Process and patterns of duff consumption in the mixedwood boreal forest

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Abstract: Positive tree recruitment in the boreal forest is restricted to patches from which the duff (organic layer) has been removed by fire. Duff consumption occurs by smoldering combustion, propagation of which is determined by bulk density, moisture content, and depth. This study investigated interactions among these factors, their spatial distribution, and spatial patterns of duff consumption in two wildfires. A hypothetical positive relationship between moisture content and depth was observed in a laboratory study. Duff characteristic data were collected from two burns and comparable unburned areas of mixedwood forest in western Canada to describe and explain patterns of duff consumption within and between top slope Pinus banksiana Lamb. – *Picea mariana* (Mill.) BSP stands and lower slope pure stands of *Picea mariana* on glaciofluvial bogs. In burned stands, bulk density did not differ significantly between stands, while depths were significantly greater in Picea stands than in Pinus–Picea stands as depth limited smoldering in the thin duff of Pinus–Picea stands. With dry duff, smoldering was propagated regardless of depth resulting in no differences between stand types. The spatial correlation between burned patches and fire-killed trees was explained by within-stand spatial variation in duff moisture due to precipitation interception by tree crowns.

Résumé : La régénération après feu en forêt boréale est limitée aux parcelles où l’humus (horizon organique) a été détruit par le feu. L’humus est consummé par la combustion limitée dont la propagation est déterminée par la densité appa- rente, la teneur en humidité et la profondeur. Cette étude a évalué les interactions entre ces facteurs, leur distribution spatiale et les patronages spatiaux de destruction de l’humus pour des feux de forêt. L’hypothèse d’une relation positive entre la teneur en humidité et la profondeur a été confirmée par une étude en laboratoire. Les données caractéristiques de l'humus ont été recueillies dans deux brûlés et des superficies non brûlées et comparables de feutre meuglé de l'intérieur du Canada pour décrire et expliquer les patrons de destruction de l'humus à l'intérieur et entre des peuplements de *Pinus banksiana* Lamb. – *Picea mariana* (Mill.) BSP de haut de pente et des peuplements purs de *Picea mariana* de bas de pente sur des versants fluvioglaciaires. Dans les peuplements moins brûlés, la densité apparente ne varie pas significativement entre ces peuplements alors que la profondeur est significativement plus importante dans les peuplements de *Picea*. Dans le cas d’un humus humide, la destruction est significativement plus prononcée dans les peuplements de *Picea* que dans ceux de *Pinus–Picea* car la profondeur limite la combustion telle dans l’humus mince des peuplements de *Pinus–Picea*. Avec un humus sec, la combustion lente se propage à peu près que soit la profondeur, n’entrainant pas de différence entre les types de peuplement. La corrélation spatiale entre les parcelles brûlées et les ar- bres tués par le feu s’explique par la variation spatiale dans la teneur en humidité de l’humus à l’intérieur des peuplements due à l’interruption des précipitations par la cime des arbres.

Introduction

North American boreal forest trees recruit primarily in the first 6 years after wildfires (DenRochers and Gagnon 1997; Gutsell and Johnson 2002). The initial post-fire robor forms the canopy of the mature forest and is not subsequently re-placed by later establishing trees because of the length of the fire cycle, which is generally shorter than the life-span of the tree species (Johnson 1992). Therefore, recruitment within the first few years after a fire is critical in determining the composition, density, and spatial distribution or trees in mature boreal forest stands. Recruitment of *Pinus banksiana* Lamb., *Picea mariana* (Mill.) BSP, and *Picea glauca* (Moench) Voss is inversely related to the amount of duff remaining after the fire (Jameson 1961; Chróściewicz 1970, 1974, 1976; Zasada et al. 1983; Thomas and Wein 1985; Weber et al. 1987). Duff is defined as the layer of organic matter on the forest floor (the F and H layers) between the litter (L) and the mineral soil (Van Wagner 1972; Canada Soil Survey Committee 1978). In the boreal forest, duff is derived from litter (leaves and twigs from the trees, shrubs, and herbaceous plants) as well as from mosses. Since successful seedling establishment is virtually re- stricted to areas from which duff has been removed by fire, there has long been an interest in duff consumption by forest fires (e.g., Chróściewicz 1959; Beaufait 1962; Adams 1966;...
Cayford (1966). Two approaches to modeling duff consumption have been used: (i) empirical regression models which correlate average duff consumption with various combinations of independent variables including indices of duff moisture (e.g., Little et al. 1986; Reithardt et al. 1989; Brown et al. 1991), and (ii) a process-based model of radiative heat transfer from the flaming front to the duff (Van Wagner 1972). These approaches predict only the mean amount of duff removed, despite observations that duff is consumed by wildfires in distinct deeply turned patches scattered among unburned or scarcely burned duff (Chrosniewicz 1976; Dytmus and Norum 1983; Zasadziska et al. 1983). Consequently, we propose a third approach here that uses an understanding of the combustion process by which duff is consumed to identify the controlling variables and to explain patterns of duff consumption within stands, among stands within fire, and between different fires.

Smoldering combustion has been recognized as the major process by which duff is consumed (Dytmus and Norum 1983; Frandsen 1991; Hungerford et al. 1995; Lathan and Williams 2001). Duff is not consumed to any extent by flaming combustion because of its relatively high content of lignin, which does not readily release volatiles upon heating, and its high packing ratio, which prevents rapid enough heat release to sustain flames (see Miyashita 2001). Smoldering combustion differs from flaming combustion in being a much slower, non-flaming oxidation of a porous, carbonized solid (Dytmus 1985; Olemmer 1985). Smoldering is generally modeled as a two-step process: an endothermic process of pyrolysis (thermal degradation) of the solid fuel, releasing volatiles, and forming char and an exothermic process of char oxidation. Propagation of smoldering depends on sufficient heat being transferred from the exothermic oxidation zone to the virgin fuel to cause pyrolysis and char formation. Thus, factors that explain extinction (non-propagation) of smoldering are those that influence either the rate of heat generation by oxidation or the rate of heat transfer from the oxidation zone to the virgin fuel.

Studies of smoldering in various materials (e.g., Moussa et al. 1976; Olemmer 1996) have led to the conclusion that the rate-limiting factor for smoldering of dry fuels is oxygen availability (i.e., the rate of diffusion of oxygen to the char oxidation zone), which determines the rate of oxidation and hence the rate of heat generation. However, Peter (1982) found that for smoldering in beds of peat or sawdust with varying moisture content, fuel moisture, rather than oxygen availability, was the limiting factor, since latent heat of vaporization constitutes a significant heat sink and, thus, decreases the heat available for pyrolysis and char formation. Also, since heat transfer within the fuel bed between the exothermic oxidation zone and the endothermic pyrolysis zone is primarily by conduction (Moussa et al. 1976), thermal diffusivity of the fuel, which is a function of fuel density, plays an important role in propagation of smoldering. Finally, heat losses can occur between the zone of oxidation, where heat is being generated, and the zone of pyrolysis, which requires sufficient heat for maintenance of the pyrolytic process. In particular, with very thin fuel beds, convective heat losses from the surface of the fuel bed can be significant enough to decrease effective heat transfer to the pyrolysis zone. Assuming horizontal propagation of smoldering, the area of the oxidation zone is larger in thicker fuel beds, and therefore, proportional convective heat loss from the fuel bed surface is less (i.e., more of the heat is trapped within the fuel bed and not lost convectively to the air above). Thus, Palmiter (1957) and Peter (1992) found critical minimum depths of dry fuel beds that could propagate smoldering. As explained above, the three variables we would expect to be controlling smoldering propagation in duff are moisture content, density, and depth. Also, given the role of fuel moisture (as a heat sink in evaporation) and depth (which influences the proportion of heat generated by char oxidation that is lost through convection) in smoldering propagation, we should expect a positive relationship between fuel moisture content and the minimum fuel depth required for smoldering propagation, i.e., the higher the fuel moisture level, the greater the minimum depth of fuel required.

Potentially, all three of these variables (moisture content, density, and depth) might be expected to vary because of both hillslope position and canopy coverage. Soil moisture varies along hillslopes (O’Leary 1981; Otis et al. 1992; Bridge and Johnson 2000) and soil and duff moisture have been shown to be controlled by capillary movement of water between the duff and mineral soil (Samara et al. 1985). In the mixedwood boreal forest of western Canada, Bridge and Johnson (2000) found a moisture-nutrient gradient on glacial till substrate that ran from drier, less nutrient-rich stands at the top slopes dominated by Pinus banksiana and Picea mariana to the wetter, more nutrient-rich, almost pure stands of Picea mariana on middle to bottom slopes. Thus, the top slope Pinus-Picea stands would be expected to have drier fuel than the middle to bottom slope Picea stands. Duff moisture would also be expected to exhibit within stand variability because of interception of precipitation and radiation by tree crowns. Precipitation interception would reduce input of moisture to the duff directly beneath tree crowns, while interception of outgoing terrestrial radiation by tree crowns at night would result in less radiative cooling at the ground surface and, hence, less dew formation. Thus, we would expect duff to be generally drier directly beneath tree crowns than between tree crowns, resulting in a distinct pattern of duff moisture within stands.

Bulk density of duff may also vary along hillslopes because of differences in litter composition, which, in turn, would be influenced by hillslope changes in species composition. Duff density is not only a factor in heat transfer (in the smoldering process) but also influences the rate at which duff dries in the absence of precipitation. Because of differences in drying rates, the Canadian Forest Fire Weather Index System (Van Wagner 1987) distinguishes two categories of soil organic matter besides litter: (i) a 7-cm layer of loosely compacted decomposing organic matter with a bulk density of 0.07 g cm⁻³ and (ii) a deep 18-cm layer of compact organic matter with a bulk density of 0.45 g cm⁻³. Examples of duff representing the first type include Pinus banksiana and Pinus resinosa Ait. stands in Ontario (Van Wagner 1972), while examples of the latter type include Abies balsamea (L.) Mill. and upland Picea mariana stands in northern Quebec (Van Wagner 1974).

Moisture content of the first type of fuel is estimated using the duff moisture code (DMC) while moisture content of
the latter type is estimated with the drought code (DC). Both indexes are numerical ratings of mean moisture content, intended to give an indication of the consumption by fire of these two fuel types (Canadian Forestry Service 1984). In addition, the DC is an indication of seasonal drought effects on forest fuels. These indexes use noot weather measurements and empirical drying curves and are formulated to increase with increasing dryness (Van Wagner 1987). Because of differences in drying rates of these two fuel types and the rainfall required to saturate them, the response rates of the DMC and DC to weather conditions differ. Furthermore, both react more slowly to changing weather conditions than the fine litter fuels whose moisture content largely determines the fire intensity.

Duff depth may also vary both between and within stands. Duff depth is a product of the relative rates of litter input and decomposition. Litter input rates would be a function of stand density and composition. Decomposition rate is both temperature and moisture dependent, as well as being influenced by litter quality characteristics such as pH, base content, and presence of polyphenols or tannins (Williams and Gray 1974; Mason 1976). Duff depths in Pinus stands are generally less than that found in Picea stands in the eastern Canadian boreal forest (Van Wagner 1972, 1974). Duff depths may also vary within stands, since needle litter from the trees would accumulate directly beneath tree crowns and to a lesser extent between tree crowns.

Therefore, if the three controlling variables of duff moisture, bulk density, and depth vary both along hillslopes and within stands, we should also expect duff consumption to vary at both scales. Furthermore, since duff moisture content is largely influenced by weather (the two duff moisture indexes, DMC and DC, are determined by daily weather data), it would also be expected to differ temporally and, hence, vary between different fires in similar stand types. Since few past studies have addressed the phenomenon of duff consumption from a process approach, one objective of this study was to apply what is known about the process of smoldering combustion to predict some general patterns of duff consumption (e.g., the relationship between moisture content and depth). We conducted a laboratory experiment to test the hypothesis that critical values of moisture content and depth required for smoldering propagation are positively related. A second objective was to investigate how duff moisture, bulk density, and depth vary between stand types along hillslopes on well-drained glaciofluvial substrate in the mixedwood boreal forest of western Canada. Finally, since few, if any, past studies of duff consumption have investigated spatial patterning of duff consumption, a third objective was to describe patterns of duff consumption in two areas burned by natural wildfires and to use the results from the first two objectives to explain these patterns.

Materials and methods

Study area

The two burns used in this study are located within the mixedwood boreal forest zone (Rowe 1972) in central Saskatchewan. The upland forests are dominated by Pinus banksiana, Picea mariana, Picea glauca, Populus tremuloides Michx., and Abies balsamea (L.) Mill. (Dix and Swan 1971; Bridge and Johnson 2000), while the lowland forests are dominated by Picea mariana and Larix laricina (Du Roi) K. Koch (Jeglum 1972, 1973).

Most fires in this region occur between April and October with >95% of the total area burned occurring in April, May, and June (Johnson et al. 1999; Weir et al. 2000). The Bittern Creek fire (53°35′N, 105°35′W) was ignited by lightning on June 5, 1996, and burned approximately 900 ha of forest within the Weyerhaeuser Forest Management Licence Area (FMLA). The Waskeeta Lake fire (54°04′N, 186°02′W) was ignited by lightning on July 7, 1998, and burned 1738 ha of forest within Prince Albert National Park and in the Weyerhaeuser FMLA. In both fires, most of the area burned
during the first 3 or 4 days. Both were crown fires (fire-line intensities of at least 6000 kW·m$^{-2}$), in which the litter layer was consumed and all trees were killed. However, dust moisture conditions differed considerably between the two fires. Figure 2 plots the DMC and DC during the fire season (May 3 to August 8) in 1996 and 1998. The values for the DMC were 20–28 on June 5–7, 1996 (Julian dates 157–159), during the Bittern fire and 45–59 on July 7–10, 1998 (Julian dates 188–191), during the Waskesiu fire. The DC values were 252–261 during the Bittern fire and 510–537 during the Waskesiu fire. Thus, the dust was obviously much lower during the 1998 Waskesiu fire than during the 1996 Bittern fire.

Data from each of the two burns were collected within a year after the fires from eight upland stands dominated by *Pinus banksiana*—*Picea mariana* and eight upland stands dominated by *Picea mariana*, braceforth referred to as *Pinus-Picea* and *Picea stands*, respectively. Only stands with no evidence of permanent standing water (i.e., gleyed or mottled mineral soils) and homogeneous in stem density and size were selected. All were mature stands when the fires occurred with ages ranging between 90 and 120 years (stand age was estimated by obtaining cores as close to the base as possible of three canopy trees in each stand). We also collected data from eight comparable unburned *Pinus-Picea* and eight unburned *Picea* stands located adjacent to the two burns (Table 1).

**Laboratory study**

To test the hypothesized relationship between dust moisture and the depth of dust at which smoldering combustion will continue or cease, we needed commercial sphagnum peat in lieu of dust in a laboratory experiment. Previous studies had found that peat is similar to dust in particle size distribution and bulk density (Fronander 1987; Hartford 1989; Hawkes 1993) as well as in chemical composition (Bracewell and Robertson 1987). The availability of relatively uniform commercial peat made replication of samples in the tests easier.

The burn box (22 x 22 x 14 cm) was constructed of 1.3 cm thick ceramic board (Corotone Corp., Brooklyn, N.Y.). Thermal conductivity of the dry ceramic (0.64 W·m$^{-1}$·K$^{-1}$ at 10°C) is similar to that reported by Hiltén (1982) for dry peat (0.56 W·m$^{-1}$·K$^{-1}$ at 10°C). The top and one end of the box were left open. The peat and ceramic board were equilibrated to the moisture content desired for 2 or 3 days before each test. For each burning trial, the box was filled to a uniform depth, which was varied from 0.2 to 5 cm; the surface area of the heated bed was constant at 308 cm$^2$ (22 x 14 cm). We attempted to maintain as much as possible a relatively constant dry bulk density of the peat through packing; mean density was 0.097 g·cm$^{-3}$. Volumetric moisture content of the peat was varied from 9 to 20%. Moisture content of each sample was measured with a ThetaProbe type ML2x and Theta-meter type HI41 (Delta-T Devices Ltd., Cambridge, U.K.). Using a singleottwo-point gravimetric calibration for peat, the ThetaProbe had an accuracy of 1%.

The vertical surface of the peat at the open end of the box was heated with a Bunsen burner until 1 cm of peat was ignited. Then, the peat was left to burn on its own. If the whole volume of peat was consumed in a trial, self-sustained smoldering propagation was determined to be successful at that depth and moisture content. If the peat ceased smoldering once the external heat source was extinguished, self-sustained smoldering propagation was considered to have failed at that depth and moisture content. A total of 56 trials with varying depth–moisture combinations were conducted.

**Field study**

As explained in the Introduction, two factors that influence propagation of smoldering combustion are bulk density and depth of the fuel. To determine the importance of differences in these factors in explaining dust consumption patterns at the hillslope scale, we collected dust samples from the unburned stands and compared depth and bulk density of dust between *Pinus-Picea* and *Picea* stands. Within each of the two stand types, eight 10 x 10 m plots were established. At the 81 intersection points of grid lines established at 1-m intervals within each plot, the litter layer was removed and a 5.4 cm diameter core of the dust was collected down to the mineral soil. Where the sampling point fell on the location of a standing or fallen tree or surface root root, no dust sample could be collected; thus, the number of samples per plot...
Table 1. General characteristics of the Pinus banksiana – Picea mariana and Picea mariana dominated stands in the Bittern and Waskesiu burns and in the comparable unburned stands.

<table>
<thead>
<tr>
<th>Pinus-Picea</th>
<th>Bittern</th>
<th>Waskesiu</th>
<th>Unburned</th>
<th>Bittern</th>
<th>Waskesiu</th>
<th>Unburned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of stand ages (years)</td>
<td>90-120</td>
<td>107-111</td>
<td>100-107</td>
<td>90-120</td>
<td>104-111</td>
<td>85-100</td>
</tr>
<tr>
<td>Mean tree density (no./100 m²)</td>
<td>33</td>
<td>40</td>
<td>40</td>
<td>67</td>
<td>81</td>
<td>81</td>
</tr>
<tr>
<td>Mean tree basal diameter (cm)</td>
<td>15.8</td>
<td>15.7</td>
<td>16.0</td>
<td>11.3</td>
<td>10.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Species composition (% of stand basal area)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pinus banksiana</td>
<td>47.2</td>
<td>50.4</td>
<td>62.6</td>
<td>1.8</td>
<td>3.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Picea mariana</td>
<td>21.1</td>
<td>49.5</td>
<td>35.0</td>
<td>88.7</td>
<td>96.6</td>
<td>93.5</td>
</tr>
<tr>
<td>Other conifers*</td>
<td>2.5</td>
<td>0</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
<td>1.9</td>
</tr>
<tr>
<td>Deciduous*</td>
<td>2.5</td>
<td>0.1</td>
<td>0.3</td>
<td>2.9</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Undetectable</td>
<td>6.7</td>
<td>0</td>
<td>0.0</td>
<td>5.7</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Picea glauca and Picea banksiana.

Note: All values are means of the eight stands in each group. Stem densities and basal diameters areas are for standing stems only (dead stems in the two burns and tree stumps in the unburned stands).

The collectors were placed on the east side of each tree. The trees were located at different sites and were selected such that their tree crowns were not touching those of adjacent trees. A rain gauge was also placed in a large opening at each site to measure precipitation. Throughout (and its inverse, interception) were calculated as a percentage of precipitation recorded in the gauge placed in the opening. Data were collected for 2-3 rain events per tree with a total of 10 rain events per species. The number of rain events differed for the five trees in the sample, because they were located at different sites and much of the summer precipitation in this area is from local convective storms. A t-test was conducted on the ascii-transformed data to compare interception by the two tree species.

Duff depths were measured in 10 x 10 m plots in the Bittern and Waskesiu burns in the same manner as described previously for unburned stands, with eight plots sampled in Pinus-Picea and eight in Picea stands within each burn. The distributions of duff depths by site (Bittern, Waskesiu, unburned) and by stand type (Pinus-Picea and Picea) were plotted, and the normality (skewness) of each distribution was tested using the z1 statistic and computing the Z, value (Zar 1996). While the unburned stands are expected to have a normal distribution of duff depths, paucity of duff consumption in the burned stands should result in a positively skewed distribution because of the large number of near-zero duff depths.

To investigate the pattern of duff consumption in the two burns, the same 10 x 10 m plots were used as above. Each plot was subdivided into one hundred 1 x 1 m subplots with grid lines at 10-cm intervals. Within each subplot, all burned holes in the duff (hereafter called patches) were mapped, and their areas were visually estimated using the grid as a guide. Also, all standing and fallen stems were mapped, identified to species where possible, and their basal diameters (cm) measured. Both burn sites were examined soon after the fire. Fallen or standing stems could be identified as having been live or dead at the time of the fire by the extent and type of charring. A distribution of patch sizes was produced for each burn with data from the Pinus-Picea and Picea stands separated. The percentage of the area in patches was compared between the two fires and also be-
tween stand types within fines. Chi-square analyses were used to determine the statistical significance of the spatial relationship between the burned patches and bases of standing stumps by comparing the observed number of stumps within or touching patches with the number expected, given both the density of stumps and the proportion of total stand area covered by patches (Nordcliff 1982).

Results

Relationship between moisture content and critical fuel depth

Of the 56 burning trials with varying combinations of fuel depth and moisture content, 22 resulted in extinction or nonpropagation of smoldering while 34 resulted in self-sustained smoldering propagation. Figure 3a shows a plot of the 22 depth-moisture combinations that resulted in extinction. Depth and moisture content were highly significantly correlated ($r = 0.83, p < 0.0001$). To use these data to determine the upper limits of depth-moisture combinations that allow smoldering propagation, a regression line was obtained ($y = 12.358 + 1.83x, F = 44.57, p < 0.0001$) and plotted (Fig. 3b). We would expect generally that depth-moisture combinations above the line would result in extinction, while those below the line would allow smoldering propagation. As shown in Fig. 3b, 30 of the 34 trials in which smoldering propagation occurred fell either extremely close to the line or below and only 4 were above the line.

Patterns of duff bulk density, depth, and moisture in the field

The results of the laboratory study indicate that if duff bulk density is similar in field situations, duff moisture and depth should be the important variables in determining smoldering propagation and, hence, duff consumption. We obtained very similar distributions of duff bulk density for unburned Pinus-Picea and Picea stands (Fig. 4) and the means of 0.092 and 0.094 g cm$^{-2}$, respectively, were not significantly different ($t = 0.66, p > 0.05$). However, duff depth in unburned stands did differ significantly between the two stand types (Fig. 5) with duff depths of 6.9 ± 0.12 cm (mean ± SE) for Pinus-Picea stands and 10.3 ± 0.11 cm for Picea stands ($t = 20.31, p < 0.0001$). Thus, duff depth varies along hillslopes with top slope Pinus-Picea stands having thinner duff than middle to bottom slope Picea stands.

As explained in the Materials and methods, we were unable to determine duff moisture differences along hillslopes, since the moisture probe did not allow measurements in the thin duff occurring in top slope Pinus-Picea stands. Howev- er, an unpublished study by S.T.K. Vo and E.A. Johnson found that in a hillslope water budget study, duff in top slope Pinus-Picea stands is drier than duff in Picea stands. We did look at duff moisture variation within two Picea-dominated stands in relation to the location of tree crowns, i.e., each of the 361 sample points in each stand was recorded as in a gap with no tree crown directly overhead or by the species of tree whose crown was directly above the sample point. The first stand was pure Picea mariana, while the second stand also had some A. balsamea, Populus balsamifera, and Populus tremuloides. The overall mean volumetric moisture contents for the duff differed significantly between the two stands (12.8 vs. 10.8%; $t = 7.54, p < 0.001$). However, since the two stands were measured on different days, we were not interested in comparing among stands but were collecting these data to investigate within stand variability in duff moisture. Within each stand, moisture contents of duff beneath tree crowns were significantly lower than in gaps. In one stand, the moisture contents were 12.4% beneath trees and 13.5% in gaps ($t = 2.68, p < 0.01$), based on 230 and 131 measurements, respectively. In the other stand, the mois- ture contents were 10.4% beneath trees and 11.2% in gaps ($t = 1.69, p < 0.05$), based on 179 and 76 measurements, re- spectively. Thus, there does appear to be variation in duff moisture based on location either beneath or between tree crowns.

To partially explain within stand variation in duff mois- ture, we measured precipitation interception by Pinus banksiana and Picea mariana. Precipitation from each rain event, as measured in the gauges in large openings, ranged from 0.8 to 24.1 mm. Throughfall, as percentage of precipi- tation, ranged from 0 to 70% (mean 2%) beneath Pinus
were highly positively skewed (Fig. 6). The $Z_0$ values at Bittern (Fig. 6a) were 11.81 ($p < 0.0001$) for *Pinus-Picea* and 14.15 ($p < 0.0001$) for *Picea* stands, while at Waskesiu (Fig. 6b) they were 8.51 ($p < 0.0001$) for *Pinus-Picea* and 7.73 ($p < 0.0001$) for *Picea* stands. From these graphs, it is obvious that the skewness is not due to a couple of extreme values but to the large number of values in the lowest depth class. Consequently, assuming that the unburned stands are representative of the burned stands before the fire, duff depths before the fire would have been more or less normally distributed, averaging 6.9 cm in *Pinus-Picea* stands and 10.3 cm in *Picea* stands. After both fires, reduction in overall duff depth was largely due to the high proportion of zero and near-zero duff depths resulting from complete, or nearly complete, duff consumption, creating the patches seen in Fig. 1. In the Bittern burn, which occurred during wetter duff conditions (see Fig. 2), most of the area of duff consumption was attributable to patches in the smallest size classes. The largest patch recorded was 15 m$^2$ in *Pinus-Picea* stands and 18 m$^2$ in *Picea* stands (Fig. 7a). The Waskesiu burn, which occurred during drier duff conditions, had a wider range of patch sizes with a maximum of 77 m$^2$ in *Pinus-Picea* stands.
Fig. 7. Distribution of percentage of total patch area by patch size class for Pinus banksiana – Picea mariana and Picea mariana dominated stands in (a) the Bittern burn and (b) the Waakebul burn.

Discussion

Despite the interest of foresters and ecologists in dust consumption because of its importance in post-fire tree regeneration and despite the recognition that the major processes involved in dust consumption is smoldering combustion, none of the previous dust consumption studies (see Miyaiishi (2000) for review) have indicated any awareness of studies on smoldering, such as those by Kibata et al. (1967), Mousa et al. (1976), Piholz et al. (1979), Leinbach (1983), Moulines et al. (1993), Di Blasi (1995), Buckmaster and Lookins (1996), and Yi et al. (1998). Although these combustion studies present a number of different models of smoldering, the understanding they all provide of the smoldering process indicate that the primary variables that determine dust consumption are bulk density, moisture content, and depth of dust. Bulk density of the dust is important because it influences diffusivity, which plays a key role in the rate of heat transfer from the heat-generating oxidation zone to the unburned dust. Latent heat of vaporization of moisture in the dust acts as a heat sink and, therefore, determines whether or not sufficient heat is available to cause pyrolysis of the unburned dust and, thus, propagate smoldering. Depth of dust determines whether or not the heat generated by the vertical oxidizing surface is sufficient to compensate for the convective heat loss from the surface of the dust. An understanding of the smoldering process also indicates how these variables are related, e.g., for a given bulk density, the greater the moisture content, the greater the critical depth of fuel required to propagate smoldering. Using commercial peat as a test fuel, we showed experimentally that there was a significant positive linear relationship between fuel depth and moisture content in determining smolder propagation. The bulk density (0.97 g cm⁻³) of the peat used in this experiment was very similar to the mean bulk densities of dust found in Pinus–Picea stands (0.092 g cm⁻³) and in Picea stands (0.094 g cm⁻³) and was, therefore, a reasonable analog of dust.

There was, however, overlap between the points representing depths–moisture combinations that propagated smoldering and those representing extinguishing conditions (Fig. 3a). The noise in the data suggests that other factors may be playing a role. In fact, from our understanding of smoldering combustion, we know that bulk density of the fuel is also a compi-
ling variable in determining the limits of smoldering propagation. Therefore, we would expect there to be a family of curves representing the upper depth-moisture limits for different bulk densities. Although we attempted to maintain a constant bulk density for all trials, some variability among trials was inevitable. Any variation in bulk density would be expected to result in overlap between the propagated and extinguished data sets. Further testing of this relationship with better control of bulk density and use of sets of trials using different density values would be useful.

In this study, we looked at patterns of duff consumption in *Pinus banksiana* – *Picea mariana* and *Picea mariana* dominated stands on glaciofluvial substrate in the mixedwood boreal forest of central Saskatchewan with respect to the above variables and their relationships. Our study found that while duff bulk density in unburned stands varied, there was no significant difference between the *Pinus-Picea* and *Picea* stands. Therefore, while bulk density is a factor determining smolder propagation, we conclude that it would not play an important role in explaining any differences in duff consumption that may be observed between these two stand types. It remains to be tested whether or not bulk density differences occur between other stand types.

As found in numerous previous studies (e.g., Van Wagner 1972; Brown et al. 1991; Little et al. 1986), moisture content of duff was related to duff consumption with significantly greater area of duff removed by smoldering in the Waskesiu fire (mean 52.9%) which occurred during drier duff conditions (as indicated by the DMC and DC values) than in the Bittern fire (mean 14.7%). The present study statistically confirmed the findings of Little et al. (1986) that during the Waskesiu fire, duff consumption is patchy and occurs preferentially around the bases of trees that had been alive at the time of the fire. We further verified that in unburned stands, the duff is generally drier beneath than between tree crowns; this within stand variation in duff moisture could be explained by interception of precipitation by tree crowns. Other factors that we did not include in our study, such as dew formation, would further enhance this effect; tree crowns intercept long-wave radiation from the ground thus inhibiting night time radiative cooling and dew formation. Thus, within-stand patchiness of duff consumption could be explained by the patchiness of duff moisture due to the influence of the tree canopy.

The positive relationship between duff depth and moisture content, in turn, leads to a better understanding of the smoldering process and supported empirically in this study can be used to explain the duff consumption patterns observed in the Waskesiu and Bittern fires. The relationship indicates that at low moisture contents, smoldering can be propagated in even very this duff, while at higher moisture contents, a thicker depth of duff is required to propagate smoldering. Thus, we can explain why there was significantly greater duff consumption (as indicated by patch sizes and total area of duff consumed) in *Picea* stands than in *Pinus-Picea* stands within the Bittern burn but not within the Waskesiu burn. Converting the DMC to moisture content (％dry mass) (Van Wagner 1987) and then converting these gravimetric moisture contents to volumetric moisture, we estimate that the volumetric duff moisture was approximately 12-16％ during the Bittern fire and approximately 5-8％ during the Waskesiu fire. Assuming peat is a reasonable analog of duff, we can see from Fig. 3 that duff depth would not likely have been a limiting factor in smoldering propagation during the Waskesiu fire. However, it is likely to have played a role in limiting propagation during the Bittern fire when duff moisture contents were higher, particularly in *Pinus-Picea* stands, which have significantly thinner duff (Fig. 5). Thus, if smoldering extinguished upon encountering the thin sections of duff in the *Pinus-Picea* stands, we would expect that most of the burned patches would be very small compared with those in the thicker duff of the *Picea* stands (Fig. 7a), where smoldering would have been more likely to be propagated. On the other hand, with the extreme dry duff conditions during the Waskesiu fire, depth would not be limiting smolder propagation, and we would not expect to find large differences in either burned patch size (Fig. 7b) or total area of patches between the two stand types.

Past duff consumption studies have only considered mean duff consumption of stands, even though it has been obvious in boreal forest burns that there is a distinct pattern of burned and unburned duff within stands. This use of mean measures of duff consumption have tended to obscure the patterns apparent both within stands and among stands located on different terrain. Our approach of studying duff consumption by an understanding of the smoldering combustion process allowed us not only to identify the key factors of moisture, depth, and bulk density determining propagation of smoldering in duff but also to discover the nature of the relationships among these variables. The interaction of moisture and depth then provided a reasonable explanation for the observed differences in duff consumption patterns between stand types in the Bittern fire as well as the lack of differences between stand types in the Waskesiu fire.

The landscape pattern of duff consumption clearly reveals the interaction of duff moisture content and duff depth. On glaciofluvial hillslopes in our study area we know there is a moisture gradient with wetter areas at the bottom of the slope (Bridge and Johnson 2000). This moisture gradient is a function of contributing area, slope angle, and soil transmissivity. The moisture gradient in turn creates the vegetation composition gradient from the top of hillslopes dominated by *Pinus banksiana* – *Picea mariana* grading into pure *Picea mariana* stands at the bottom as a result of the moisture tolerances of these species. Duff depth also varies along the hillslope, with thin duff in the *Pinus-Picea* stands at the top of glaciofluvial hillslopes and thicker duff in the *Picea* stands at middle to bottom slope positions. All of these environmental gradients (soil moisture, vegetation composition, duff moisture, and duff depth), thus, are determined ultimately by the hillslope hydrology. Note that the hydrology is dependent on the contributing area, slope angle, and soil transmissivity but also on weather (precipitation and temperature), which was clearly shown by the differences between the two fire events. Consequently, as concluded by Bridge and Johnson (2000), the hillslope is the fundamental unit for understanding patterns of recruitment, not only because it creates the moisture gradient and hence the species composition gradient but also, as we have shown, because it determines the patterns of duff consumption which in turn determine tree seedling recruitment. Thus, to
be able to better predict patterns of diffusion consumption both within stands and across the landscape, we need to have better hydrologic models that predict patterns of dung moisture at varying scales.

Acknowledgements

We gratefully acknowledge M.J. Bajtala, S. Chipman, S.T.K. Yu, S. Berry, S. Bouchard, T. To, K. Webster, and M. Wong for their assistance in collection of field data; S. Vo for conducting the laboratory study on smoldering; M.J. Bajtala for the spatial analyses; S.L. Gutsell and two anonymous reviewers for helpful comments on an earlier draft of the paper; and M. Puddister for drafting the figures. This project was funded by a grant through the Sustainable Forest Management Network and a Natural Sciences and Engineering Research Council operating grant to E.A.J.

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