heat flux duration from smouldering deep mounds and the protective attributes of the bark, primarily thickness. Ryan and Frandsen (1991) point out that as trees grow, conflicting characteristics ultimately determine extent of cambium injury; larger trees typically have thicker bark for greater protection but also greater duff biomass with extended burning times. It is noteworthy that substantial bark consumption as seen here has rarely been reported. Ryan and Frandsen (1991) also noted that the reduction in bark thickness brings the combustion zone closer to the cambium. Ryan (1982) developed bark char categories as surrogates to destructive sampling and indicators of injury. They generally indicate a significant increase in probability of tree mortality under the most severe bark char condition, e.g. Beverly and Martell (2003), Peterson and Arbaugh (1986) and McHugh and Kolb (2003). However, Hood (2010) points out that there are clear species differences in sustained injury as thin bark trees frequently suffer damage with light charring and thick bark trees may incur little damage from deep char. The current study of thick bark larch adds validity to this assessment.

With thick basal bark common on large western larch significant cambium mortality even under deeply charred bark may not be expected, as suggested by Hood *et al.* (2008). Cambium vitality was assessed where bole charring was most striking (Fig. 2) because it was clear by the burned concave profiles that moderate to substantial amounts of bark had been consumed. This indicates that the combustion zone had moved closer to the cambium and perhaps the outer bark had even become an additional heat source rather than a continuous insulator. An example in eucalypts demonstrates that one thicker bark species, *Eucalyptus obliqua* (L.Her) is more prone to fire-caused cambium death than is a thinner bark species, *Eucalyptus radiata* (D.Don), because of highly flammable bark on the former (Gill and Ashton 1968). This is somewhat similar to duff initially insulating mineral soil from heat of a surface fire until it burns and then conducts heat directly into the soil (Frandsen and Ryan 1986; Michaletz and Johnson 2007).

The relationship between final bark thickness and cambium vitality shown in Fig. 5 reveals a critical bark depth for living cambium at ~1.5 cm, at which >80% of samples survived. This suggests that, under the conditions of this study, bark thickness values >1.5 cm have sufficient insulating properties to protect the underlying living tissue even with the close combustion zone. Near-complete tissue mortality was found beneath <1.0-cm bark, indicating that sufficient heat load is reaching the cambium to exceed the lethal limit. In the 1.0–1.3-cm range conducted heat is evidently bordering the lethal threshold given that 35–45% of the samples survived. Peterson and Ryan (1986) estimated that 4 cm of bark was generally sufficient to protect cambium of several conifer species in logging slash burns. Comparing results to this larch study, cambium may be protected under thinner residual bark due to the lower intensity of duff mound burning.

Even with considerable duff mound consumption and bark burning, 78% of the trees had only 10% or less of the circumference with dead cambium (Fig. 3). However, the remaining 22% of trees had up to 36% circumference dead, which signifies that a level of vulnerability does exist. Studies that have examined fire injury have generally found some dead cambium but, like here, little or no mortality. In the only other study where the complete circumference was examined, Fowler *et al.* (2010) found cambium injury averaging 15–25 cm wide in 17% of the ponderosa pine in a duff burning study. In California, Hood *et al.* (2007) discovered that 8, 33 and 48% of quadrant samples (four per tree) were dead in 191 fire-injured pines in three prescribed burns and Ryan and Frandsen (1991) found 45% mortality of ponderosa pine cambium samples from duff burning in Montana. From studies that have examined basal cambium injury from duff mound burning, a fundamental question has apparently not been asked: if partial girdling is common, isn't extensive girdling possible?

For the western larch in this study, explanations for the extents of cambium mortality occurring on some trees and at irregular locations (Fig. 3) are not obvious. If tree diameter is a relative gauge of bark thickness (Ryan and Frandsen 1991; Hood 2010) and duff depth consumed is an indicator of burning residence time (Sackett 1988; Ryan and Frandsen 1991), Fig. 4 suggests no clear relationship between these features and cambium death. With this coarse assessment of bark thickness and mean duff consumption failing to explain cambium vitality, a finer scale evaluation of the variability of these key opposing factors was made at the subsample level.

Pre-burn basal bark thickness was not measured on burn trees but bark thickness data were available from five similar size larch in an adjacent area as indicators of probable thickness for the study trees. With four basal bark measurements per tree in the cardinal directions, the average thickness per tree varied from 10.2 to 16.0 cm with a thickness range per tree of a low of 2.5 cm to a high of 9.1 cm. Therefore, the expected variable bark thickness on individual trees could play a role in potential irregular heating effects also suggested by Peterson and Ryan (1986) and Jones *et al.* (2004). In addition, the duff consumption depths in Fig. 4 are means per tree but an estimation of pre-burn depth variability is evident by comparing point samples around each tree. The data reveal that 24% of the trees had maximum to minimum duff depths varying by ~5 cm, 51% had depths varying by ~10 cm and 25% had depths varying by >20 cm. This implies that burning residence time would likely be significantly longer at one point near a tree than at another point, given equal consumption rates per unit depth. Therefore, the mean duff depth per tree could have limited value for injury appraisal for thick bark trees if variability is high. This suggests that the variability of both bark thickness and duff depth around a tree is potentially high enough such that adjoining combinations of relatively thin bark and deep duff may occur randomly resulting in intermittent cambium kill. Ryan and Frandsen (1991) found variable duff depths around individual ponderosa pine where deeper duff apparently led to greater adjacent cambium mortality. Bark thickness variability was not discussed, however.

Tree girdling studies have suggested variously that without supporting damage, such as crown scorch or bark beetle attack, tree mortality is probable only if >75% of the circumference has dead cambium (Ryan 1982; Filip *et al.* 2007) whereas others indicated that near 100% girdling is necessary (Noel 1970; Michaletz and Johnson 2007). Fowler *et al.* (2010) found two south-western ponderosa pine in their study with up to 75% dead cambium that were alive after 3 years, and Ryan and Frandsen (1991) reported that four of six ponderosa pine with three to four dead samples from four quadrants died within 6 years. No larch mortality has occurred within 7 years of the prescribed burn in the current study. This was not surprising given the modest amount of cambium mortality discovered. This level of discontinuous cambium injury was conceivably due to the infrequent spatial coincidence of relatively thin bark and deep duff. Supplementary testing of this theory in subsequent research should examine micro-site relationships between adjacent duff depth burned, bark consumed and remaining, and cambium injury. Additionally, continuing research should evaluate the effects of sub-lethal cambium injury on subsequent growth rates to determine if vigour has been compromised (Skov *et al.* 2005).

In summary, the conditions of this autumn prescribed burn with this site's old growth larch and duff mound characteristics resulted in nearly 100% consumption of deep duff mounds and considerable basal charring including bark burning on all sample trees. Nonetheless, because basal injury on all trees was sub-lethal after 7 years, the use of prescribed fire for old growth larch management under similar conditions should be considered without duff mound hazard mitigation. It is noteworthy, however, that Agee (2003) found delayed fire injury mortality in old conifers up to 13 years after fire.

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