

# PREDICTING FOREST FLOOR CONSUMPTION FROM WILDLAND FIRE IN BOREAL FORESTS OF ALASKA—PRELIMINARY RESULTS

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## ABSTRACT

Research to quantify fuel consumption in boreal forest types is critical for effective modeling of fire effects. There is considerable amount of forest floor consumption research completed in the contiguous United States; however, the unique lichen, moss, and duff forest floors typical of the boreal forests of Alaska have received little attention. Forest floor reduction was measured on 14 black spruce, white spruce, and birch–aspen prescribed burns in Alaska between 1990 and 1999. Three of the sites were part of the large international FrostFire project near Fairbanks, Alaska, and were used as an independent test data set. Several forest floor reduction equations were developed, of which one is presented in this paper. The double parameter equation uses upper forest floor fuel moisture content and pre-burn forest floor depth as independent variables. The fuel moisture content of the upper forest floor can be obtained from forest floor samples that are collected, oven dried, and weighed to determine a gravimetric fuel moisture content. The pre-burn forest floor depths require on-site measurements to be collected. Research to quantify forest floor consumption is critical for effective modeling of fire effects (e.g., smoke emissions, regional haze, permafrost melting, erosion, and plant succession) and landscape management if prescribed burning is to become an important land management technique.

*keywords:* Alaska, boreal forest, forest floor consumption, wildland fire.

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## INTRODUCTION

Thousands of hectares are burned annually from wildland fires in the black spruce (*Picea mariana*), white spruce (*Picea glauca*), and birch–aspen (*Betula papyrifera*–*Populus tremuloides*) forests of Alaska (Kasischke et al. 2002). Thousands of tons of pollutants are generated, including CO, CO<sub>2</sub>, and particulate matter. These pollutants are a direct result of the inefficient combustion of forest fuels including tree crowns, shrub stems and leaves, dead woody debris, litter, and deep forest floor layers composed of lichen, moss, peat, and duff. Although the consumption of the tree crowns, shrub layer, downed woody material, and litter can be a significant source of pollutants, they represent <20% of the total fuel available for consumption in the boreal forest ecosystem (Ottmar and Vihnanek 1998, 2002). The forest floor has the greatest potential for emitting large masses of pollutants because it may reach depths of over 30 cm, which can result in 150 Mg/ha (5 Mg/cm) of biomass or that potentially could become available to consume. In addition, most of the forest floor is consumed during the smoldering phase when the combustion efficiency is low. Using smoldering emission factors for Douglas-fir (*Pseudotsuga menziesii*) and

western hemlock (*Tsuga heterophylla*) fuels of 13.0 g/kg for PM<sub>2.5</sub>, 236 g/kg for CO, and 1,402 g/kg for CO<sub>2</sub> (Hardy 1995), forest floor consumption during a wildland fire could generate nearly 2.0 Mg/ha of PM<sub>2.5</sub>, 34.7 Mg/ha of CO, and 210.3 Mg/ha of CO<sub>2</sub>. Because the forest floor can contribute most of the air pollutants produced by fire and consumption of the forest floor is often the major contributor to fire effects at a site, an accurate assessment of forest floor consumption is needed to estimate sources strength.

Between 1990 and 1999, a study was undertaken by the Fire and Environmental Research Applications team, Pacific Northwest Research Station, to assess the consumption of the lichen, moss, and duff layers during prescribed fires in the black spruce and white spruce forests of Alaska. This paper discusses the preliminary results. Our main objective was to build models to estimate reduction of the forest floor as a function of independent variables measurable by managers.

## REVIEW

Considerable evidence exists indicating that the amount of forest floor consumed during a wildland fire depends on the pre-fire forest floor depth, moisture

profile of the forest floor layers, woody fuel consumption, or some sort of weather parameter such as days since significant rainfall as a surrogate for moisture content, and the heat supplied from the burning of above-ground biomass. Van Wagner (1972) relates the weight of duff consumed to fire duration and the duff moisture code in pine stands in eastern Canada. Shearer (1975) and Norum (1977) present tools for estimating duff consumption based on the moisture content of the lower half of the duff layer. Experimental burns in northern Idaho were used to develop duff consumption relations by Brown et al. (1991) who found that duff depth reduction to be related to pre-burn duff depth and, to a lesser extent, to duff moisture content.

Sandberg (1980) theorized that consumption of the duff by fire depends on woody fuel consumption or woody fuel diameter reduction. Under conditions when the duff is wet (National Fire Danger Rating System's 1000-hour fuel moisture content [NFDR-Th] is  $\geq 25\%$ ), duff reduction is limited by the heat available to vaporize free moisture. Total heat load (i.e., woody fuel consumed) will determine how much duff is consumed. Under conditions when the duff is dry (NFDR-Th between 19% and 24%), a dry layer exists and the rate of heat penetration through the duff is reduced. Fire duration (i.e., woody fuel diameter reduction) will determine how much duff is consumed. This was confirmed by Ottmar et al. (1985) in clearcut and understory burns conducted in Washington and Oregon. Shearer (1975) and Norum (1977) note that duff will burn independently of woody fuels if the duff moisture content is  $< 30\%$ . This very dry duff moisture regime corresponds to NFDRS-Th of  $< 19\%$  (Sandberg 1980).

Although a considerable amount of forest floor consumption research has been completed for understory and clearcut burns in the western United States (Norum 1977, Sandberg 1980, Ottmar et al. 1985, Brown et al. 1991), little work had been conducted in the unique lichen, moss, and duff forest floors typical of the boreal forests of Alaska. Viereck and Dyrness (1979) burned four small units at a site near Fairbanks. They observed that the forest floor reduction from the fire was not dependent on consumption of the woody materials. Dyrness and Norum (1983) burned seven 2-ha units between 19 July and 8 August 1978, over a range of conditions typical of most fire seasons in Alaska. A multiple linear equation to predict forest floor reduction was developed that was based on pre-burn forest floor depth, lower moss fuel moisture, and lower duff moisture. Finally, Lawson et al. (1997) developed a probability curve relating probability of sustained smoldering ignition of the forest floor as a function of duff moisture content.

## STUDY AREA AND METHODS

Forest floor consumption was measured at 14 black spruce- and white spruce-forested sites on U.S. Fish and Wildlife Service, Alaska State Department of Natural Resources, and University of Alaska lands in

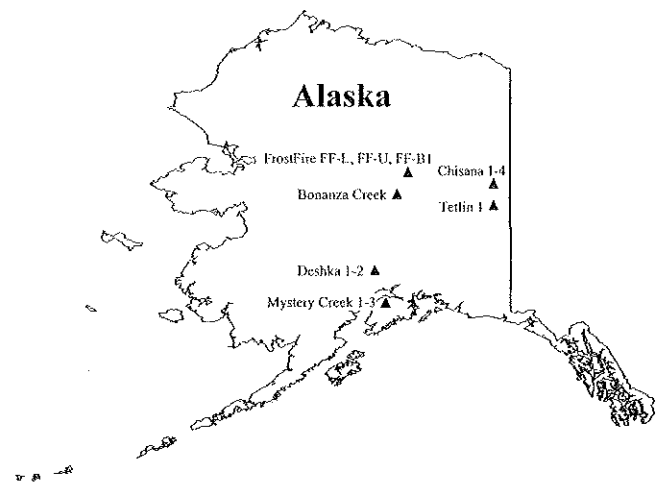


Fig. 1. Location of black spruce, white spruce, and birch-aspen prescribed burn units, Alaska, 1990–1999.

Alaska (Figure 1). Three of the units, FrostFire Large Black Spruce (FF-L), FrostFire Upper Black Spruce (FF-U), and FrostFire Birch 1 (FF-B1), were part of the large international FrostFire project that culminated in a 1,000-ha sub-watershed prescribed burn north of Fairbanks, Alaska, in 1999. These data were used as an independent data set to test regression equations developed by this study. The units were selected to span the geographical area characteristic of black spruce and white spruce (Table 1). Weather and logistical problems did not allow us to study range of forest floor moisture regimes. No sites were burned when the upper forest floor was extremely wet or frozen ( $> 200\%$ ) or extremely dry ( $< 30\%$ ).

Forest floor reduction was measured according to procedures adapted from Beaufait et al. (1977). Eighteen permanent plots were laid out in an area within a larger burn unit. Sixteen forest floor pins were inserted into the forest floor, then clipped flush with the lichen, moss, or duff surface around each plot (Figure 2). Because the forest floor often is very deep, lightweight welding rod  $> 60$  cm in length was used as forest floor reduction pins.

Samples to determine forest floor bulk densities were collected at each site. The sampling occurred mainly in feather moss and leaf litter types. A metal square with a known volume was pressed into the forest floor. A plug was removed, oven dried, and bulk density was calculated. The bulk density was multiplied by the forest floor depth and reduction to determine mass of the forest floor before burning and the amount of forest floor consumed after the burn.

Several possible independent variables were measured. Twenty small woody fuel (0.64–2.54 cm in diameter), large woody fuel ( $> 7.6$  cm in diameter), and litter moisture-content samples were collected for each unit. Upper and lower forest floor moisture samples were also collected. Three forest floor plugs about 15.24 cm<sup>2</sup> were collected near each permanent plot. Each plug was separated into live moss, dead moss, upper duff, and lower duff. All samples were oven dried at 70 °C for 96 h.

Table 1. Unit and fuel data summary for forest floor reduction study on black spruce, white spruce, and birch-aspen prescribed burns, Alaska, 1990-1999.

Burn unit	Stand type	Location	Burn date	Small woody fuels <sup>a</sup> (Mg/ha)	Large woody fuels <sup>b</sup> (Mg/ha)	Total woody fuels (Mg/ha)	Forest floor mass (Mg/ha)	Total biomass (Mg/ha)	Forest floor depth (cm)	Mean upper forest floor moisture (%)
Mystery Creek 1	Black spruce	Soldotna	20 Jun 1991	15.7	8.7	24.4	63.9	112.7	11.2	124
Mystery Creek 2	Black spruce	Soldotna	20 Jun 1991	8.7	7.8	16.6	73.8	90.4	12.7	131
Mystery Creek 3	Black spruce	Soldotna	20 Jun 1991	8.3	7.0	15.2	53.8	69.0	8.1	68
Deshka 1	Black spruce	Palmer	13 Jul 1993	10.5	0.0	10.5	76.9	87.4	12.7	65
Deshka 2	Black spruce	Palmer	13 Jul 1993	9.0	0.2	9.2	72	81.2	12.2	65
Tetlin 1	White spruce	Tetlin Wildlife Refuge	23 Jun 1992	2.7	8.3	11.0	67.5	78.5	11.9	149
Chisana 1	White spruce	Tetlin Wildlife Refuge	24 Jun 1992	2.0	5.4	7.4	100.5	107.9	18.8	149
Chisana 2	Black spruce	Tetlin Wildlife Refuge	24 Jun 1992	2.2	4.9	7.2	115.7	122.9	18.0	163
Chisana 3	Black spruce	Tetlin Wildlife Refuge	23 Jun 1992	1.6	4.0	5.6	102	107.6	18.5	104
Chisana 4	Black spruce	Tetlin Wildlife Refuge	23 Jun 1992	2.2	10.8	13.0	94.4	107.4	16.0	104
Bonanza Creek	White spruce	Fairbanks	27 Jun 1990	7.4	26.0	33.4	58.1	91.5	9.9	34
FrostFire-L	Black spruce	Fairbanks	09 Jul 1999	3.1	0.7	3.8	100.4	104.2	20.2	163
FrostFire-U	Black spruce	Fairbanks	11 Jul 1999	1.7	0.5	2.2	79.4	81.6	18.3	154
FrostFire-Birch 1	Birch-aspen	Fairbanks	11 Jul 1999	7.2	1.5	8.7	56.7	65.4	11.6	83

<sup>a</sup> 0.0-7.6 cm in diameter.<sup>b</sup> >7.6 cm in diameter.

Loadings of the large fuels for each unit were estimated from a planar intersect inventory (Brown 1974). The sampling density consisted of three 20-m transects radiating outward from each of the 18 permanent plots (Figure 2). Other variables measured included the number of trees, tree heights, diameters, and crown mass and grass and shrub loadings.

Consumption of large fuels was measured as diameter reduction (which was converted to volume reduction) from about 20 randomly chosen logs >7.6 cm in diameter. Logs were those intersecting fuel inventory lines established at each permanent plot or, in cases where few large woody fuels occurred, within 20 m of the plot center. Wires were tightly wrapped around the logs before burning and cinched up after burning. The exposed wire lengths were measured. Numbered steel tags were used to identify the logs.

Weather data collected at the site before the burn included temperature, wind speed, and relative humidity. At the three FrostFire sites, weather stations were established 2 months before the burn; continuous temperature, relative humidity, wind speed and direction, rainfall total and duration, and forest floor moisture content were recorded.

To develop predictive equations, forest floor reduction was regressed on several independent variables. Single and multiple regressions were fitted. Three forest floor duff reduction measurements from FrostFire were used as an independent data set to test the equation.

## RESULTS

### Pre-burn Fuel

Woody fuel loading and forest floor depths differed among units (Table 1). Loadings of the small woody fuels (0.0-7.6 cm in diameter) ranged from 1.6 Mg/ha at Chisana 3, a black spruce site on the Tetlin Wildlife Refuge to 15.7 Mg/ha, at Mystery Creek #1 a dense, black spruce site on the Kenai Peninsula. Large woody material (>7.6 cm in diameter) ranged from no material on the black spruce site at Deshka #1 to a high of 26.0 Mg/ha in the white spruce Bonanza Creek clearcut site which contained logging slash. The average forest floor depth differed with geographic location and forest species composition and ranged from 8.1 cm (53.8 Mg/ha) at Mystery Creek 3, a black spruce stand regenerated after the 1947 wildfire, to 20.2 cm (100.4 Mg/ha) at FrostFire FF-L, a mature black spruce stand. The mean forest floor bulk densities determined for each unit through sampling were used to calculate forest floor mass.

### Fuel Moisture

The units were burned under a moist forest floor moisture regime because of the narrow burning window that occurs in Alaska due to weather, logistics, and limited resource availability for prescribed burning during drought periods or early in the season (Table 1). No burns occurred when the upper forest floor was

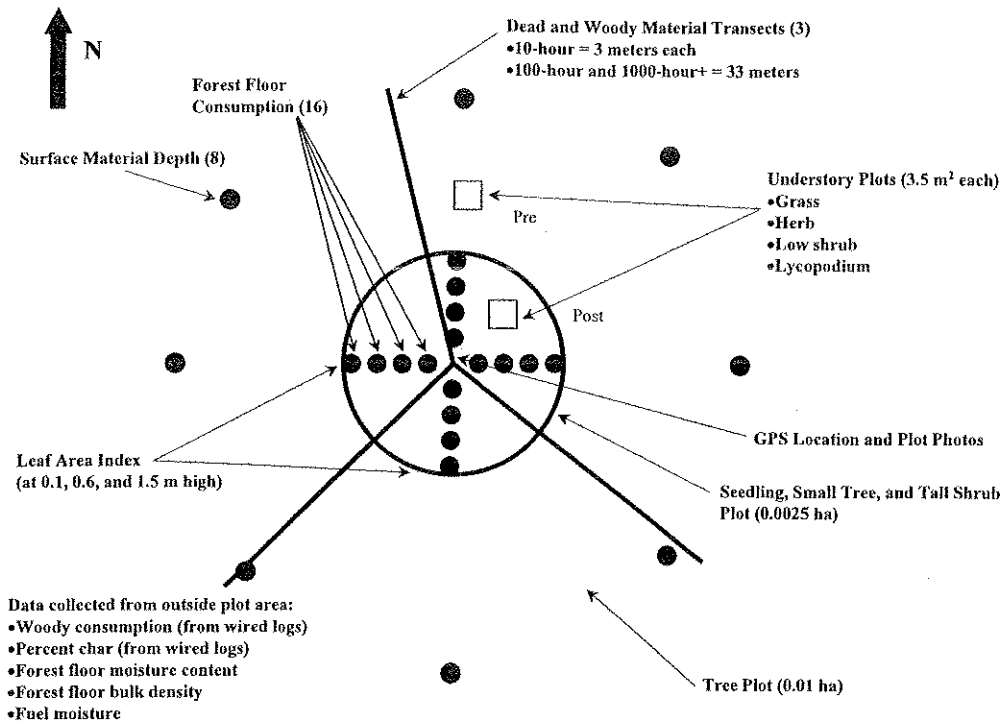


Fig. 2. Plot layout in black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999.

very dry (<30% moisture content) or very wet (>200%). Within the study areas, the measured upper forest floor fuel moistures ranged from a low of 34% at Bonanza Creek to a high of 163% at Chisana 2 and FrostFire FF-L (Figure 3). The litter and surface material were generally <30% and the 10-hour fuel sticks were <20% for a majority of the sites.

Site Weather

Ignition of all burns occurred when the relative humidity was <50%, temperatures were between 15.5 and 27 °C, and wind speeds averaged <4.5 m/s. No rain occurred during ignition.

Fuel Consumption and Forest Floor Reduction

More than 50% of the small fuels were consumed at most units (Table 2). Consumption ranged from no consumption at FrostFire FF-U to 13.2 Mg/ha at Mystery Creek #1. Large woody fuel consumption was <1.5 Mg/ha because of the few logs found at the sites. The exception to this was Bonanza Creek where logging slash was present and 13.5 Mg/ha was consumed. Forest floor reduction ranged from 2.5 cm (14.2 Mg/ha) at Tetlin 1 to 10.4 cm (61.5 Mg/ha) at Chisana 4.

Average unit forest floor reduction was regressed against several independent variables. Duff reduction was best correlated with upper forest floor moisture content and pre-burn forest floor depth:

$$FFRED = 0.8431(FFDEPTH) - 0.0458(UFFM),$$

where FFRED = forest floor reduction depth (cm), FFDEPTH = pre-burn forest floor depth (cm), and UFFM = upper forest floor moisture content (%).

The number of cases was 11, the  $r^2$  (coefficient of

determination) was 0.82, and the significance was 0.0007. Because the initial  $Y$ -intercept term was not significantly different from zero ( $P = 0.8641$ ), we forced the regression through the origin. This makes physical sense because there will be no forest floor reduction if no forest floor is initially present. Figure 4 displays the observed and predicted forest floor reduction for units used to develop the regression and for the FrostFire study.

Graphs of the residuals revealed a relatively uniform pattern around zero with no obvious bias, although the variability increased as the forest floor reduction increased (Figure 5). This confirms the assessment that further data points are necessary to increase the robustness of the regression to include conditions when the forest floor is dry and will burn deeply.

Measured forest floor reductions from the three FrostFire units were used to test the regression. Measured forest floor depth and upper forest floor moisture content before ignition were used to populate the regression. The regression equation overpredicted the FrostFire independent data by between 1 and 2 cm (Figure 6).

DISCUSSION

The forest floor equation presented above demonstrates that the combustion of the forest floor usually occurs under the influence of the upper forest floor moisture content and the pre-burn depth of the forest floor. This will occur if 1) the upper forest floor layer is <200% fuel moisture content; 2) the relative humidity is <50% to enable the fire to carry across the

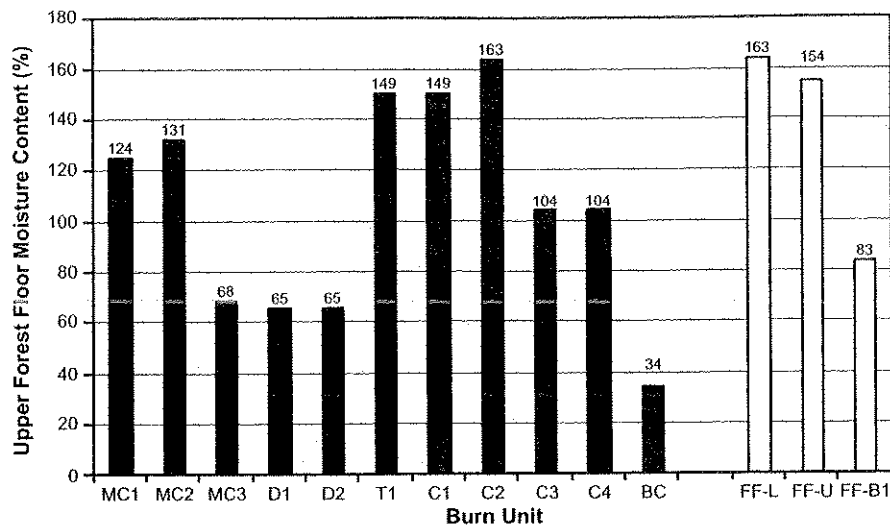


Fig. 3. Upper forest floor moisture content on black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999. Burn units: Bonanza Creek (BC), Chisana 1 (C1), Chisana 2 (C2), Chisana 3 (C3), Chisana 4 (C4), Deshka 1 (D1), Deshka 2 (D2), FrostFire-L (FF-L), FrostFire-U (FF-U), FrostFire-Birch 1 (FF-B1), Mystery Creek 1 (MC1), Mystery Creek 2 (MC2), Mystery Creek 3 (MC3), Tetlin 1 (T1).

surface material of the forest floor; and 3) the surface layer is dry enough to sustain combustion to ignite the lower layers of the forest floor (generally <30%). If these three conditions occur, the moss and duff layer will then burn independently until the combustion zone encounters a wet or frozen layer or is quenched by rainfall.

Currently, upper forest floor moisture content can be obtained by collecting forest floor plugs, separating into upper and lower forest floor samples, weighing, and oven drying to obtain a gravimetric moisture content expressed as a percentage. Ongoing research by Ferguson et al. (*this volume*) is attempting to develop predictive models to adequately estimate the moisture content of the forest floor found under black spruce and white spruce in Alaska. Forest floor moisture probes and moisture content measuring instruments also are being tested. Both research products will enable managers to determine the upper forest floor

moisture content with relative ease. The forest floor depth, on the other hand, cannot be predicted and can be obtained only by cutting 10 to 20 plugs from around the unit and measuring the forest floor depth from them.

The forest floor equation resulting from this study has its limitations and should be used only under the conditions for which it was developed:

*When the Forest Floor Burns Independently of Forest Floor Moisture Content.*—Insufficient data have been collected to model forest floor consumption during periods of drought when mean upper forest floor moisture contents are <30%. The forest floor will continue to burn until the entire forest floor is consumed regardless of the upper forest floor moisture content.

*When the Forest Floor is Wet or Frozen.*—Forest floor consumption is currently unpredictable under these conditions. Insufficient data have been collected

Table 2. Fuel consumption and forest floor reduction summary for black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999.

Burn unit	Small woody fuels <sup>a</sup> (Mg/ha)	Large woody fuels <sup>b</sup> (Mg/ha)	Total woody fuels (Mg/ha)	Forest floor mass (Mg/ha)	Total biomass consumed (Mg/ha)	Forest floor reduction (cm)
Mystery Creek 1	13.2	0.7	13.9	24.5	38.4	4.3
Mystery Creek 2	5.4	0.2	5.6	25.0	30.6	4.3
Mystery Creek 3	5.6	0.2	5.8	23.9	29.7	3.6
Deshka 1	9.4	0.0	9.4	46.0	55.4	7.6
Deshka 2	6.5	0.2	6.7	40.7	47.4	6.9
Tetlin 1	2.2	1.1	3.4	14.2	17.6	2.5
Chisana 1	1.1	0.9	2.0	38.0	40.0	7.1
Chisana 2	2.2	0.9	3.1	62.3	65.4	9.7
Chisana 3	1.6	0.7	2.2	54.6	56.8	9.9
Chisana 4	2.2	0.4	2.7	61.4	64.1	10.4
Bonanza Creek	7.4	13.5	20.9	43.4	64.3	7.4
FrostFire-L	1.1	0.0	1.1	23.5	24.6	7.8
FrostFire-U	0.0	0.0	0.0	19.9	19.9	6.3
FrostFire-Birch 1	2.8	0.9	3.7	14.1	17.8	4.4

<sup>a</sup> 0.0–7.6 cm in diameter.

<sup>b</sup> >7.6 cm in diameter.

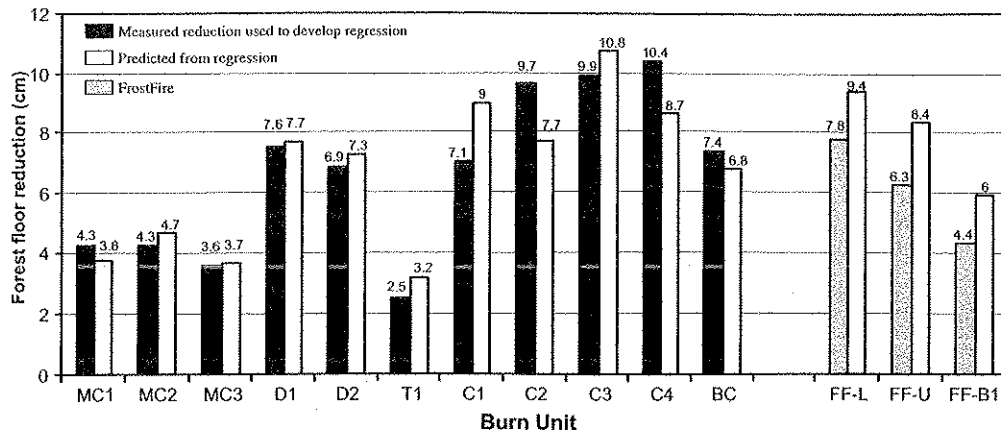


Fig. 4. Observed and predicted forest floor reduction on black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999. Burn units: Bonanza Creek (BC), Chisana 1 (C1), Chisana 2 (C2), Chisana 3 (C3), Chisana 4 (C4), Dshka 1 (D1), Dshka 2 (D2), FrostFire-L (FF-L), FrostFire-U (FF-U), FrostFire-Birch 1 (FF-B1), Mystery Creek 1 (MC1), Mystery Creek 2 (MC2), Mystery Creek 3 (MC3), Tetlin 1 (T1).

to model the event, but in most cases the mean forest floor moisture content will be >200%, which can occur in spring or during an extensive rain event in summer months. The forest floor can remain frozen well into May or even June depending on the location. We predict that <10% of the forest floor will burn under these conditions and, in most cases, only the litter layer will be consumed.

*When Rain Occurs Within a Few Hours After Ignition and the Smoldering Stage is Terminated Prematurely by the Precipitation.*—In this case, the forest floor consumption was determined more by the occurrence of rain than by the upper forest floor moisture content and pre-burn forest floor depth.

*When Sustained Surface Winds >4.5 m/s Increase Consumption During the Smoldering Stage.*—More forest floor is consumed than accounted for by the upper forest floor moisture content and pre-burn forest floor depth.

Only 82% of the forest floor variation is explained by the upper forest floor moisture content and pre-burn

duff depth. Other factors such as relative humidity, surface material moisture, and lower duff moisture content may influence how much the forest floor is burned. Including these variables in future analysis may improve the predictive capability of the model.

### MANAGEMENT IMPLICATIONS

The amount of forest floor consumed during a wildland fire in boreal forests depends on the moisture profile of the forest floor and the pre-burn depth of the forest floor providing the relative humidity is <50%, surface material is dry enough to carry fire, and the upper forest floor moisture content is between 30% and 200%. Although managers often do not have the ability to manipulate the depth of the forest floor, they do have the ability to schedule prescribed burns to achieve a specific forest floor reduction to meet smoke

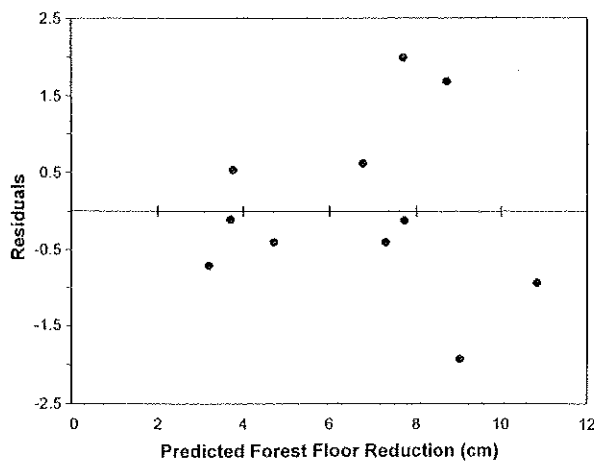


Fig. 5. Residuals of observed versus predicted forest floor reduction for black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999, used to develop the regression equation.

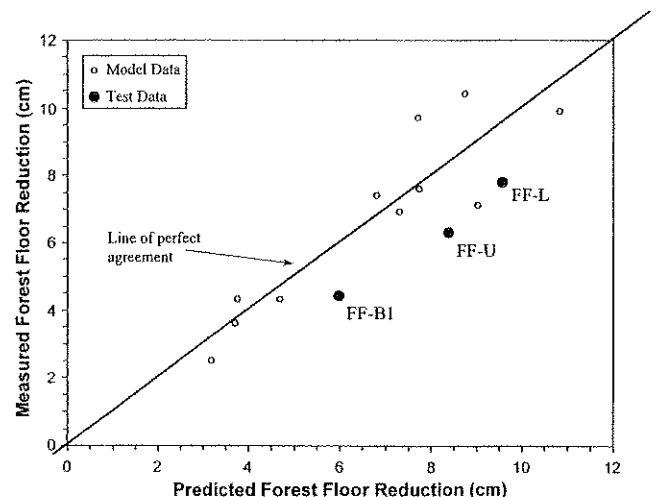


Fig. 6. Forest floor reduction values measured at FrostFire sites (FF-B1, FF-L, and FF-U) versus those calculated by the forest floor reduction regression for black spruce, white spruce, and birch–aspen prescribed burn units, Alaska, 1990–1999. The solid line indicates a perfect fit.

management and other fire effect objectives. For example, if the average forest floor depth of a planned burn unit is 20 cm and the upper forest floor moisture content is 50%, about 14.5 cm of the forest floor will be consumed and produce nearly 1 Mg/ha of PM<sub>2.5</sub> emissions. Burning with the forest floor moisture much higher at 150%, 9.9 cm of forest floor would be consumed and result in 0.6 Mg/ha of PM<sub>2.5</sub> being generated. This is nearly a 40% reduction in emissions produced. This could be accomplished only if the prescribed fire plan objectives were still being met under these higher forest floor fuel moisture conditions.

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