FOREST MANAGEMENT NOTE

Northern Forestry Centre

Note 63

PROBABILITY OF SUSTAINED SMOLDERING IGNITION FOR SOME BOREAL FOREST DUFF TYPES

FOREWORD

The idea for a collaborative study of boreal forest fire ignition between Canadian and U.S. fire researchers was sparked in 1992 at a time when the Alaska Fire Service was evaluating the Canadian Forest Fire Danger Rating System for operational implementation. Canadian Forest Service researchers had just gathered new duff moisture data from the Yukon that could be tied in with Alaska-based work by the U.S. Forest Service on smoldering ignition probability. The resulting model presented here can be used by fire managers in both countries in managing fire across the vast boreal forests of Alaska and northern Canada. This report is an example of informal but effective collaboration between scientists and managers, state and territory, and in a larger sense, two countries that jointly protect and care for the North American portion of the great northern forest.

INTRODUCTION

Wildfires continue to threaten the forest resources of the boreal forest, as well as human life and property in Canada and the State of Alaska. There has been an increased understanding of the natural role of fire in these ecosystems, and prescribed fire is a tool being used more frequently by fire managers to maintain biodiversity. The prediction of sustained smoldering ignition is important to fire managers because of its usefulness in determining the occurrence of holdover lightning- and person-caused fires. These holdover fires can tax fire-fighting resources; multiple fires can flare-up after ignition when more severe fire weather conditions occur. Also, when fire managers are applying fire as a landscape tool, prediction of long-term smoldering can assist in determining potential fire effects and judging how much effort will be needed to contain and extinguish the prescribed fire.

The purpose of this report is to link the results of two separate research studies into simple, practical models of smoldering fire potential for use by fire managers in the boreal forests of Alaska and northwestern Canada. The first study, by Frandsen (1997), developed equations of smoldering ignition probability for various Alaska forest floor (duff) layers. Ignition probability was found to depend on duff moisture content, inorganic (ash) content, and organic bulk density.

In order for the ignition probability equations to be useful in daily fire management, the fuel moisture content variable must be transformed into a

Natural Resources Canada · Ressources naturelles Canada
Canadian Forest Service · Service canadien des forêts
Canada

variable that is readily available on a daily basis for many locations; it is impractical for fire managers to measure forest floor moisture content directly over broad temporal and spatial scales. Potts et al. (1986) found that even with stratification based on topographic position, a 14-ha prescribed burn unit may require 16 samples of duff moisture content in order to adequately estimate this variable.

The Duff Moisture Code (DMC) and Drought Code (DC) of the Canadian Forest Fire Weather Index (FWI) System can provide the necessary transformations between observations of daily fire weather and duff moisture content (Van Wagner 1987). It may be more appropriate, however, for this application to use site- or ecoregion-specific relationships that relate DMC and DC to their moisture content equivalents, rather than the national standard equations. In a second separate study, Lawson and Dalrymple (1996a) and Lawson et al. (1997) developed equations linking moisture contents at specific depths of boreal forest duff types to DMC or DC values, based on a field sampling study near Whitehorse, Yukon.

This report presents equations and graphs of smoldering ignition probability for boreal forest feather moss (*Hylocomium splendens* and *Pleurozium schreberi*), sphagnum moss (*Sphagnum* spp.), reindeer lichen (*Cladina* spp.), and white spruce (*Picea glauca* [Moench] Voss) duff, as dependent on daily values of DMC or DC. Practical applications of the ignition probability models are discussed.

DERIVATION OF THE SMOLDERING IGNITION EQUATIONS

Study Sites

Samples of feather moss, sphagnum moss, reindeer lichen-covered feather moss and white spruce duff were collected near the Tetlin National Wildlife Refuge (NWR), 16 km east of Tok, Alaska (63°18′ north latitude, 142°40′ west longitude), in an open black spruce (*Picea mariana* [Mill.] BSP) forest (Fig. 1). White spruce duff samples were collected beneath the crown of a white spruce tree in the same general area but at a slightly higher elevation.

Experimental Methods and Results

From each fuel type, 23 to 29 samples were collected, each 10 × 10 × 5 cm. Individual average sample volumes were obtained by computing the average of all volume combinations from two measurements of each dimension. Inorganic contents were determined by ashing sub-samples of each sample in the laboratory. Moisture content was varied in the lab over a range designed to determine the smoldering ignition threshold.

Figure 1. Black spruce stand and duff types, Tetlin National Wildlife Refuge, Alaska. Chisana prescribed burn was conducted on this site July 17–18, 1993; duff samples for the smoldering ignition laboratory study were taken from a similar site less than 500 m away. Photo courtesy of L. Vanderlinden, U.S. Fish and Wildlife Service.

Ignition tests were conducted by placing duff samples in an ignition box designed so that ignition took place on the sample's 5- × 10-cm side. Samples were ignited by exposing a layer of dry peat moss adjacent to the side of the duff sample to an electrically heated coil. The smoldering dry peat moss then served as the ignition source for the duff sample, transferring heat laterally, as in a typical smoldering fire in the field.

Successful sustained smoldering ignition was said to occur if a sample was completely consumed, overcoming the heat requirements due to moisture and inorganic content.

Logistic regression was used to analyze the results of ignition success or failure for each duff type as a function of moisture content, inorganic content, and bulk density.

Ignition Probability Equation, Ig-1:

$$P = 1/\{1 + exp[-(B_0 + B_1 \times MC + B_2 \times Ash + B_3 \times Rho)]\}$$

where:

- P = probability of ignition
- exp = exponential
- MC = moisture content, percentage oven dry weight
- Ash = inorganic content, percentage oven dry weight
- Rho = organic bulk density, kg/m^3
- $B_{0, 1, 2, 3}$ = constants determined through logistic regression

Ignition probability can be expressed as a function of moisture content alone (Fig. 2) using average values for the inorganic content and organic bulk density (Table 1) for each duff type. Parameter values (B_0, B_1, B_2, and B_3) for the ignition probability equation for each duff type are listed in Table 2, along with overall model goodness of fit (R^2) and success of prediction (percentage correct). The effects of ash and Rho are included through the use of their mean values in the final equations because their effects improve the equations statistically over equations based on moisture content alone. It is important to note, however, that ignition tests were conducted on duff samples as retrieved from the field, with respect to individual ash and Rho values; only moisture content was varied over a range (Table 1) in the lab. The moisture content at 50% probability can be interpreted as the moisture ignition limit for each duff type.

Frandsen (1997) presented a single equation for feather moss because the upper and lower data sets produced nearly identical probability curves with similar average inorganic content and bulk density. However, separate equations for upper and lower feather moss were obtained from the author for inclusion here because the moisture contents of upper and lower feather moss can be better predicted from two different moisture codes of the FWI System.

HOW TO MEASURE AND/OR PREDICT SMOLDERING IGNITION VARIABLES IN THE FIELD

Forest Floor Moisture Content

Guidelines and methodology for destructive sampling of duff moisture are available (Lawson and Dalrymple 1996a; Norum and Miller 1984). These techniques require time, some degree of skill and training, and special equipment (laboratory balance, drying oven, sample tins). They are appropriate for initial calibration, but impractical for daily fire management operations. An indirect alternative is required.

Prediction from Fuel Moisture Codes

Two of the fuel moisture codes in the Canadian FWI System, DMC and DC, can be related to the moisture content of the forest floor at specific depths. The DMC represents the F or fermentation layer of Canadian boreal forests, with an average depth of 7 cm and an oven-dry weight of 5 kg/m^2 (Van Wagner 1987). The national standard equation used to relate DMC to forest floor moisture content is Equation MC-1. The DC represents the moisture content of much deeper, more compact F and H (humus) layers, which average 18-cm deep and weigh 25 kg/m^2 (Van Wagner 1987). The moisture equivalent of the DC is described using Equation MC-5, but the saturated moisture equivalent of 800% reflects a defined 200-mm moisture reservoir rather than actual well-drained forest floor moisture contents. Specific calibration studies such as Lawson and Dalrymple (1996a) and Lawson et al.

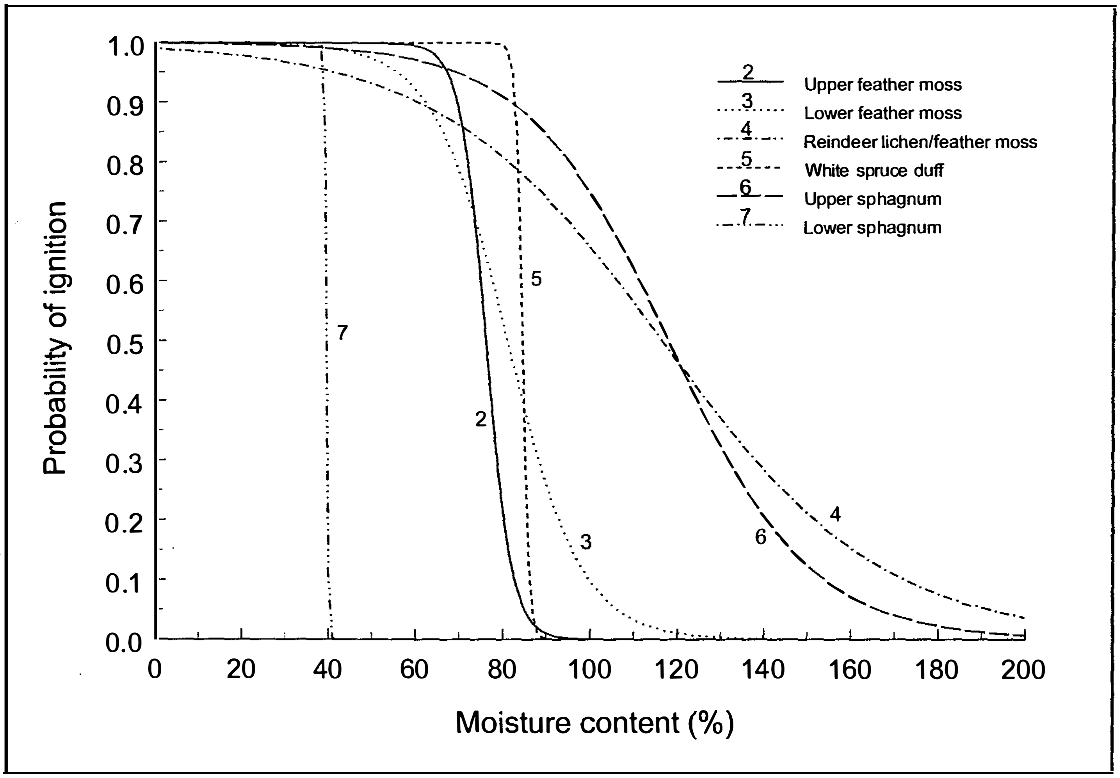

Figure 2. Probability of sustained smoldering ignition as a function of duff moisture content for several boreal forest duff types.

Table 1. Average inorganic (ash) content, average organic bulk density, moisture range, and depth tested by duff type

Duff type	Average inorganic content (ash, %)	Average organic bulk density (Rho, kg/m^3)	Depth (cm)	Moisture content range (%)
Upper feather moss	17.2	46.4	0–5	0–191
Lower feather moss	19.1	38.9	5–25	0–141
Reindeer lichen/feather moss	26.1	56.3	0–5	22–204
White spruce duff	35.9	122.0	0–5	34–125
Upper sphagnum	12.4	21.8	0–5	50–437
Lower sphagnum	56.5	119.0	5–25	15–80

Table 2. Parameter values and goodness of fit statistics for ignition probability equation by duff type

Duff type	B_0	B_1	B_2	B_3	Model R^2	% correct
Upper feather moss	13.9873	−0.3296	0.4904	0.0568	0.58	96
Lower feather moss	13.2628	−0.1167	0.3308	−0.2604	0.50	96
Reindeer lichen/feather moss	8.0359	−0.0393	−0.0591	−0.0340	0.28	75
White spruce duff	332.5604	−1.2220	−2.1024	−1.2619	0.62	100
Upper sphagnum	−8.8306	−0.0608	0.8095	0.2735	0.51	89
Lower sphagnum	327.3347	−3.7655	−8.7849	2.6684	0.62	100

(1997), however, have provided equations suitable for converting DMC and DC into boreal forest floor moisture content:

Equation MC-1:
DMC national standard:
$$MC = exp[(DMC - 244.7)/-43.4] + 20$$

Equation MC-2:
Sphagnum, feather moss, and undifferentiated duff (2–4 cm):
$$MC = exp[(DMC - 157.3)/-24.6] + 20$$

Equation MC-3:
Reindeer lichen (2–4 cm):
$$MC = exp[(DMC - 106.7)/-14.9] + 20$$

Equation MC-4:
White spruce duff (2–4 cm):
$$MC = exp[(DMC - 149.6)/-20.9]$$

Equation MC-5:
DC national standard:
$$MC = 800/exp(DC/400)$$

Equation MC-6:
White spruce duff (6–10 cm):
$$MC = 488.4/exp(DC/267.9)$$

The specified depths in these equations refer to the portion of the duff layer for which the moisture content was used to determine its relationship to DMC or DC; they are not the average total duff depths sampled, but the depths for which moisture content was best correlated to DMC or DC.

It is important to note that Equation MC-6 is recommended for predicting moisture content of deep organic layers on mesic, well-drained boreal forest sites from DC values. The national standard equation (MC-5) correlates well with moisture contents on poorly drained boreal black spruce sites in Alaska, which have an underlying permafrost layer. Data compiled by Vanderlinden[1] suggest a strong correlation between the actual moisture content at a depth of 15–18 cm for a poorly drained black spruce forest floor on the Tetlin NWR and the national standard DC relationship (Equation MC-5), possibly because an underlying ice layer restricts moisture drainage.

Forest Floor Bulk Density and Inorganic Content

Organic bulk density (Rho) and inorganic content (ash) of the forest floor, while important variables in the ignition process, do not need to be measured in the field in order to use the ignition probability equations presented here because the equations are presented for the average Rho and ash values measured in the Alaska study. However, a user could determine organic bulk density values for a duff type of interest for comparison with values presented here using the methodology in Lawson and Dalrymple (1996a). Inorganic content determination requires a high-temperature muffle furnace in order to burn a duff sample to its residual ash content and is therefore not a procedure available to most practitioners.

[1] L. Vanderlinden, Regional Fire Management Coordinator, U.S. Department of Interior, Fish and Wildlife Service, Anchorage, Alaska, personal communication, June 1996.

RESULTS AND DISCUSSION

Models of smoldering ignition probability for four boreal forest duff types as predicted by either DMC or DC are presented in Figure 3. Models were derived by converting DMC and DC to MC (moisture content) using equations MC-1 through MC-6, and forming the associated probability expressions for DMC and DC from equation Ig-1. The probability of smoldering ignition of upper feather moss is described by way of Equation MC-2, using the DMC (Fig. 3A), whereas lower feather moss ignition is based on Equation MC-6, using DC (Fig. 3B). Probability of smoldering ignition in reindeer lichen/feather moss is described using Equation MC-3, while upper sphagnum ignition is described using Equation MC-2, both based on the DMC (Fig. 3A).

Probability of ignition in white spruce duff is described using Equation MC-4, based on DMC, and for lower sphagnum, ignition probability is described using Equation MC-6, based on DC.

White spruce duff (0–5 cm) and Lower Sphagnum (10–25 cm) are not presented as graphs in Figure 3 because their entire range of smoldering ignition probability occurs within a very small range of moisture content values (Fig. 2). It is more practical to depict these two duff types as simply being either above or below the conditions required for smoldering ignition, as shown in Table 3. The moisture contents, DMC or DC values corresponding to the threshold values for ignition probability (P = 0.5) are shown in Table 3 for all six duff types.

Lower sphagnum exhibits a moisture content ignition limit that decreases with increasing inorganic content similar to peat moss. Lower sphagnum lies closer to the peat moss limit than upper sphagnum (Frandsen 1997). This may be attributed to the higher bulk density of lower sphagnum (six times that of upper sphagnum). Hartford (1989) found that increasing organic bulk density decreased the probability of ignition. Established peat fires can successfully spread horizontally underground at much higher moisture contents. Sofronov and Volokitina (1986) and Artsybashev (1974) reported smoldering peat fires in Siberia spreading horizontally at moisture contents of 400–500%.

Drought Code values of 670–700, corresponding to the lower sphagnum threshold moisture content of 35–40%, while common in non-boreal southern British Columbia, are only reached occasionally in the northern boreal forest, as indicated by McAlpine's (1990) Drought Code climatology; actual DCs run considerably higher than McAlpine's averages because he did not overwinter the DC in his analysis. However, the 1992 Whitehorse study that produced equation MC-6, linked here to lower sphagnum ignition, was based on sampled moistures at DCs less than 610; therefore, caution is required in the use of the lower sphagnum model.

Upper sphagnum patches, on the other hand, were observed to not ignite or spread during a June, 1995 wildfire (DL3-18-95) in Alberta that spread with crowning through a black spruce–sphagnum–feather moss–Cladonia forest.[2] Duff Moisture Code was 87, well above the upper sphagnum ignition threshold presented here. Therefore, caution is also warranted in application of the upper sphagnum model until field tested. Indeed, all the models presented here should be used with caution until field tested.

Field Test of Ignition Model in White Spruce Duff

A limited number of field tests of the smoldering ignition threshold for white spruce duff have been carried out in a mature Engelmann spruce (*P. engelmannii* Parry ex Engelm.)–subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) (ESSF biogeoclimatic zone) forest near Quesnel, B.C. (53°11′0″ north latitude, 122°01′15″ west longitude), at an elevation of 1400 m. Two variants of Engelmann spruce duff were selected for comparative ignition trials. Ignition results were compared for duff at the base of the tree boles, ranging in depth from 5 to 8 cm, and duff away from the sheltering influence of the tree canopy, averaging 4 cm deep. Each morning and afternoon between September 13 and 21, 1995 (except September 16), an ignition test was attempted in each duff type. A 7-cm diameter core of the forest floor was removed to mineral soil, and the void filled with dry smoldering peat moss, pre-ignited and stirred on a portable camp stove. A successful ignition consumed all the peat moss and continued smoldering in the adjacent duff for at least 2 h,

2 Marty Alexander, Fire Research Officer, Canadian Forest Service, Edmonton, Alberta, personal communication, August 1996.

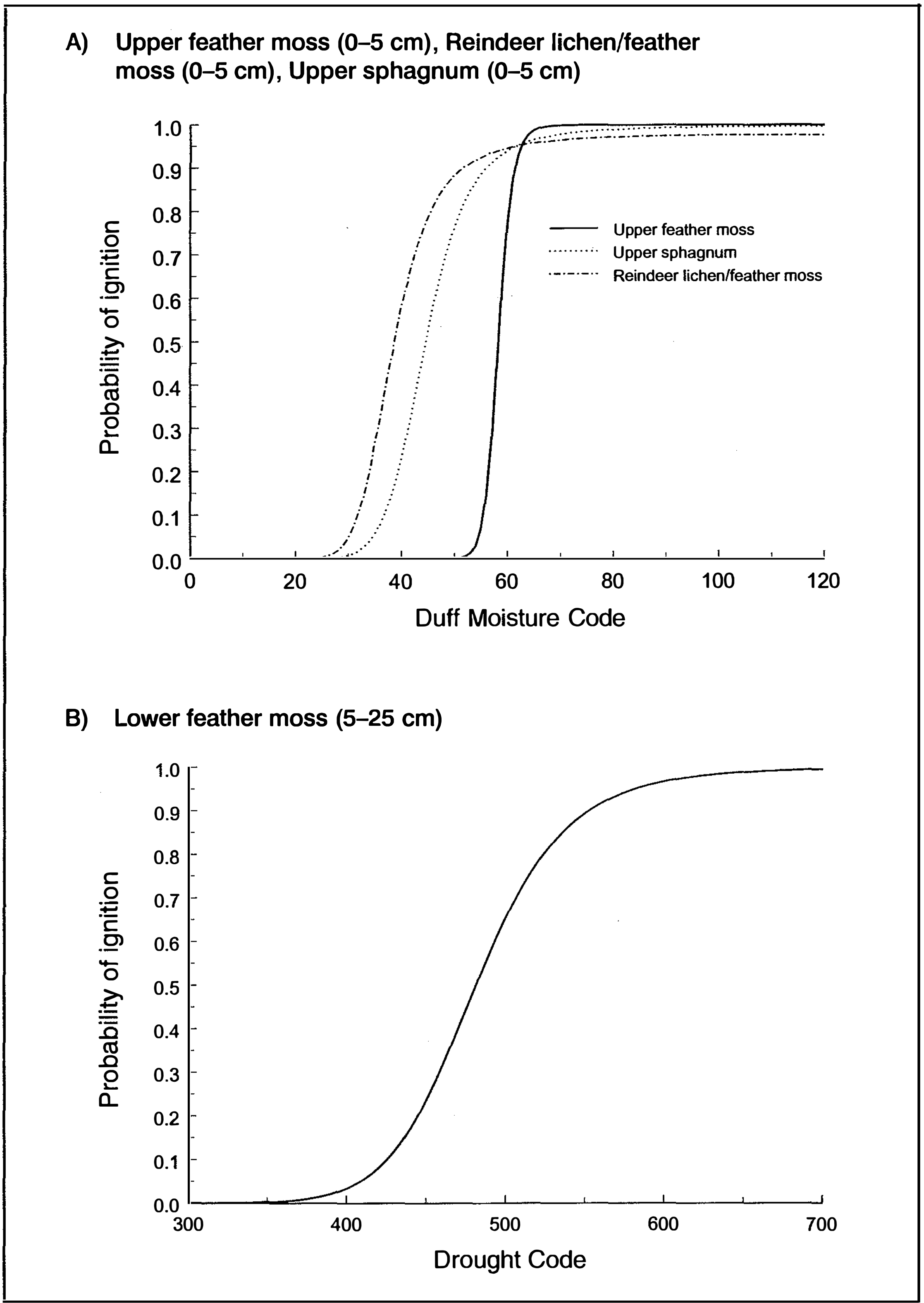

Figure 3. Probability of smoldering ignition determined as a function of Duff Moisture Code or Drought Code.

Table 3. Smoldering ignition threshold moisture content, DMC, or DC by duff type

Duff type	Ignition threshold value or range[a]		
	Moisture content (%)	Duff Moisture Code	Dought Code
Upper feather moss	76	58	–[b]
Lower feather moss	81	–	482
Reindeer lichen/feather moss	116	39	–
White spruce duff	80–90	55–60	–
Upper sphagnum	118	44	–
Lowee sphagnum	35–40	–	670–700

[a] Probability of smoldering ignition threshold value is shown for P = 0.5; duff types shown with ranges extend from P = 0.0 to P = 1.0.

[b] Dashes indicate that this moisture code does not represent this duff type.

Table 4. Smoldering ignition field test results in an Engelmann spruce–subalpine fir stand near Quesnel, B.C., September 1995

Duff type	Depth (cm)	Bulk density range (kg/m³)	Ignition	No ignition
			2–4 cm moisture content mean (range)	
Engelmann spruce tree bole	8	95–123	90 (62–145)[a]	111 (80–139)[b]
Engelmann spruce duff	6	56–110	–[c]	117 (58–213)[d]

Note: Smoldering ignition field tests were conducted with a Duff Moisture Code (DMC) range of 17–26 and a Drought Code (DC) range of 88–119.

[a] Number of tests (n = 9).

[b] Number of tests (n = 7).

[c] No successful smoldering ignition was obtained because adequate DMC and DC levels were not met during burning tests.

[d] Number of tests (n = 16).

requiring extinguishment. An unsuccessful test did not persist in the adjacent duff after the peat moss burned out. Duff cores from the test fire holes were stratified into 2-cm depths, and their moisture content determined using oven-drying. A standard fire weather station (Turner and Lawson 1978) in an adjacent opening provided FWI System components, and in-stand wind speed was recorded at a height of 2 m adjacent to the fire. Preliminary results of these 32 test fires are presented in Table 4.

While limited, these test results suggest that Engelmann spruce duff at the base of tree boles in the Quesnel study, in a different ecoregion from the Alaska boreal forest sites for which the ignition model has been developed, follows a similar moisture content threshold for smoldering ignition, and exhibits a narrow range of moisture contents separating successful from unsuccessful ignition. The influences of organic bulk density, ash content and in-stand wind speed on the probability of smoldering ignition have not yet been analyzed, and more data are required.

Nonetheless, these interim results are encouraging from the standpoint of similarity of moisture content relationship for one duff type, comparing a boreal and non-boreal forest type; however, the relationship between DMC and boreal vs. non-boreal Engelmann spruce duff moisture is obviously quite different. The boreal forest model presented here suggests a DMC threshold of ignition in white spruce duff of DMC 55–60 (Table 3), while the non-boreal Engelmann spruce duff near tree boles at Quesnel ignited when DMCs were between 18 and 26 (although the Engelmann spruce duff away from tree boles has a higher, as yet undetermined, DMC threshold). The dense-crowned Engelmann spruce trees on the Quesnel ignition test site effectively intercept much of the precipitation before it reaches the duff near the tree boles. This would explain why a higher DMC threshold is predicted for white spruce duff than observed for the Engelmann spruce tree bole duff type at Quesnel, as the white spruce duff moisture content equation (MC-4) is based on duff moisture content as sampled away from the tree boles where more precipitation is received at the duff layer.

PRACTICAL APPLICATIONS OF THE MODELS

Holdover Lightning and Person-caused Fires

Anderson (1997) described three stages involved in the physical development of a lightning fire: ignition, survival, and arrival. Lightning triggers an ignition, generally within the forest floor, that survives by smoldering within the duff layers for hours, days or weeks until conditions favor flaming combustion, at which point the fire bursts into flames and is considered to have arrived. The test fires in the present study were lit from smoldering ignition sources adjacent to the duff and regarded as successes only if they consumed the available fuel by persistent smoldering. Therefore, the models reported here could be regarded as probabilistic indicators of lightning fire survival.

Given that a cigarette is a smoldering source, it may seem reasonable to apply the smoldering ignition probability models presented here to the probability of cigarette-caused fire starts. The differences, however, in fire brand size and placement (i.e., tests used much larger ignition sources placed adjacent to, not on top of, the duff samples) would suggest that these models are probably not applicable directly to cigarette-caused fires. Frandsen (1997) shows that most of the moisture thresholds of ignition for duff types lie above Frandsen's (1987) ignition limit for peat moss, determined by placing a red glowing coil at the top of the peat sample for 3 min. Frandsen (1987) and Hartford's (1989) peat moss ignition limits may be more directly applicable to the probability of cigarette-caused fire starts, as the experimental methodology of those studies more closely approaches the discarded cigarette scenario.

Current models of sustained flaming ignition (Lawson et al. 1994; Lawson and Dalrymple 1996b) are mainly driven by the Initial Spread Index (ISI) component of the FWI System, indicating that flaming ignition is predominantly a response to fine fuel moisture content and wind speed, with a secondary influence of duff fuel moisture. In contrast, the models of sustained smoldering ignition presented here are a function of duff fuel moisture content, without considering the influence of wind. Wind may also be important to smoldering ignition persistence, but it was not tested in the laboratory study reported here. Wind speed, however, will affect the arrival of either lightning- or person-caused fires. For practical application, the ignition probability models presented here can be related to survival likelihood of fires starting from smoldering material, while the models of Lawson et al. (1994) and Lawson and Dalrymple (1996b) relate to the survival likelihood of fires started from flaming sources.

Prescribed Fire Effects and Mop-up Implications

The smoldering ignition models were developed primarily to increase understanding of prescribed fire effects on organic soils, including the effects of moisture content, inorganic content and bulk density on vertical and lateral heat transfer. From a practical standpoint, however, the persistence of smoldering ignition in various duff types can be included in burning prescriptions to either limit or ensure involvement of the duff layer in combustion, depending on burn objectives (Fig. 4). Van Wagner (1972) found a curved relationship between duff consumption and moisture content in fires in eastern Canadian jack pine and red and white pine standing forest. Duff consumption decreased as duff moisture content increased, reaching zero duff consumption at 134% moisture content. This moisture content corresponded to a DMC of 25 at the threshold of duff consumption, as calculated for his series of burns. This duff moisture content is similar to the smoldering ignition threshold moisture content for the reindeer lichen/feather moss duff type reported here (Table 3), although the DMC equivalent is lower than the threshold DMC for any of the boreal duff types reported here. Smoldering persistence by duff type and burning conditions can also be used to

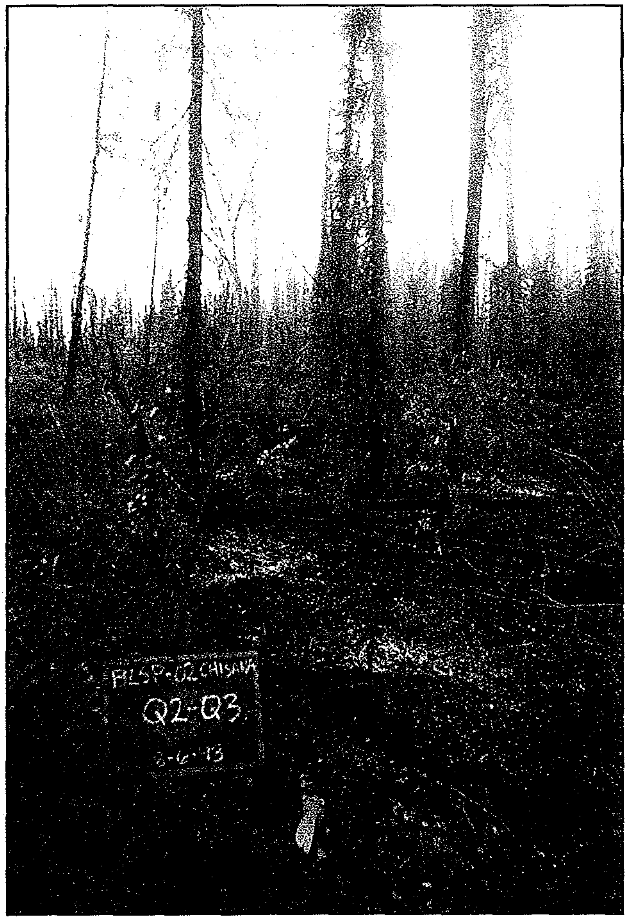

Figure 4. Post-burn, duff consumption as of August 5, 1993 on area shown in Figure 1. Fuels were not ignited here initially, but fire crept and smoldered, consuming duff in area shown over a period of several days. DMC = 78, DC = 437 at TWR RAWS, about 20 km from the site, on July 17, 1993. Photo courtesy of L. Vanderlinden, U.S. Fish and Wildlife Service.

judge mop-up effort required on either prescribed burns or wildfires.

Despite preliminary results that suggest that smoldering ignition threshold DMC and DC values may be similar for boreal and non-boreal forest duff types, the equations presented here should be used only for boreal forest types until rigorous testing confirms their validity. Similarly, the effect of wind on smoldering ignition probability should be evaluated in any field-testing of these models.

ACKNOWLEDGMENTS

The Alaska ignition study was supported by the U.S. Department of Interior Fire Coordinating Committee, administered by the U.S. Fish and Wildlife Service. The Yukon fuel moisture study was supported by Indian and Northern Affairs Canada, Yukon Forest Service Fire Management Program and Canada's Green Plan. Former University of Victoria Co-op student Robin Pike assisted with data analysis. Rolly Kopas collected the field data. Brad Armitage and Karen Sherman collected and analyzed field data, and conducted inorganic content analysis. Karen Sherman also assisted with preparation of the manuscript.

Marty Alexander and Kerry Anderson, Canadian Forest Service (CFS), Edmonton, Steve Taylor, CFS, Victoria, and Judi Beck, B.C. Forest Service Protection Program, provided helpful reviews of the manuscript. Larry Vanderlinden, U.S. Department of Interior, Fish and Wildlife Service, Anchorage, Alaska provided data, advice on field sites, photographs, and helpful comments on the manuscript. The Quesnel, B.C. tests were sponsored by B.C. Forest Service Protection Program, Canadian Forest Service Fire Network, Parks Canada, and West Fraser Mills Ltd.

B.D. Lawson
W.H. Frandsen
B.C. Hawkes
G.N. Dalrymple
December 1997

REFERENCES

Anderson, K. 1997. A model to predict lightning-caused fire occurrences. *In* Proc. Seventh Western Region Fire Weather Committee Scientific and Technical Seminar, November 22, 1994, Edmonton, Alberta. West. Reg. Fire Weather Comm. (forthcoming).

Artsybashev, E.S. 1974. Forest fires and their control. Lesnaya Promyshlenost Publ., Moscow. Translated from Russian by Amerind Publ. Co. Pvt. Ltd., New Delhi for U.S. Dep. Agric. and Natl. Sci. Found., Washington, D.C. (1983).

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17:1540–1544.

Frandsen, W.H. 1997. Ignition probability of organic soils. Can. J. For. Res. 27:1471–1477.

Hartford, R.A. 1989. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. Pages 282–286 *in* D.C. MacIver, H. Auld, and R. Whitewood, eds. Proc. Tenth Conf. on Fire and Forest Meteorology, April 17–21, 1989, Ottawa, Ontario. Petawawa Natl. For. Inst., Chalk River, Ontario.

Lawson, B.D.; Armitage, O.B.; Dalrymple, G.N. 1994. Ignition probabilities for simulated people-caused fires in British Columbia's lodgepole pine and white spruce-subalpine fir forests. Pages 493–505 *in* Proc. Twelvth Conf. on Fire and Forest Meteorology, October 26–28, 1993, Jekyll Island, Georgia. Soc. Am. For. Bethesda, Maryland.

Lawson, B.D.; Dalrymple, G.N. 1996a. Ground-truthing the Drought Code: field verification of overwinter recharge of forest floor moisture. Canada-B.C. Partnership Agreement on For. Resour. Dev.: FRDA II, Can. For. Serv., Victoria, British Columbia. FRDA Rep. 268.

Lawson, B.D.; Dalrymple, G.N. 1996b. Probabilities of sustained ignition in lodgepole pine, interior Douglas-fir, and white spruce-subalpine fir forest types. Canada-B.C. Partnership Agreement on For. Resour. Dev.: FRDA II. Suppl. 1 to: Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System, Can. For. Serv., Victoria, British Columbia. FRDA Handb. 12.

Lawson, B.D.; Dalrymple, G.N.; Hawkes, B.C. 1997. Predicting forest floor moisture contents from Duff Moisture Code values. Nat. Resour. Can., Can. For. Serv., Pac. For. Cent., Victoria, British Columbia. Tech. Transfer Note 6.

McAlpine, R.S. 1990. Seasonal trends in the Drought Code component of the Canadian Forest Fire Weather Index System. For. Can., Petawawa Natl. For. Inst., Chalk River, Ontario. Inf. Rep. PI-X-97 E/F.

Norum, R.A.; Miller, M. 1984. Measuring fuel moisture content in Alaska: standard methods and procedures. U.S. Dep. Agric., For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oregon. Gen. Tech. Rep. PNW-171.

Potts, D.F.; Ryan, K.C.; Zuuring, H.R. 1986. Stratified sampling for determining duff moisture in mountainous terrain. West. J. Appl. For. 1(1):29–30.

Sofronov, M.A.; Volokitina, A.V. 1986. Ground/peat fires in the south of western Siberia. Lesnoe-Khozyaistvo 5:56–58. (English summary available in Forestry Abstracts).

Turner, J.A.; Lawson, B.D. 1978. Weather in the Canadian Forest Fire Danger Rating System: A user guide to national standards and practices. Fish. Environ. Can., Can. For. Serv., Pac. For. Cent., Victoria, British Columbia. Inf. Rep. BC-X-177.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, Ontario. For. Tech. Rep. 35.

Van Wagner, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. 2:34–39.

CONTACTS:

Bruce D. Lawson, R.P.F.
Canadian Forest Service (retired)
Current address:
Ember Research Services Ltd.
4345 Northridge Crescent
Victoria, BC V8Z 4Z4

Dr. William H. Frandsen
U.S. Forest Service (retired)
Current address:
2509 Valley View Drive
Missoula, MT 59803

Dr. Brad C. Hawkes, R.P.F. and George N. Dalrymple
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria, BC V8Z 1M5
250-363-0600
e-mail: bhawkes@pfc.forestry.ca
gdalrymple@pfc.forestry.ca

Lawson, B.D.; Frandsen, W.H.; Hawkes, B.C.; Dalrymple, G.N. 1997. Probability of sustained smoldering ignition for some boreal forest duff types. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. For. Manage. Note 63.

Natural Resources Canada
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton, Alberta T6H 3S5

Cat. No. Fo29-2/63-1997E
ISBN 0-660-17329-8
ISSN 0714-1181