DIURNAL FINE FUEL MOISTURE CHARACTERISTICS AT A NORTHERN LATITUDE

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ABSTRACT

As part of the International Crown Fire Modelling Experiment (ICFME), destructive sampling was carried out over two seasons (1999 and 2000) to evaluate trends in diurnal fine fuel moisture content and fine fuel moisture code (FFMC) characteristics at northern latitudes. The moisture content of various fuels, including black spruce (*Picea mariana*) bark flakes, feathermoss (*Pleurozium schreberi*) tips, jack pine (*Pinus banksiana*) needles, twigs (<0.5 cm and 0.5–1 cm diameter classes), litter (0–2 cm), and the forest floor profile, was sampled on an hourly basis at two sites, one with and one without a significant understory of black spruce. Automatic weather stations and 10-hour fuel moisture sticks were established within stand at each of the two sampling areas, as well as in the open, and hourly or better values of rainfall, wind speed, wind direction, temperature, and relative humidity were recorded. The effects of the presence or absence of an understory (2,350 stems/ha) on microscale weather and fuel moisture characteristics were evaluated. Temperature and relative humidity values were greater at the site with an understory than at that with no understory. Within-stand wind speeds at the site with no understory were significantly higher than those measured at the site with an understory. Despite temperature, relative humidity, and wind speed differences, discernible site differences in moisture content were only significant for duff (0–2 cm) and bark flake fuels. The moisture content data for feathermoss and needle litter were used to assess the performance of the diurnal and hourly FFMC models, and notable differences between the FFMCs computed are reported. For dry days, the diurnal model best described the amplitude of the moisture content of feathermoss fuels throughout the day, whereas the amplitude of jack pine needle moisture content was better described by the hourly FFMC. Both the hourly and diurnal models overestimated the minimum moisture content of needles and feathermoss on dry days, and both models overestimated needle moisture content and underestimated feathermoss moisture content following rain.

keywords: day length, destructive sampling, diurnal, fine fuel, Fine Fuel Moisture Code, fire behavior, hourly, latitude, moisture content, Northwest Territories.

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INTRODUCTION

The Canadian Forest Fire Danger Rating System (CFFDRS) is used throughout Canada to predict fire behavior (Stocks et al. 1989, Alexander et al. 1996, Van Nest and Alexander 1999, Alexander and Cole 2001) and comprises two major subsystems: the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1984, Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992, Taylor et al. 1997). The FWI is based on the moisture content of three classes of forest fuels and the effect of wind on fire behavior for a reference pine fuel type comprised of mature jack pine (*Pinus banksiana*) or lodgepole pine (*Pinus contorta*) on level terrain, based on a continuous record of weather observations (Turner and Lawson 1978). The FWI system comprises six components (Van Wagner 1987): three primary subindexes represent fuel moisture (Fine Fuel Moisture Code [FFMC], Duff Moisture Code [DMC], and Drought Code [DC]), two intermediate subindexes represent rate of spread (Initial Spread Index [ISI]) and fuel consumption (Buildup Index [BUI]), and the final index represents Byram's (1959) fire intensity (Fire Weather Index [FWI]).

The FFMC is the component of the Canadian Forest FWI System that tracks the moisture content, in code form, of fine, dead forest fuels. One of three methods can be used to calculate an FFMC: 1) the standard daily FFMC can be calculated using the FWI System

(Canadian Forestry Service 1984, Van Wagner and Pickett 1985); 2) typical diurnal weather trends can be applied to adjust the standard daily FFMC for time of day (Lawson et al. 1996, Taylor et al. 1997); or 3) Van Wagner's (1977) hourly FFMC model can be applied given continuous hourly weather inputs and an hourly FFMC program (e.g., Alexander et al. 1984, Finn 2001).

The standard daily FFMC is computed from weather observations, namely dry-bulb temperature, relative humidity, 10-m open wind speed, and 24-h accumulated rainfall, taken at approximately solar noon or 1300 DST (Daylight Savings Time). The daily FFMC is meant to depict the moisture content of fine fuels at about 1700 DST during the peak of the burning period. Although a daily FFMC estimate is usually adequate for fire prevention and preparedness planning, greater resolution of the predicted moisture content of fine fuels has been advocated for quantitative predictions of fire behavior using the FBP System (Alexander et al. 1984; Lawson et al. 1996; Beck 2001; Beck et al. 2001*a*,*b*).

The daily FFMC value can be adjusted for various times throughout the day using equations or tables that assume a typical afternoon pattern of change in temperature and relative humidity on dry days (Lawson et al. 1996, Taylor et al. 1997). These relationships were developed for litter composed of lodgepole pine needles, and the tips of both feathermoss and reindeer lichen (*Cladonia* sp.). These diurnal trends in FFMC were developed for a site (lat 54°22′N, long 122°38′W) 60 km north of Prince George (Russell and Péch 1968), British Columbia, and hence are typical of mid-latitude trends in Canada. The relationships developed by Lawson et al. (1996) may not be applicable for latitudes north of 60°, where litter moisture can remain at mid-afternoon levels through the early evening hours. It should also be noted that these diurnal trends were not intended to account for afternoon rainfall events. The third method is thus the preferred calculation option for hourly FFMCs, and the standard diurnal trends should only be applied to generate hourly FFMCs when current or forecast hourly data are unavailable (Lawson et al. 1996).

Actual or forecasted hourly weather data can be used to compute hourly FFMC values (Van Wagner 1977, Alexander et al. 1984, Finn 2001). Although it requires more weather data, this computational method is preferable because any particular weather cycle may deviate considerably from the standard diurnal trend depending on latitude, season or day length, and terrain. North of 60° latitude, day length may have a significant impact on the timing of and duration of the minimum fine fuel moisture content (Lawson et al. 1996), due to the fact that maximum overnight humidities are significantly lower and maximum overnight temperatures are higher than at lower latitudes (Kiil and Quintilio 1975).

Van Wagner (1977) developed the hourly FFMC model via simple modifications to the daily FFMC model, under the assumption that the fine fuels represented by the FFMC dry quickly enough to undergo a substantial diurnal trend in moisture content that can be superimposed on the larger day-to-day trend. In the derivation of the daily FFMC in the absence of rain, a log wetting or drying rate in units of log moisture content per day or per 24-h period was assumed (Van Wagner 1977), and the moisture content of fine fuels increases or decreases towards its equilibrium. For practical purposes, wetting and drying rates are actually described mathematically using exponential functions (Van Wagner 1977, 1979, 1987).

By trial and error, hourly drying and wetting rates were chosen to yield the desired day-to-day trend while producing realistic hourly trends (Van Wagner 1977). Rates of change equal to one-eighth of the standard daily rates appeared to yield the best results, when evaluated occularly against typical trends for jack pine needle litter at selected sites near the Petawawa Forest Research Institute in Ontario. These litter samples were presumably in trays under plastic shelters that were weighed periodically rather than having been collected by way of continuous destructive sampling (Van Wagner 1977).

The effect of rainfall on the moisture content of fine fuels is similar in both the daily and hourly FFMC models (Van Wagner and Pickett 1985), except the first 0.5 mm of rain over a 24-h period is ignored in the daily FFMC model, whereas the first 0.5 mm of rain is not excluded in the hourly model (Alexander et al. 1984). The effects of hourly rainfall were not studied in detail and have yet to be field validated. Moreover, Van Wagner (1977) acknowledged that a complete verification of the hourly and daily FFMC models would require a great deal of field work. These models clearly merit further investigation and testing. For example, Péch (1989) found the FFMC to be a dubious predictor of lichen moisture content, and produced a variation on the FFMC that improved day-to-day prediction of the moisture content of the top 3–4 cm layer of reindeer lichen (*Cladonia rangiferina*).

STUDY AREA AND METHODS

The ICFME (Alexander et al. 2001; Alexander and Stocks, *this volume*) presented the opportunity to study diurnal fine fuel moisture content and FFMC characteristics at a northern location. The International Crown Fire Modelling Experiment study site was located approximately 50 km north of Fort Providence in the Northwest Territories (lat 61°35′N, long 117°10′W). Two sites adjacent to the ICFME burn plots were selected for destructive sampling for fuel moisture content, and the data collected were used to assess the performance of the hourly (Van Wagner 1977) and diurnal FFMC models. Both sites had an overstory of jack pine and black spruce, but Site 1 had a significant understory of black spruce that was absent at the second site (Table 1, Figure 1). These two sites provided the opportunity to also study the effects of the presence or absence of an understory on microscale weather and moisture characteristics (Figure 1).

To reduce site disturbance due to frequent and repeated destructive sampling, we established a transect along which 24 pins were placed at 1-m intervals. Each pin had a designated hour associated with it and after each hourly sampling was collected, the corresponding pin was moved forward 1 m perpendicular to the transect to indicate where the next sampling for that particular hour should occur. In this way, fuel sampling personnel always approached the transect from the same direction and never trampled that portion of the study area yet to be sampled.

Figure 1. Two sites designated for destructive sampling for fuel moisture content, Northwest Territories, Canada, 1999–2000. Both sites had an overstory of jack pine and black spruce but Site 1 (top) had a significant understory of black spruce that was absent at Site 2 (bottom).

Weather Data

Weather data were collected at three locations within the ICFME study area (Alexander and Stocks, *this volume*). An automatic weather station was established according to the standards set by Turner and Lawson (1978) in the open to collect fire weather data hourly. Temperature, relative humidity, wind speed and direction, and precipitation measurements were recorded hourly. The tipping-bucket rain gauge associated with this automatic weather station had a precision of 0.25 mm.

Within-stand weather stations were established at both destructive fuel sampling sites. The within-stand weather stations recorded temperature and relative humidity at the standard height, and wind speed and direction were measured 1.5 m above the ground. Within-stand wind speed and direction were only measured during the 2000 field season. Two manual rain gauges were established at each end of the fuel sampling transects at each site. Within-stand rainfall was

Table 1. Stand details for two sites selected for destructive sampling for fuel moisture content, Northwest Territories, Canada, 1999–2000.

Site	Canopy cover (%)	Species	Overstory stocking (stems/ha)	Understory stocking (stems/ha)	Mean height (m)	Mean DBH (cm)
1	61	Black spruce	1452	2350	1.29	1.59
		Jack pine	2489	0	10.76	9.26
2	59	Black spruce	215	0	4.00	3.93
		Jack pine	2438	0	12.54	13.49

recorded to the nearest 0.05 mm, which was measured periodically rather than hourly.

Calculating FFMCs and Predicted Fuel Moisture Contents

Hourly FFMC values were computed using weather observations from the standard open weather station. Both Van Wagner's (1977) hourly model and the diurnal adjustments of Lawson et al. (1996) were applied to compute hourly FFMC values, and these were converted into predicted moisture contents (M) using the standard relationship that was developed by Van Wagner (1987) for jack or lodgepole pine needles:

$$M\,(\%) = \frac{147.2\,(101 - \mathrm{FFMC})}{59.5 + \mathrm{FFMC}}. \qquad (1)$$

Destructive Sampling to Determine Actual Fuel Moisture Content

Actual fuel moisture content was obtained using destructive sampling techniques. Fuel moisture samples were collected hourly, with Site 1 (with an understory) and Site 2 sampled approximately 30 min apart. Approximately 20–50 g each of needles, feathermoss tips, small twigs (<0.5 cm in diameter), large twigs (0.5–1.0 cm in diameter), and bark flakes from the bole (at approximately breast height) of black spruce trees were collected at hourly intervals. In addition, a 10-cm^2 forest floor sample was collected at depths of 0–2 cm. With the exception of bark flakes, which were collected at a height of approximately 1.3 m, all sample material collected was in contact with the forest floor. Destructive sampling was conducted every hour from approximately 0500 to 2200, and approximately 200 sets of hourly samples were collected at each of the study sites during a total of 17 days from 19 June 1999 through 2 July 1999 and from 15 June 2000 through 26 June 2000.

Each sample was collected in a metal tin, and the tin and sample were weighed to 0.1 g immediately after collection. Samples were oven dried at 100 °C until the sample weight stabilized and a dry weight could be obtained. The tare weight of the tin was measured after the sample was discarded. Moisture content (M) was then calculated as a percentage of the oven-dried weight of the fuel:

$$M\,(\%) = \frac{\mathrm{WetWt} - \mathrm{DryWt}}{\mathrm{DryWt}} \times 100, \qquad (2)$$

where WetWt is the wet weight of the sample minus the tin weight, and DryWt is the oven-dried weight of the sample minus the tin weight.

Fuel Moisture Sticks

Fuel moisture sticks, which comprise an array of wooden dowels, are used as a surrogate for the moisture content of dead fuels that have a time lag (i.e., the amount of time required for a fuel to lose 1 – 1/e or approximately two-thirds of free moisture above equilibrium) of approximately 10 h (Latham and Nelson 1994). When sticks are left in situ and then weighed, the weight in excess of the oven-dried weight represents fuel moisture. Sticks are manufactured to a specified level of tolerance and are constructed from oven-dried dowels to weigh exactly 100 g.

In British Columbia, sticks are constructed of Douglas-fir (*Pseudotsuga menziesii*), whereas ponderosa pine (*Pinus ponderosa*) is used in the United States. One set of each type of fuel moisture sticks was placed at each of the destructive fuel sampling sites, and four sets of each stick type were placed in an open, fully exposed area. New sticks were used at the beginning of each field season, and were oven dried and checked against the specified weight at the end of the yearly sampling season.

Sticks were placed horizontally on metal supports 20 cm above the fuel bed with a north–south orientation, with the brass screw hook pointing north. Fuel moisture sticks were weighed at each study site while destructive samples were being taken, and the fuel moisture sticks in the open site were weighed in between sampling at the two study sites. Stick weights were recorded to 0.1 gram, and fuel moistures were calculated from the weights and expressed as a percentage.

RESULTS AND DISCUSSION

Comparison of Within-Stand Weather

Within-stand weather characteristics are summarized in Table 2. Significant nonzero skewness statistics indicate that the distributions of temperature and relative humidity data at both study sites were marginally asymmetric rather than normal. The distribution of wind data was very skewed with a long right tail. Kurtosis values for relative humidity at both sites were significantly greater than zero, which indicates that the distributions of these data are flatter than a normal distribution.

We performed Wilcoxon signed-rank tests to determine if temperature, relative humidity, or wind speed differed as a result of the presence or absence of an understory. Temperature and relative humidity values were significantly ($P < 0.0005$) greater at the site with an understory than at that with no understory. A Wilcoxon signed-rank test also indicated that within-

Table 2. Summary statistics for within-stand weather parameters recorded during 2000 at two sites selected for destructive sampling for fuel moisture content, Northwest Territories, Canada, 1999–2000. Site 1 had an understory of black spruce and Site 2 lacked an understory beneath a jack pine and black spruce overstory.

Site	Weather parameter	N	Minimum	Maximum	Mean	Standard deviation	Skewness	Kurtosis
1	Temperature (°C)	192	0.53	31.57	17.84	6.81	–0.35	–0.33
	Relative humidity (%)	192	14.92	86.10	44.81	19.48	0.36	–1.15
	Wind speed (km/h)	192	0.14	4.00	1.11	0.96	0.85	–0.06
2	Temperature (°C)	192	–0.07	31.25	17.45	6.87	–0.38	–0.27
	Relative humidity (%)	192	15.04	89.0	44.17	19.40	0.37	–1.00
	Wind speed (km/h)	192	0.14	4.80	1.40	1.20	0.77	–0.15

stand wind speeds at the site with no understory (Site 2) tended to be significantly higher ($P < 0.0005$) than those measured at the site with an understory (Site 1). Although mean temperature, relative humidity, and wind speed differences (Site 1 – Site 2) appeared to be nominal at 0.39 °C, 0.64% and –0.29 km/h, respectively, these differences should be examined for their combined effects on fuel moisture.

Comparison of Within-Stand Fuel Moisture

Fuel moisture characteristics are summarized in Table 3. Significant nonzero skewness statistics indicate that the distributions of the moisture content of all fuel components sampled were asymmetric rather than normal. Kurtosis values indicated that the moisture content data were distributed with a longer-than-normal tail for all fuel components sampled except duff, which had a flatter-than-normal distribution. In general, low moisture contents were more prevalent than high moisture contents because more sampling was carried out on dry rather than wet days.

We performed Wilcoxon signed-rank tests to determine whether the presence or absence of an understory had an effect on the moisture content of the various fuel components sampled. Discernible site differences in moisture content were significant only for duff and bark flake fuels. Duff samples were drier at Site 1 than at Site 2 ($P > 0.0005$), while bark flakes were wetter at Site 1 than at Site 2 ($P = 0.007$). These results suggest that differences in the understory and overstory stand densities measured at the two sites (see Table 1) did not have a significant effect on the moisture content of fine fuels such as moss tips and needle litter, which are described by the FFMC.

While the presence or absence of an understory did not have a significant effect on the moisture content of

Table 3. Summary statistics for the moisture content (%) of the various fuels sampled at two sites selected for destructive sampling for fuel moisture content, Northwest Territories, Canada, 1999–2000. Site 1 had an understory of black spruce, and Site 2 lacked an understory beneath a jack pine and black spruce overstory.

Site	Fuel component	N	Minimum	Maximum	Mean	Standard deviation	Skewness	Kurtosis
1	Moss tips	193	1.92	363.46	75.62	79.92	1.59	2.29
	Needle litter	194	1.37	109.86	21.79	17.94	2.07	5.34
	Bark flakes	176	4.76	29.36	13.10	5.03	0.89	0.42
	Small twigs (<0.5 cm)	189	3.68	112.40	19.72	17.64	3.01	11.41
	Large twigs (0.5–1 cm)	190	5.07	103.25	20.58	16.98	2.35	6.26
	Duff (0–2 cm)	191	6.86	232.73	81.83	49.99	0.36	–0.32
	Douglas-fir sticks	222	6.02	28.41	12.11	4.12	1.055	1.66
	Ponderosa pine sticks	222	5.85	49.04	14.11	7.26	2.04	5.51
2	Moss tips	184	4.28	386.67	87.95	95.27	1.44	1.13
	Needle litter	191	2.56	98.75	22.17	18.76	1.87	3.48
	Bark flakes	182	3.96	26.19	11.81	4.27	0.96	0.59
	Small twigs (<0.5 cm)	191	2.47	101.94	20.19	17.16	2.33	5.87
	Large twigs (0.5–1 cm)	191	3.07	117.78	24.93	23.55	2.05	3.82
	Duff (0–2 cm)	188	10.58	256.94	91.38	53.65	0.23	–0.74
	Douglas-fir sticks	214	5.39	28.92	11.92	4.00	1.07	1.78
	Ponderosa pine sticks	216	5.52	49.08	13.77	7.15	2.17	6.38

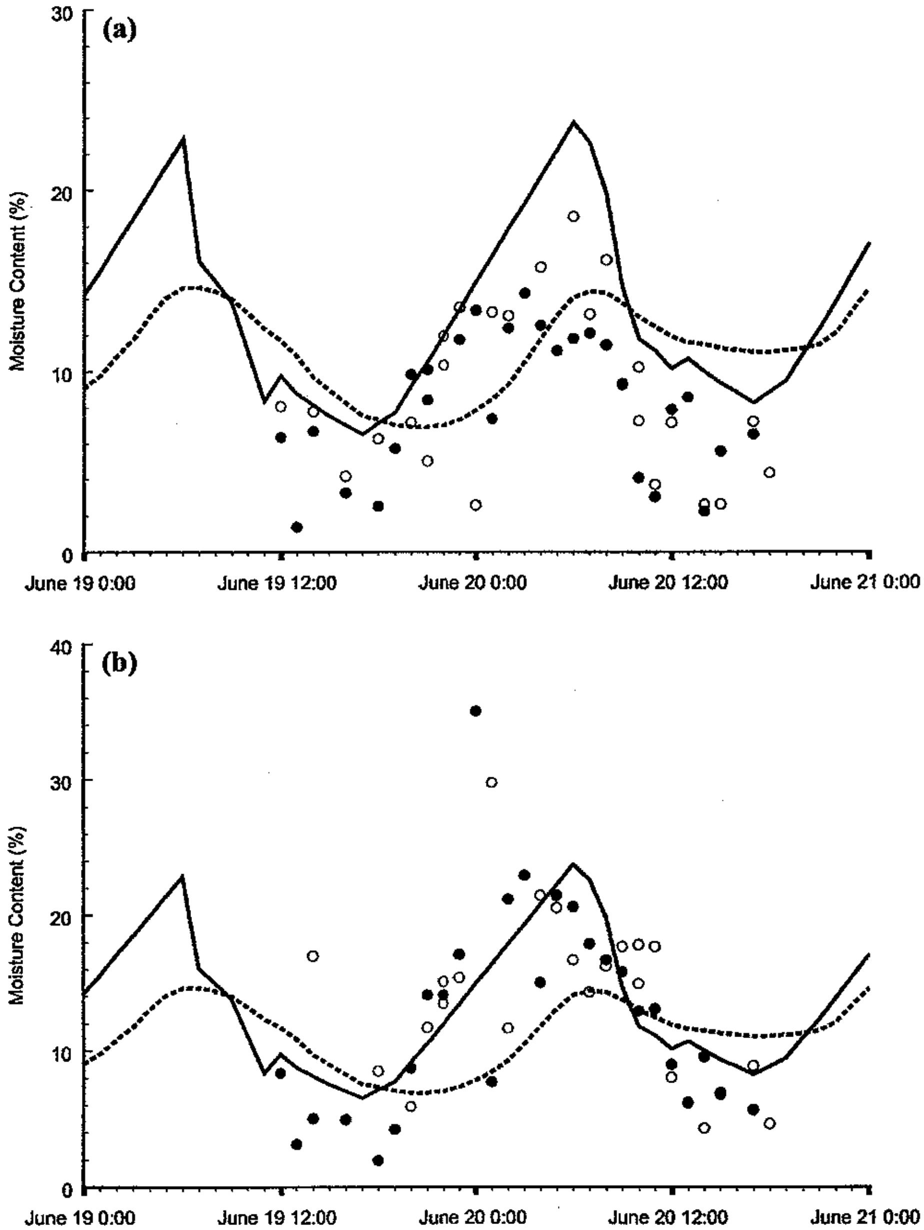
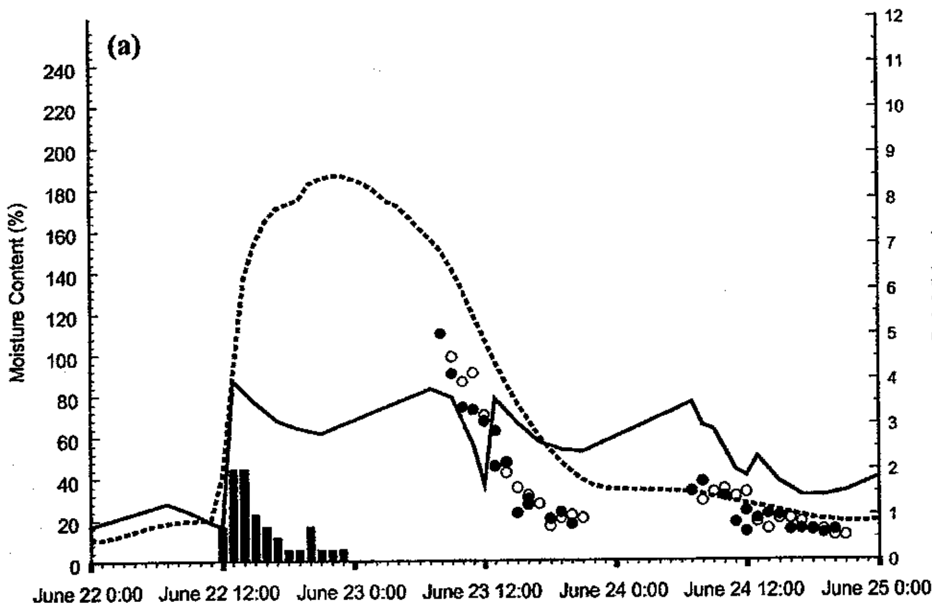


Figure 2. Hourly jack pine needle (a) and feathermoss (b) moisture content and that predicted using standard diurnal (solid line) trends to adjust the daily fine fuel moisture code (FFMC) value for time of day (Lawson et al. 1996) and Van Wagner's (1977) hourly (dashed line) FFMC model on typical dry days. Actual moisture contents were sampled at two sites selected for destructive sampling with (solid circles) and without (open circles) an understory of black spruce, Northwest Territories, Canada, 1999–2000.

ponderosa pine and Douglas-fir fuel moisture sticks, a Wilcoxen signed-rank test indicated that species had a significant ($P > 0.0005$) effect on the moisture content of fuel sticks. Fuel moisture sticks made of ponderosa pine tended to be wetter than those made of Douglas-fir. This was especially noticeable following a rainfall event when sticks made of ponderosa pine absorbed more moisture than those made of Douglas-fir, shown by the different maximum moisture contents thereof (Table 3).

Predicted and Observed Moisture Contents

Trends in actual hourly moisture content of jack pine needles and feathermoss were plotted with those predicted using the hourly (Van Wagner 1977) and diurnal (Lawson et al. 1996) models for typical dry days (Figure 2) and those following a significant rain event (Figure 3). Predicted moisture contents from the diurnal and hourly FFMC models coincide at 1700 DST. Jack pine needles and feathermoss exhibited distinct



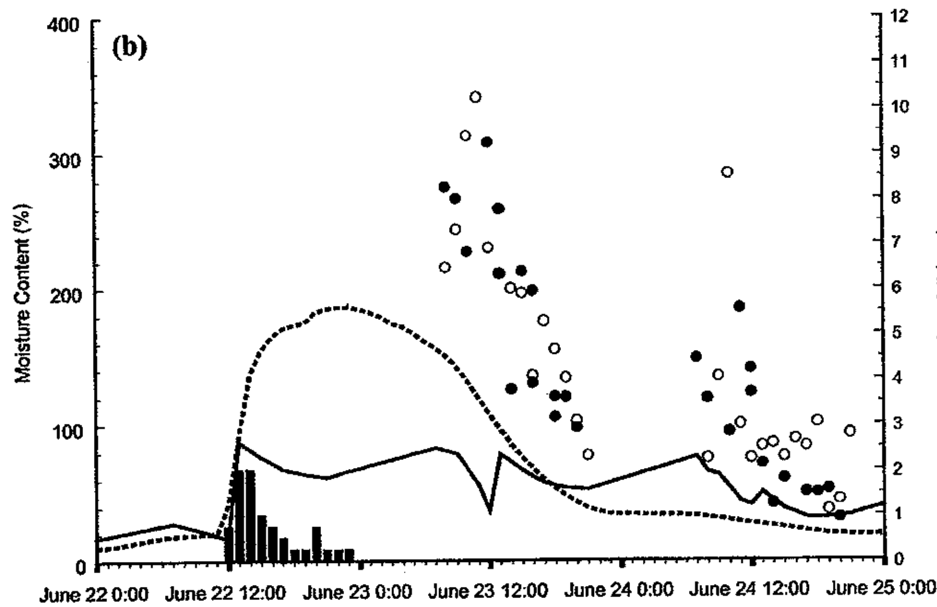


Figure 3. Hourly jack pine needle (a) and feathermoss (b) moisture content and that predicted using standard diurnal (solid line) trends to adjust the daily fine fuel moisture code (FFMC) value for time of day (Lawson et al. 1996) and Van Wagner's (1977) hourly (dashed line) FFMC model after 9.12 mm of rain on 22 June 1999. Actual moisture contents were sampled at two sites selected for destructive sampling with (solid circles) and without (open circles) an understory of black spruce, Northwest Territories, Canada, 1999–2000.

diurnal trends in moisture content throughout the day; however, the data show evidence of considerable natural variation about these trends. On dry days, both needles and feathermoss reached a minimum moisture content in the late afternoon, which then increased rapidly to an overnight maximum that is maintained until drying began in the early morning.

There are notable differences between FFMCs computed using the standard diurnal trends (Lawson et al. 1996) and those calculated by way of Van Wagner's (1977) hourly model. In particular, given a normal dry day (Figure 2), the amplitude of the predicted moisture content of needle litter and feathermoss is much greater using the standard diurnal trends (Lawson et al. 1996) than the hourly FFMC model (Van Wagner 1977). For example, the standard diurnal model suggests that fine fuel moisture should vary from 6% on 19 June at 1700 DST (Figure 2) to 24% on 20 June at 0600 DST, whereas the hourly model suggests that fuel moisture should vary from 6% to 12% during this

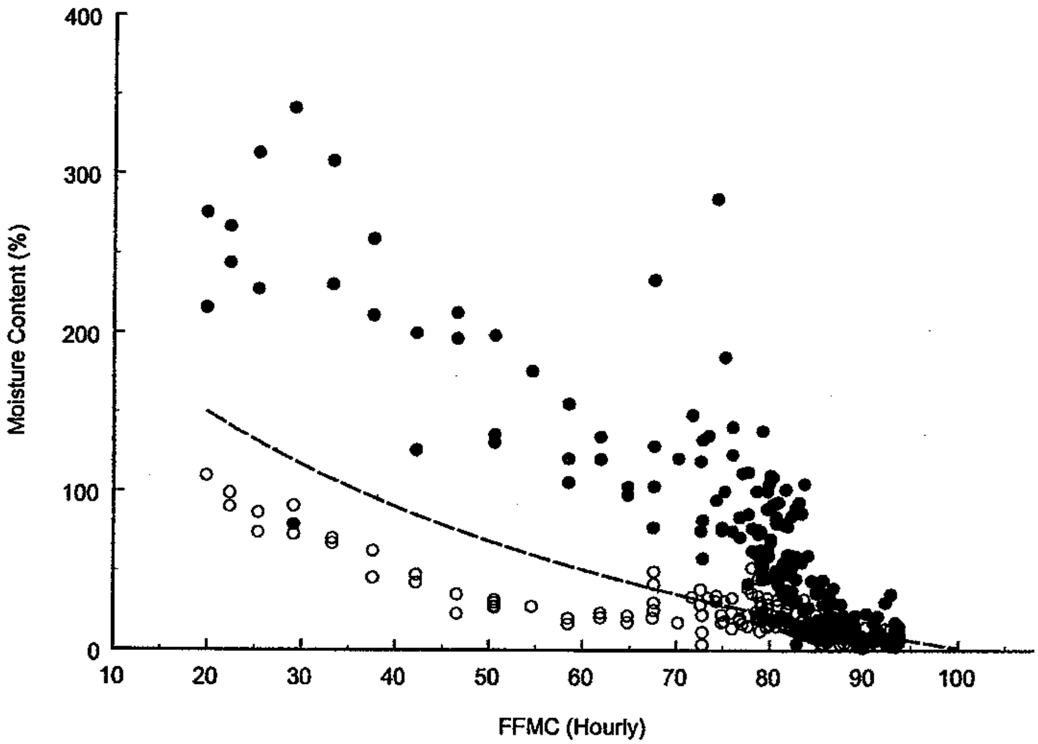


Figure 4. The standard relationship (dashed line; see Equation 1 in text) developed to describe how the moisture content of pine needle litter varies with fine fuel moisture code (FFMC) (Van Wagner 1987) slightly overestimated the moisture content of jack pine needles (open circles) and greatly underestimated the moisture content of feathermoss (solid circles), Northwest Territories, Canada, 1999–2000. Data from two study sites with and without an understory of black spruce have been pooled.

time period. During this same time period, actual moisture contents varied from 4% to 18% and 4% to 24% for needle litter and feathermoss fuels, respectively. Both the hourly and diurnal models consistently overestimated the minimum moisture content of jack pine needles and feathermoss on dry days.

On dry days (Figure 2), the diurnal model best described the amplitude of the moisture content of feathermoss fuels throughout the day, whereas trends in the amplitude of jack pine needle moisture content were better described by the hourly model. This was to be expected given that the performance of the theoretical hourly model (Van Wagner 1977) was checked against data from trays of jack pine needle litter, whereas the diurnal model (Lawson et al. 1996) was developed for litter that was composed of lodgepole pine needles, and the tips of both feathermoss and reindeer lichen.

Differences in the amplitude of the models occur because the standard equation (Equation 1) that was used to relate FFMC and moisture content (Van Wagner 1987) was not strictly applicable to the fuels samples in our study. Equation 1 is a theoretical curve that was developed to describe the relationship between FFMC and the moisture content of pine needle litter. Van Wagner (1987) does not describe the source of the data for this curve, although it may have been based on earlier work (Van Wagner 1972). Regardless, this equation slightly overestimated the moisture content of jack pine needles and greatly underestimated the moisture content of feathermoss (Figure 4), although differences decreased and became small for both litter fuel components within the range of flammability (FFMC > 77).

Differences between the moisture content of needle fuels sampled by Van Wagner (1977) and those collected at ICFME may be attributed to the fact that Van Wagner (1977) worked with a needle litterbed in sample trays under plastic shelters. Using destructive fuel sampling techniques, we studied natural wetting and drying regimes empirically and for the development of the diurnal model (Lawson et al. 1996).

Not only were differences in the type of litter fuels sampled significant from a moisture modeling standpoint, but so were differences in stand characteristics such as height, density, and crown closure. For example, the diurnal FFMC model (Lawson et al. 1996) was developed for a 120-year-old dry pine stand (Russell and Péch 1968) with 1,667 stems/ha, a mean average height of 16.5 m, and a mean stand diameter of 13.4 cm. This dry pine stand was slightly taller and less dense than the moisture sampling sites we studied (Table 2). Van Wagner (1977) does not describe stand conditions for the sites used to verify the hourly FFMC model.

The hourly model produces a smooth, continuous trend in moisture content that oscillates diurnally on dry days and responds rapidly to rainfall events. On dry days, the hourly model does not appear to adequately describe the wetting and drying rates of the two fuels studied. The feathermoss and needle fuels we studied appeared to lose and gain moisture more quickly than was currently reflected by the hourly model (Figure 2), although more work would be required to accurately quantify these wetting and drying rates.

Using the diurnal model, we estimated afternoon or overnight (1300–0659 DST) FFMCs, and hence moisture contents, by adjusting the current day's standard FFMC, whereas the previous day's FFMC was applied along with relative humidity to estimate FFMCs in the morning (0700–1259 DST). Hence discontinuities occurred at the transition phases (0700 and 1300) of the model (Figures 2 and 3). Such discontinuities are especially noticeable given early morning drying followed by a significant increase in moisture at 1300, when afternoon rainfall from the previous day was applied to reset the current day's FFMC (see 23 June, Figure 3).

Unlike the diurnal model which could not account for rainfall, the hourly model responded quickly to rainfall events and appeared to track drying trends on the day following a rainfall event reasonably well (Figure 3). The hourly and diurnal models overestimated needle moisture content and underestimated feathermoss moisture content following rain.

CONCLUSIONS

Despite differences in temperature, relative humidity, and wind speed, discernible site differences in moisture content were only significant for duff (0–2 cm) and bark flake fuels, and were not significant for jack pine needles, feathermoss, small twigs (<0.5 cm), large twigs (0.5–1.0 cm) or 10-h fuel moisture sticks. Duff samples were drier at the site with an understory, while bark flakes were wetter at the site with an understory. These results suggest that differences in the understory and overstory stand densities measured at the two sites do not have a significant effect on the moisture content of fine fuels such as feathermoss and needle litter, which are described by the FFMC. Care should be taken before pooling such data in the development of moisture models, however, since a high moisture content of the partially decomposed lower horizons of the duff may slow the drying rate of the top layer of duff or litter (Wright 1935).

In the absence of ignition trials, it cannot be inferred that fire behavior characteristics at the two sites will be similar. Wind speed and duff moisture differences, as well as the presence of an understory that represents plentiful ladder fuels, can be expected to produce different fire behavior characteristics at the two sites.

The moisture content data for feathermoss and needle litter have been used to assess the performance of the diurnal (Lawson et al. 1996) and hourly (Van Wagner 1977) FFMC models. The diurnal model developed by Lawson et al. (1996) best described the amplitude of the moisture content of feathermoss fuels throughout the day, whereas the amplitude of jack pine needle moisture content was better described by way of the hourly FFMC (Van Wagner 1977, Alexander et al. 1984).

Differences between the actual and predicted moisture contents using both the hourly and diurnal models occurred because the theoretical equation (Equation 1) that relates moisture content to FFMC was not strictly applicable to the needle or feathermoss fuels we studied. The hourly and diurnal FFMC models, which were developed for lodgepole pine needle litter and litter that was composed of the tips of both feathermoss and reindeer lichen, respectively, were not in synchrony, even on typical dry days when they should have been, because they were based on slightly different fuel types with different amplitudes in moisture content throughout the day.

In the present study, we did not attempt to assess the significance of the differences in the diurnal and hourly FFMC model to determine how they might affect fire behavior predictions. Moreover, it has yet to be determined whether the dominant influence on the flammability of the forest floor fuels within the stands studied is governed by the moisture content of feathermoss or needle litter, or some combination thereof. Further research should be conducted to address these issues.

Discontinuities in the diurnal model occur at the transition phases (0700 and 1300 DST) of the model, and these are especially noticeable when rainfall occurs. Once a rainfall event begins, outputs from the diurnal model should not be considered applicable until the rain stops, and all rainfall effects have been applied to reset the current day's FFMC.

Fixed stand characteristics and a common standard fuel should be used for the models that support daily and hourly FFMC and moisture predictions within the Canadian Forest Fire Danger Rating System. Given an appropriate model to predict fuel moisture from FFMC, the hourly FFMC model needs to be studied in more detail and possibly reparameterized to correctly describe the wetting and drying rates of jack pine needles or feathermoss.

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