DUFF MOISTURE DYNAMICS IN BLACK SPRUCE FEATHER MOSS STANDS AND THEIR RELATION TO THE CANADIAN FOREST FIRE DANGER RATING SYSTEM

A

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Abstract

The Canadian Forest Fire Danger Rating System's Fire Weather Index (FWI) System models 3 levels of fuel moisture within the forest floor using simple environmental inputs. Wildland fire managers in interior Alaska have expressed concern that the FWI System does not take northern latitude factors such as long day lengths and permafrost into account. During the 1999 fire season destructive sampling methods were employed to monitor moisture content throughout the feather moss profile in 3 interior Alaska black spruce stands. Measured moisture contents were compared to the FWI System's fuel moisture predictions. The FWI System followed general trends of the seasonal fuel moisture within the feather moss profile. However, the short-term response of the interior Alaska moss profile is more dynamic than the FWI System's fuel moisture code predictions. Hydraulic properties that have been linked to bulk density may be the causative agent for the observed short-term discrepancy.

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Acronyms and Abbreviations Used in this Document:

NFDRS	National Fire Danger Rating System
CFFDRS	Canadian Forest Fire Danger Rating System
FWI	Fire Weather Index
FFMC	Fine Fuel Moisture Code
DMC	Duff Moisture Code
DC	Drought Code
ISI	Initial Spread Index
BUI	Buildup Index
USFS	United States Forest Service
BLM	Bureau of Land Management
AFS	Alaska Fire Service
RAWS	Remote Automated Weather Station
FBK	Fairbanks
CPK	Caribou Peak
LST	Local standard time
FTWW1	Ft. Wainwright plot #1
FTWW2	Ft. Wainwright plot #2
FTWW3	Ft. Wainwright plot #3
LGBS	Large black spruce plot
UPBS	Upper black spruce plot
LM	Live moss

DM	Dead moss
UD	Upper Duff
LD	Lower Duff
MC	Moisture content
FDR	Frequency Domain Reflectometry
TDR	Time Domain Reflectometry
MANOVA	Multivariate Analysis of Variance

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"The two great forces shaping the vegetative mosaic of interior Alaska are fire and permafrost, an incessant antagonism of heat and cold, aridity and moisture."

Stephen J. Pyne, 1982, Fire in America

1 Introduction

Fire is a dominant disturbance factor in the black spruce boreal forest ecosystem in interior Alaska. In an attempt to prepare for or emulate fire events, fire personnel rely on widely spaced weather stations that provide environmental inputs into a fire danger rating index.

A fire danger rating index, or system, is an efficient method of tracking several components of fire behavior and fire danger over large geographic areas. Traditionally, the models are used for strategic resource allocation and efficient fire suppression tactics. The emerging interest in fire management has provided new avenues for application of fire danger rating systems. In fire management, fire-use and prescribed fires are often predicted to burn with expected results.

In boreal forest ecosystems, organic ground cover or "duff' consumption contributes to fire severity and directly influences fire effects. Previous studies have examined the dependence of post-fire thermal regime (Viereck 1973, Viereck et al. 1979), nutrient cycling (Dyrness and Norum 1983), and successional trajectory (Foote 1983) on the depth of duff consumption. In addition, emissions from smoldering duff contain products of incomplete combustion that have been found to make up a large percentage of the pollutants produced in a fire (Ward et al. 1992, Nance et al. 1993). At northern latitudes these pollutants may be a major factor contributing to global climate change (Kasischke et al.1995). It is therefore essential to have a fire danger rating system that accurately reflects the amount of forest floor fuel available for consumption.

From the early 1970's through the early 1990's the National Fire Danger Rating System (NFDRS) (Deeming et al. 1978) was used in Alaska to forecast fire danger. The NFDRS was unable to provide useful fire danger information for boreal forest fuels (Malotte, unpublished). Lack of success can be attributed to the model's fuel moisture prediction module. The NFDRS fuel moisture module models dead cylindrical woody fuels that are not abundant in the black spruce feather moss ecotypes common in interior Alaska. The NFDRS fuel moisture predictions are based on theoretical diffusion for dead woody fuels and are much lower than moistures encountered in O-horizon fuels. Solutions to the inadequacies of the NFDRS were expected in the Canadian Forest Fire Danger Rating System (CFFDRS). One of the potential strengths of the CFFDRS was the Canadian Forest Fire Weather Index System (FWI) (Van Wagner 1987), an empirical fuel moisture module that models fuel moisture content at 3 depths in the forest floor providing information on potential flammability and fuel consumption.

The FWI System uses simple weather observations to model 3 distinct moisture regimes within the O-horizon of the forest floor. The fuel moisture codes are empirically derived 'bookkeeping' systems wherein incoming moisture is added to that of the previous day and evaporating moisture is subtracted. The fuel moisture codes are constructed so that higher numbers indicate decreasing fuel moisture and hence, increasing fire potential.

To facilitate the transition from NFDRS to the FWI System, the BLM Alaska Fire Service (AFS) initiated a 'Fire Weather - Fuel Conditions' project (Miller 1980, unpublished). Weather and fuel moisture data were collected at several locations throughout Interior Alaska to evaluate the predictive capabilities of the NFDRS and the CFFDRS. Unfortunately, the project was abandoned after 1 season, 1980, and the data were never analyzed or published (Miller 1998, personal communication). Regardless, by the early 1990's most agencies had officially adopted the CFFDRS (Alexander and Cole 1995).

Three major concerns are associated with the adoption of an empirically derived model that has not been calibrated to the local environment: 1) the original fuel moisture algorithms in the FWI System were developed in Jack pine and Douglas-fir duff fuels, 2) the fixed day length factors in the fuel moisture algorithms used to estimate evapotranspiration do not reflect seasonal radiation in far northern latitudes, and 3) drainage restrictions due to the presence of permafrost, which is common in interior Alaska, are not addressed in the FWI System's fuel moisture codes.

2 Study Objectives

The goal of this study was to assess the adequacy of the CFFDRS FWI System's fuel moisture prediction capabilities in a boreal forest permafrost environment. Data collection during the 1999 season focused on destructive sampling to assess the physical properties, moisture retention, and moisture distribution processes of feather moss fuels. Specific study objectives include:

1) Determine physical properties of typical interior Alaska feather moss duff fuels.
2) Examine moisture regimes in interior Alaska feather moss duff fuels.
3) Compare measured feather moss duff moisture contents and CFFDRS FWI System's fuel moisture codes.
4) Explore alternative methods of relating the FWI System's fuel moisture codes to interior Alaska feather moss duff moisture contents.
5) Evaluate current methods of adjusting slow drying fuels represented by the FWI System's drought code to reflect long-term drought.

The 2000 season focused on the calibration and utility of Frequency Domain Reflectometry (FDR) probes in the deep organic layers common in northern boreal forests. The FDR results are presented as an addendum to this research. It is hoped that the research included in the thesis and addendum will be of value to fire and resource management in the pursuit of increased efficiency in all aspects of wildland fire.

3 Literature Review

3.1 Ecological Effects of Duff Consumption by Forest Fires in Interior Alaska

Combustion of the duff layer has several consequences. The thermal regime of a burned boreal forest site is highly influenced by the amount of insulating duff that is removed. Studies in interior Alaska have shown that complete or significant consumption of the O-horizon promotes prolonged soil warming and active layer increase (Viereck 1973, Viereck et al. 1979, and Yoshikawa et al. 2000). Viereck and Schandelmeier (1980) report that the active layer has usually returned to its original thickness when complete canopy coverage has been reestablished, a process that requires 50 to 70 years in black spruce ecosystems (Foote 1983). Recently, Hinzeman et al. (2000) have observed even longer periods of increased active layer depths and suggest that severe fires in combination with global warming may be eliminating permafrost in severely burned sites.

Nutrient availability can be significantly enhanced in moderate and severely burned boreal forest sites (Viereck and Schandelmeier 1980). Dyrness and Norum (1983) documented significant increases in soil pH and total and available P in moderate and severely burned areas. Total nitrogen increased on the moderate burned sites but decreased on the severely burned sites. The loss of N in the severely burned sites is suspected to be the result nitrogen volatilization.

The successional trajectory of a burned site is directly related to the depth of duff consumption. Lightly burned areas encourage sprouting while severely burned sites are invaded by species disseminated by wind-borne propagules (Dyrness and Norum 1983, and Foote 1983). As a result, the vegetation in sites experiencing low severity fires will closely resemble the pre-burn community. In severely burned sites, shrubs and seedlings will be minor components while the mosses and liverworts will be the dominant early succession vegetation.

3.2 The Role of Duff Consumption in Fire Behavior

Fine surface fuels contribute to ease of ignition and rate of fire spread while larger diameter woody fuels and duff contribute to total fire intensity (Lawson et al. 1997a) and fire severity (Viereck and Schandelmeier 1980). Pyrolysis of the duff generally occurs slowly during the smoldering phase of the fire with flaming combustion rarely being exhibited (Frandsen 1991). The probability that a duff fuel will ignite and smolder is related to 3 duff properties: bulk density, percentage of inorganic substrate, and moisture content (Frandsen 1987 and Hungerford et al. 1995). Bulk density controls moisture characteristics (Boelter 1969) and is a measure of the fuels available energy (Kane et al. 1978). Inorganic materials within the fuel matrix absorb heat that could contribute to the vaporization of water (Frandsen 1987). The moisture content determines the amount of heat required to vaporize the water and raise the temperature of the fuel to ignition temperature (Debano et al. 1998). Moisture content is generally considered the controlling factor as it rapidly responds to dynamic environmental factors.

3.3 Decomposition Features that Affect Duff Moisture Characteristics

In coniferous forests the O-horizon is commonly termed “duff” and is described as having 3 layers, the litter or L-horizon, the fermentation or F-horizon, and the humus or H-horizon. A similar stratification is found in boreal forest organic soils comprised of decomposing moss. In decomposing mosses, the horizons are better described by Brady and Weil’s (1996) organic horizons: the fibric Oi-horizon is slightly decomposed moss material, the hemic Oe-horizon is intermediately decomposed moss material, and sapric Oa-horizon is highly decomposed humus.

The degree of decomposition within the O-horizon has been acknowledged to have a strong influence on the hydraulic conductivity and moisture retention characteristics of the duff layers (Boelter 1969). Plamondon et al. (1972) found hydraulic properties between the L, F, and H-horizons to be significantly different. In slightly decomposed material, large pore spaces promote hydraulic conductivity. As decomposition proceeds, the size of the organic particles decreases resulting in smaller pores with higher moisture retention properties. Thus, hydraulic conductivity decreases significantly with degree of decomposition (Lauren and Heiskanen 1997). In addition Sharratt (1997) determined differences in water retention within the moss profile to be related to disparities in porosity. Boelter (1969), Weiss et al. (1998) and Sharratt (1997) have concluded that bulk density is a useful indicator of pore size distribution and hence, hydraulic conductivity and moisture retention in organic soils.

3.4 Morphological Features of Feather Moss Affecting Moisture Movement

Skre et al. (1983) found the green portion of several feather moss species stems to have much greater variability in moisture content than the lower brown dead portion of the stems. Furthermore, the hydration and desiccation cycles of the surface portions of feather mosses were controlled more strongly by environmental factors than by ground water availability. This supports Busby and Whitefield's (1978) conclusion that the moisture content in the green moss responds more rapidly to fluctuations in vapor pressure and wind speed than to changes in light intensity, and that decreased evaporation at depth contributes to observed increases in moisture content with depth.

Busby (1976) also surmised that beneath the moss surface, density, orientation, and external structure of the stem leaves determine the rate and direction of water movement. Vertical moisture distribution appears to be facilitated by paraphyllia, filamentus branched structures on leaves and stems that wick moisture from depths of 6 to 8 cm using capillary action. This roughly corresponds to Sharratt's (1997) observation that moisture retention characteristics in the moss profile differ above and below the 10 cm depth. In addition, Busby and Whitfield (1978) found moisture retention characteristics in *Pleurozium schreberi* and *Hylocomium splendens* to be very similar.

Resistance to ascending and descending water movement will increase as moisture contents decrease and the capillary connections along the stem collapse (Busby 1976). Internal vapor diffusion processes controlled by temperature and relative humidity (Van Wagner 1970) will begin to dominate the moisture regime when all surface water has been lost from the system.

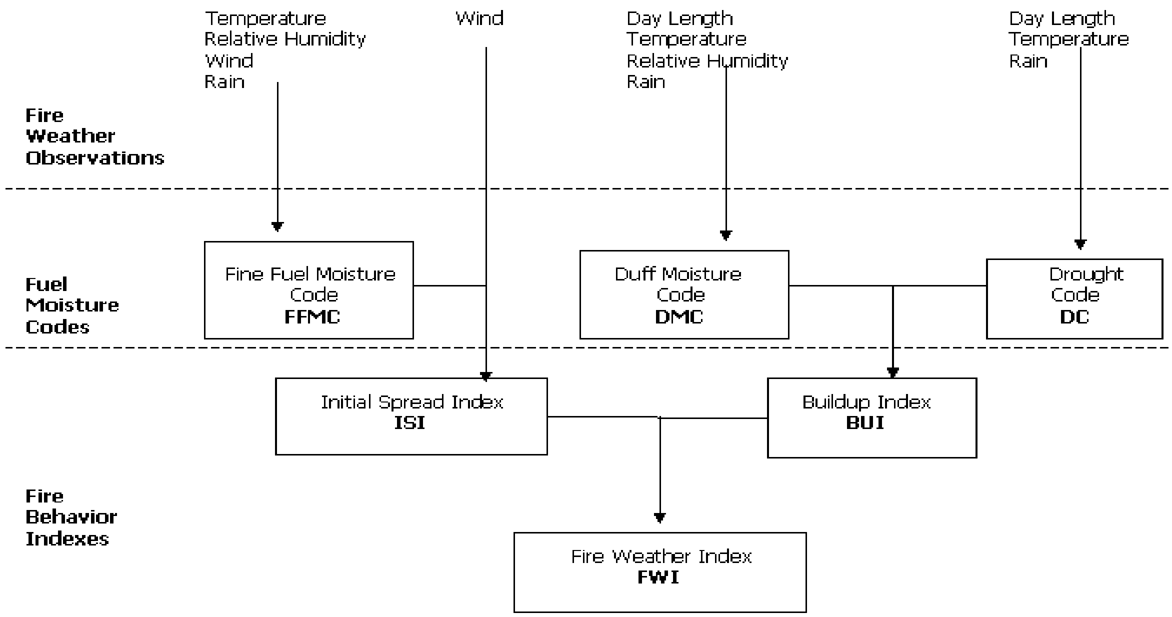
3.5 The Canadian Forest Fire Danger Rating System's Fire Weather Index Module

Because it is costly and inefficient for fire personnel to measure fuel moisture directly, some type of index is commonly used to model fuel moisture based on simple weather observations. In the Canadian Forest Fire Danger Rating System the fuel moisture module, 1of 4 major modules, is called the Canadian Forest Fire Weather Index (FWI) System (Stocks et al. 1989).

The FWI System (Figure 1) has 3 fuel moisture codes that were designed to model 3 distinct drying rates within the O-horizon of the forest floor (Van Wagner 1987). The daily index for each drying rate is computed from environmental observations thought to have the greatest influence on the moisture regime of the modeled fuel.

The 3 FWI System fuel moisture indexes are: the Fine Fuel Moisture Code (FFMC), representing the moisture content of fine surface litter or L-horizon, the Duff Moisture Code (DMC), representing the moisture content of loosely compacted duff of moderate depth or the F-horizon, and the Drought Code (DC) representing the moisture content of deep compacted organic matter or the H-horizon.

Figure 1. Structure of the Canadian Forest Fire Weather Index System. Adapted from Canadian Forestry Service 1984.



The FWI System is designed to enable the 3 fuel moisture code components to stand alone as models of fuel moisture, or to allow them to be further incorporated into 3 indexes of fire behavior: the Initial Spread Index (ISI), an estimation of spread rate, and the Buildup Index (BUI), an estimation of fuel consumption. A final measure of fire danger, the Fire Weather Index (FWI) component itself, is a measure fire intensity per unit of fire front derived from the other 2 intermediate fire behavior indexes (Van Wagner 1987).

3.5.1 The Fine Fuel Moisture Code

The Fine Fuel Moisture Code (FFMC) is a numerical rating of the moisture content of the fine surface fuels. Fine fuels are characterized by large surface area to volume ratios that promote rapid moisture exchange. Several studies have addressed the liquid and vapor exchange dynamics associated with fine fuels (Fosberg 1971, Viney 1992, and Lawson et al. 1996) and they will not be discussed further in this research which is concerned with duff consumption rather than fire spread.

3.5.2 The Duff Moisture Code

The Duff Moisture Code (DMC) was developed by Van Wagner (1970) to model the slow drying F-horizon in pine duff fuels. Duff moisture measurements for the empirical derivation of the DMC were collected near Petawawa, Ontario at a latitude of 46^{o}N. Moisture content data were obtained from large samples of duff (including all material from the surface to mineral soil) that had been placed in wire mesh trays and inserted in the ground. The trays were weighed daily from May through October. The physical properties of the pine duff fuel are shown in Table 1.

Van Wagner (1987) summarized the DMC assumptions and code derivations as follows:

Drying phase:

1) Day to day drying in constant weather is exponential.
2) The duff layer has for all practical purposes, a constant equilibrium (hygroscopic) moisture content of 20 percent.

3) The logarithmic ($\log_e$) drying rate is proportional to temperature, becoming negligible at about $-1\,^{o}$C.
4) The logarithmic drying rate is proportional to the deficit in relative humidity.
5) The daylength, varying with season, has an effect roughly proportional to 3 less than the number of hours between sunrise and sunset.

Wetting phase:

1) Increases in moisture content per unit of rain are inversely proportional to the amount of a rainfall event.
2) The wetting effect of a rainfall decreases with increasing initial moisture content.

The DMC works as a simple bookkeeping system that adds points to the code value on drying days and subtracts them on wetting days. A DMC value is equated to a moisture content (MC) with the following empirical equation developed from the pine duff fuels at Petawawa, Ontario:

$$MC = \exp[(DMC - 244.7)/ -43.4] + 20 \qquad [1]$$

Where the constant 20 is the theoretic equilibrium moisture content of the F-horizon. A single equilibrium moisture content is justified in Van Wagner's (1970) original DMC work. The F-horizon fuels in the study rarely yielded moisture contents less than 20 percent and the logarithmic drying rate of the F-horizon fuels was not influenced by deviations of a few percent above or below the 20 percent level.

Table 1. Properties of the FWI System's fuel moisture codes. Adapted from Van Wagner 1987.

Fuel Moisture Code	Soil horizon	Water capacity mm	Rain fall thresholds mm	Timelag* days	Nominal fuel depth cm	Bulk density Mg/m^3
FFMC	L	0.62	0.6	2/3	1.2	0.021
DMC	F	15	1.5	15	7	0.071
DC	H	100	2.9	53	18	0.139

* A fuels time-lag is expressed as that amount of time required for the fuel to lose 1 – 1/e (about 2/3) of the free moisture above equilibrium on a standard day (noon temperature of 21.1^{o}C, relative humidity of 45%, 13 km/h wind, during the month of July) (Merrill and Alexander 1987).

Several studies have compared in-situ moisture contents with the DMC. Chrosciewicz (1989) found the DMC to be good predictor of moisture content trends in all decompositional states of *Pleurozium schreberi* at a site in Saskatchewan. Granstrom and Schimmel (1998) observed strong correlations between the DMC and moisture contents in the moss-lichen-litter layer of 4 different stand types near Vasterbotten, Sweden, indicating that seasonal moisture trends are being tracked by the DMC. However, large differences were observed in duff drying rates between stands of different stem density. Near Whitehorse, Yukon Territory, moisture contents in the duff layer exceeded that predicted by Van Wagner's (1970) original empirical equation early in the spring (Lawson et al. 1997b). The elevated moisture contents were presumed to be the result of frozen soils restricting drainage. As the season progressed the moisture contents fell below those predicted by the DMC suggesting that the log drying rate of feather moss duff exceeds that of pine duff.

3.5.3 The Drought Code

The Drought Code (DC) is a long-term seasonal drought indicator (Taylor and Lawson 1997). In its original form the DC was essentially a simple water balance equation that was not intended to represent any specific class of fuel (Turner 1972). The model subtracts daily moisture loss, through evapotranspiration, from a 200 mm reservoir. Precipitation events are additive, recharging the reservoir. Potential monthly evapotranspirtation rates are calculated using a slight variation of the Thornthwaite-Mather model (Turner 1972).

Having an exponential drying curve, the DC has been determined suitable as a moisture index for the deep compact humus or H-horizon, but should not be expected to relate closely to the moisture content of duff since it is based on evaporation from a reservoir not a forest floor (Lawson and Dalrymple 1996). Turner (1972) developed an empirical equation (Eq. 2) to convert the DC into a moisture equivalent in the Vancouver, British Columbia area (latitude 48^{o}N) using forest soils (organic and mineral) in a Douglas-fir stand:

$$MC = 800/e^{(DC/400)} \qquad [2]$$

Physical properties representing the Douglas-fir DC fuel type are given in Table 1.

Few studies have related moisture content of the humus layer to the DC north of 60° latitude. Near Whitehorse, Yukon Territory, Lawson and Dalrymple (1996) found that feather moss 6-10 cm in depth correlated well with the DC. As with the DMC fuels at the Whitehorse site, spring moisture contents were high but decreased rapidly as frozen soils thawed.

3.5.4 Adjusting Slow Drying Fuels Represented by the DC to Reflect Long-term Drought

Each spring the FWI System's calculations are initiated 3 days after snowmelt (Lawson and Dalrymple1996). The FFMC and DMC, having short weather histories (2/3 day and 15 days respectively), adjust to the ambient environmental conditions within 2 weeks. Early spring DC values however, having a timelag of 53 days, (and presumably being frozen) reflect the weather history of the previous fall and winter. If the water equivalent in the winter snowpack is not sufficient to recharge the theoretical reservoir, the DC is initiated with an elevated value to reflect the deficit. Lawson and Dalrymple (1996) advise elevating initial spring DC values in areas receiving less than 200 mm of winter precipitation.

The procedures for adjusting the DC to reflect deficient winter precipitation are outlined in Lawson and Dalrymple (1996) as follows:

$$Q_s = a\ Q_f + b3.94\ P \qquad [3]$$

Where Q_s = starting spring moisture equivalent of DC value

Q_f = final fall moisture equivalent of DC value (Eq. 2)

P = winter precipitation (mm)

a,b = user defined values (Table 2)

In interior Alaska, a = 1.0, the DC is calculated until the soils are frozen, and b = 0.9 for poorly drained boggy sites with deep organic layers.

The starting spring DC value is then:

$$DC_s = 400 \ln (800/Q_s) \qquad [4]$$

Table 2. DC overwintering criteria. User selected values and criteria for (a) carryover fraction of last fall's moisture, and (b) effectiveness of winter precipitation in recharging moisture reserves in spring. From Lawson and Dalrymple (1996).

Value	Criteria (a)	Value	Criteria (b)
1.00	Daily DC calculated up to Nov. 1, continuous snow cover, or freeze up, whichever comes first	**0.90**	Poorly drained, boggy sites with deep organic layers
0.75	Daily DC calculations stopped before any of the above conditions met or the area is subject to occasional winter "chinook" conditions, leaving the ground bare and subject to moisture depletion	**0.75**	Deep ground frost does not occur until late fall, if at all. Moderately drained sites that allow infiltration of most of the melting snowpack
0.50	Forested areas subject to long periods in fall or winter that favor soil moisture depletion	**0.50**	Chinook-prone areas and areas subject to early and deep ground frost. Well-drained soils favoring rapid percolation or topography favoring rapid runoff prior to melting of ground frost.

4 Methods

4.1 Site Description

Fire history accumulated over the last 50 years shows that the majority of Alaska's wildland fires occur in the interior, the large area bordered by the Alaska Range to the south and the Brooks Range to the north (AFS fire history records, 1950 to present). Black spruce is the predominant vegetation in this fire-adapted ecosystem (Viereck et al. 1986). The Canadian Forest Fire Behavior Prediction System's C-2 Boreal Spruce fuel model gives a good description of these sites (Forestry Canada Fire Danger Group 1992):

> Fuel Type C-2 (boreal spruce): This fuel type is characterized by pure, moderately well-stocked black spruce stands on lowland (excluding *Sphagnum* bogs) and upland sites. Tree crowns extend to or near the ground and dead branches are typically draped with bearded lichens (*Usnea* sp.). The flaky nature of the bark on the lower portion of stem boles is pronounced. Low to moderate volumes of down woody material are present. Labrador tea (*Ledum groenlandicum* Oeder) is often the major shrub component. The forest floor is dominated by a carpet of feather mosses and /or ground dwelling lichens (chiefly Cladonia). A compacted organic layer commonly exceeds a depth of 20-30 cm.

To address the concerns of the fire agencies utilizing the CFFDRS FWI System, a site representative of a typical interior black spruce stand was selected on the

Ft. Wainwright military base near Fairbanks, Alaska (lat. 64^{o}N,long. 147^{o}W, elev. 140 m) (Figure 2). Permafrost was present in the stand enabling an evaluation of the applicability of the FWI System's fuel moisture codes in a restricted drainage environment. Topographic relief in the site was negligible to reduce the confounding effects of slope run-off.

Ft. Wainwright is situated within the Fairbanks lowlands adjacent to the Tanana River. Abandoned-floodplain cover deposits and occasional bogs dominate the lowlands. These poorly drained alluvial flats are underlain with nearly continuous permafrost. The cold Gelisol soils retard decomposition causing a build-up of undecomposed organic matter that can be over 20 cm thick. Mineral soils in the area are comprised of Tanana silt loam (Jorgenson et al. 1998).

The climate in interior Alaska is continental, with extreme ranges in annual temperature variations, low precipitation and light surface winds. The average annual temperature in the Fairbanks area is –3.3^{o}C with average annual precipitation of 297 mm (Racine et al. 1997). Heavy isolated rains begin in May in conjunction with convective storms while widespread southwesterly flow brings consistent moisture in July and August, followed by a drying period from September through December. The fire season begins in conjunction with the convective activity in mid-May, and fires will continue to smolder late into the fall.

Vegetation on these poorly drained permafrost sites is typical of the Canadian Forest Fire Behavior Prediction System's C-2 boreal forest fuel types and is also described by Viereck et al. (1992) as Open Black Spruce – White Spruce Forest type. The ground fuels in the sampling area were dominated by *Hylocomium splendens* with a light component of *Pleurozium schreberi*. The O-horizon averaged over 20 cm in depth when completely thawed. *Vaccinium vitis-idaea* and *Ledum groenlandicum* comprised the low shrub layer. The overstory was a mix of open white and black spruce (*Picea glauca* and *Picea mariana*). Individual characteristics of the three sampling areas identified within the representative fuel type are described in Table 3. Fire scarred boles and the presence of charcoal in the soil profile indicate previous wildfire events have occurred on this site.

Table 3. Characteristics of the Ft. Wainwright sampling plots.

	FTWW1	FTWW2	FTWW3
Overstory canopy cover	30%	25%	50%
Conifer basal area	6.9 m^2/ha	2.3 m^2/ha	34.4 m^2/ha
Average stand age	120 yrs	120 yrs	85 yrs
Low shrub canopy cover	50%	60%	70%
Average depth of O-horizon	21 cm	18 cm	17 cm

The fire weather data and fuel moisture codes were obtained from the Fairbanks Remote Automated Weather Station (FBK RAWS) located 3 km north of the sampling area. The area was judged to be snow free on April 24, 1999. Calculation of the FWI System's fuel moisture codes were initiated April 27, 1999 three days past the snow free date as specified in “Tables for the Canadian Forest Fire Weather Index System” (Canadian Forestry Service 1987). The FFMC and DMC were initialized with default values (i.e., 85 and 6, respectively). The DC at the FBK RAWS was initiated with a value of 245 based on an on site snow survey conducted in March, 1999 that indicated a snow water equivalency of 54.1 mm at the site. The 245 value was derived from the Lawson and Dalrymple (1996) overwintering equations (Equations 2 and 3) using 1.0 and 0.90 for coefficients a and b respectively.

4.2 Field Methods

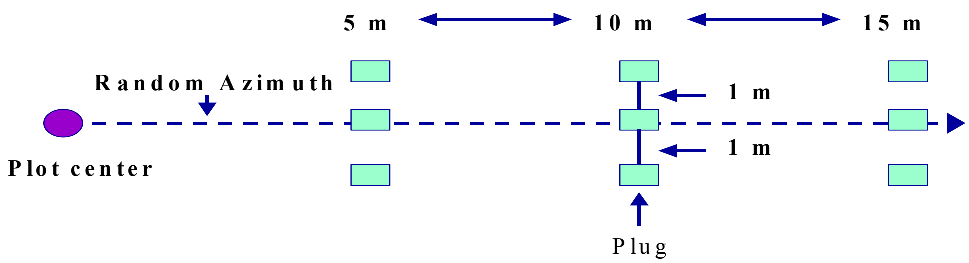
Fieldwork was conducted during the 1999 fire season. Latitude and longitude coordinates were used to determine each corner of a roughly rectangular representative sampling area. Random latitude and longitude coordinates were paired to identify 3 permanent plot centers (or points). Two of the randomly paired points were in close proximity and very similar (FTWW1 and FTWW2). To increase the scope of inference a third point (FTWW3) with different surrounding stand characteristics was hand selected. Samples were collected bi-weekly and a goal of 30 sampling periods was achieved at the FTWW3 plot. Weather conditions reduced the number of sampling periods at FTWW1 and FTWW2 to 29 and 28 respectively. Because the destructive sampling procedure was slow (about 4 hours per plot), only 2 plots could be sampled in a single day. Consequently, the FTWW1 and FTWW2 plots were usually sampled jointly. FTWW1 was sampled in the morning and FTWW2 was sampled in the afternoon. FTWW3 was usually sampled in the morning of the following day.

Each sampling day a random azimuth (generated by Excel's random number function) was run out 15 m from each of the permanent plot centers. Three plugs were extracted at 5 m intervals. A center plug was dug on the azimuth line and 2 additional plugs were dug on either side of the azimuth at least 1 meter from the center plug (Figure 3). Care was taken to avoid areas immediately adjacent to tree boles, areas that were not feather moss, and areas that were compacted. When these constraints were encountered the plug site was moved in 1 meter intervals to a more representative location. Because the moisture regime in the boreal forest duff is highly variable, the mean moisture content from the 9 plugs was used in an attempt to capture the overall moisture content of the plot.

To avoid compaction, a keyhole saw was used to cut a 15 to 20 cm^2 plug to the depth of mineral soil or permafrost. The plug was removed intact by hand or with a long bladed shovel. Although the original intent of the study was to characterize the moisture regime of the entire organic layer several factors precluded this goal. Early in the season the frozen active layer prevented a complete organic profile. As the active layer increased to include the mineral soil, large roots within the O-horizon were difficult to sever and often caused the plugs to separate upon removal from the forest floor.

Once extracted, the thickness of the upright plug was recorded. Occasional spot checks confirmed that plug thickness was equal to hole depth. The plug was then laid on its side and marked into 5 cm increments from the surface downward on all four faces. Care was taken to assure the thickness measurement of the upright plug was maintained when the

Figure 3. Sampling transect layout.



plug was laid on its side. Each 5 cm segment was carefully cut away using the markers as a guide. To determine bulk density, samples of a known volume were required. Hence, these 5 cm deep squares were further trimmed into a 10.16 cm x 10.16 cm x 5 cm sample using a 4 inch (10.16 cm) gridded square and a 1 inch gridded cutting mat. This resulted in a sample sized to 516 cm^3.

To accomplish the objective of determining if depth or fuel layer was better correlated with the FWI System's fuel moisture codes the 516 cm^3 samples were further dissected into fuel layers. Fuel layers were determined visually by degree of decomposition (Norum and Miller 1984): Live Moss – the green photosynthesizing portion of the stem. Dead Moss – light brown moss that is no longer photosynthesizing but has not begun decomposing. Upper Duff – brown moss material that has begun decomposing and is mostly comprised of fine stems. Lower Duff – fully decomposed material that is very dark brown and humified. These stratifications correspond to the morphological (Busby 1976) and physical properties that have been found to determine moisture characteristics in feather moss duff (Boelter 1969).

Sample depth (to the nearest 0.5 cm), fuel layer and tare number were recorded in the field. All samples were stored in labeled autoclavable nalgene straight wide mouth bottles and transported to the lab for weighting and drying. Weights were recorded to the nearest 0.10 g. Samples were dried in the bottles to a constant weight at 100^{o}C. Bulk density, gravimetric and volumetric moisture contents were computed using the following equations (Hillel 1998):

Bulk Density = dry wt. / sample volume [5]

Gravimetric Moisture Content = [(wet wt. – dry wt.) / dry wt.] x 100 [6]

Volumetric Moisture Content = gravimetric moisture content x bulk density [7]

4.3 Statistical Methods

An Excel spreadsheet was generated to compile the data into bulk density, volumetric and gravimetric moisture contents. Analysis of variance (ANOVA, MANOVA) and general linear model regression analysis were preformed with STATISTICA (1999) software.

4.3.1 Physical Properties of Feather Moss Duff

Plot data were sorted into bulk density data sets of 5 cm increments and fuel layer. Descriptive statistics were computed for each 5 cm increment and fuel layer. MANOVA's were employed to test the homogeneity of bulk densities of similar depths and fuel layers within and among sites. The MANOVA's were tested with a post hoc Tukey multiple means comparison test for unequal sample sizes. The Tukey test was chosen for its reported robustness to the ANOVA violations that are present in these data sets (Zar 1984); specifically, the standard deviations tend to be correlated with the population means.

4.3.2 Moisture Regimes in Feather Moss Duff

Gravimetric and volumetric moisture contents were compiled and the plot data were sorted by fuel layer. Descriptive statistics were computed for each layer. A MANOVA was used to test significant differences between the fuel layer means. A post hoc Tukey test was applied to account for multiple mean comparisons and unequal sample sizes.

4.3.3 Comparing Observed Moisture Contents to the FWI System's Fuel Moisture Codes

Gravimetric moisture contents from each plot were compiled by fuel layer. The FWI System's fuel moisture codes were converted to gravimetric moisture contents (Equation 1 and 2) to eliminate the non-linear association between code values and predicted moisture content equivalents (Van Wagner 1983). Correlation and general linear model regression analysis were used to assess the relationship between measured moisture content and moisture contents predicted by the fuel moisture code values. The Durbin Watson test was employed to detect autocorrelation that is common in time series data.

4.3.4 Testing Alternative Methods of Estimating Moisture Content in Feather Moss Duff

Coefficients of determination were used to appraise multiple equations fit to Excel scatter plots of measured fuel moisture (dependent variable) and the corresponding DC value (independent variable). The equation producing the best relationship between measured fuel moisture and the DC was applied to four independent data sets. The robustness of the new DC fuel moisture relationship was evaluated with general linear model regression analysis. The independent data were collected at the following sites throughout Alaska in 1999 and 2000:

FTWW 2000 (lat. 64°N, long. 147°W): This plot was within 200 m of the 1999 FTWW1 and FTWW2 plots and displayed similar site characteristics.

Galena (lat. 64°N, long. 156°W): A BLM/AFS fuels-specialist collected data during the 1999 fire season near Galena, Alaska. The sampling plot was located in an open, mature, white spruce, floodplain habitat. The forest floor was carpeted in *Hylocomium splendens* and *Rhytidiadelphus triquetrus*. The O-horizon averaged 21 cm deep when completely thawed. No snow survey data were available at Galena so the FWI System's fuel moisture codes at the FWSAKRX3 RAWS were started with default values.

FROSTFIRE – LGBS and UPBS (lat.65^{o} N, long.147 ^{o}W): Fuel moisture samples were collected by the author and USFS fire research personnel in conjunction with the International FROSTFIRE prescribed fire project (FROSTFIRE 1999). The FROSTFIRE project is located in the Caribou Poker Creek research watershed northeast of Fairbanks, Alaska. LGBS was situated in a closed canopy stand at the lower end of the watershed. The O-horizon consisted of *Pleurozium schreberi* and *Hylocomium splendens* and had an average depth of 22.5 cm. UPBS was located in an open stand along the southern ridge of the watershed. The O-horizon averaged 16 cm in depth and was comprised of *Hylocomium splendens*. The fuel moisture codes at the CPK (Caribou Peak) RAWS were started with default values.

4.3.5 Evaluating the Concept of Overwintering the Drought Code

A general linear model regression analysis was used to evaluate the moisture content prediction capabilities of the 1999 FBK RAWS DC initiated to reflect saturated conditions versus the 1999 FBK RAWS DC initiated to reflect overwinter drought.

5 Results

5.1 Physical Properties of Feather Moss Duff

The bulk density data was compiled by depth in 5 cm increments and by fuel layer (Tables 4 and 5). Bulk densities increased with increasing depth and advancing degrees of decomposition (i.e. fuel layer). Stratification by depth tended to reduce the range of bulk density measurements, whereas stratification by fuel layer produced mean measurements with less variability. MANOVA's were employed to test the homogeneity of bulk densities at similar depths and fuel layers among sites and to confirm the premise that stratification by fuel layer resulted in distinctly different fuel layers whereas stratification by depth did not. The bulk densities reported in this study are consistent with other feather moss studies in interior Alaska (Kane et al. 1978, Barney et al. 1981, Frandsen 1997, and Sharratt 1997).

Stratification by depth did not produce 5 cm layers that were statistically different from the adjacent layers (Table 4). Neither was the bulk density at a given depth consistent from plot to plot.

Stratification by fuel layer did produce distinct bulk densities at all three plots (Table 5). In addition, a given fuel layer displayed consistent bulk density from plot to plot. Consequently, all of the following data analysis will be based on stratification of the O-horizon into fuel layer. Mean bulk densities reported for the 'standard' FWI System's fuel moisture codes (Table 1) are; FFMC = 0.021 Mg/m^3, DMC = 0.071 Mg/m^3 and DC= 0.139 Mg/m^3 (Van Wagner 1987).

Table 4. Bulk density (Mg/m^3) measurements of feather moss duff stratified by depth (mean ± 1 SE for each plot).

	0 – 5 cm	5 – 10 cm	10 – 15 cm	15 – 20 cm
FTWW1	0.017 ± 0.0005 n = 205	0.025 ± 0.0008 n = 137	0.042 ± 0.0020 n = 123	0.070 ± 0.0040 n = 78
FTWW2	0.022 ±0.0006 n = 177	0.035 ± 0.0016 n = 171	0.054 ± 0.0024 n = 135	0.071 ± 0.0035 n = 66
FTWW3	0.021 ± 0.0004 n = 232	0.031 ± 0.0008 n = 226	0.051 ± 0.0021 n = 161	0.081 ± 0.0049 n = 51
Mean	0.020 ± 0.0003 n = 614	0.031 ± 0.0007 n = 534	0.049 ± 0.0013 n = 419	0.073 ± 0.0024 n = 195

Table 5. Bulk density (Mg/m^3) measurements of feather moss duff stratified by fuel layer (mean ± 1 SE for each plot).

	Live Moss	Dead Moss	Upper Duff	Lower Duff
FTWW1	0.012 ± 0.0003 n = 234	0.021 ± 0.0003 n = 238	0.041 ± 0.0008 n = 221	0.107 ± 0.0039 n = 59
FTWW2	0.016 ±0.0005 n = 212	0.023 ± 0.0004 n = 196	0.049 ± 0.0010 n = 193	0.114 ± 0.0041 n = 53
FTWW3	0.014 ± 0.0004 n = 231	0.025 ± 0.0004 n = 230	0.042 ± 0.0009 n = 219	0.113 ± 0.0039 n = 54
Mean	0.014 ± 0.0002 n = 677	0.023 ± 0.0002 n = 664	0.044 ± 0.0005 n = 633	0.111 ± 0.0030 n = 166

5.2 Feather Moss Moisture Content and Fuel Moisture Code Trends

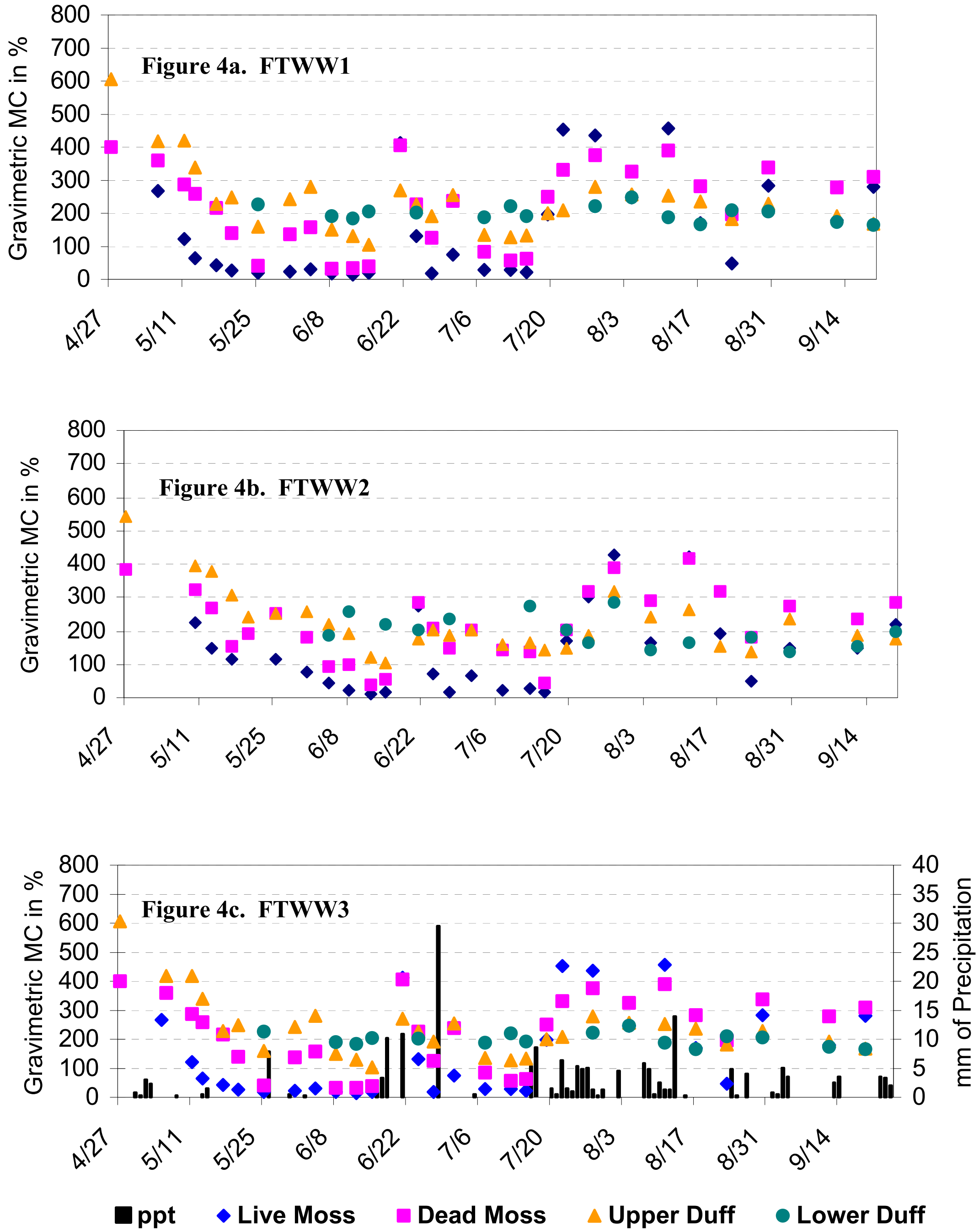
5.2.1 Moisture Trends Observed in Feather Moss Duff

The standard method for computing fuel moisture in fire danger rating systems is to use a dry weight based, or gravimetric, moisture content. Soil scientists and hydrologists however, prefer volumetric moisture contents as they are a measure of the total amount of water within a given volume sample. Therefore, whenever possible, fuel moistures in this study were calculated using both methods. The gravimetric and volumetric moisture contents for the 4 fuel layers at each plot are shown in Figures 4a-c and 5a-c respectively. Standard errors are not shown in these figures, but moisture content variability was positively correlated with the moisture means (Appendix B).

Gravimetric moisture content data (Figures 4a-c) reveal that the live moss fuel exhibited the greatest variation in moisture content and that the magnitude of variance in each successive fuel is dampened. Hinzeman et al. (1991) has reported similar observations in the O-horizon at a site in northwest Alaska.

The FTWW1 and FTWW2 plots showed similar moisture content trends throughout the season. Live moss fuels at both plots declined steadily beginning in early May reaching minimum values of 14% and 12% respectively on June 12. Dead moss moisture contents followed a similar pattern (FTWW1 32% on June 8, FTWW2 39% on June 12). The upper duff displayed a multi-day lag-time reaching minimum moisture contents of 104%

Figure 4a-c. Gravimetric moisture content trends by fuel layer.



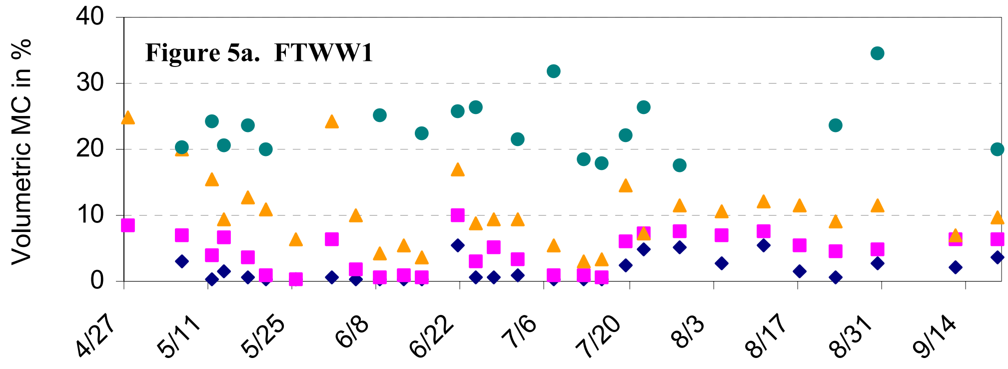
at both plots on June 15. Intermittent precipitation events between June 17 and June 28 elevated moisture contents in the entire O-horizon to over 200%.

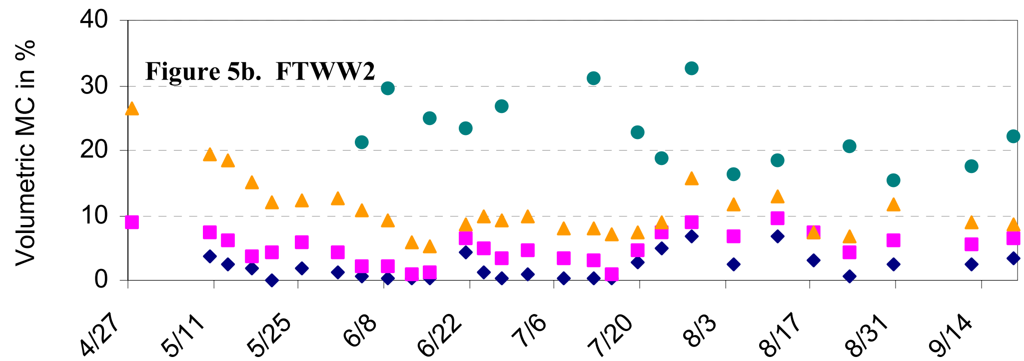
A second period of low moisture contents occurred during a 17-day rain-free period between June 29 and July 15. Minimum live, dead, and upper duff moisture contents were attained at the FTWW3 plot during this second dry period. The FTWW3 live and dead moss reached minimum moisture contents of 23% and 93% respectively on July 13. The upper duff at FTWW3 did not reach its seasonal low of 144% until July 20, again exhibiting a lag-time of several days.

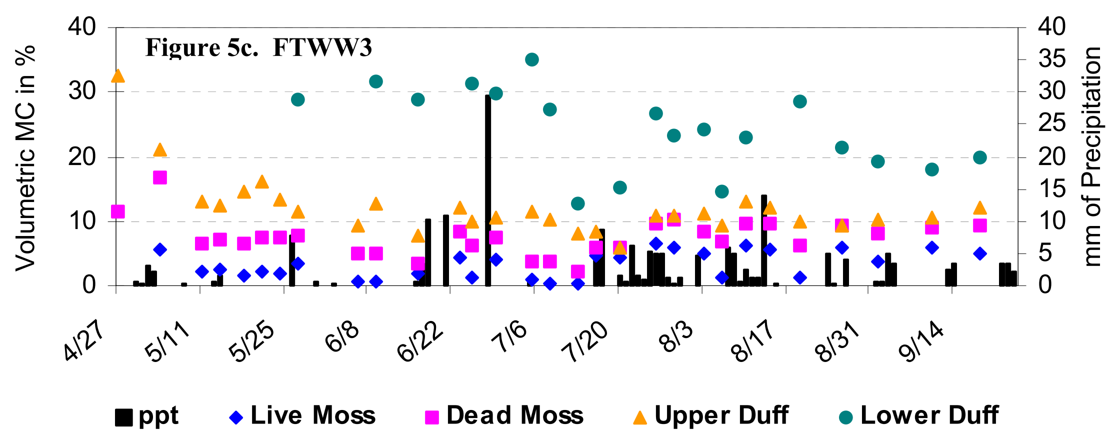
Consistent moisture patterns in the lower duff are harder to decipher. Good quality lower duff samples were difficult to obtain. Early in the season the lower duff fuels remained frozen. As the active layer increased, giving access to lower duff fuels, the presence of large roots (>5 mm) began to limit good quality volume samples. Consequently, many of the sample days produced fewer than three replicate samples. Replicates also tended to be equidistant along the transect line and may not reflect the true moisture content of the plot. However, the range of moisture contents in the lower duff was less than 200% over the course of the season, and generally, minimum values were not achieved until late in the season.

The volumetric data plotted in Figures 5a-c were computed by multiplying the gravimetric moisture contents by the mean fuel bulk density for each plot. Therefore,

Figure 5a - c. Volumetric moisture content trends by fuel layer.







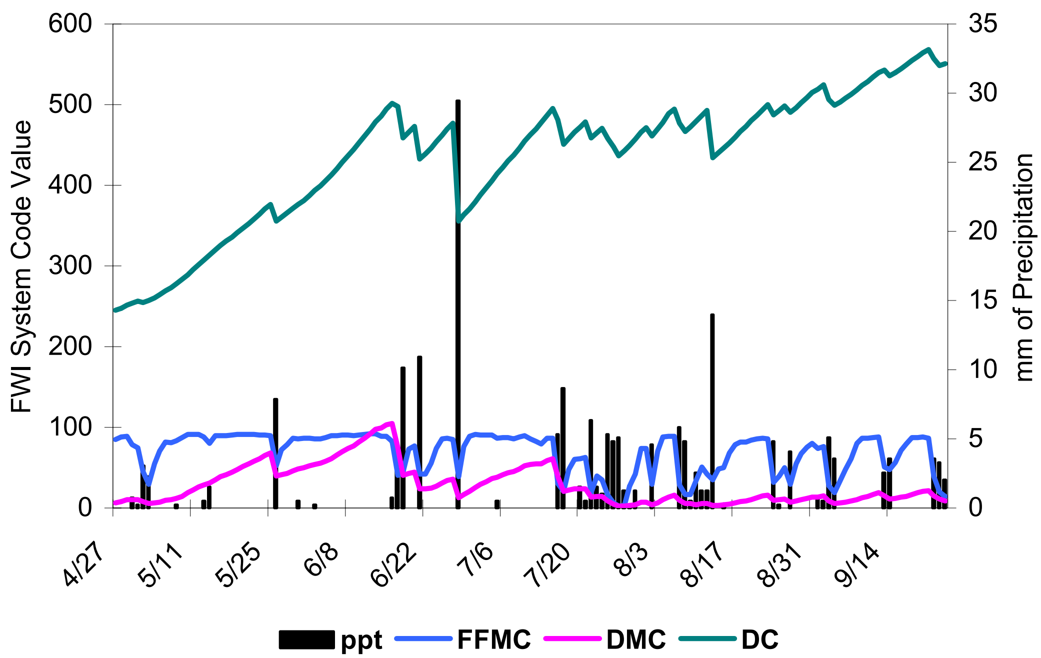
timing of the observed maximum and minimum volumetric moisture contents is identical to that of the gravimetric data. The volumetric moisture content trends of the 4 fuel layers do not cross and rarely overlap. Volumetric moisture content, being a measure of the total amount of water held within the fuel matrix, shows the live moss to have the smallest range of variability while the lower duff exhibits the most variation. The volumetric data were used in a MANOVA analyzing the fuel layers for unique moisture regimes. The MANOVA found the mean moisture content of each fuel to be significantly different from that of the other fuel layers ($\alpha = 0.05$).

5.2.2 Seasonal Trends in the FWI System's Fuel Moisture Codes

The FWI System's fuel moisture codes (Figure 6) are inversely related to fuel moisture with the intent that increasing codes signify decreasing moisture content, hence increasing fire potential (Appendix C). The FFMC, modeling surface fuels and being primarily dependent on wind and relative humidity, is highly variable on a daily basis. The FFMC was initiated on April 27 with a value of 85. A peak value of 92 was reached on June 13. This coincided with a 1300 LST temperature reading of 32^{o}C (the warmest day recorded during the 1999 fire season at the FBK RAWS) after 17 days without any significant precipitation (< 0.6 mm) (Figure 6).

The DMC model does not include a wind parameter, rendering it more stable than the FFMC. On April 27, 1999 the DMC was initiated with a value of 6. The DMC increased to a maximum value of 105 on June 16, 3 days after the FFMC peak. Two weeks of intermittent rain at the end of June, culminating in a 29.5 mm thunderstorm on June 28 (Figure 6), reduced all 3 of the fuel moisture codes. A second run of 17 rain-free days began on June 29. In this second dry period the DMC reached a maximum of 60 on July 15. Threshold precipitation events (> 1.5 mm) occurred on a regular basis after mid July thereby reducing as well as stabilizing the DMC at very low values for the remainder of the fire season.

Figure 6. Fairbanks RAWS FWI System's fuel moisture codes. Computed from environmental observations and precipitation events recorded at the Fairbanks RAWS Ft. Wainwright, AK from April 27 through September 28,1999.



The DC was initiated with a value of 245 on April 27, based on the 1998 ending DC value and the 1998-99 winter's total precipitation. Rain events were rarely of a sufficient amount (> 2.9 mm) (Figure 6) to cause a decline in the DC. With few exceptions the DC continually climbed and reached a maximum value of 568 on September 21.

5.3 Comparing Measured Fuel Moistures to the Fuel Moisture Codes

5.3.1 Pairing a Fuel Layer to the Appropriate Fuel Moisture Code

To keep the study focused on duff consumption and fire severity, only the moisture prediction capabilities of the DMC and DC were evaluated. In accordance with the 1983 Van Wagner report detailing the development of the original FWI System's fuel moisture codes, the DMC and DC were converted into moisture contents using the 'standard' moisture conversion equations (Equations 1 and 2 respectively). Correlation and linear regression analysis were performed between measured gravimetric moisture contents and moisture contents derived from the standard fuel moisture equations, instead of the codes themselves. Converting the fuel moisture code values into equivalent moisture contents eliminates the non-linearity contained in the code equations.

Correlations between the measured dead moss moisture contents and the DMC-equivalent moisture contents were strong in all 3 plots (Table 6). However, to eliminate autocorrelation detected with the Durbin-Watson test, the data sets were transformed to reflect moisture content change per day between sampling periods. Moisture content change per day was determined by subtracting the measured moisture contents from those of the previous sampling period, then dividing the difference by the number of days between sampling periods. The same procedure was applied to the DMC and DC moisture content equivalents. The transformation slightly reduces the strength of the relationships but, eliminates the non-independence of the error terms, providing more accurate variance estimates for the regression coefficients and the error terms (Neter et al. 1996).

Correlation coefficients and regression results for the measured and FWI System's predicted moisture contents and the transformed data are shown in Table 6. No consistent statistical relationships were found between upper duff moisture contents and the DMC or between lower duff moisture contents and the DMC.

The DC moisture content equivalent best modeled upper duff moisture trends, although the relationship was not as strong as the dead moss-DMC relationship (Table 6). A change per day transformation was again required to eliminate autocorrelation in the DC and upper duff data sets. The transformed upper duff moisture content data consistently showed a stronger relationship with the transformed DMC moisture contents than the transformed DC moisture contents. Relationships derived from the transformed FTWW3 upper duff moisture contents were not significant with either the DMC or DC-moisture equivalents.

FTWW3 was the only plot that showed a significant relationship between measured lower duff moisture contents and DC moisture content equivalent (Table 6) and the

Durbin-Watson test did not detect autocorrelation in this relationship. No strong statistical relationships were found between the DC and the dead moss.

Table 6. Correlation and regression coefficients between measured and predicted fuel moisture contents. (Moisture contents predicted from the FBK RAWS FWI System's fuel moisture codes.)

	Regression					Intercept			Slope		
FTWW1	n	r	R^2	p	SE	b_o	$s(b_o)$	p	b_1	$s(b_1)$	p
DM / DMC MC	29	0.91	0.83	0.00	51.57	-48.42	24.98	0.06	1.60	0.14	0.00
DM / DC MC	29	0.19	0.04	0.33	124.15	111.77	111.40	0.32	0.19	0.39	0.33
Transformed DM / DMC	28	0.83	0.69	0.00	14.04	-0.37	2.66	0.88	2.25	0.29	0.00
UD / DMC MC	29	0.55	0.30	0.00	89.45	100.51	43.32	0.03	0.81	0.24	0.00
UD / DC MC	29	0.79	0.62	0.00	65.54	-148.67	58.81	0.02	1.37	0.20	0.00
Transformed UD / DMC	28	0.72	0.51	0.00	11.07	-2.90	2.10	0.17	1.20	0.23	0.00
Transformed UD / DC	28	0.63	0.39	0.00	12.34	-0.16	2.50	0.95	1.97	0.47	0.00
LD / DC MC	16	0.41	0.17	0.12	21.48	115.65	50.06	0.04	0.34	0.20	0.12
FTWW2											
DM / DMC MC	28	0.88	0.77	0.00	50.85	4.97	24.80	0.84	1.30	0.14	0.00
DM / DC MC	28	0.23	0.05	0.24	103.30	102.49	98.8	0.31	0.42	0.35	0.24
Transformed DM / DMC	27	0.78	0.61	0.00	12.66	-0.57	2.44	0.82	1.68	0.27	0.00
UD / DMC MC	28	0.39	0.15	0.04	88.97	137.01	43.43	0.00	0.53	0.24	0.04
UD / DC MC	28	0.82	0.68	0.00	55.04	-156.16	52.64	0.01	1.38	0.19	0.00
Transformed UD / DMC	27	0.60	0.36	0.00	8.93	-2.18	1.72	0.22	0.72	0.19	0.00
Transformed UD / DC	27	0.41	0.17	0.03	10.22	-0.98	2.09	0.64	0.89	0.40	0.03
LD / DC MC	15	0.39	0.16	0.14	44.66	14.20	120.21	0.91	0.76	0.49	0.14
FTWW3											
DM / DMC MC	30	0.72	0.52	0.00	79.51	91.9	39.87	0.03	1.13	0.20	0.00
DM / DC MC	30	0.36	0.13	0.05	107.19	106.30	94.98	0.27	0.68	0.33	0.05
Transformed DM / DMC	29	0.68	0.46	0.00	16.74	0.47	3.11	0.88	1.58	0.33	0.00
UD / DMC MC	30	0.25	0.06	0.18	112.30	213.72	56.32	0.00	0.40	0.29	0.18
UD / DC MC	30	0.75	0.56	0.00	76.73	-113.43	67.98	0.11	1.423	0.24	0.00
Transformed UD / DMC	29	0.33	0.11	0.08	14.87	-3.00	2.76	0.28	0.53	0.29	0.08
Transformed UD / DC	29	0.23	0.05	0.22	15.32	-2.12	3.0	0.48	0.71	0.57	0.22
LD / DC MC	19	0.58	0.34	0.01	47.00	-39.45	86.64	0.65	1.01	0.34	0.01

5.3.2 Comparing Moisture Content Trends of the Paired Data

In Figures 7 through 10 the predicted DMC and DC moisture contents can be viewed concurrently with the dead moss and upper duff moisture contents observed at the Ft. Wainwright plots. In all figures, the DMC and DC are less responsive to wetting and drying events than the feather moss fuels they are modeling.

Figure 7 indicates low DMC's underpredict the moisture content of the dead moss fuel. However, Figures 8a and 8b indicate that moisture contents predicted by the DMC are in close agreement with the observed dead moss moisture contents during the peak fire season (mid May thru mid July).

Figure 7. Dead moss moisture content in relation to the standard FWI System DMC-MC equation. Moisture content (MC) predicted by the 'standard' DMC equation (Eq. 1) versus observed dead moss moisture contents.

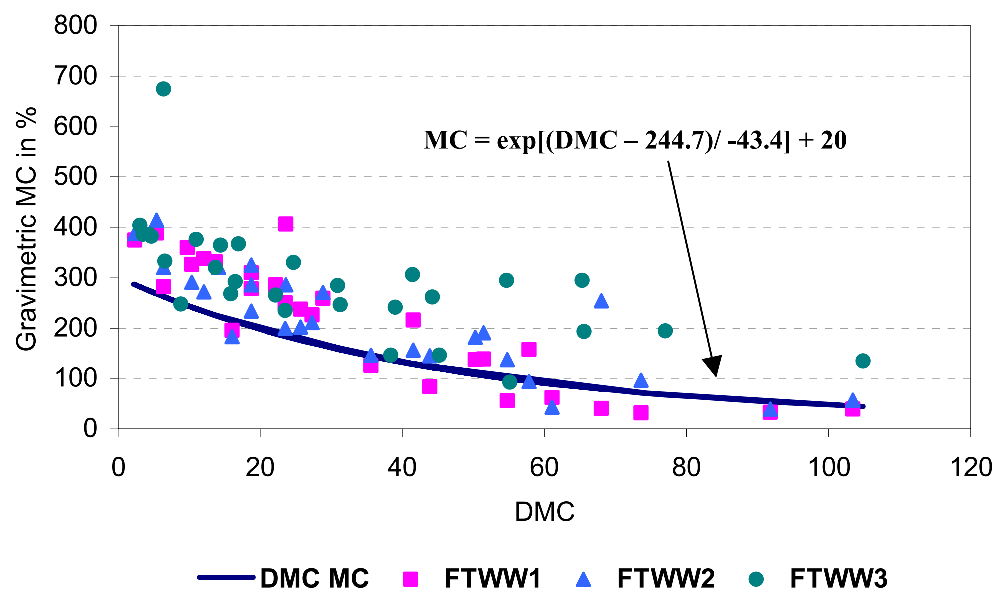
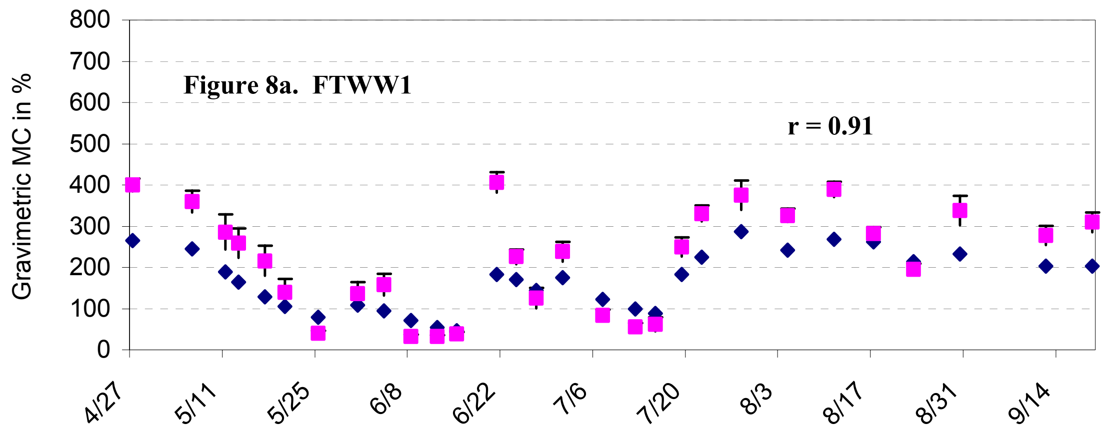


Figure 8a and b. Comparison of dead moss moisture contents and DMC predicted moisture contents. Dead moss data points are means ± 1 SE. The FTWW2 plot, showing trends similar to the FTWW1 plot is not shown.



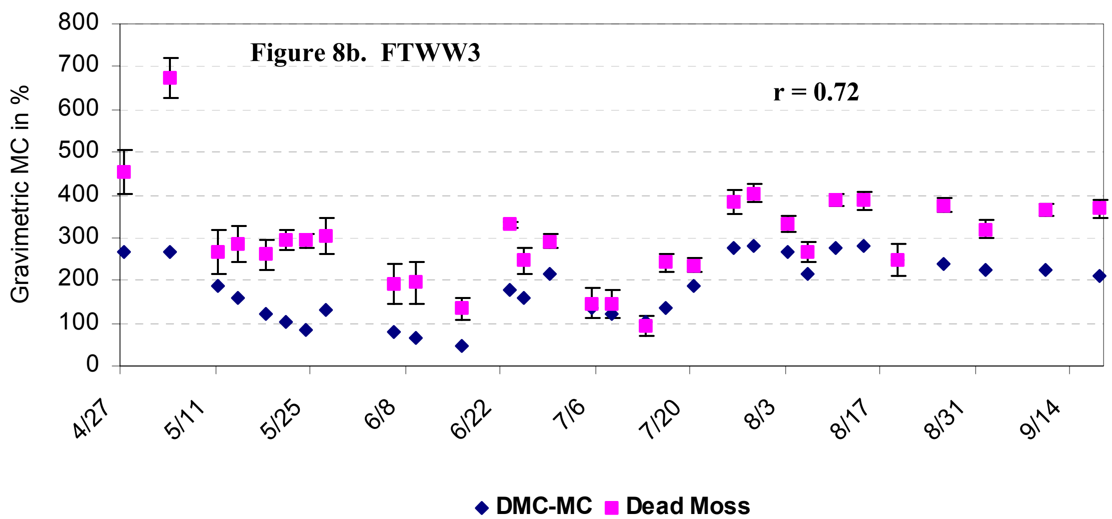


Figure 9 shows the DC, adjusted for insufficient winter precipitation and the previous fall's ending DC, tends to overpredict the moisture content of the upper duff fuel. The predicted moisture contents did not come into agreement with the moisture contents observed in the upper duff until the later part of July (Figures 10a-b) when persistent rains, insufficient to reduce the DC, began to rehydrate the upper duff fuels. At high DC values (>350) moisture contents in the upper duff fuel were very inconsistent for a given DC value. In fact, the moisture contents at a single site could differ by more than 150% over a DC spread less than10 points.

Figure 9. Upper duff moisture content in relation to the standard FWI System DC-MC equation. Moisture content (MC) predicted by the 'standard' DC equation (Eq. 2) versus the observed upper duff moisture contents.

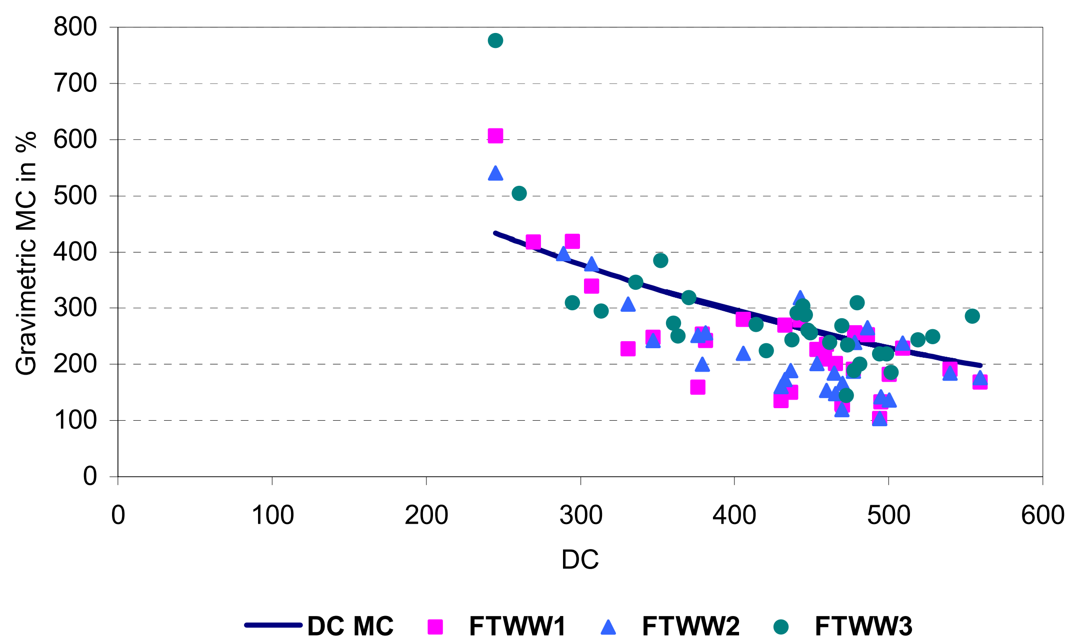
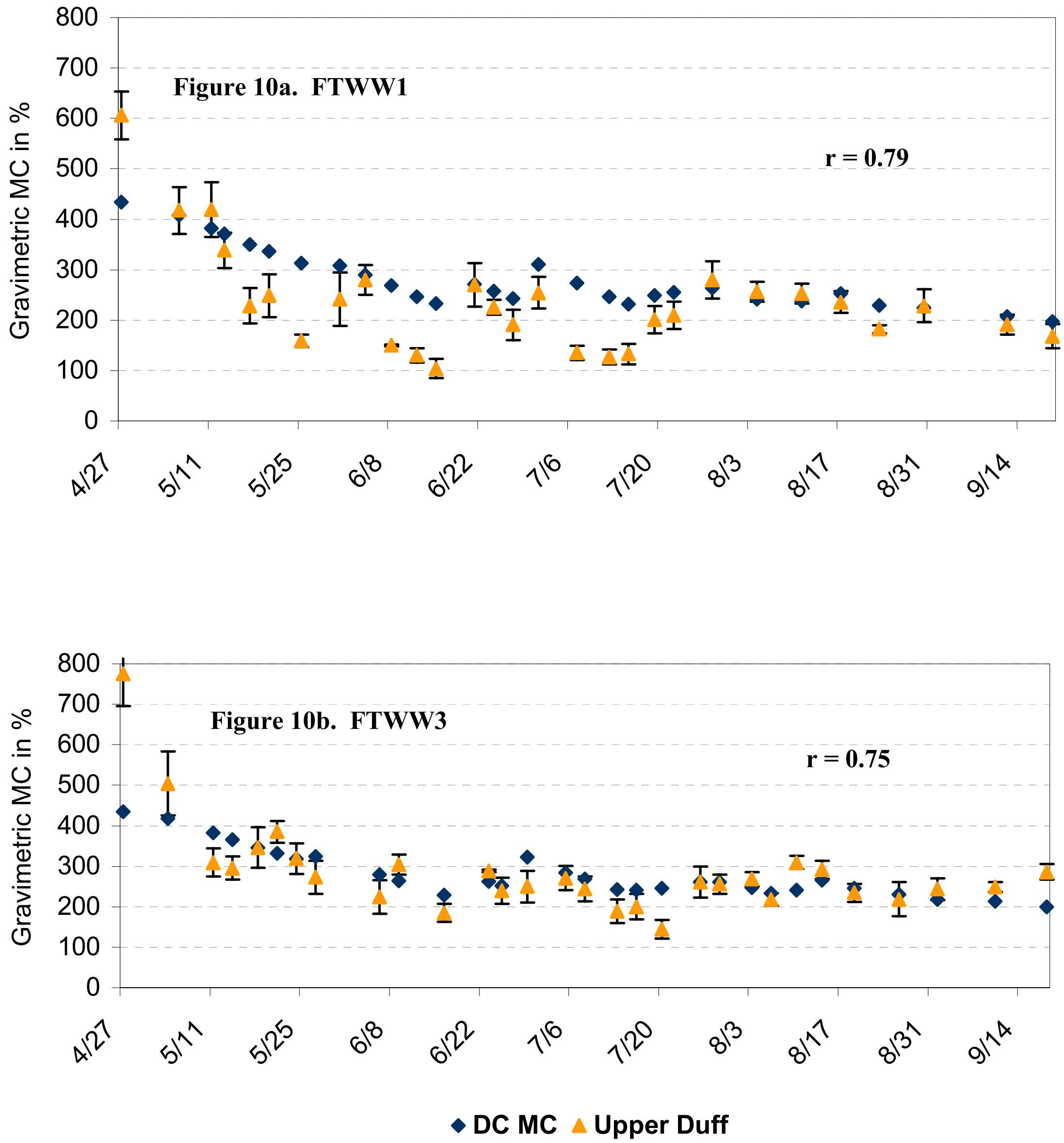


Figure 10a and b. Comparison of upper duff moisture contents and DC predicted moisture contents. Upper duff data points are means ± 1 SE. The FTWW2 plot showing trends similar to the FTWW1 plot is not shown.



5.4 Alternative Methods of Relating Duff Moisture Contents to the FWI System's Fuel Moisture Codes

The in-situ destructive sampling approach used to collect the moisture content data does not allow for detailed investigations into the wetting and drying characteristics of the O-horizon fuels. However, a close examination of the fuel moisture code assumptions provide ideas for coarse scale equation manipulation to better represent the wetting and drying trends observed in the O-horizon. Due to the robust statistical results (Table 6) and the close agreement of the moisture data during peak fire season (Figures 8a and b), the DMC environmental parameters and moisture content equivalent equations were not adjusted.

To represent the accelerated loss of moisture early in the Alaska fire season (Figure 9), the day length factors representing evapotranspiration in the DC algorithm were adjusted. Patric and Black (1968) found evaporation pan losses in the Fairbanks, AK area to be greatest in May, June and July, with losses in June (135 mm) being slightly higher than in May (114 mm) and July (118 mm). By August and September evaporation has decreased to 81 mm and 38 mm respectively. The day length factors representing evapotranspiration losses in the FWI System lose the greatest amount of water later in the season. Loses ranked from high to low occur in this order; July, June, August, May and September (Turner 1972, Canadian Forestry Service 1984 and Van Wagner 1987).

Because the bulk density of the upper duff is more similar to fuel modeled by the DMC than the DC, the effective precipitation equation of the DC was replaced with that of the

DMC. It was anticipated that this simple adjustment would more closely model the upper duffs response to rain events. To account for the saturated duff layers encountered early in the 1999 season (presence of standing water in the extracted plug hole) all equation manipulations were performed on default initiated indices (DC = 15 = 770% moisture content).

The high moisture contents predicted by the default initiated DC over-predicted all but the 4 highest FTWW3 data points (Figure 11). The defaulted DC began to parallel observed moisture contents when the DC became greater than 350. Adjusting the evapotranspiration factors to correspond with the findings of Patric and Black (1968) caused the predicted DC moisture contents to continually drop from a starting value of 770% to 235% on September 19. Increasing precipitation effectiveness in conjunction with the evapotranspiration adjustment resulted in higher moisture contents throughout the season. Neither of these adjustments was able to model the steep decline in moisture content early in the season nor the amplitude of the moisture content fluctuations observed in the upper duff.

In light of the poor results obtained with the evapotranspiration and precipitation adjustments, upper duff moisture contents (dependent variable) from FTWW1-3 were charted in scatter graph form with each sampling days defaulted DC value (independent variable) and various equations were fit to the data. The fit of the model was evaluated by examining the proportion of the variance explained by the equation, ie., the coefficient of determination. Results of the model evaluation are shown in Table 7.

Table 7. Linear and non-linear models fit to the defaulted DC - upper duff moisture content relationship.

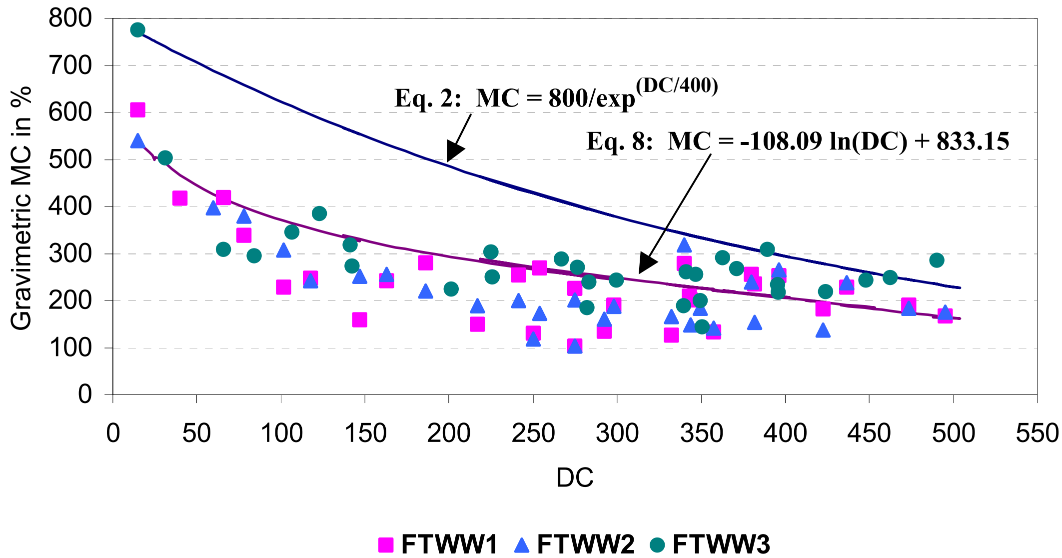
Equation Form	**R^2**
Linear: $Y = -0.4887X + 382.46$	0.354
Polynomial: $Y = 0.0032X^2 – 2.1039X + 529.81$	0.619
Exponential: $Y = 354.07e^{-0.0016X}$	0.296
Power: $Y = 1360.3X^{-0.3276}$	0.480
Logarithmic: $Y = -108.09\ln(X) + 833.15$	0.632

A logarithmic equation (Equation 8) provided the best least squares relationship between the 2 data sets. Equation 8 converts the DC into a moisture content equivalent. Equation 9 allows conversion of a measured moisture content to a DC value. Converting the DC to a moisture content using equation 8 produced stronger relationships at each of the FTWWW plots than the standard DC regardless of the initial starting value (Table 8). In addition, Equation 8 captures the accelerated moisture loss early in the season as well as some of the daily fluctuations (Figure 12).

$$MC = -108.09 \ln(DC) + 833.15 \qquad [8]$$

$$DC= 1/\exp^{((MC-833.15)/108.09)} \qquad [9]$$

Figure 11. Upper duff moisture content in relation to the standard defaulted DC-MC equation (Eq. 2) and the Ft. Wainwright, AK DC-MC equation (Eq.8).



The robustness of the new equation was further tested with independent data sets. Destructively sampled moisture contents were regressed against the moisture contents predicted by the standard DC moisture equivalent equation (Eq. 2) and the newly derived DC moisture equivalent equation (Eq.8). Coefficients of determination for the 4 independent data sets (FTWW2000, Galena, and Frostfire LGBS and UPBS) are displayed in Table 8. The new logarithmic equation explains more of the variance in moisture content than the standard DC equation. The relationships at the FTWW2000 and LGBS sites were not significant, but p-values are reduced in most cases using the new relationship. Small sample sizes at these sites (n = 7) may be contributing to the lack of significance. An overwintered DC moisture equivalent was not available for the Galena or Frostfire sites due to lack of snow survey data. The FTWW2000 site was evaluated with a snow survey in the spring of 2000 that indicated the DC fuels had been sufficiently recharged to initiate the code at the default value of 15.

Table 8. R^2 comparison of the overwintered and defaulted standard DC-MC equation (Eq.2) and the newly derived Ft. Wainwright, AK DC-MC equation (Eq. 8).

Plot	**Overwintered DC** $MC = 800/e^{(DC/400)}$	**Defaulted DC** $MC = 800/e^{(DC/400)}$	**New DC-MC eq.** $MC = -108.09 \ln(DC) + 833.15$
FTWW1	0.62	0.46	0.64
FTWW2	0.68	0.53	0.68
FTWW3	0.56	0.49	0.70
FTWW2000 n = 7	NA	0.16* (p = 0.29)	0.28* (p = 0.14)
Galena (1999) n = 21	NA	0.54	0.67
Frostfire(LGBS) n = 7	NA	0.31* (p = 0.19)	0.33* (p = 0.17)
Frostfire(UPBS) n = 7	NA	0.66	0.65

* Relationship was not significant ($\alpha = 0.05$).

5.5 Evaluating the DC Overwintering Theory

Permafrost affects soil moisture in many complex ways (Kane et al. 1978, Mackay 1983, Hinzman et al.1991, Romanovsky et al. 2000, and Yoshikawa et al. 2000) that were not addressed in this study. However, observations of early season moisture in the upper and lower duff during the 1999 and 2000 season do warrant comment (Table 9).

Table 9. Comparison of an overwintered (1999) and a defaulted (2000) DC year at

Ft. Wainwright, AK.

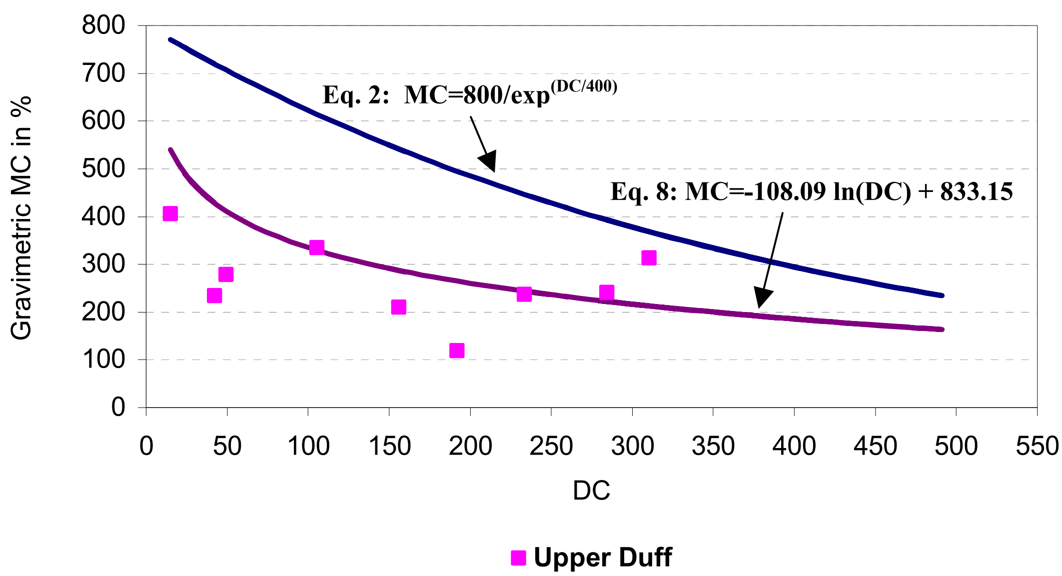
Observations	1999	2000
Previous fall's moisture content (destructively sampled)	190% (9/9/98)	161% (9/19/99)
Previous fall's ending DC (recorded at FBK RAWS)	461 (10/25/98)	465 (9/30/99)
Winter precipitation (spring snow survey)	51 mm	144 mm
Initial spring moisture content (destructively sampled)	573% (4/27/99)	425% (5/10/00)
Initial spring DC (based on criteria in Table 2)	245 (4/27/99)	15 (5/14/00)
Moisture content at the end of May (destructively sampled)	249% (5/31/99)	278% (5/30/00)
Lowest moisture contents observed during the fire season (destructively sampled)	104% (6/15/99)	119% (6/21/99)

The 2000 (FTWW2000) site was located within 200 m of the 1999 (FTWW1 and FTWW2) sites and exhibited similar stand characteristics. Destructively sampled moisture contents in the upper duff fuels were very similar in the fall of the 1998 and 1999 as were ending DC values. A snow survey conducted at the Ft. Wainwright sampling site in March of 1999 indicted 51 mm of water present in the snow pack. Using values of 1.0 and 0.9 in Equation 3 for coefficients a and b respectively (Table 2) compute a DC value of 245 as the appropriate beginning DC value for the 1999 fire season. Upper duff moisture content samples collected in April and early May of 1999 slightly exceeded the overwintered predicted moisture content (Figure 8). In fact, the first few sampling periods, 2 –3 cm of standing water was recorded in most of the holes after the plugs had been extracted. The standing water ceased to exist by mid May and Figures 11a and b indicate that the drying rate stabilizes at this time. After mid May the moisture content of the upper duff dropped below the overwintered predicted moisture content and remained lower throughout the season (Figure 8).

Cool spring temperatures in 2000 delayed melt of the snowpack so the fuel moisture code calculations at the FBK RAWS were not initiated until May 14. A snow survey conducted at the Ft. Wainwright site in April, 2000 indicated 144 mm of water present in the snow pack which was sufficient to default the DC. Fuel samples taken in conjunction with the start of the FWI System's calculations did not reflect the high moisture content predicted by the defaulted DC (Table 9). Despite the greater than 2 fold increase in total winter precipitation, no standing water was observed when plugs were removed from the forest floor and the initial moisture content of 425% in the upper duff is less than reported in 1999. Although only 9 sampling days were achieved during the 2000 season, the moisture contents trends are similar to the 1999 data. A significant loss of moisture occurred in the 2 weeks following the start of the fuel moisture code calculations (Figure 12). At the end of May upper duff moisture contents between the 2 years were very similar (Table 9). In addition, the lowest upper duff moisture content recorded June 21, 2000 was 119% as compared to the 104% low recorded June15, 1999 (Appendix B). Moisture contents increased in the fall of both years.

The fit of the newly derived empirical equation (Equation 8) is also shown in Figure 12. Despite the low coefficient of determination (0.28) the curve more closely models observed moisture contents than the 'standard' DC equation (Equation 2).

Figure 12. FTWW2000 observed upper duff versus the standard DC-MC predicted moisture contents (Eq. 2) and the Ft. Wainwright, AK DC-MC equation (Eq.8).



6 Discussion

6.1 Physical Properties of Feather Moss Duff

Bulk density was chosen to appraise the physical properties of the feather moss duff as several studies have shown that bulk density is a reliable indicator of hydraulic conductivity and moisture retention characteristics (Boelter 1969, Lauren and Heiskanen 1997, and Sharratt 1997). Fuels representing the FWI System's fuel moisture codes are also described by bulk density and by depth (see Table 1).

Research concerning the fuel moisture codes and observed fuel moistures have occasionally utilized depth rather than the O-horizon stratifications for evaluation (Lawson and Dalrymple 1996, and Lawson et al. 1997b). Kane et al. (1978) and Barney et al. (1981) disagree with this approach, arguing that bulk density by depth is extremely variable in feather moss ground cover as it is related to the overall depth of the organic mat. Barney et al. (1981) found significant linear relationships between depths and bulk densities but described them as too weak for prediction purposes. Therefore, a major focus of this study was to explore whether stratification of the O-horizon by depth or by stage of decomposition (fuel layer) was a more reliable indicator of the physical properties (bulk density) affecting moisture retention and distribution characteristics.

The smaller range of bulk density measurements between layers stratified by depth (Table 4) can be attributed to the tendency of the 5 cm depth increments to incorporate more than one fuel layer. The 0 –5 cm depth was normally a combination of live and dead moss, the 5 – 10 cm depth typically consisted of dead moss and upper duff, and the 15 – 20 cm depth could have components of both upper and lower duff.

MANOVA's support the premise that stratification by fuel layer is more desirable than stratification by depth in 5 cm increments. In all cases stratification by fuel layer resulted in distinct fuel layer bulk densities whereas stratification by depth did not (Tables 4 and 5). The upper duff in FTWW2 was unique unto itself having an average bulk density significantly higher than that of the other 2 plots. Fewer upper duff samples were collected in the FTWW2 plot and the variance was higher than was observed in the FTWW1 and FTWW2 plots (Appendix A). Field notes reveal that the FTWW2 plot included several upper duff samples containing ectomycorrhizal growth. Samples infected were much denser and drier than samples that were not infected which may have contributed to the unique bulk density. It is however, arguable whether this statistical difference is important to the overall intent of the project as the bulk density of the upper duff is still very different from that of the lower duff.

6.2 Moisture Content Trends in Feather Moss Duff

6.2.1 Moisture Content Differences Between Fuels

Gravimetric data, being dependent on the dry weight of the fuel, does not lend itself to the analysis of variance techniques employed in determining whether the 4 fuels moisture regimes were unique. In other words, the amount of water represented by 200% moisture content in the live moss is not comparable to the amount of water represented by 200%

moisture content in the upper duff because of the dry weight of the fuel matrix. Consequently, only the volumetric data were used to analyze moisture regimes among fuel layers. MANOVA results support the conclusions of Plamondon et al. (1972) that moisture regimes are significantly different between the L, F, and H-horizons.

The gravimetric moisture content data demonstrate the range of moisture contents encountered in each fuel layer (Figures 4a-c). Increasingly stable moisture contents are obvious with advancing stages of decomposition. The mid-summer moisture reversal revealed in Figures 4a-c is common in feather moss duff (Kiil 1970, Henderson and Muraro1968, and Skre et al.1983) and can reportedly produce unwanted results in prescribed and wildland fire situations (Lawson and Dalrymple 1996). In a reversal situation, the deeper fuels are reported to be 'drier' than the upper fuels. Theoretically, an ignition sustained in the 'drier' deeper fuels produces enough heat to dry and ignite the overlying fuels resulting in excessive (and perhaps unplanned) duff consumption. The data in Figures 4a-c show the initiation of the reversal occurred after the DC had reached 450. Lawson and Dalrymple (1996) urge fire personnel to consider the possibility of this situation occurring at DC's greater than 500.

The volumetric moisture content data (a measure of the total water contained in a given sample) do not show the reversal phenomenon (Figures 5a-c) signifying the deeper fuels are not retaining less water (are not 'drier') than the overlying fuels. The discrepancy between the 2 data sets emphasizes the need for accurate fuel descriptions and moisture code – fuel moisture relationships. If the amount of water present in a fuel is the determining ignition factor, the fact that a dry weight-based moisture reversal exits does not necessarily guarantee sustained ignition in the deeper fuels. It is hoped that the moisture of extinguishment research produced by Hawkes (1993), Frandsen (1997) and Lawson et al. (1997a), will eventually provide fire managers with more reliable predictors of deep duff consumption.

6.2.2 Moisture Content Differences Between Plots

Comparable minimum moisture contents observed at the FTWW1 and FTWW2 plots indicate moisture stability after extended periods of dry weather. Several factors, working in unison, are probable causes for the elevated moisture contents observed at FTWW3 (Figures 4c and 5c). The overstory canopy cover at FTWW3 was two times greater (50%) than at FTWW1 and FTWW2 (30% and 25% respectively). FTWW3 also had the greatest amount of basal area, 34.4m^2/ha, a 5 fold increase over FTWW1 (6.9m^2/ha) and a 15 fold increase over FTWW2 (2.3m^2/ha). Wind shelter provided by a denser stand may have contributed to the elevated live moss moisture contents. Shading induced by the closed canopy may have reduced incoming solar radiation sufficiently to offset the increased transpiration of a denser stand. Similar results were observed in Sweden in stands with increasing stem density (Granstrom and Schimmel 1998).

The lack of solar radiation also retarded the rate of active layer increase early in the season. The prolonged influence of the active layer in combination with the morphological features of the feather moss may be the reason for the fairly stable moisture contents at this plot. Busby (1976) found the feather mosses *Hylocomium splendens* and *Pleurozium schreberi,* capable of transporting water to the frond apex from a depth of 6 to 8 cm. The depth of transport is directly related to the presence of paraphyllia, filamentus branched structures, on the leaves and stems that wick the moisture upward using capillary action. The live and dead moss at FTWW3 may be wicking water from the melting upper and lower duff layers to the surface for evaporation, therefore retaining higher moisture contents over plots that had adequate drainage. In addition, moisture contents of the upper and lower duff would not decrease substantially until the mineral soil had thawed and drainage was established. Soil thawing, of course, is also retarded by canopy shade.

6.3 Comparing Measured Fuel Moisture Contents to the Moisture Contents Predicted by the Fuel Moisture Codes

The robustness of the correlation and regression data signify seasonal moisture trends are being tracked by the FWI System's fuel moisture codes (Table 6). Van Wagner (1983) advocates that the fuel moisture code – moisture content relationship is sufficient in its current form if the correlation coefficient and coefficient of determination are high, even when the slope of the regression line is significantly different from 1. However, Viney and Hatton (1989) argue that regression analysis reveals little information about the bias of the fuel moisture predictions.

The upper duff - DC moisture content relationships reported in Table 6 support Viney and Hatton (1989). Correlation and regression relationships that were strong in the comparison between upper duff measured moisture contents and DC moisture content equivalents weaken in the moisture content change per day transformation. It is suspected that the former relationships are predominantly influenced by seasonal trends. The transformed data allows comparison of moisture contents on a short time scale. The transformed upper duff moisture contents are better modeled by the transformed DMC moisture contents because the DMC is a more responsive model that reflects more of the short term upper duff fuel variability. Figures 8a-b and 10a-b also illustrate the bias associated with the 'standard' DMC and DC fuel moisture predictions.

The dead moss fuels tended to hold more moisture than predicted when DMC values were less than 40 (Figure 7). Figure 8 shows the majority of the low DMC values occurring late in the season due to persistent precipitation events after July 15. This suggests the dead moss is storing more water than anticipated. One possible explanation may be that the capillary action of the paraphyllia on the moss stems and leaves (Busby 1976) is retarding vertical drainage.

Restricted drainage is probably responsible for the few elevated upper duff moisture contents that rapidly decrease below the predicted level (Figures 9 and 10a-b) as the active layer recedes early in the season. The Douglas-fir duff used to calibrate the DC is much denser than feather moss duff. For this reason, the DC anticipates higher moisture contents and less variability than were observed in the upper duff fuels at the Ft. Wainwright plots (Figures 10a-b).

The principles of hydraulic conductivity and moisture retention that influence the moisture regime in the O-horizon are apparent when comparing moisture characteristics of the feather moss duff fuels with the FWI System's pine and Douglas-fir duff fuels. Bulk densities found in the O-horizon in this study are very different from the fuels modeled in the original DMC and DC fuel moisture codes. Assuming that the DMC represents the dead moss and that the DC represents either the upper and/or lower duff, the data show that the DMC and DC fuels are much denser than the feather moss fuels (Tables 1 and 5). The difference in bulk density is presumably related to the DMC and DC's inability to model the rapid response of the feather moss fuels to wetting and drying events.

A reduction in hydraulic conductivity due to increasing bulk density is evident in the fuel moistures in Figures 4a-c and 5a-c. As decomposition advances, pore size decreases, enhancing the fuels ability to hold water at higher suctions. Thus, water distribution is restricted and moisture contents increase (Boelter 1969, Lauren and Heiskanen 1997, and Sharratt 1997) in the fuels exhibiting advanced stages of decomposition. Evaporation effects are also less pronounced with increasing depth (Busby and Whitfield 1978 and Skre et al. 1983), further promoting higher moisture contents deep in the O-horizon.

6.4 Alternative Methods of Relating Duff Moisture Contents to FWI System's Fuel Moisture Codes

The new empirical DC moisture equivalent equation (Eq. 8), with the exception of the FTWW3 plot, does not produce a stronger statistical relationship than the overwintered 'standard' DC moisture equivalent equation (Table 8). The strength of the empirically derived logarithmic equation lies in its ability to model the steep drying phase in the spring starting from a saturated condition. This, in effect, captures the suspected drainage that is occurring as the active layer recedes. The standard DC moisture equivalent must be initiated at an elevated value to accurately estimate the moisture contents that are the result of the receding active layer. Problems associated with overwintering the DC are discussed in the following section. Unfortunately, continued fall drying is still inherent in the new equation and precipitation induced moisture content increases are still underestimated.

The methods employed in developing the new DC – upper duff moisture content relationship (Equation 8) are not statistically sound. Only 4 equation shapes were investigated and these were evaluated solely on the coefficient of determination (Table 6). Exploration of additional non-linear estimation techniques could potentially model fuel moisture code – duff moisture content relationships in a more precise manner.

6.5 Evaluating the DC Overwintering Theory

Data collected near the FTWW1 and FTWW2 plots in September of 1998 (Wilmore, unpublished) show the moisture content of the upper duff fuels to be about 200%. The jet stream produced very little snow over the course of the winter and the longest historical stretch of –34°C and colder days were recorded at Fairbanks International Airport (Alaska Climatology 1961 – 1990). It is possible that the poor insulating qualities provided by the low snow pack allowed the extended period of extremely cold temperatures to penetrate deep into the O-horizon. Consequently, more of the tightly bound liquid water (McBrierty et al. 1996) was frozen creating an impermeable frost layer. Hence, lack of infiltration early in the season. This is supported by active layer research (Kane et al. 1978 and Mackay 1983) that suggests water moves upward during the winter in response to thermal gradients. Ice rich pores develop at the surface as a result of this migration and reduce infiltration rates. In addition, Ferguson et al. (2000 in press) have observed a sudden decrease in the O-horizon's moisture content once the soil warms above O°C. This would account for the large loss of moisture that occurred concurrent with the disappearance of the standing water.

The 1999 fall data also show the upper duff moisture content to be about 200% in September. However, the increased insulating efficiency of the deeper snow pack resulted in less of the tightly bound water being frozen, so drainage was not significantly compromised. Hence, no pooled water in the spring and moisture trends are similar to that of the post-drainage 1999 data.

The comparison of the 1999 and 2000 data (Table 9) indicate that the Lawson and Dalrymple (1996) overwintering procedures do not address all of the processes affecting initial spring moisture contents in boreal forest feather moss sites. The amount of overwinter precipitation does not appear to have an effect on the spring moisture content of the O-horizon. Research in permafrost soils suggests that fall moisture contents (Hinzeman et al. 1991) affect the depth and rate of freezing. Therefore, fall moisture contents in conjunction with snowpack insulation effectiveness may be more appropriate indicators of spring soil moisture recharge in permafrost sites.

7 Conclusions

There do appear to be discernable fuel layer characteristics within the O-horizon that are reliable for determining moisture regimes. MANOVA techniques found the 4 fuel layers identified in this study did produce significantly different bulk densities and moisture regimes. Moisture retention was positively related to bulk density while hydraulic conductivity was inversely related. Stratifying the O-horizon into 5 cm increments combines fuel layers thus, diminishing distinct bulk density and moisture regime differences between depths (Appendix A). It therefore appears essential that fuel moisture sampling and depth of consumption estimates, be based on actual fuel layer characteristics rather than standardized depths associated with the existing FWI System's fuel moisture codes.

Moisture contents at all 3 of the Ft. Wainwright, AK fuel moisture sampling plots followed the same general trends throughout the fire season. Initial moisture contents were high but decreased sharply as the active layer receded enhancing drainage in the lower soil layers. The high moisture contents observed in the early spring were not approached again throughout the remainder of the season. Seasonal lows were observed twice during the 1999 season. Both occurred after two weeks of rain free drying. Moisture contents increased in response to persistent rain events late in the summer although, the trend in the upper duff was still in a general drying direction.

The FWI System's fuel moisture codes produced strong statistical relationships with seasonal fuel moisture trends in the dead moss and upper duff fuels. The standard DMC moisture equivalent equation underpredicted the moisture contents observed in the dead moss in the spring and fall. However, it closely matched the moisture contents observed from mid May through mid July, the peak interior Alaska fire season. Fire personnel in Interior Alaska should feel comfortable using the standard DMC moisture equivalent equation to predict moisture contents in dead moss fuels when the DMC rises above 40.

The moisture regime of the upper duff showed greater variation on a day to day basis than the DC model allowed. The bulk density of the feather moss upper duff is less dense than the original DC fuel. Therefore, it is not surprising that the DC model shows less variability. The DC tends to overpredict moisture contents until the end of fire season when southwesterly flow begins to dominate the weather pattern bringing frequent precipitation events.

The empirically derived DC moisture equivalent equation developed in this study will reduce the margin of error in the overpredicted moisture content but will not eliminate it. The strength of the new equation lies in its ability to model the rapid decrease in spring moisture content as the active layer recedes, increasing infiltration rates. The robustness of the new equation is evident in the high r^2 of the independent data sets that included comparisons of both overwintered and defaulted DC's.

The overwintering procedures described in Lawson and Dalrymple (1996) does not appear to completely address the processes that affect O-horizon moisture regimes in permafrost sites. Restricted drainage rather than overwinter precipitation seems to be the factor determining spring moisture contents in the O-horizon. However, some means is required to decrease the moisture contents predicted by the DC during peak fire season. The new equation appears to be capable of performing this task without any adjustment to the initial DC value.

Although the new DC moisture equivalent equation was derived from and tested on more data points than other eco-region specific equations (Lawson and Dalrymple 1996), fire personnel should still exercise caution when applying this formula as it does not address the actual processes affecting moisture movement in the feather moss fuel layers. The destructive sampling methodology used in this study did not provide the information needed to truly analyze wetting and drying characteristics of the O-horizon. In spite of this, the empirically derived equation can aid fire mangers in anticipating critical duff consumption that will impact long-term post-fire effects.

8 Addendum: The Utility of FDR Probes for Fuel Moisture Sampling

8.1 What are Frequency Domain Reflectometry Probes?

In recent years, time domain reflectomerty (TDR) and frequency domain reflectometry (FDR) techniques have been found to be efficient methods of estimating soil moisture. TDR and FDR moisture sensing probes respond to a mediums dielectric constant (the tendency of a medium to orient its molecules in an electrostatic force field) (Hillel 1998). Soils and air have low dielectric constants (3 to 5 and 1 respectively) while water has a very high dielectric constant (81). Therefore, the dielectric constant of a soil is primarily determined by its volumetric moisture content (Hillel 1998).

The FDR probes investigated in this study generate a 100 MHz sinusoidal signal into the soil along an array of steel rods. The impedance of the rod array affects the reflection of the sinusoidal signal. Reflections are combined with the applied 100 MHz signal to form a standing voltage wave along the steel rods. The voltage, recorded by the data logger, is an analogue voltage proportional to the difference in amplitude of this standing wave at two points. The analogue voltage gives a precise measure of soil moisture content (Miller and Gaskin 1999).

8.2 Objectives of this Study

Currently, fire managers in Alaska's boreal forest region rely on fire danger indices and destructive sampling methods to measure the O-horizon moisture content for estimates of duff consumption. While there are advantages to the current methods, the first approach provides only a general picture of moisture trends deep in the O-horizon based on generic fuel properties. The second method, destructive sampling, is time consuming and is only appropriate on a small local scale. Given that previous boreal forest studies have successfully used TDR to estimate moisture content of the forest floor (Stein and Kane 1983, Hinzeman et al. 1991, and Peck et al.1997) it seemed logical to experiment with the technology for fire management purposes.

The objective of this study was to test the accuracy of FDR in the various decompositional stages (i.e. fuel layers) found in a typical boreal forest floor O-horizon. If accurate moisture contents can be estimated with FDR, probes could be connected to RAWS for direct real-time moisture measurements, eliminating the need for extensive destructive sampling and reliance on a very general fire index.

8.3 Methods

8.3.1 FDR Probe Calibration

Organic soil moisture at the Ft. Wainwright, AK study site was estimated with the Delta-T ThetaProbe model ML2x. The ThetaProbe was chosen for its reported accuracy in a variety of soil types (Hanson 1999) and its compatibility with the RAWS currently used by the fire management agencies (Jim Schaff, 2001 personal communication). ThetaProbe data can be logged in terms of voltage, volumetric mineral soil moisture content, or volumetric organic soil moisture content. The organic soil calibration has been optimized for soils that are comprised of 40% carbon and have a bulk density range of 0.2 to 0.7 Mg/m^3 (Delta-T Devices 1999). Therefore, a soil specific calibration was required to model moisture characteristics of the interior Alaska boreal forest O-horizon that exhibits bulk densities near or less than 0.1 Mg/m^3. Details regarding the calibration method described in the Delta-T Devices owners manual followed in this study are summarized as follows.

Two intact O-horizon cores were removed from the forest floor near FTWW2000 and transferred to the laboratory in April, 2000. The cores were set in an upright position and allowed to drain for 24 hours. Next, each core was cut into a sample of known volume and homogenous fuel layer. The FDR probe was inserted into each sample in several locations. The voltage from each insertion was read with the hand-held mobile ThetaMeter model HH1. A mean was calculated from the recorded voltage responses.

Each known volume sample was weighed wet, then dried to a constant weight at 100^{o}C. The samples were probed again post-drying and the actual volumetric moisture content was computed. The wet and dry voltage means were used to determine custom organic soil parameters to be used in a volumetric moisture content (θ_v) equation (Equation 1A). Data and equations employed in the custom parameter derivation can be viewed in Appendix F. The custom parameters, 1.099 and 8.03, were used exclusively in this study when determining moisture contents regardless of fuel layer.

$$\theta_v = \frac{[1.07 + 6.4V - 6.4V^2 + 4.7V^3] - a_o}{a_1} \qquad [1A]$$

where V = voltage

a_o = 1.099

$a_1 = 8.03$

(a_o and a_1 have been determined from interior Alaska boreal forest upper duff organic soils with average bulk densities of 0.045 Mg/m^3.)

8.3.2 Field Use of the FDR Probes

Two ThetaProbes were inserted into the upper duff fuel near the FTWW2000 plot at the Ft. Wainwright sampling site in the fall of 1999. A 15 cm^2 plug was removed from the forest floor and the probes were inserted horizontally in the O-horizon at approximately 15 and 20 cm below the surface. The degree of decomposition at this depth determined the fuel to be upper duff. The extracted plug was used to refill the hole around the probes that were left in-situ for the winter.

On April 27, 2000 both probes were connected to a Delta-T model DL2e two-channel data logger. The logger was programmed to record twice daily at approximately 0400 and 1600. The 1600 reporting time was chosen to correspond to the daily FWI calculations that use noon LST to predict the 1600 fuel moisture contents (Van Wagner, 1987). Data was continually logged until September 7, 2000. Equation 1A was used to estimate volumetric moisture content from the recorded voltage.

In addition to the two in-situ probes, a single probe was connected to the hand-held meter and used in conjunction with destructive sampling methods during the 2000 fire season. In this case, each of the 516 cm^3 samples was probed in at least 4 locations and the mean voltage computed. The known volume sample was further dissected into fuel layer, if appropriate, and the volumetric moisture content determined in 5 cm increments and by fuel layer.

To accommodate the samples comprising the 0 – 5 cm increment, that were difficult to probe in the manner just described, the probe was gently inserted into the forest floor until the probes housing was even with the surface. This was a rapid method for acquiring near surface moisture contents at multiple locations along the transect line and in the vicinity of the extracted plugs. A mean voltage was determined from the recorded voltage readings.

Volumetric moisture content was estimated with Equation 1A from the mean voltage for samples of similar depths and fuel layers. The moisture contents computed from Equation 1A were then compared to the mean moisture contents of the destructive samples.

To be consistent with fire behavior and fire danger literature, volumetric moisture contents should be converted to dry weight based measurements. Equation 2A (Hillel 1998) equates volumetric moisture content to gravimetric moisture content.

$$\theta_g = \theta_v * (\rho_w / \rho_b) \qquad [2A]$$

where

θ_g = gravimetric moisture content

θ_v = volumetric moisture content

ρ_w = density of water (1.0 Mg/m^3)

ρ_b = bulk density of the fuel

8.4 Results and Discussion

8.4.1 Boreal Forest Calibration vs. the Delta-T Organic Soil Moisture Characteristic Curve

The Delta-T organic soil moisture estimates were consistently lower than the custom boreal forest estimates. In dry live and dead moss fuels, such as those encountered in the 0 – 5 cm increment on June 26, the Delta-T organic soil moisture parameters actually produced negative moisture contents (Figure 1A). In contrast, the Delta-T calibration produced results similar to the boreal forest calibration in lower duff fuels deeper than 20 cm. It is assumed that these trends can be attributed to bulk density as the dissimilarities become negligible when bulk densities approach the optimal ThetaProbe calibration range of 0.2 Mg/m^3.

8.4.2 FDR Moisture Estimates vs. Measured Moisture Contents

The handheld meter proved to be an efficient method for estimating moisture contents in the field. Figure 2A compares the FDR estimates with moisture contents destructively sampled in 5 cm increments. In most cases the estimated and actual means are in close agreement and in all cases the FDR means are within ± 1 standard deviation of the observed means and vise versa. There does not appear to be a consistent pattern of over or under estimation at any depth or moisture content.

Figure 1A. Comparison of FDR probe calibrations. The Delta-T organic soil moisture calibration and the custom boreal forest calibration at various depths in the O-horizon at FTWW2000 on June 26, 2000.

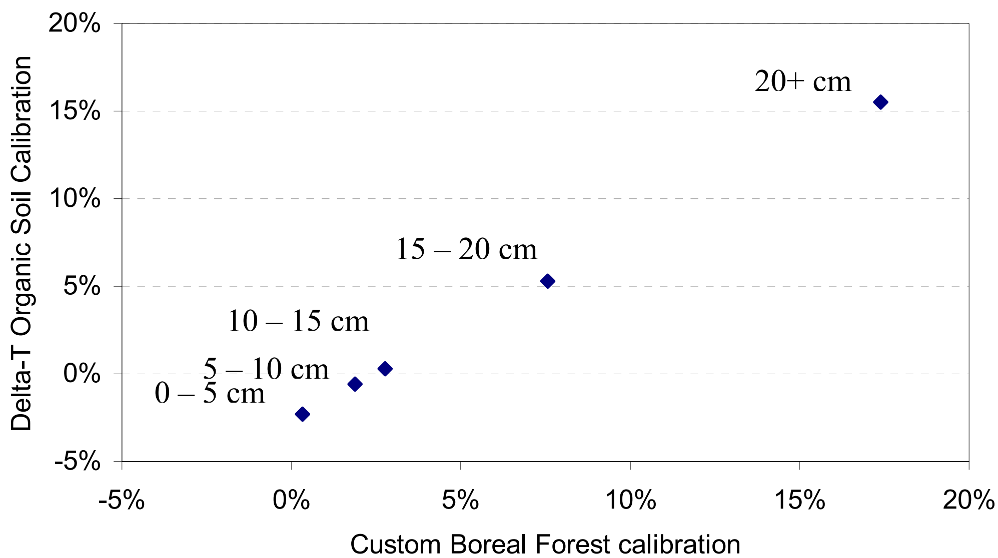
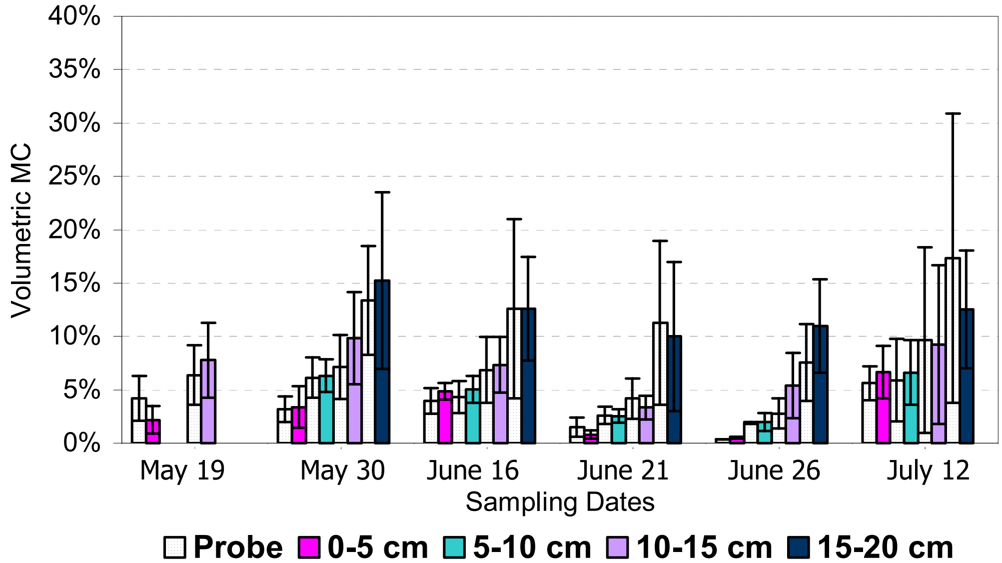


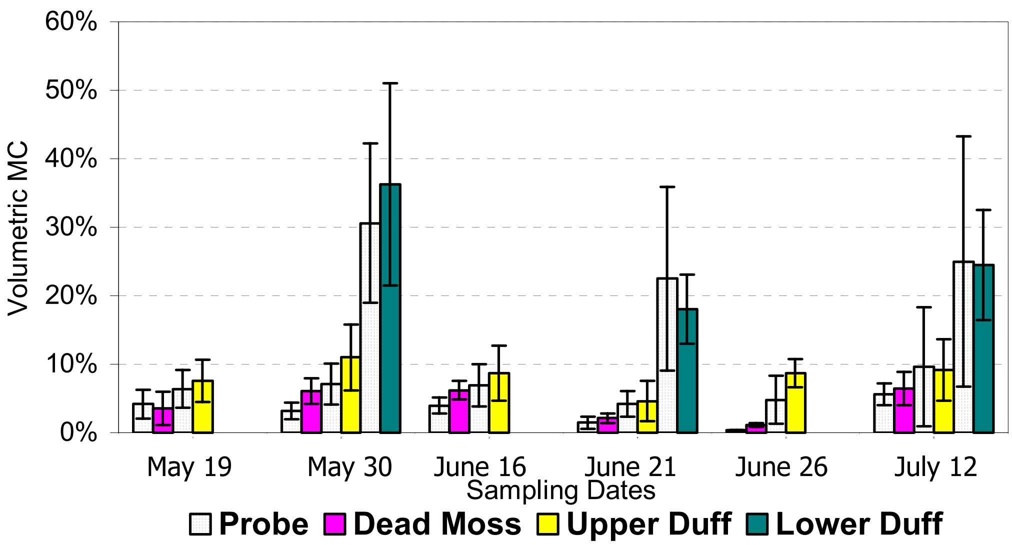
Figure 2A. Comparison of FDR estimated and observed volumetric moisture contents by depth. Samples collected in 5 cm depths at Ft. Wainwright, AK, 2000. Data points are means ± 1 SD. (FDR probe data for each depth proceeds the observed moisture content for that depth.)



The FDR data were next compiled into groups by fuel layer and evaluated with the destructively sampled fuel layer moisture contents (Figure 3A). Live moss fuel moistures cannot be estimated with FDR as the live moss is usually very porous (significant air flow) and averages only 2 cm deep. The 0 – 5 cm increment used in the comparison with dead moss may not be an appropriate choice since the 0 – 5 cm layer is usually comprised of both live and dead moss. The live moss can have a distinctly different moisture regime than the dead moss just below it. An interface between two distinct moisture regimes may confuse the FDR reading (Hinzeman, 2000 personal communication). Improved precision in the dead moss fuel could presumably be obtained if the probed sample was a homogenous fuel layer and a specific dead moss calibration completed. FDR readings from 10 – 15 and 15 – 20 cm increments were pooled to give estimates of upper duff moisture content. Field notes indicate that these depths were comprised predominantly of upper duff. Figure 2A indicates a large difference in moisture content and degree of variance between the 10 – 15 and 15 – 20 cm layers.

Interestingly, the combined FDR data representing upper duff in figure 3A tend to follow the lower 10 – 15 cm increment moisture content and variance trends. The elevated variance and means associated with the 15 – 20 cm layer are the result of a few outlying wet data points. Consequently, the entire upper duff fuel strata may become available for consumption sooner than is anticipated with a simple depth increment sampling scheme.

Figure 3A. Comparison of FDR estimated and observed moisture contents by fuel layer. Data points are means ± 1 SD. (FDR probe data for each depth proceeds the observed moisture content for that fuel layer.)



Lower duff moisture contents were estimated with FDR data from the 20+ cm depth. Field notes confirm this depth predominately consisted of lower duff fuels. The 2.5 to 3-

fold increase in lower duff fuel moistures (estimated and actual) also support evaluation of potential fuel consumption by a defined fuel layer rather than a generic depth.

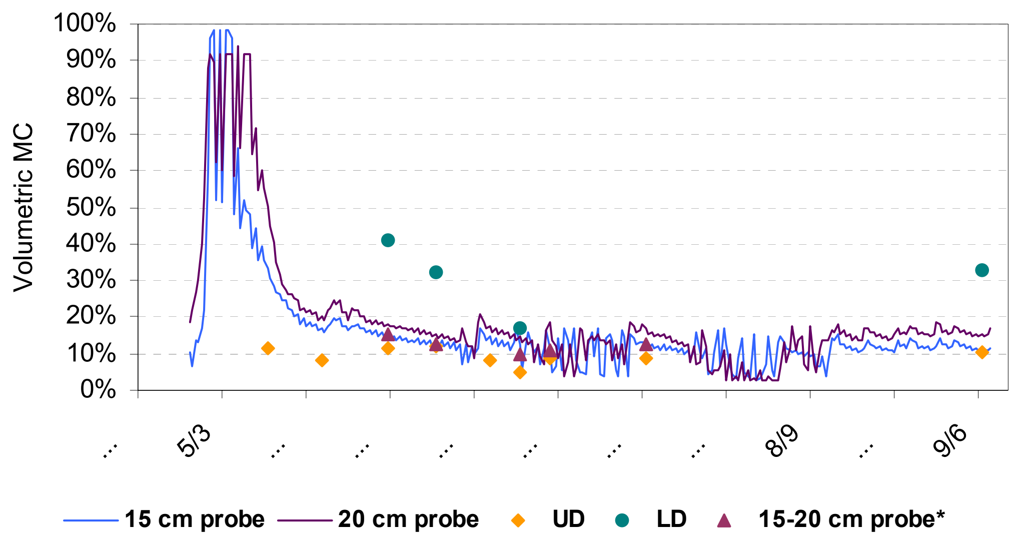
No consistent pattern of over or under estimation of moisture content in any of the fuel layers was observed. Moisture thresholds and trends indicating divergence of actual and FDR estimated moisture contents may not be evident due to the small sample size (n = 6). Despite the small sample size, and the single calibration parameters being applied to all fuel layers, the agreement between FDR estimated and actual moisture contents appears to be quite good.

8.4.3 The Utility of In-Situ FDR Probes

In the final evaluation of the FDR moisture sensing probes, data from the two in-situ probes was overlaid on data points obtained with the hand-held probe and the destructively sampled moisture contents. Hand-held probe estimates taken on samples from the 15 – 20 cm increment fall directly on the data stream produced by the in-situ probe inserted 15 cm below the surface (Figure 4A.). The correlation coefficient for the relationship was r = 0.86. Furthermore, estimates from the hand-held probe are within ±1 SD of the data stream originating from the in-situ probe inserted at 20 cm (Appendix E).

Destructively sampled upper and lower duff moisture contents are included in Figure 4A to illustrate the need for multiple probe profiles. Lower duff fuels at the FTWW2000 site tended to be deeper than 20 cm consequently, containing more water than was encountered by the probe inserted at 20 cm. Upper duff fuel depths ranged from 5 to 20 cm so, only the deepest portion of the upper duff fuel is represented by estimates from the probe inserted at 15 cm. Additional probes, buried at 5 cm intervals beginning 5 or 10 cm beneath the surface, would greatly enhance understanding of the O-horizon moisture profile.

Figure 4A. Data streams from permanently placed FDR probes. Probes permanently inserted 15 and 20 cm beneath the surface of the forest floor (upper duff fuel) at Ft. Wainwright, AK, 2000. Individual data points depict the moisture content estimates from the mobile probe unit and actual moisture contents measured in the upper and lower duff fuels.



* Data points obtained with the mobile probe unit 15 - 20 cm beneath the surface of the forest floor.

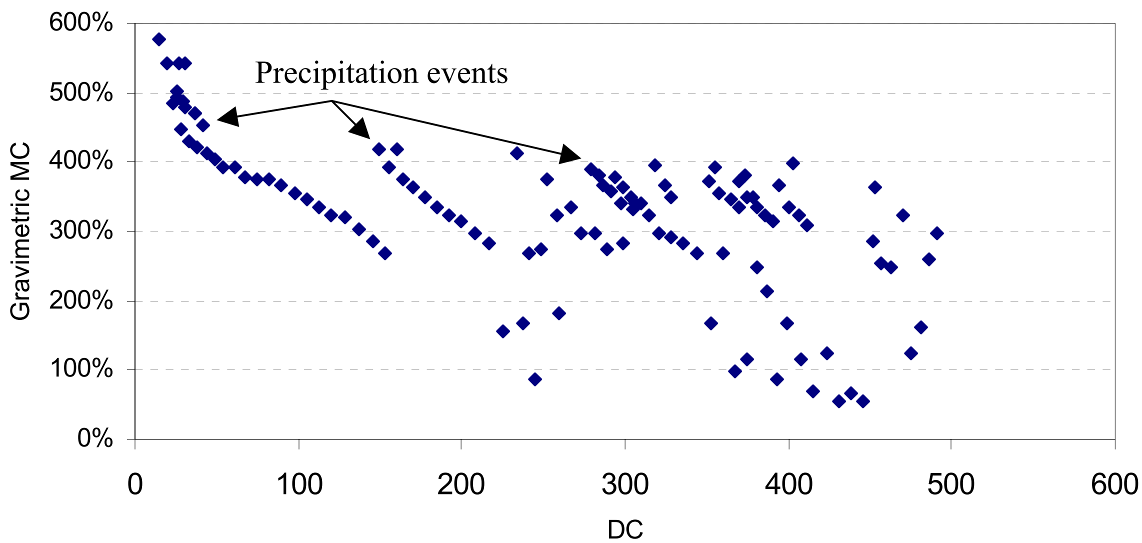
The jagged data streams in Figure 4A depict the FDR probes response to freezing and thawing, diurnal moisture fluctuations and precipitation events. Percolation from snow melt in late April and early May are assumed responsible for the extreme early season moisture contents. Refreezing of liquid water during the night presumably induced the large diurnal fluctuations seen in the first few days of May. The FDR data streams Data points obtained with the mobile probe unit 15 – 20 cm beneath the surface of the forest floor. convincingly support the sudden drainage suggested in the 1999 destructively sampled data. Figure 4A also indicates a drainage timelag between the 15 and 20 cm depths. Accelerated drainage at the 20 cm depth commenced 3 days after drainage at 15 cm.

Precipitation events account for distinct increases in estimated moisture contents from mid-May through mid-June and after mid-August. Unfortunately, few of large fluctuations occurring June 21 through July 9 and again July 21 through August 10 can be explained with environmental inputs. In some instances the two probes are reporting opposite trends. No viable explanation is presently available for this phenomenon.

8.4.4 Using FDR to Enhance Understanding of the O-Horizon - FWI System Fuel Moisture Code Relationship

The continuous nature of the TDR or FDR data provides insights into the boreal forest O-horizons response to environmental inputs as compared to the FWI System's fuel moisture codes. Figure 5A depicts a scatter plot of the DC component of the CFFDRS FWI System with upper duff moisture contents. The parallel pattern that emerges signifies drying trends separated by precipitation events and is consistent with the other studies (Fergusen et al. 2000, Bolten et al. 2000). The random pattern of points in the center and lower right corner of Figure 5A (between DC 200 and 300 and DC 350 to 500) correspond to the mysterious fluctuations exhibited in Figure 4A. With the exception of the mysterious fluctuations, the results in Figure 5A support the 1999 conclusions that the upper duff fuel is more responsive to precipitation events than the CFFDRS drought code.

Figure 5A. Scatter plot of the CFFDRS FWI System's DC with upper duff moisture content. Upper duff moisture content is estimated from the in-situ probe inserted at 20 cm near FTWW2000, Ft. Wainwright, AK, 2000. The 1600 FDR volumetric moisture content data was converted to a gravimetric measurement using Equation 2A.



8.5 Conclusions

Despite the sparse data collection, FDR technology does have fire management potential. The obvious disadvantages of FDR are the inability to model porous surface fuels (live and dead moss) that promote fire spread and the mysterious fluctuations that the permanent probes exhibited during peak fire season. In addition, permanently buried probes relate moisture trends from a very small specific locality.

Advantages of FDR include efficient estimates of fuel moisture in the subsurface fuel layers that contribute to fire severity and post-fire effects. Moisture profile transects across a prescribed burn unit can be easily attained with the mobile FDR unit, providing fire mangers with moisture data to estimate depth of duff consumption for achievement of resource objectives. In-situ probes, attached to a RAWS, could supply moisture profiles to fire managers reducing the error inherent in fire index predictions of fuel moisture used in wildland and prescribed fire decisions. Furthermore, the continuous quality of the data lend it to the study of freezing and thawing phenomenon, diurnal variation, and fuel response to wetting and drying events, data that could significantly enhance understanding of boreal forest fuels moisture regimes and fire danger rating systems.

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Appendix A: Bulk Density MANOVA Results

Bulk Density MANOVA Results for Feather Moss Fuels Stratified in 5 cm Increments

P-values of bulk densities by depth at Ft. Wainwright, AK, 1999 as determined by Tukey's honestly significant difference test for unequal sample size (α = 0.05), Homogenous depths are indicated with bold face type.

PLOT and DEPTH	FTWW1 0 – 5 cm	FTWW1 5 – 10 cm	FTWW1 10 – 15 cm	FTWW1 15 – 20 cm	FTWW2 0 – 5 cm	FTWW2 5 – 10 cm	FTWW2 10 – 15 cm	FTWW2 15 – 20 cm	FTWW3 0 –5 cm	FTWW3 5 –10 cm	FTWW3 10 -15cm	FTWW3 15 – 20 cm
FTWW1 0 – 5cm		**0.23835**	0.00017	0.00017	**0.454874**	0.00017	0.00017	0.00017	**0.697612**	0.00017	0.00017	0.00017
FTWW1 5 – 10cm	0.023835		0.00017	0.00017	**0.954183**	0.000423	0.00017	0.00017	**0.780239**	**0.263660**	0.00017	0.00017
FTWW1 10 - 15cm	0.000017	0.00017		0.00017	0.00017	**0.317955**	0.000036	0.00017	0.00017	0.000988	0.005281	0.00017
FTWW1 15 – 20cm	0.000017	0.00017	0.00017		0.00017	0.00017	0.000032	**0.999998**	0.00017	0.00017	0.00017	**0.093582**
FTWW2 0 – 5 cm	**0.454874**	**0.954183**	0.00017	0.00017		0.00017	0.00017	0.00017	**0.99999**	0.000238	0.00017	0.00017
FTWW2 5 – 10 cm	0.000017	0.000423	**0.317955**	0.00017	0.00017		0.00017	0.00017	0.00017	**0.626230**	0.00017	0.00017

FTWW2 10 – 15 cm	0.000017	0.00017	0.000036	0.000032	0.00017	0.00017		0.000028	0.00017	0.00017	**0.984199**	0.00017
FTWW2 15 – 20 cm	0.00017	0.00017	0.00017	**0.999998**	0.00017	0.00017	0.000028		0.00017	0.00017	0.00017	**0.262398**
FTWW3 0 – 5 cm	**0.697612**	**0.780239**	0.00017	0.00017	**0.99999**	0.00017	0.00017	0.00017		0.00017	0.00017	0.00017
FTWW3 5 – 10 cm	0.00017	**0.263660**	0.000988	0.00017	0.000238	**0.626230**	0.00017	0.00017	0.00017		0.00017	0.00017
FTWW3 10 – 15 cm	0.00017	0.00017	0.005281	0.00017	0.00017	0.00017	**.984199**	0.00017	0.00017	0.00017		0.00017
FTWW3 15 – 20 cm	0.00017	0.00017	0.00017	**0.093582**	0.00017	0.00017	0.00017	**0.262398**	0.00017	0.00017	0.00017	

Bulk Density MANOVA Results for Feather Moss Fuels Stratified by Fuel Layer

P-values of bulk densities by depth at Ft. Wainwright, AK, 1999 as determined by Tukey's honestly significant difference test for unequal sample size ($\alpha = 0.05$). Homogenous depths are indicated with bold face layer.

PLOT and FUEL LAYER	FTWW1 LM	FTWW1 DM	FTWW1 UD	FTWW1 LD	FTWW2 LM	FTWW2 DM	FTWW2 UD	FTWW2 LD	FTWW3 LM	FTWW3 DM	FTWW3 UD	FTWW3 LD
FTWW1 LM		0.000017	0.000017	0.000017	**0.085399**	0.000017	0.000017	0.000017	**0.817463**	0.000017	0.000017	0.000017
FTWW1 DM	0.000017		0.000017	0.000017	0.000128	**0.806857**	0.000017	0.000017	0.000017	0.025248	0.000017	0.000017
FTWW1 UD	0.000017	0.000017		0.000017	0.000017	0.000017	0.000017	0.000017	0.000017	0.000017	**0.995548**	0.000017
FTWW1 LD	0.000017	0.000017	0.000017		0.000017	0.000017	0.000017	**0.096266**	0.000017	0.000017	0.000017	**0.191176**
FTWW2 LM	**0.85399**	0.000128	0.000017	0.000017		0.000017	0.000017	0.000017	**0.970754**	0.000017	0.000017	0.000017
FTWW2 DM	0.000017	**0.806857**	0.000017	0.000017	0.000017		0.000017	0.000017	0.000017	**0.965451**	0.000017	0.000017
FTWW2 UD	0.000017	0.000017	0.000017	0.000017	0.000017	0.000017		0.000017	0.000017	0.000017	0.000020	0.000017

FTWW2 LD	0.000017	0.000017	0.000017	**0.096266**	0.000017	0.000017	0.000017		0.000017	0.000017	0.000017	**1.00000**
FTWW3 LM	**0.817463**	0.000017	0.000017	0.000017	**0.970754**	0.000017	0.000017	0.000017		0.000017	0.000017	0.000017
FTWW3 DM	0.000017	0.025248	0.000017	0.000017	0.000017	**0.95451**	0.000017	0.000017	0.000017		0.000017	0.000017
FTWW3 UD	0.000017	0.000017	**0.995548**	0.000017	0.000017	0.000017	0.000020	0.000017	0.000017	0.000017		0.000017
FTWW3 LD	0.000017	0.000017	0.000017	**0.191176**	0.000017	0.000017	0.000017	**1.00000**	0.000017	0.000017	0.000017	

LM = Live Moss, DM = Dead Moss, UD = Upper Duff, LD = Lower Duff

Appendix B: Gravimetric Moisture Content Data for FTWW1-3 and FTWW2000

1999 Gravimetric Fuel Moisture Content Data for Plot FTWW1

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
4/27				400	44	9	606	134	9			
5/6	267	82	8	360	73	9	418	130	9			
5/11	121	124	9	286	120	9	419	152	9			
5/13	64	38	9	259	101	9	339	99	8			
5/17	42	16	9	216	101	8	228	228	7			
5/20	26	6	6	139	100	6	248	108	6			
5/25	19	4	9	41	14	8	159	34	8	227	63	2
5/31	23	9	9	137	80	9	242	150	9			
6/4	31	8	9	158	75	9	280	86	8			
6/8	18	3	9	32	13	8	150	68	9	191	50	7
6/12	14	4	9	33	6	9	130	41	9	184	50	2
6/15	19	3	9	39	11	9	104	52	8	205	24	2
6/21	412	34	9	406	72	8	270	123	8			
6/24	131	48	9	226	50	6	226	42	8	202	39	2
6/27	18	14	9	126	71	9	191	86	7			
7/1	75	41	9	238	68	9	254	89	9			
7/7	28	7	9	84	36	9	135	41	8	188	5	2
7/12	28	3	9	56	26	9	127	42	6	221	34	4
7/15	22	8	9	62	49	9	133	57	9	191	24	5
7/19	197	45	9	250	65	9	201	78	9			
7/22	453	66	9	331	53	9	209	75	8			
7/28	436	122	9	375	102	9	279	105	7	222	63	2
8/4	247	82	9	326	45	8	256	56	9	247	48	3

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
8/11	457	64	9	389	51	8	253	56	9	188	30	6
8/17	170	66	8	282	44	8	236	61	6	166	64	4
8/23	47	29	9	196	36	9	182	23	7	209	31	2
8/30	282	112	9	338	99	9	229	93	6	206	42	4
9/12	179	101	9	278	64	9	191	55	9	174	18	2
9/19	280	138	9	310	69	9	168	67	9	165	28	5

1999 Gravimetric Fuel Moisture Content Data for Plot FTWW2

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
4/27				386	74	9	540	196	9			
5/3				475	89	9	478	207	9			
5/10	224	167	9	325	152	9	397	156	9			
5/13	145	171	9	270	173	9	379	196	8			
5/17	113	129	9	156	177	3	307	98	9			
5/20		47	9	191	117	9	242	72	9			
5/25	116	120	9	254	151	4	252	155	9			
5/31	75	136	9	182	132	5	256	111	4			

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
6/4	43	46	8	94	76	7	220	29	4	186	36	4
6/8	19	4	4	96	88	4	189	65	7	259	66	6
6/12	12	4	3	39	14	3	119	40	4			
6/15	14	6	9	57	50	8	104	72	7	219	49	2
6/21	273	100	9	286	36	9	173	47	8	204	56	3
6/24	69	29	7	211	55	7	201	86	6			
6/27	19	8	8	146	63	7	188	81	6	234	44	2
7/1	65	30	8	202	71	8	200	62	9			
7/7	25	13	9	145	110	7	161	89	7			
7/12	28	12	7	137	130	7	166	61	8	273	71	2
7/15	19	3	8	43	20	7	142	35	7			
7/19	168	60	9	200	57	9	148	70	8	200	6	3
7/23	300	63	9	320	38	7	184	77	9	164	28	3
7/28	425	96	9	387	64	9	319	76	8	287	99	2
8/4	163	70	8	291	64	9	239	113	4	144	48	3
8/11	421	103	7	414	68	8	265	46	7	163	22	3
8/17	190	41	4	320	75	5	154	41	3			
8/23	48	28	9	183	80	9	137	31	6	181	9	4
8/30	146	45	9	272	33	9	238	56	7	135	27	2
9/12	147	86	8	234	48	8	184	77	8	153	59	4
9/19	218	109	9	286	72	7	176	75	8	195	12	2

1999 Gravimetric Fuel Moisture Content Data for Plot FTWW3

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
4/27				453	135	9	776	208	9			
5/4	400	68	6	674	106	6	504	177	5			
5/11	159	132	8	266	111	6	309	78	6			
5/14	174	79	6	285	91	6	295	76	8			
5/18	106	95	9	261	103	9	346	122	7			
5/21	148	89	7	294	59	7	385	75	9			
5/24	132	91	7	294	39	7	319	84	6			
5/27	240	94	8	306	111	8	273	107	8	255	23	3
6/6	45	47	9	193	116	7	224	108	8			
6/9	50	20	6	194	110	6	304	70	9	279	28	2
6/16	126	56	9	134	76	9	185	63	9	256	28	3
6/23	306	41	9	330	28	9	288	32	7			
6/25	93	58	9	246	82	8	239	84	8	277	61	2
6/29	286	37	8	292	44	9	250	110	9	264	46	2
7/5	58	29	8	146	93	8	271	85	9	309	58	2
7/8	33	15	9	146	92	9	244	83	8	241	49	4
7/13	27	4	8	93	60	8	189	58	5	113	5	2
7/16	336	56	9	241	60	9	200	63	5			
7/20	305	53	9	235	48	9	144	556	7	136	42	2
7/26	467	53	7	382	80	9	261	85	6	236	12	2
7/29	416	45	7	404	54	8	256	64	7	205	68	3
8/3	361	49	9	333	44	7	268	51	9	214	24	2
8/6	89	26	9	268	65	9	218	43	9	129	11	2
8/10	438	59	9	386	41	9	309	40	7	202	48	2
8/14	405	67	8	386	52	8	291	64	9			
8/19	89	37	8	247	94	8	234	57	8	253	67	4
8/26	425	40	9	376	48	8	219	102	7	189	15	5
9/1	270	95	9	320	59	9	244	77	9	169	25	3

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
9/10	418	58	7	364	40	8	249	33	9	160	18	3
9/18	363	59	6	367	46	6	286	42	6	175	34	3

Gravimetric Fuel Moisture Content Data for Plot FTWW2000

Date	Live Moss			Dead Moss			Upper Duff			Lower Duff		
	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n	Mean	1 SD	n
5/10	151	113	6	272	83	5	425	193	6			
5/19	62	56	9	200	132	9	254	119	9			
5/30	123	49	9	281	77	9	278	82	9	357	79	3
6/7	99	137	9	213	146	9	332	94	9	327	79	7
6/16	327	46	8	337	34	8	218	106	9	314	46	5
6/21	44	37	9	108	44	9	129	80	9	200	63	9
6/26	20	4	6	72	25	6	242	88	6	294	20	2
7/12	447	92	9	325	130	8	240	56	9	256	35	9
9/6	545	62	5	462	119	5	315	41	4	294	40	4

Appendix C

1999 Fairbanks RAWS Weather and FWI

Date	Time	Temp (^oF)	RH	WSPD (mph)	ppt (in)	FFMC	DMC	DC	ISI	BUI	FWI
4/27	1200	42.0	38.0	7.0	0.00	85.0	6.0	15.0	4.7	21.7	7.9
4/28	1200	52.0	33.0	4.0	0.00	87.7	8.0	18.0	4.2	7.9	4.0
4/29	1200	58.0	32.0	4.0	0.00	89.2	10.6	21.6	5.2	10.5	5.8
4/30	1200	43.0	95.0	1.0	0.03	78.8	10.7	23.7	1.1	10.6	0.7
5/1	1200	33.0	100.0	5.0	0.01	75.0	10.7	24.8	1.1	10.7	0.7
5/2	1200	38.0	90.0	4.0	0.12	45.4	7.6	25.2	0.1	8.6	0.1
5/3	1200	38.0	100.0	5.0	0.09	29.0	5.7	28.2	0.0	7.6	0.0
5/4	1200	39.0	49.0	9.0	0.00	54.6	6.4	31.3	0.6	8.4	0.3
5/5	1200	47.0	56.0	7.0	0.00	70.7	7.5	35.2	1.1	9.8	0.7
5/6	1200	57.0	43.0	4.0	0.00	81.6	9.7	40.1	1.9	12.1	1.8
5/7	1200	46.0	83.0	4.0	0.00	81.1	10.1	43.9	1.8	12.8	1.7
5/8	1200	56.0	59.0	4.0	0.01	83.3	11.7	48.7	2.3	14.6	2.9
5/9	1200	61.0	37.0	4.0	0.00	87.4	14.6	54.0	4.1	17.4	6.1
5/10	1200	67.0	25.0	5.0	0.00	91.1	18.7	59.9	7.5	21.0	11.5
5/11	1200	66.0	33.0	4.0	0.00	91.1	22.2	65.7	6.9	24.1	11.6
5/12	1200	73.0	34.0	5.0	0.00	91.1	26.3	72.2	7.5	27.6	13.2
5/13	1200	66.0	53.0	5.0	0.02	88.3	28.8	78.0	5.0	29.9	10.0
5/14	1200	69.0	50.0	2.0	0.06	80.1	30.9	84.1	1.3	32.2	2.8
5/15	1200	71.0	27.0	6.0	0.00	89.8	35.3	90.4	6.8	35.7	14.0
5/16	1200	66.0	35.0	4.0	0.00	89.9	38.7	96.2	5.8	38.7	13.0
5/17	1200	63.0	41.0	5.0	0.00	89.9	41.5	101.7	6.3	41.5	14.4
5/18	1200	56.0	28.0	7.0	0.00	90.3	44.2	106.5	7.9	44.2	17.5
5/19	1200	65.0	26.0	5.0	0.00	91.4	48.0	112.2	7.8	47.9	18.2
5/20	1200	63.0	30.0	6.0	0.00	91.4	51.4	117.7	8.5	51.3	20.1
5/21	1200	61.0	28.0	7.0	0.00	91.4	54.7	123.0	9.2	54.6	22.0
5/22	1200	66.0	33.0	3.0	0.00	91.4	58.2	128.8	6.7	58.1	18.0
5/23	1200	67.0	42.0	5.0	0.00	90.7	61.3	134.7	7.1	61.2	19.3

Date	Time	Temp (°F)	RH	WSPD (mph)	ppt (in)	FFMC	DMC	DC	ISI	BUI	FWI
5/24	1200	72.0	35.0	4.0	0.00	90.7	65.3	141.1	6.6	65.2	18.8
5/25	1200	66.0	49.0	5.0	0.00	89.6	68.0	146.9	6.0	67.9	18.1
5/26	1200	58.0	61.0	4.0	0.31	52.5	39.5	137.2	0.3	46.0	0.5
5/27	1200	59.0	54.0	4.0	0.00	72.1	41.4	142.3	0.9	48.0	2.5
5/28	1200	57.0	59.0	1.0	0.00	78.6	43.0	147.2	1.1	49.7	3.1
5/29	1200	66.0	37.0	5.0	0.00	86.8	46.3	153.0	4.1	52.7	11.6
5/30	1200	59.0	51.0	4.0	0.02	85.7	48.4	158.1	3.2	54.8	9.7
5/31	1200	56.0	49.0	9.0	0.00	86.3	50.3	162.9	5.2	56.8	14.6
6/1	1200	62.0	53.0	4.0	0.00	86.3	52.5	168.3	3.5	59.0	10.9
6/2	1200	55.0	67.0	5.0	0.01	85.4	53.7	174.0	3.3	60.6	10.7
6/3	1200	56.0	61.0	4.0	0.00	85.4	55.2	179.8	3.1	62.4	10.2
6/4	1200	62.0	45.0	5.0	0.00	87.1	57.8	186.2	4.2	65.1	13.4
6/5	1200	69.0	35.0	4.0	0.00	89.5	61.5	193.3	5.5	68.5	17.0
6/6	1200	77.0	40.0	3.0	0.00	89.9	65.6	201.2	5.4	72.3	17.2
6/7	1200	79.0	36.0	3.0	0.00	90.8	70.2	209.3	6.1	76.4	19.4
6/8	1200	76.0	50.0	2.0	0.00	90.1	73.6	217.1	5.0	79.7	17.3
6/9	1200	75.0	48.0	5.0	0.00	90.0	77.0	224.8	6.4	83.0	21.0
6/10	1200	81.0	39.0	3.0	0.00	90.5	81.5	233.1	5.8	87.0	20.2
6/11	1200	82.0	33.0	3.0	0.00	91.6	86.6	241.5	6.9	91.3	23.3
6/12	1200	84.0	34.0	3.0	0.00	91.8	91.8	250.1	7.0	95.7	24.2
6/13	1200	90.0	36.0	4.0	0.00	92.0	97.4	259.3	7.8	100.5	26.7
6/14	1200	68.0	64.0	0.0	0.00	88.6	99.4	266.3	3.5	102.8	15.0
6/15	1200	82.0	47.0	0.0	0.00	89.0	103.4	274.7	3.7	106.6	16.1
6/16	1200	73.0	76.0	3.0	0.03	82.9	104.9	282.2	2.0	108.7	10.0
6/17	1200	59.0	100.0	0.0	0.13	40.3	74.4	282.5	0.0	89.7	0.1
6/18	1200	67.0	69.0	6.0	0.40	44.8	40.4	261.8	0.1	58.3	0.2
6/19	1200	72.0	57.0	5.0	0.00	73.1	43.0	269.2	1.0	61.5	3.6
6/20	1200	71.0	77.0	0.0	0.00	76.6	44.4	276.5	0.8	63.3	2.8
6/21	1200	67.0	69.0	1.0	0.43	42.0	23.6	253.9	0.1	38.3	0.1
6/22	1200	60.0	100.0	4.0	0.00	42.0	23.6	260.1	0.1	38.5	0.1
6/23	1200	66.0	80.0	1.0	0.00	55.7	24.7	266.9	0.3	40.1	0.5
6/24	1200	76.0	62.0	1.0	0.00	73.8	27.3	274.7	0.8	43.7	1.7

6/25	1200	81.0	47.0	2.0	0.00	85.6	31.3	283.0	2.7	49.0	7.8
6/26	1200	78.0	60.0	2.0	0.00	86.3	34.1	291.0	3.0	52.8	8.9
6/27	1200	70.0	74.0	6.0	0.00	85.2	35.6	298.2	3.5	54.9	10.5
6/28	1200	62.0	78.0	6.0	1.16	38.5	13.0	218.4	0.0	22.7	0.0
6/29	1200	71.0	42.0	8.0	0.00	76.3	16.5	225.7	1.6	27.9	3.0
6/30	1200	74.0	33.0	9.0	0.00	88.8	20.8	233.3	7.4	34.0	14.7
7/1	1200	80.0	33.0	2.0	0.00	91.1	25.7	241.5	5.9	40.6	13.4
7/2	1200	81.0	48.0	2.0	0.00	90.7	29.2	250.1	5.5	45.2	13.6
7/3	1200	84.0	47.0	5.0	0.00	90.7	32.9	259.0	7.1	50.0	17.3
7/4	1200	85.0	51.0	4.0	0.00	90.4	36.4	268.0	6.3	54.4	16.5
7/5	1200	77.0	68.0	3.0	0.02	86.9	38.4	276.2	3.5	56.9	10.7
7/6	1200	76.0	53.0	6.0	0.00	87.5	41.2	284.3	4.8	60.5	14.3
7/7	1200	76.0	55.0	5.0	0.00	87.5	43.9	292.4	4.5	63.8	14.0
7/8	1200	66.0	72.0	4.0	0.00	85.7	45.2	299.5	3.2	65.7	10.8
7/9	1200	79.0	48.0	3.0	0.00	88.1	48.5	307.9	4.1	69.6	13.8
7/10	1200	86.0	43.0	3.0	0.00	90.0	52.7	317.0	5.4	74.4	17.6
7/11	1200	72.0	75.0	3.0	0.00	86.1	54.1	324.7	3.1	76.4	11.6
7/12	1200	72.0	87.0	4.0	0.00	82.6	54.8	332.4	2.1	77.6	8.5
7/13	1200	68.0	94.0	3.0	0.00	79.2	55.1	339.7	1.3	78.4	5.6
7/14	1200	85.0	54.0	4.0	0.00	86.6	58.4	348.7	3.6	82.3	13.7
7/15	1200	81.0	60.0	3.0	0.00	86.8	61.1	357.3	3.4	85.6	13.4
7/16	1200	65.0	100.0	2.0	0.21	30.0	39.0	349.4	0.0	61.0	0.0
7/17	1200	61.0	90.0	4.0	0.34	20.4	20.9	329.1	0.0	36.1	0.0
7/18	1200	69.0	66.0	1.0	0.00	47.8	22.6	336.5	0.1	38.7	0.2
Date	**Time**	**Temp (^{o}F)**	**RH**	**WSPD (mph)**	**ppt (in)**	**FFMC**	**DMC**	**DC**	**ISI**	**BUI**	**FWI**
7/19	1200	67.0	82.0	2.0	0.00	60.7	23.5	343.7	0.5	40.1	0.7
7/20	1200	63.0	85.0	8.0	0.06	61.2	23.5	350.5	0.8	40.2	1.7
7/21	1200	55.0	95.0	6.0	0.02	62.5	23.7	356.5	0.8	40.6	1.4
7/22	1200	49.0	100.0	5.0	0.25	19.4	13.7	343.1	0.0	24.9	0.0
7/23	1200	57.0	74.0	4.0	0.06	39.8	14.1	349.3	0.0	25.6	0.0
7/24	1200	53.0	100.0	4.0	0.04	35.2	14.1	355.1	0.0	25.7	0.0
7/25	1200	62.0	98.0	5.0	0.21	15.8	8.4	347.0	0.0	15.8	0.0
7/26	1200	62.0	100.0	0.0	0.19	6.2	4.7	341.1	0.0	9.1	0.0

7/27	1200	59.0	100.0	3.0	0.20	2.1	2.2	334.1	0.0	4.3	0.0
7/28	1200	54.0	98.0	3.0	0.05	3.1	2.3	340.0	0.0	4.5	0.0
7/29	1200	62.0	82.0	5.0	0.01	26.7	3.1	346.7	0.0	6.0	0.0
7/30	1200	70.0	83.0	2.0	0.05	41.7	4.0	354.2	0.1	7.8	0.0
7/31	1200	81.0	53.0	2.0	0.00	73.9	7.1	362.8	0.8	13.6	0.6
8/1	1200	65.0	95.0	2.0	0.00	74.2	7.3	369.8	0.9	14.0	0.6
8/2	1200	58.0	100.0	1.0	0.18	29.1	4.0	363.1	0.0	7.8	0.0
8/3	1200	82.0	56.0	4.0	0.00	70.7	6.6	371.1	0.9	12.7	0.6
8/4	1200	88.0	43.0	4.0	0.00	87.7	10.4	379.7	4.2	19.5	6.7
8/5	1200	83.0	48.0	2.0	0.00	88.8	13.6	387.8	4.2	24.9	7.8
8/6	1200	81.0	60.0	1.0	0.00	88.5	15.9	395.7	3.7	29.0	7.6
8/7	1200	65.0	100.0	1.0	0.23	28.6	9.2	383.5	0.0	17.3	0.0
8/8	1200	70.0	96.0	2.0	0.19	16.9	5.4	376.5	0.0	10.4	0.0
8/9	1200	63.0	100.0	1.0	0.02	16.6	5.4	382.6	0.0	10.4	0.0
8/10	1200	71.0	83.0	3.0	0.10	33.8	4.3	389.5	0.0	8.5	0.0
8/11	1200	70.0	76.0	2.0	0.05	51.1	5.4	396.3	0.2	10.4	0.1
8/12	1200	65.0	100.0	0.0	0.05	42.1	5.4	402.6	0.1	10.4	0.0
8/13	1200	64.0	80.0	7.0	0.55	35.0	2.9	356.7	0.0	5.7	0.0
8/14	1200	61.0	84.0	2.0	0.00	48.5	3.5	362.6	0.2	6.8	0.1
8/15	1200	59.0	98.0	3.0	0.01	50.2	3.6	368.3	0.2	7.0	0.1
8/16	1200	68.0	71.0	3.0	0.00	68.1	4.9	374.9	0.8	9.4	0.4
8/17	1200	71.0	68.0	3.0	0.00	78.2	6.4	381.8	1.2	12.3	0.8
8/18	1200	71.0	72.0	2.0	0.00	81.4	7.7	388.7	1.6	14.7	1.6
8/19	1200	69.0	76.0	1.0	0.00	82.1	8.8	395.4	1.6	16.6	1.8
8/20	1200	68.0	64.0	2.0	0.00	83.9	10.4	402.0	2.1	19.5	3.3
8/21	1200	71.0	54.0	3.0	0.00	86.1	12.6	408.9	3.1	23.3	5.6
8/22	1200	73.0	56.0	4.0	0.00	86.6	14.8	416.0	3.6	27.1	7.1
8/23	1200	66.0	71.0	2.0	0.00	85.6	16.0	422.4	2.7	29.2	5.6
8/24	1200	54.0	100.0	3.0	0.19	31.8	9.9	412.4	0.0	18.7	0.0
8/25	1200	59.0	90.0	1.0	0.01	39.9	10.2	418.1	0.0	19.3	0.0
8/26	1200	61.0	78.0	0.0	0.00	49.8	11.0	424.0	0.2	20.6	0.1
8/27	1200	58.0	86.0	0.0	0.16	29.2	7.3	417.8	0.0	14.0	0.0
8/28	1200	65.0	61.0	1.0	0.00	54.6	8.9	424.1	0.3	16.8	0.2
8/29	1200	64.0	59.0	0.0	0.00	67.7	10.5	430.3	0.6	19.8	0.5

8/30	1200	66.0	62.0	0.0	0.00	75.5	12.1	436.7	0.8	22.6	0.8
8/31	1200	65.0	59.0	0.0	0.00	80.3	13.7	443.0	1.2	25.5	1.8
Date	**Time**	**Temp (^oF)**	**RH**	**WSPD (mph)**	**ppt (in)**	**FFMC**	**DMC**	**DC**	**ISI**	**BUI**	**FWI**
9/1	1200	53.0	100.0	0.0	0.03	73.5	13.7	448.1	0.7	25.5	0.8
9/2	1200	66.0	70.0	0.0	0.02	76.3	14.8	453.2	0.8	27.3	0.9
9/3	1200	48.0	100.0	3.0	0.20	27.7	8.9	438.9	0.0	17.0	0.0
9/4	1200	54.0	95.0	3.0	0.14	19.4	5.7	433.0	0.0	11.1	0.0
9/5	1200	61.0	74.0	0.0	0.00	33.8	6.5	437.6	0.0	12.5	0.0
9/6	1200	62.0	72.0	0.0	0.00	47.5	7.4	442.3	0.1	14.2	0.1
9/7	1200	63.0	64.0	0.0	0.00	61.2	8.6	447.1	0.4	16.4	0.4
9/8	1200	68.0	46.0	5.0	0.00	80.5	10.6	452.4	1.8	20.1	2.7
9/9	1200	66.0	42.0	5.0	0.00	86.5	12.7	457.5	3.9	23.7	7.0
9/10	1200	66.0	51.0	0.0	0.00	86.8	14.4	462.6	2.7	26.8	5.3
9/11	1200	70.0	49.0	0.0	0.00	87.4	16.4	468.1	2.9	30.2	6.2
9/12	1200	70.0	43.0	1.0	0.00	88.4	18.7	473.6	3.7	34.0	8.2
9/13	1200	51.0	100.0	1.0	0.10	50.5	15.0	477.2	0.2	27.8	0.2
9/14	1200	65.0	68.0	1.0	0.14	47.9	11.4	471.4	0.1	21.5	0.1
9/15	1200	57.0	75.0	0.0	0.00	56.7	12.1	475.6	0.3	22.7	0.3
9/16	1200	62.0	62.0	2.0	0.00	71.7	13.3	480.3	0.8	24.9	0.8
9/17	1200	60.0	62.0	5.0	0.00	79.7	14.4	484.8	1.6	26.9	3.1
9/18	1200	71.0	39.0	4.0	0.00	87.4	16.9	490.4	4.0	31.1	8.5
9/19	1200	64.0	46.0	0.0	0.00	87.6	18.7	495.3	3.0	34.2	6.9
9/20	1200	66.0	44.0	4.0	0.00	88.1	20.7	500.4	4.5	37.5	10.3
9/21	1200	51.0	64.0	1.0	0.00	86.5	21.4	504.0	2.8	38.8	7.0
9/22	1200	42.0	100.0	6.0	0.14	39.8	15.3	495.2	0.1	28.4	0.1
9/23	1200	43.0	100.0	0.0	0.13	20.2	10.9	488.1	0.0	20.6	0.0
9/24	1200	39.0	100.0	3.0	0.08	14.2	9.1	490.5	0.0	17.4	0.0

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Date	Time	Temp (°F)	RH	WSPD (mph)	ppt (in)	FFMC	DMC	DC	ISI	BUI	FWI
5/14	1200					85.0	6	15			
5/15	1200	58	18	9	0.00	91.2	9.4	20	10.5	9.3	10.2
5/16	1200	64	19	3	0.00	92.8	13.4	25.6	8.1	13.3	9.7
5/17	1200	63	21	2	0.00	92.8	17.2	31.1	7.5	17	10.3
5/18	1200	61	28	4	0.00	92.6	20.5	36.4	8.5	20.3	12.5
5/19	1200	65	27	2	0.00	92.6	24.2	42.1	7.3	24	12
5/20	1200	43	100	4	0.41	20.4	11.7	29.8	0	11.8	0
5/21	1200	55	43	2	0.23	40.3	8.6	27	0	9.6	0
5/22	1200	50	68	2	0.07	48.1	8.4	31.2	0.2	10	0.1
5/23	1200	59	34	3	0.00	73.7	11.2	36.3	0.9	12.6	0.6
5/24	1200	40	99	3	0.37	18.3	5.4	25.7	0	7.1	0
5/25	1200	54	28	4	0.21	47.4	5.1	23.7	0.2	6.7	0.1
5/26	1200	53	27	4	0.00	73.3	7.6	28.2	1	9.1	0.6
5/27	1200	54	35	4	0.00	83.3	9.9	32.8	2.3	11.3	2.4
5/28	1200	60	30	6	0.00	88.6	12.9	38	5.7	14	7.3
5/29	1200	63	26	3	0.09	79.4	14	43.5	1.4	15.5	1.3
5/30	1200	66	23	3	0.00	89.2	18	49.3	4.9	18.9	7.5
5/31	1200	56	78	6	0.10	64.7	15.3	54.1	0.8	17.9	0.7
6/1	1200	69	31	4	0.01	84.5	19.2	61.2	2.7	21.5	4.6
6/2	1200	59	50	3	0.05	79.3	21.3	67.3	1.4	23.8	2.1
6/3	1200	69	31	1	0.00	87.6	25.3	74.4	3.3	27.3	6.5
6/4	1200	71	26	4	0.00	91.4	29.7	81.7	7.2	31.1	13.6
6/5	1200	74	20	4	0.00	93.5	34.8	89.4	9.7	35.3	18.3
6/6	1200	84	15	4	0.00	95.7	41.5	98	13.3	41.5	24.7
6/7	1200	74	28	3	0.00	94.4	46.2	105.6	10.1	46.1	21.5
6/8	1200	73	27	3	0.00	93.9	50.8	113.1	9.5	50.7	21.7
6/9	1200	73	41	4	0.00	91.8	54.5	120.6	7.6	54.4	19.1
6/10	1200	80	25	2	0.00	93.1	60	128.8	7.8	59.8	20.4
6/11	1200	76	25	3	0.00	93.1	65	136.6	8.5	64.9	22.7

6/12	1200	84	17	1	0.00	95.2	71.6	145.2	9.6	71.4	25.9
6/13	1200	78	26	4	0.00	94.6	76.7	153.2	11.4	76.6	30.1
6/14	1200	66	45	4	0.04	86.2	79.6	160	3.4	79.4	12.9
6/15	1200	61	53	4	0.34	55.5	45.6	149.3	0.4	51.7	0.7
6/16	1200	66	39	2	0.00	77.5	48.8	156.1	1.1	54.8	3.3
6/17	1200	73	32	3	0.00	88.2	53.1	163.6	4.2	58.6	12.7
6/18	1200	65	53	6	0.00	88.2	55.5	170.3	5.4	61.2	15.7
6/19	1200	69	35	2	0.00	89.7	59.2	177.5	4.8	64.6	14.9
6/20	1200	68	28	4	0.00	91.2	63.2	184.5	7	68.1	20.2
6/21	1200	73	30	1	0.00	91.5	67.6	192	5.8	71.9	18.1
6/22	1200	78	34	2	0.10	81.6	60.5	200	1.6	68.9	6.1
6/23	1200	82	23	1	0.02	91.6	66.3	208.4	5.9	73.9	18.6
6/24	1200	85	18	1	0.00	94.8	72.9	217.1	9.2	79.3	26.5
6/25	1200	83	23	4	0.00	94.9	78.9	225.6	11.8	84.2	32.3

Date	Time	Temp (°F)	RH	WSPD (mph)	ppt (in)	FFMC	DMC	DC	ISI	BUI	FWI
6/26	1200	77	33	4	0.00	93.4	83.5	233.5	9.6	88.2	28.9
6/27	1200	73	32	2	0.00	93.0	87.8	241	7.7	91.9	25.2
6/28	1200	72	40	3	0.00	91.7	91.5	248.4	6.9	95.2	23.9
6/29	1200	61	75	2	0.29	45.8	52.9	237.3	0.1	67.9	0.2
6/30	1200	73	30	2	0.00	78.5	57.3	244.8	1.2	72.3	4.5
7/1	1200	71	39	4	0.00	87.1	60.5	252.4	3.9	75.7	13.8
7/2	1200	70	52	2	0.00	87.2	63	259.9	3.4	78.5	12.6
7/3	1200	59	86	1	0.16	46.5	44.8	258.5	0.1	62.6	0.2
7/4	1200	78	37	3	0.04	78.1	48.8	266.8	1.2	67	4.5
7/5	1200	61	80	3	0.00	79.5	49.6	273.4	1.4	68.2	5.2
7/6	1200	73	33	3	0.00	88.5	53.4	281.2	4.4	72.4	14.8
7/7	1200	78	36	2	0.00	90.4	57.4	289.5	5.3	76.7	17.7
7/8	1200	83	37	3	0.00	91.0	61.7	298.3	6.3	81.4	20.7
7/9	1200	67	82	2	0.07	70.7	58.2	305.5	0.8	78.9	3
7/10	1200	66	77	1	0.45	35.3	29.7	279.3	0	46.9	0
7/11	1200	69	71	3	0.02	59.8	31.2	286.7	0.5	49	0.9
7/12	1200	64	52	4	0.17	59.7	23.3	284.4	0.6	38.6	0.8
7/13	1200	61	43	4	0.00	78.2	25.6	291	1.3	41.9	3.4
7/14	1200	63	70	4	0.01	81.3	26.8	297.8	1.8	43.8	5

7/15	1200	77	40	6	0.00	88.6	30.5	306	5.7	48.9	14.4
7/16	1200	78	37	1	0.00	90.2	34.5	314.3	4.8	54.1	13.4
7/17	1200	66	59	1	0.10	69.5	30.5	321.4	0.7	49.4	1.5
7/18	1200	63	49	2	0.00	80.5	32.7	328.2	1.4	52.4	4.4
7/19	1200	74	34	1	0.00	88.2	36.5	336.1	3.6	57.4	11
7/20	1200	77	29	2	0.00	91.4	40.9	344.4	6.2	63	17.7
7/21	1200	73	43	1	0.00	90.9	44.1	352.2	5.3	67.1	16.3
7/22	1200	74	42	1	0.00	90.9	47.4	360.1	5.3	71.3	16.9
7/23	1200	64	72	4	0.01	86.2	48.6	367	3.4	73.1	12.3
7/24	1200	66	58	5	0.01	86.2	50.6	374.1	3.8	75.6	13.4
7/25	1200	57	57	2	0.01	86.3	52.1	380.3	3	77.6	11.3
7/26	1200	60	41	3	0.01	87.6	54.4	386.8	3.9	80.5	14.3
7/27	1200	52	90	1	0.05	71.7	54.7	392.5	0.7	81.2	2.9
7/28	1200	64	45	2	0.01	82.2	57.2	399.4	1.7	84.2	7.5
7/29	1200	73	36	2	0.00	88.4	60.8	407.2	4	88.5	15.5
7/30	1200	76	35	1	0.00	90.3	64.7	415.3	4.9	93.1	18.3
7/31	1200	78	32	2	0.00	91.4	68.9	423.6	6.2	98	22.4
8/1	1200	74	34	2	0.00	91.5	72.2	430.8	6.2	101.8	22.9
8/2	1200	76	37	3	0.00	91.5	75.6	438.2	6.8	105.6	24.8
8/3	1200	81	33	2	0.00	91.7	79.5	446.1	6.4	110	24.4
8/4	1200	57	97	2	0.05	73.4	79.6	451.6	0.8	110.5	4.4
8/5	1200	57	69	5	0.10	62.7	65.8	457.1	0.7	96.8	3.4
8/6	1200	64	44	4	0.01	79.9	68	463.3	1.6	99.5	7.6
8/7	1200	65	45	1	0.04	80.8	70.2	469.6	1.4	102.2	6.8
8/8	1200	63	49	5	0.00	85.3	72.1	475.7	3.3	104.6	14.5
8/9	1200	56	66	1	0.01	85.2	73.2	481.1	2.3	106	11.2
Date	**Time**	**Temp (^oF)**	**RH**	**WSPD (mph)**	**ppt (in)**	**FFMC**	**DMC**	**DC**	**ISI**	**BUI**	**FWI**
8/10	1200	52	93	4	0.08	59.5	64.9	486.1	0.5	97.3	2.4
8/11	1200	52	96	3	0.09	41.2	55.7	491.1	0.1	86.8	0.1
8/12	1200	60	100	4	0.39	8.5	28.7	452.8	0	49.6	0
8/13	1200	57	100	5	0.52	0.7	12.6	403.1	0	23.4	0
8/14	1200	49	71	4	0.18	23.3	8.3	394.4	0	15.9	0
8/15	1200	61	35	7	0.00	65.2	10.7	400.3	0.9	20	0.8
8/16	1200	65	29	1	0.00	82.2	13.5	406.6	1.6	24.9	2.8

8/17	1200	54	64	2	0.00	83.0	14.5	411.8	1.9	26.6	3.7
8/18	1200	52	96	5	0.49	21.9	6.8	369.8	0	13	0
8/19	1200	53	62	1	0.03	42.4	7.8	374.9	0.1	14.8	0
8/20	1200	58	45	0	0.01	61.3	9.6	380.5	0.4	18	0.4
8/21	1200	59	57	3	0.00	75.0	11	386.2	1	20.5	0.9
8/22	1200	49	80	5	0.01	77.2	11.4	390.9	1.3	21.3	1.8
8/23	1200	51	68	1	0.27	41.0	6.8	373.3	0	13	0
8/24	1200	56	59	3	0.00	62.6	8	378.7	0.6	15.2	0.5
8/25	1200	46	97	4	0.33	19.2	3.8	355.2	0	7.5	0
8/26	1200	51	53	2	0.15	36.9	3	351.2	0	5.8	0
8/27	1200	66	31	3	0.00	72.3	5.8	357.6	0.9	11.1	0.6
8/28	1200	69	35	2	0.00	85.1	8.7	364.3	2.5	16.4	3.6
8/29	1200	62	43	2	0.00	87.1	10.8	370.3	3.3	20.1	5.4
8/30	1200	53	85	4	0.65	30.5	5.1	318	0	9.7	0
8/31	1200	64	50	6	0.00	65.7	7	324.2	0.9	13.3	0.6
9/1	1200	56	63	1	0.00	74.2	8	328.3	0.8	15	0.6
9/2	1200	61	52	3	0.49	49.5	4.9	294.3	0.2	9.5	0.1
9/3	1200	60	48	2	0.00	70.6	6.5	298.8	0.8	12.3	0.5
9/4	1200	58	59	2	0.00	78.5	7.6	303.1	1.2	14.3	0.9
9/5	1200	50	68	1	0.00	80.3	8.2	306.6	1.3	15.5	1
9/6	1200	51	76	3	0.00	80.7	8.7	310.2	1.6	16.3	1.8

Appendix D

5/9/00	Wet Wt (g)	Dry Wt. (g)	Sam. Vol. (cm^3)	Vol MC	BD	Fuel Type	Probe Depth	Volts (Wet)	Volts (Dry)
sam 1	146.6	28.4	1032	0.115	0.028	upper duff	15 cm	0.186	0.002
sam 2	192.9	31.6	516	0.313	0.061	upper duff	22 cm	0.573	0.007
sam 3	149.8	26.1	1032	0.120	0.025	upper duff	15 cm	0.181	0.002

FDR Probe Calibration Data

Mean wet voltage at 15 cm = 0.184

Mean wet voltage at 22 cm = 0.573

Mean dry voltage at 15 cm = 0.002

Mean dry voltage at 22 cm = 0.007

Step 1. Find the dielectric constant ($\sqrt{\varepsilon}$) for the mean wet voltage (0.184 and 0.573) with the following equation:

$$\sqrt{\varepsilon_w} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3$$

where:

$\sqrt{\varepsilon_w} = 2.060$ at 15 cm

$\sqrt{\varepsilon_w} = 3.520$ at 22 cm

Step 2. Repeat step 1 with the mean dry voltage (0.002 and 0.007). The resulting dielectric constant will be the a_0 parameter in the volumetric moisture content equation.

where:

$\sqrt{\varepsilon_d} = a_0 = 1.083$ at 15 cm

$\sqrt{\varepsilon_d} = a_0 = 1.115$ at 22 cm

Mean $a_0 = 1.13$

Step 3. The a_1 parameter in the volumetric moisture content equation is derived from the wet and dry dielectric constants and the true volumetric moisture content of the sample:

$$a_1 = \frac{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_d}}{\theta}$$

where:

a_1 = 8.35 at 15 cm

a_1 = 7.71 at 22 cm

Mean a_1 = 8.03

Step 4. Using the mean a_0 and a_1 found is steps 2 and 3, find the volumetric moisture content (θ) from the following equation:

$$\theta = \frac{[1.07 + 6.4V - 6.4V^2 + 4.7V^3] - a_0}{a_1}$$

θ = 12% at 15 cm, true volumetric moisture content was 11.75% (see table at top of page).

θ = 30% at 22 cm, true volumetric moisture content was 31% (see table at top of page).

Appendix E

Delta-T Organic Soil Moisture Calibration Compared to the Custom Boreal Forest Calibration and Destructively Sampled Volumetric Moisture Contents. Volumetric moisture contents (%) computed from voltage readings using the Delta-T preprogrammed organic soil moisture (OSM) parameters and the custom parameters derived in this study from data collected at Ft. Wainwright, AK 2000. Table denotes means ± 1SD.

Date	0 – 5 cm			5 – 10 cm			10 – 15 cm			15 – 20 cm			20+cm		
	Actual	Custom	OSM	Actual	Custom	OSM	Actual	Custom	OSM	Actual	Custom	OSM	Actual	Custom	OSM
5/19/00	2.17 ± 1.30	4.20 ± 2.10	1.80 ± 0.40	6.54 ± 2.82	NA	NA	7.78 ±3.52	6.37 ± 2.80	4.00 ± 0.30	10.16 ± 5.07	NA	NA	NA	37.93 ± 11.60	36.9 ± 9.50
5/30/00	3.36 ± 1.95	3.17 ± 1.20	0.70 ± 1.40	6.32 ± 1.55	6.13 ± 1.90	3.80 ± 0.60	9.85 ± 4.31	7.11 ± 3.00	4.80 ± 0.50	15.25 ± 8.27	13.38 ± 5.10	11.30 ± 2.80	34.28 ± 15.10	30.55 ± 11.60	29.3 ± 9.40
6/16/00	4.87 ± 0.77	3.96 ± 1.20	1.50 ± 1.30	5.04 ± 1.25	4.35 ± 1.50	1.90 ± 0.01	7.34 ± 2.62	6.86 ± 3.10	4.50 ± .060	12.61 ± 4.86	12.60 ± 8.40	10.50 ± 6.20	14.27 ± 2.11	52.07 ± 6.50	51.70 ± 4.20
6/21/00	0.81 ± 0.37	1.47 ± 0.90	-1.10 ± 1.70	2.53 ± 0.63	2.60 ± 0.80	0.10 ± 1.80	3.33 ± 1.12	4.17 ± 1.90	1.70 ± 0.60	9.99 ± 7.01	11.28 ± 7.70	9.10 ± 5.40	23.12 ± 10.99	22.46 ± 13.40	20.80 ±11.30

6/26/00	0.52 ± 0.08	0.34 ± 0.00	2.30 ± 2.60	1.98 ±0.86	1.88 ± 0.10	-0.60 ± 2.60	5.39 ± 3.08	2.77 ± 1.40	0.30 ± 1.10	10.99 ± 4.38	7.56 ± 3.60	5.30 ± 1 10	23.65 ± 13.55	17.39 ± 8.90	15.50 ± 6.70
7/12/00	6.64 ± 2.47	5.60 ± 1.57	3.20 ± 1.00	6.62 ± 3.01	5.90 ± 3.86	3.50 ± 1.40	9.25 ± 7.45	9.60 ± 8.71	7.40 ± 6.50	12.53 ± 5.54	17.30 ± 13.56	15.50 ±11.50	NA	25.00 ± 18.31	23.40 ±16.50