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UNIVERSITY OF ALBERTA

GROUND FUEL HYDRATION IN ASPEN STANDS OF CENTRAL ALBERTA

BY

© SUPPARAT SAMRAN

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

DEPARTMENT OF FOREST SCIENCE

EDMONTON, ALBERTA

FALL, 1991

ISBN 0-315-70151-X

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: SUPPARAT SAMRAN

TITLE OF THESIS: GROUND FUEL HYDRATION IN ASPEN STANDS OF CENTRAL ALBERTA

DEGREE: MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED: FALL, 1991

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ABSTRACT

A determination of ground fuel hydration in aspen forest was carried out in Elk Island National Park, Edmonton, Alberta during May 24, 1990 to August 27, 1990. The objectives of the study were: 1) to determine the relative contribution of precipitation and soil water to the upper and lower ground fuel layers, 2) to determine if the upper and lower ground fuel moisture contents were affected by relative slope positions or distance to a water body, and 3) to determine the drying rates for upper and lower ground fuel layers in aspen stands of central Alberta.

Three locations, similar in habitat, were selected for this study. Sampling plots were located at top, middle and bottom slope positions at each location. Ground fuel moisture contents were periodically sampled under three treatments, which were full hydration by precipitation and soil water, hydration only by soil water, and no hydration by either precipitation or soil water.

Sampling showed moisture contents were significantly different among three treatments which indicated ground fuels were affected not only by precipitation but also by other sources of water. Differences in moisture content among sample treatments, higher moisture contents in underlying soil than in fuel layer, and higher water potential in underlying soil than in fuel layer indicated precipitation and soil water were respectively the primary and secondary sources of water affecting ground fuels. Precipitation was more important for the upper fuel layer while soil water was more important for the lower one. Precipitation

and soil water contributed about 64% and 36% of water to fuel moisture contents to the upper layer and 41% and 59% to the lower layer, respectively. Moisture contents were significantly different among slope positions at 90% confidence level. According to multiple comparisons, only moisture content at the bottom position was significantly different from other positions. Higher moisture content at the bottom position was possibly influenced by wet soil condition because of proximity to open water bodies and shallow water tables. In the absence of any hydration ground fuels dried to ignition and reached the equilibrium moisture contents of 15% and 21.7% for the upper and lower layers, respectively. The upper layer reached an equilibrium moisture content before the lower layer because of its initial lower moisture content and direct exposure to radiation and air movement. Only the drying rate of the lower layer was best described by an exponential drying curve.

ACKNOWLEDGMENTS

A number of individuals and organizations have contributed to the completion of my study. I wish to express my sincere thanks and deepest gratitude to all of them.

I wish to thank Canadian International Development Agency (CIDA) for the financial support of my study under the ASEAN Institute of Forest Management (AIFM) and also the Royal Forest Department (RFD), Thailand, for granting me the opportunity to study abroad.

I am sincerely grateful to my co-supervisor, Dr. Richard L. Rothwell and Dr. Paul M. Woodard for their advice, support, and insistence on a high quality thesis. They have been very patient about my progress and have also cared about my living in Canada. Without their encouragement, the study would not have been finished. I also thank my graduate committee members: Dr. Arthur W. Bailey and Dr. Janusz J. Zwiazek for their critical reading of the manuscript and helpful comments. Thanks also goes to Dr. Robert T. Hardin and Dr. Stephen J. Titus for their statistical advice. I also would like to give a special thanks to Mr. Apiwat Sretarugsa for helping and encouraging me to study in Canada.

I would like to thank Parks Canada, Western Region for allowing me to take samples out of Elk Island National Park. I would like to thank Mr. Neil R. Miller, Alberta Spruce Industries Ltd., for providing me lumber to make frames in my research. A special thanks also goes to Mr. Uldis Silin for patiently helping me set up and calibrate weather instruments. Also, I would like to thank Mr. Surat

Kanjanakunchorn and Mrs. Babara Koch for their tedious work with me in the field.

In addition, I would like to thank the Department of Forest Science and staff, also fellow graduate students, and Thai students of University of Alberta for their company, cheerfulness, and warmth during my stay in Canada.

Specially, I would like to express my gratitude to my parents and all family members for their prayers and support and for their patience in looking forward to my success.

But most of all, I would like to devote my success to my wife, Suthera, for her patience, loneliness, and misery during my stay thousands of miles away from her. I also would like to dedicate my success to my first baby, Supissara, who was just born on June 6, 1991 without the presence of her father on her birthday.

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1. INTRODUCTION

1.1 General

The Canadian Forest Fire Weather Index (CFFWI) system (Van Wagner 1987) is used throughout Canada to predict downed and dead fuel availability in forest stands. Available fuel is defined as the amount of fuel in a particular fuel type that would be consumed under specific burning conditions (Merrill and Alexander 1987). The biomass that remains after burning is termed residual fuel (Brown and Davis 1973).

The amount of fuel consumed by a fire is highly influenced by the moisture in the fuel particles (Chandler et al. 1983, Pyne 1984). The CFFWI uses noon (1200 h) readings of temperature, relative humidity, wind speed and the total amount of rain over the last 24 hours (noon to noon) to estimate fuel availability in the upper (<18 cm deep) organic layers of the soil profile. Similar approaches are used in the United States to estimate fuel availability and the behavior of a fire if ignition occurs (Burgan 1988). In general, precipitation is normally assumed to be the prime source of fuel hydration in medium and larger diameter roundwood fuels (>0.7 cm), as well as organic material below the soil-surface interface (Van Wagner 1987). Hence, precipitation and those factors such as relative humidity, wind and temperature, which are responsible for the rate of drying are frequently used to estimate fuel availability.

Ground water, which is not considered in most fuel availability models, may also affect the moisture status of downed and dead woody fuels. Ground water could be an important source of fuel hydration in Aspen Parklands of central Alberta, where high water tables are common, soils are shallow and fine textured, and the physiography is undulating. In Aspen Parklands, as a part of the Boreal Forest Region, soil water is plentiful (Rowe 1972). Work by Johnston and Woodard (1985) suggested precipitation may not be the only factor affecting fuel availability and fire behavior in the aspen parklands of Alberta. They mentioned that the duff was still moist enough to fully protect burning, although, the weather conditions in the area were extreme for burning.

1.2 Objectives and Hypotheses

The objectives of this study were:

1. To determine the relative contribution of precipitation and soil water to the upper and lower ground fuel layers.
2. To determine if the upper and lower ground fuel moisture contents were affected by relative slope positions or distance to a water body.
3. To determine the drying rate for upper and lower ground fuel layers in aspen stands of central Alberta.

The hypotheses proposed for testing were:

1. **That precipitation was not the only water source affecting the moisture content of ground fuels in aspen stands in the Boreal Forests of Alberta.** The

plentiful soil water, which is a characteristic of the Boreal Forest Region, could affect ground fuel moisture content by capillary movement. The effect of soil water could be as important as the effect of precipitation and keep ground fuels always wetter than their ignition point.

2. **That moisture content of ground fuels in aspen stands varied along the slope positions.** Ground fuel moisture contents could decrease from the bottom to top slope positions because of the accumulation of rainfall as soil water at the lower slope positions. Slope gradient would affect lateral flow of precipitation. High elevation would also limit upward soil water movement if there was an effect of soil water on ground fuel moisture contents.

3. **That drying rates for the upper and lower fuel layers were similar.** The drying rates of both layers could be described by an exponential drying curve which is a typical trend of drying fuel. The equilibrium moisture contents of both layers should be suitable for ignition.

2. STUDY AREA

2.1 Study area

The study was conducted at Elk Island National Park, which is approximately 37 km east of Edmonton, Alberta (Figure 1). The park, which comprises an area of 19,690 ha, is situated in a region of morainal deposits known as the Cooking Lake Moraine, and is elevated some 30-60 meters above the surrounding lacustrine plain (Crown 1977). The site was selected because it is covered with a mosaic of aspen poplar and mixedwood boreal vegetation (Parks Canada 1986). Soils in the area are the Brunisolic, Gleysolic, Luvisolic, Solonetzic, and Organic Orders, which have generally developed under forest vegetation (Crown 1977). Thus, subsurface soil profiles are generally similar throughout the Park. Surface profiles are variable especially in terms of colour, thickness and organic matter content (Crown 1977) due to animal use patterns, disturbance by prescribed fires, and other natural factors.

Local topography is characterized by hummocks and hollows with slopes that range from 5 to 15%. The highest elevation in the park is 760 metres while the lowest point is 704 metres a.s.l. Most of the park lies between 710 and 740 metres a.s.l. (Crown 1977). Soils in the park are moderately well to well drained. However, low lying areas are frequently flooded due to beaver (Castor canadensis) activity and in some cases the absence of slope is sufficient to slow water run-off.

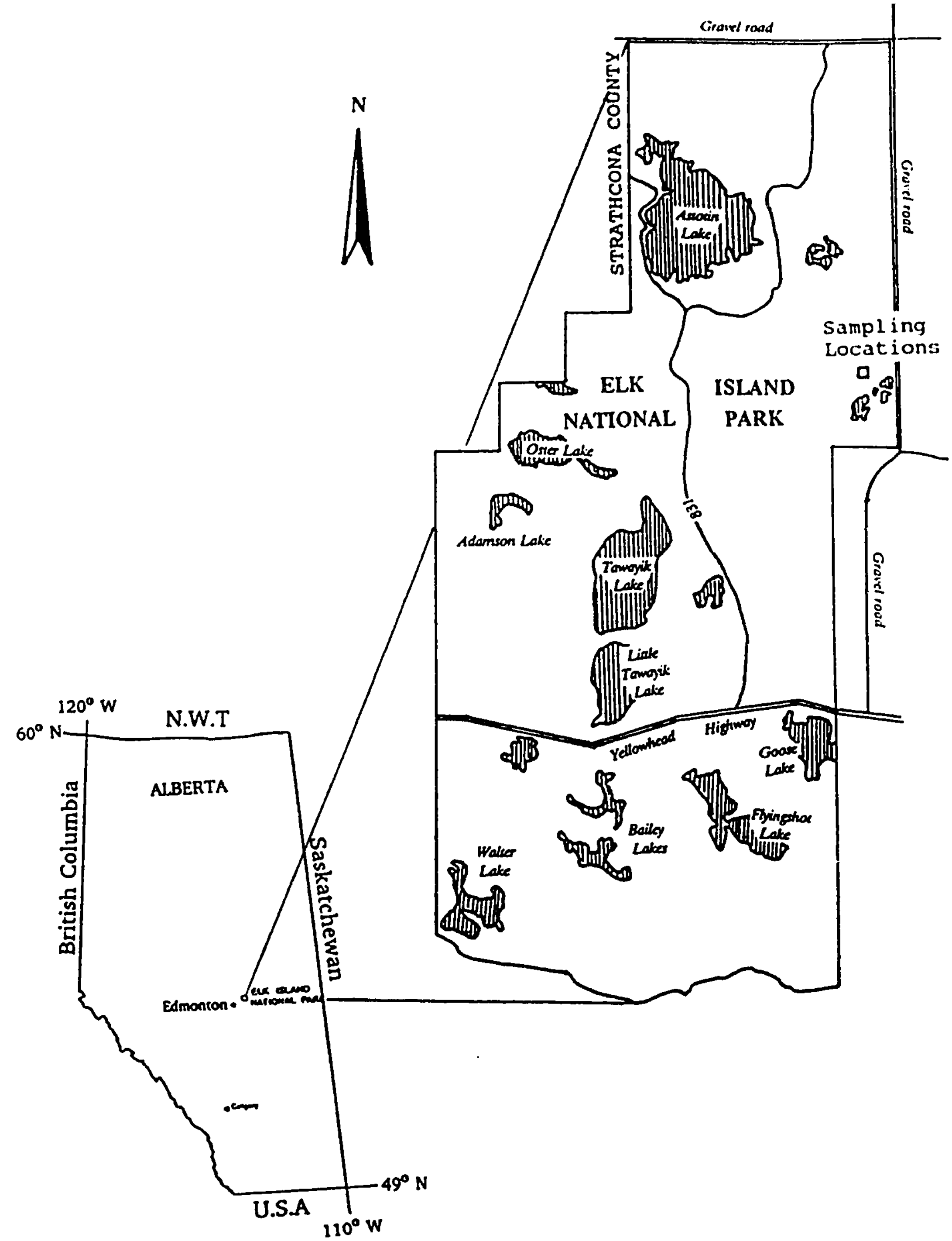


FIGURE 1. Location of study area at Elk Island National Park, Alberta, Canada. The park is located 37 km east of Edmonton around T53 R20 W4M.

The climate of the area is classed as continental (Crown, 1977). Mean maximum daily summer temperatures are 23.4 °C in June, and mean minimum winter temperatures are -22.2 °C in January (Parks Canada 1986). The climate is relatively uniform, being controlled by large Maritime and polar air masses. Mean annual precipitation is between 400 mm to 500 mm with the greatest proportion of precipitation occurring as rain from May to September (Parks Canada 1986). Snow fall accounts for 30 percent of annual precipitation.

2.2 Sampling locations

Three sampling locations were located in the east-central part of Elk Island National Park, between Latitude 53° 38' N and Longitude 112° 47' W (Figure 2). All selected sampling locations had the following site characteristics: 1) slope, 2) a water body at the foot of the slope, 3) similar habitat as determined from visual characteristics of the plant community, 4) same slope aspect, and 5) close proximity to each other. Some physical characteristics of the sampling locations are summarized in Table 1.

The vegetation on the sampling locations fell into the Taraxacum Sub-type of the Corylus-Rosa Upland Group (Polster and Watson 1979). The area is dominated by an overstory of trembling aspen. Tree crown cover of the site ranged between 40% and 75%. The shrub stratum was 100 cm tall, and consisted mostly of beaked hazelnut (Corylus spp.) and prickly rose (Rosa spp.). The forest floor was composed mostly of aspen leaf litter under trees and grass in

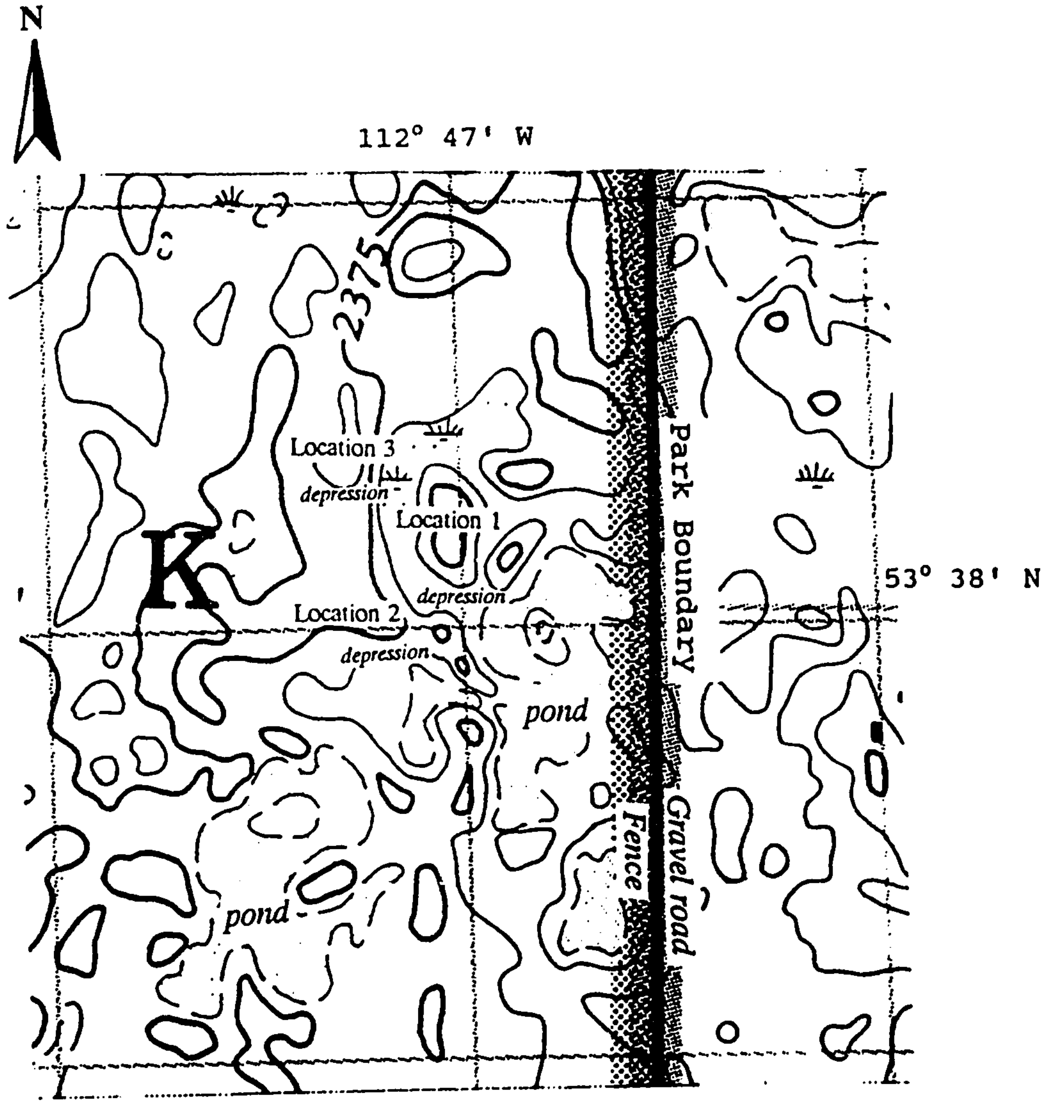


FIGURE 2. Topographic map of the approximate sampling locations in Elk Island National Park, Alberta (map sheet NTS 83H/10, 1987).

TABLE 1. The physical characteristics of the three sampling locations at Elk Island National Park

Description	n	Range	Average
Slope gradient (%)	3	14.0-25.0	20.3(±2.7)
Slope length (m)	3	27.50-42.00	34.67(±3.42)
Slope height (m)	3	3.81-10.19	7.14(±1.51)
Aspect	3	SE-SE	SE
Fuel depth (cm)	510	2.5-12.2	6.5(±0.07)
Fuel bulk density ($g\ cm^{-3}$)	510	0.03-0.45	0.14(±0.002)
Soil bulk density ($g\ cm^{-3}$)	171	0.09-2.26	1.24(±0.03)

open spots. The shrub stratum also contributed to the litter complex. Dead and down woody fuel contributed very little to the total litter complex, although there were some downed aspen stems scattered throughout the study site.

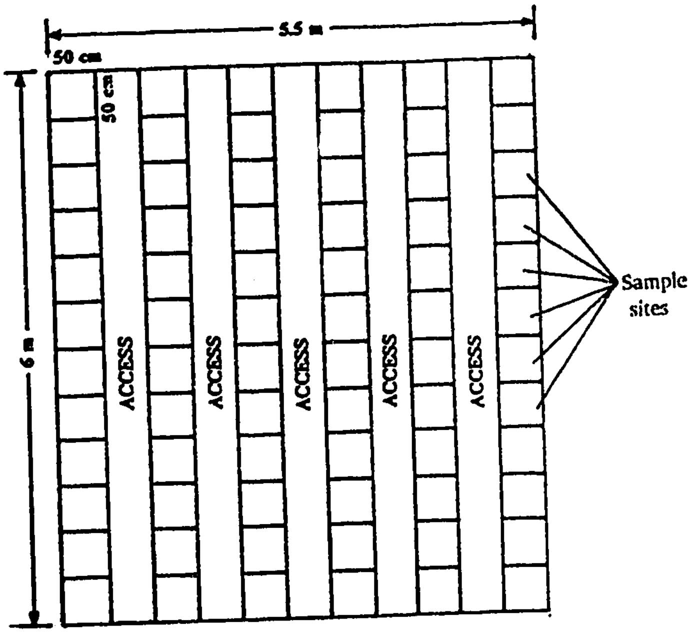
3. STUDY DESIGN AND METHODS

3.1 Sampling plot establishment

Three 5.5 m x 6.0 m sampling plots were established at the top, middle, and bottom slope positions at each sampling location. The total number of plots were 9 (i.e. 3 locations x 3 positions = 9). Ground vegetation such as shrubs, small trees and tall grass in every plot was cleared for access prior to installing sample treatments. The overstory canopy of mature trees and the ground fuels (ie. litter layer) were left intact. Each plot was divided into a 50 x 50 cm grid that was used to locate specific sample sites and access lanes. The access lanes were marked to avoid disturbing sample sites. There was a total of 12 sample sites within each of 6 columns on each plot (Figure 3a). All sampling plots were roped off using 1-cm diameter nylon rope to reduce damage due to animal traffic. Three strands of rope at various heights above ground were tied to living tree trunks (Figure 3b).

Sampling times and treatments were randomly determined for specific sample sites. Each row of sample sites in each plot was randomly assigned a sampling time. Treatments were then randomly allocated within each row of sample sites. Therefore at a given time, samples within a plot were taken from the same row of sample sites to avoid the bias of slope. The row of sample sites, however, were usually different between plots because of random selection.

(a)



(b)

FIGURE 3. (a) A diagram of how sample plots were laid out, and
(b) A photograph of a sample plot.

3.2 Treatment allocation

Ground fuels were defined to include all flammable material lying on or immediately above the mineral soil. In the forest fire literature, this zone of fuel is generally referred as the L, F and H layers of the soil profile or the litter and duff layers (Brown 1974). The principle fuels in these layers were aspen leaves and shrubs. Tree roots, grass, fine dead round-wood and animal dung also contributed a small amount of biomass to this fuel loading. Three treatment conditions were applied to ground fuel in each row of sample sites. Each treatment was composed of two replications.

The control treatment consisted of undisturbed ground fuels, completely exposed to hydration by precipitation and soil water flow. This represented how fuels are hydrated under natural conditions (MC_c). Treatment 1 (T_1) was designed to prevent hydration of ground fuels by precipitation (MC_{t1}). This was accomplished by covering the sample sites with a 40x40 cm wooden frame covered with 4 mm clear plastic and chicken wire, which intercepted incoming precipitation. The frames were elevated 7.5-15 cm above the ground to allow air exchange and evaporative fluxes at the ground surface. This prevented a build-up of energy and humidity at the soil/air interface. Also, the 50% (7.5-15 cm) pitch of the frame allowed intercepted water to drain easily from the top of the frame. A total of 216 sample sites were covered as a test of T_1.

It was considered that lateral flow (ie. overland flow) in the fuel layer rarely occurred, but could on occasion affect ground fuel moisture contents for the control and T_1. All rainfall was assumed to infiltrate into the soil (Scace & Associates Ltd. 1976 and Crown 1977), except for that portion held by matric forces in the litter layer. Hence, the lateral flow was assumed zero. Treatment 2 (T_2) was designed to prevent hydration of ground fuels from precipitation and soil water flow (MC_{t2}). The movement of soil water flow was prevented by carefully cutting cylindrical fuel samples from the forest floor, lining the excavated hole with a piece of 4 mm polyethylene plastic sheeting and replacing the fuel sample in the original hole. A 2x7 cm piece of metal flashing was bent into a circle and placed around each sample. This flashing maintained the peripheral integrity of samples, kept plastic liner in place and prevented overland water flow from washing into the sample. Precipitation input was obstructed by covering these sample sites with the same type of frames as those used for T_1. A total of 216 sample sites were also prepared in this way, at the start of the study and sampled through the summer. Diagrams illustrating possible sources of hydration and dehydration for each of treatment are shown in Figure 4.

3.3 Field weather data

A temporary weather station was installed at sampling location 2 (Figure 2). A CR-21 data logger was used to record data of precipitation (Ppt) from a tipping-bucket recording raingauge, fuel temperature (FT) and soil temperature (ST) from thermistors, windspeed (WS) from an anemometer, and relative humidity (RH) and air temperature (AT) from a RH-probe, respectively. A "True

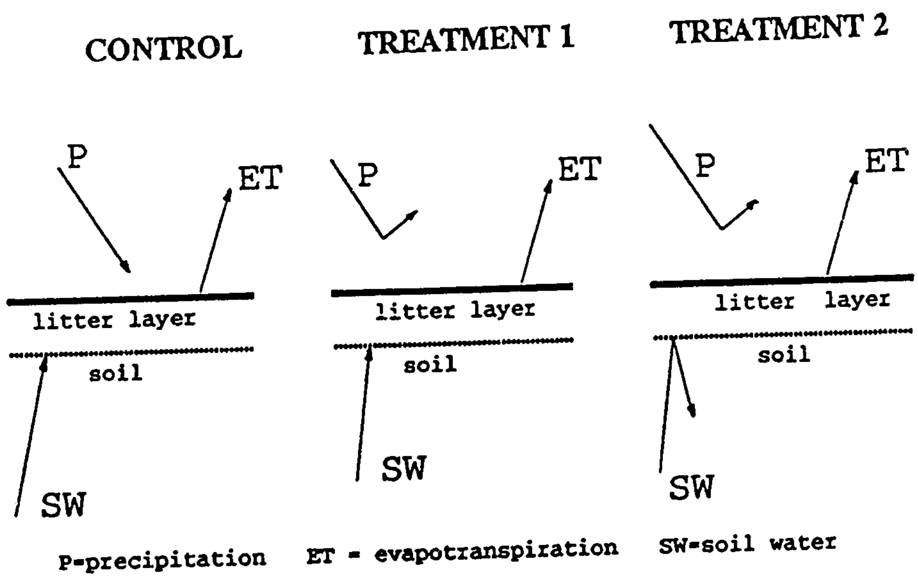


FIGURE 4. Possible sources of ground fuel hydration for condition study.

Check" raingauge was used as a back-up on each experimental plot. The data logger was set up to record daily values of each parameter. The Ppt, FT, ST, WS, RH, and AT were measured at heights of: +70, -2, -10, +90, +30, and +30 cm relative mean ground level, respectively.

3.4 Sampling date

Sampling dates were selected to represent wet and dry fuel conditions. The wet conditions were usually sampled within a day after rainfall. The dry fuel conditions were sampled 7-19 days after rainfall, which was often a day before rainfall. Weather forecasts were used to schedule sampling times. In addition, some ground fuels were sampled 3-4 days after rainfall and provided an intermediate value between wet and dry conditions. Attempts were made to take replicate samples for all times since rainfall events.

3.5 Fuel sample analysis

Sampling for all three conditions was done with a 15-cm diameter cylindrical sampler (Holowaychuk et al. 1965). The extractor was driven into the ground, after the perimeter had been cut with a serrated knife to minimize compression. Samples were taken to the depth of the A-horizon. The samples were extracted from the sampler and the L, F, H, organic layers and other fuels were separated from the mineral soil. Then, each sample was divided into upper and lower layers.

The upper layer, was the material that was recently deposited to the partly decomposed litter. It could still be identified as leaves, grass tillers, and dead wood (ie. L and F horizon). The lower layer was fully decomposed material, that could not be identified to original organic source (ie. H horizon), except for some roots that grew in this layer. The depth of each layer was measured before separation, and then sealed in plastic bags to prevent moisture loss.

All samples were weighed and oven dried immediately after returning from the field. Ovens were set at 70 °C and fuels were dried until a constant weight was obtained. Moisture contents were expressed as percent oven dry weight. Some of the covered samples (5.3% of all treatment samples) were excluded from analysis because their covers had been overturned by small mammals and the sites exposed to precipitation.

Supplemental mineral soil samples were obtained to determine volumetric moisture content and bulk density. After excavating ground fuel samples for the control, mineral soil samples were taken from the A-horizon using a 5 cm inside diameter and 3.5 cm high cylindrical soil core sampler. Eighteen samples were obtained on each sampling date.

3.6 Fuel moisture content recording

Fiberglass soil moisture sensors (Gardner 1965) were installed at sampling location 3 (Figure 2) in mid August. These sensors were used to measure hourly soil moisture and fuel moisture indices. These measurements allowed evaluation of the continuity between ground fuel and soil moisture contents. Data were collected on a CR-10 data logger. The moisture index was obtained by taking the reciprocal of the moisture sensors' voltage where voltage at saturation and air dry water contents were 0.04 mv and 0.99 mv, respectively (ie. saturated conditions 1/.04 = 25, dry conditions 1/.99 = 1.0). A pair of soil moisture sensors were placed at three different locations. One was inside the middle slope plot, the others were inside the bottom slope plot and outside the bottom slope plot, respectively. Each pair were placed with one sensor 2-4 cm above the organic layer-mineral soil interface, and the other 2-4 cm below the same interface (Figure 5).

3.7 Desorption curves of ground fuels and mineral soils

Water retention characteristics were determined for undisturbed ground fuel and mineral soil samples. Ten samples from the humus layer were excavated from each plot at the first location. Paired soil samples were obtained immediately beneath each ground sample. A total of thirty ground fuel samples and forty-five soil samples were excavated using a 5-cm diameter soil core. All samples were transported to the laboratory to determine desorption curves of volumetric water content versus matric potential.

Water retention at matric potentials of 0 to -0.01 MPa of both ground fuel and soil samples were measured on a tension table following procedures described by Topp and Zebchuk (1979). Aluminum oxide, 35 microns in

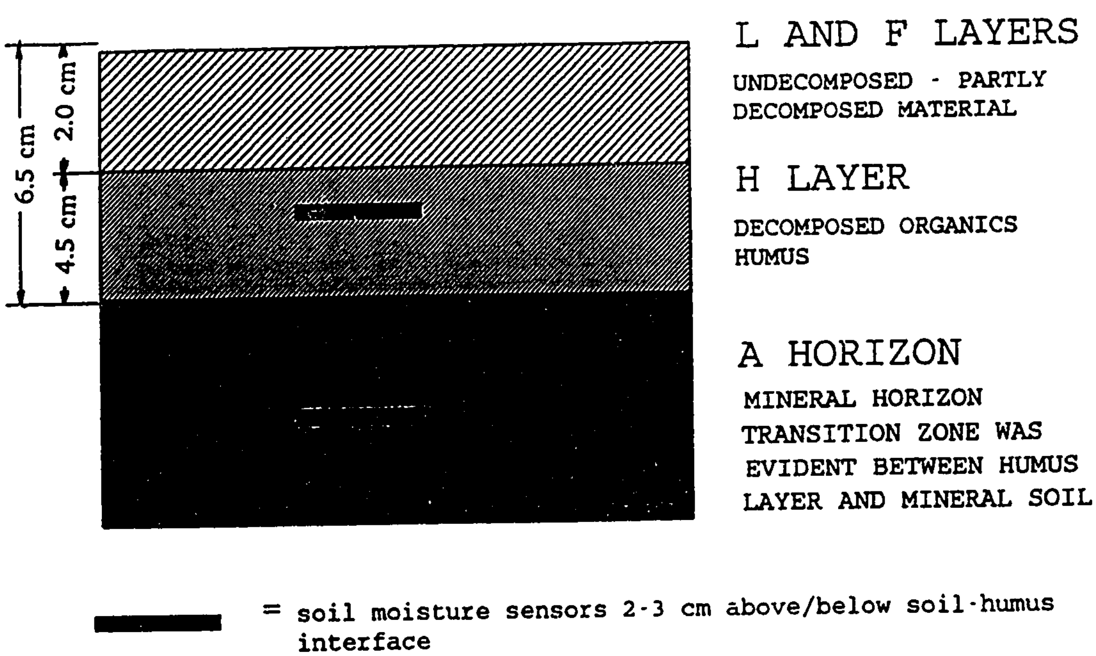


FIGURE 5. The relative placement of the fiberglass moisture sensors in the soil profile.

diameter, was the tension medium used. Water retention at matric potentials of -0.01 MPa to -1.5 MPa were measured on pressure membrane apparatus similar to that described by Richards (1965).

3.8 Data analyses

Analyses of variance (ANOVA) was used to test for differences in moisture content among sources of hydration and among slope positions. Null hypotheses for the differences among sources of hydration and differences among slope positions were:

Ho_1: $MC_c = MC_{t1} = MC_{t2}$, and

Ho_2: $MC_{top} = MC_{mid} = MC_{bot}$

where MC_c, MC_{t1}, and MC_{t2} are ground fuel moisture contents for the control, Treatment 1, and Treatment 2, respectively, and

MC_{top}, MC_{mid}, and MC_{bot} are ground fuel moisture contents for the top, middle, and bottom positions, respectively.

The experimental design using all treatments was a split-split plot replicated three times (Anderson and McLean 1974). The locations (S=3) formed the replications (blocks), the whole plots were positions (P=3). The treatments (H=3) were randomly allocated to two (O=2) of the six split plots within each time, resulting in two observations within each time. The layers (L=2) were the split-split plots. The error terms in both analyses were calculated by pooling all interaction with the locations (ie. replications).

If the ANOVA test showed statistically significant differences among means then a multiple comparison procedure was used to determine which means were significantly different from each other. Differences in treatment means supporting hypothesis No. 1 are outlined in Table 2. Duncan's multiple-range test (Duncan 1955) was used to identify the mean differences for multiple comparison. Duncan's multiple-range test was also used to determine the effect of slope position on water contribution by comparing mean differences for each factor (ie. precipitation and soil water) among three slope positions.

The average contribution of precipitation and soil water to ground fuels were determined by analyzing the differences in moisture content between treatments. Hydration by precipitation alone was obtained by subtracting the average moisture content of T_1 from the control (Table 2). Hydration from soil water was obtained by subtracting the average moisture content of T_2 from T_1 (Table 2). These differences were expressed as percents by dividing by the total contribution. The total contribution was obtained by subtracting the average moisture content of T_2 from the control. The following equations express these relationships more exactly.

$$\%Ppt = \frac{MC_c - MC_{t1}}{MC_c - MC_{t2}} \times 100$$

$$= \frac{\text{average precipitation contribution}}{\text{average total contribution}} \times 100 \qquad [1]$$

$$\%SW = \frac{MC_{t1} - MC_{t2}}{MC_c - MC_{t2}} \times 100$$

TABLE 2. An outline of a determination of differences in moisture content for paired treatments which will be tested by Duncan's multiple-range test

Hydration by precipitation (Ppt) only	$MC_c - MC_{t1} = (Ppt + SW + ET) - (SW + ET) > 0$
	$MC_{t1} - MC_{t2} = (SW + ET) - (ET) = 0$
	So $MC_c > MC_{t1} = MC_{t2}$
Hydration by both precipitation (Ppt) and soil water (SW)	$MC_c - MC_{t1} = (Ppt + SW + ET) - (SW + ET) > 0$
	$MC_{t1} - MC_{t2} = (SW + ET) - (ET) > 0$
	So $MC_c > MC_{t1} > MC_{t2}$

NOTE: MC_c = moisture content for the control resulting from full hydration.
MC_{t1} = moisture content for Treatment 1 resulting from no atmospheric hydration.
MC_{t2} = moisture content for Treatment 2 or residual moisture content affected only by evaporation conditions.
ET = evapotranspiration.

$$= \frac{\text{average soil water contribution}}{\text{average total contribution}} \times 100 \qquad [2]$$

where: %Ppt = percentage of precipitation affecting fuel moisture content

%SW = percentage of soil water affecting fuel moisture content

MC = average gravimetric fuel moisture content (% dry weight) of the 7 samples

subscripts c, t1 and t2 represent Control, Treatment 1 and Treatment 2.

4. RESULTS

4.1 An overview of sampling conditions

The physical characteristics of the three sampling locations were similar (Table 3). There were no statistically significant differences in fuel depth, soil bulk density or soil porosity among sampling locations. Fuel bulk density at Location 2 was significantly greater than at the other two locations but the magnitude of this difference was not considered to be of physical importance. In general, the three sampling locations were considered similar.

Climatic conditions at the study site varied during the field season (May 24 to September 20, 1990) (Table 4). Rainfall was more frequent and greater at the beginning of the study period (late May - early July) than at any other time (Figure 6b). Most of these rain events were light showers. The total rainfall during the study season was 268 mm, which was lower than the long term average (1982-1988) of 353 mm for the same period (Anonymous 1982, 1983, 1984, 1985, 1986, 1987, 1988).

The longest non-rainfall period was 13 days, which occurred between late July and early August. The longest period with rainfall less than 1 mm was 19 days. Weather conditions during the study season were considered intermediate to wet due to high average relative humidity of 73% and moderate average air temperature of 14.9 °C, even though total rainfall was below the long term average.

TABLE 3. Comparison of physical characteristics among the three sampling locations

Characteristic	n	Location		
		1	2	3
Fuel depth (cm)	171	6.6(±0.13)a	6.3(±0.12)a	6.7(±0.12)a
Fuel bulk density (g cm^{-3})	171	0.13(±.003)a	0.16(±.005)b	0.12(±.003)a
Soil bulk density (g cm^{-3})	57	1.19(±.053)a	1.32(±.045)a	1.21(±.066)a
Soil porosity (%)	57	55(±1.9)a	50(±1.5)a	54(±2.2)a

Note: Values in each row are means (± SE) follwed by the same letter(s) are not significantly different by Duncan's multiple-range test ($p > 0.05$).

TABLE 4. Weather conditions at the three sampling locations in Elk Island National Park, Alberta during May 24 and September 20, 1990

Parameters	n	Minimum	Maximum	Average	Total
Rainfall (mm/day)1/	40*	< 1	74	7(±2)	268
RH (%)2/	112	35	94	73(±1.3)	-
Air temp.(°C)2/	112	6.40	22.93	14.9(±.34)	-
Fuel temp.(°C)3/	112	7.00	23.59	15.0(±.29)	-
Soil temp.(°C)4/	112	7.61	17.96	13.3(±.21)	-
Windspeed (m sec^{-1})5/	112	0.45	1.51	0.68(±.02)	-

1/ measured at a height of 70 cm above ground surface.
2/ measured at a height of 30 cm above ground surface.
3/ measured at a depth of 2 cm below ground surface.
4/ measured at a depth of 10 cm below ground surface.
5/ measured at a height of 90 cm above ground surface.
* n = 40 days of precipitation out of a total sample period of 112 days.

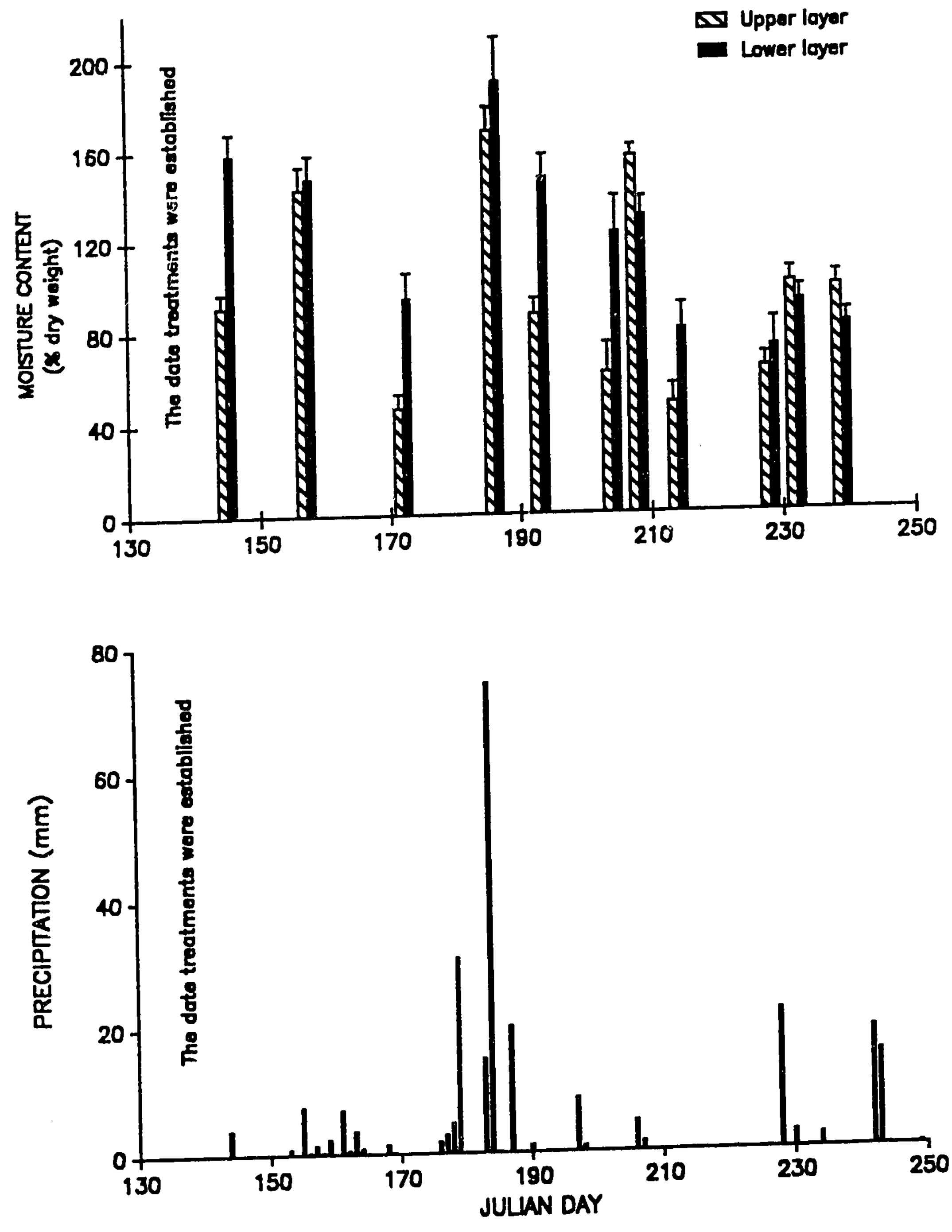


FIGURE 6. (a) Average ground fuel moisture contents with standard error bars for the control treatment (n=18) showing a frequency of sampling over study season, and (b) Daily rainfall measured by Tipping-bucket recording raingauge during study season.

4.2 Ground fuel moisture contents between upper and lower layers

Sampling was done throughout the study season (Figure 6a). Natural ground fuel moisture contents varied with time and precipitation. The responses of fuel moisture contents to precipitation were determined by the magnitude and frequency of precipitation and the duration of non-precipitation periods.

Moisture contents were significantly different between the fuel layers, $p<0.0001$ (Table 5). The moisture contents of the lower fuel layer was usually greater than those of the upper layer. This was because the upper layer had higher evaporation rates due to its direct exposure to radiation and air movement. The largest difference in moisture content between the upper and lower layers occurred after long dry periods, where the surface layer dried at a faster rate than the lower layer. The largest difference in moisture content of 62% occurred on Julian day 204; after a 6-day drying period.

The differences in moisture content between the upper and lower layers were small following rainfall events. Moisture content of the upper layer was more variable than the lower layer with rapid increases and decreases because of direct exposure to precipitation and evaporation. Therefore, after large storm events or frequent small storms the differences in moisture content between the upper and lower layer were the smallest.

Toward the end of the sampling period, the moisture contents of the upper layer following rainfall events often were greater than those of the lower layer. This occurred because of the quick hydration of the upper fuel layer with

TABLE 5. ANOVA table for testing the effects of hypothesized factors on ground fuel moisture contents at Elk Island National Park, Alberta during July 12 and August 27, 1990

Source	df	F	Probability
Location (S)	2	-	
Position (P)	2	4.45	0.0962
Error	4		
Hydration (H)	2	348.88	<0.0001
HxP	4	4.37	0.0029
Error	84		
Layer (L)	1	197.59	<0.0001
LxP	2	2.25	0.1091
LxH	2	28.52	<0.0001
LxPxH	4	0.72	0.5768
Error	126		

precipitation. Most of the late season rainfall was intercepted and retained by the upper layer due to water deficits in this fuel zone as a result of drying. Examples of these phenomena occurred on Julian days 208, 232, and 239 (Figure 6a). Furthermore, precipitation events during the late summer period were small on average, thus allowing most water to be held within the surface fuel layer. If the storms during this time period had been big enough and long enough, then full hydration would have occurred.

4.3 Ground fuel moisture contents among slope positions

Ground fuel moisture contents among the three slope positions were significantly different at the 0.10 level, $p=0.0962$ (Table 5). The differences existed only between the bottom position and the two upper positions for the control and T_1 (Table 6 and Figure 7). Moisture contents of the top and middle positions were similar regardless of fuel layer. The higher moisture contents on bottom slopes were attributed to drainage and proximity to the water table and open water near the foot of slopes. Average horizontal distance between the bottom positions and open water bodies was only 9 m compared to 23 m and 37 m for the middle and top positions, respectively. As would be expected no significant differences in moisture content between slope positions were detected for T_2.

The higher moisture content for the bottom position occurred for both the upper and lower layers. At the upper layer, the average moisture content was

TABLE 6. Average seasonal gravimetric ground fuel moisture content (%DW) and (±SE) for the upper and lower layers among three treatments at different slope positions during July 12 and August 27, 1990, (n = 42)

Layer	Slope position	Treatment (%DW ± SE)			Mean
		Control	Treatment 1	Treatment 2	
Upper	Top	78.8(±6.7)g	37.7(±2.2)i	15.9(±1.5)k	44.6(±3.4)
	Middle	80.8(±6.3)g	40.1(±2.2)i	15.0(±0.7)k	46.3(±3.4)
	Bottom	102.1(±6.9)h	48.4(±4.1)j	14.1(±1.6)k	57.5(±4.6)
	Mean	87.3(±4.1)a	42.0(±1.6)b	15.0(±0.8)c	-
Lower	Top	93.8(±5.2)l	64.0(±3.1)n	22.3(±2.2)p	60.6(±3.4)
	Middle	95.4(±5.6)l	69.6(±3.6)n	21.4(±1.4)p	63.5(±3.6)
	Bottom	121.6(±10.0)m	87.1(±9.4)o	21.4(±5.9)p	79.8(±6.2)
	Mean	103.6(±4.6)d	73.6(±3.2)e	21.7(±1.1)f	-

NOTE: Different letters in each row indicate significant differences in moisture content between treatments ($p<0.05$).

Different letters in each column indicate significant differences in moisture content between slope positions ($p<0.05$).

Similar letters in each column indicate no significant differences in moisture content between slope positions ($p<0.05$).

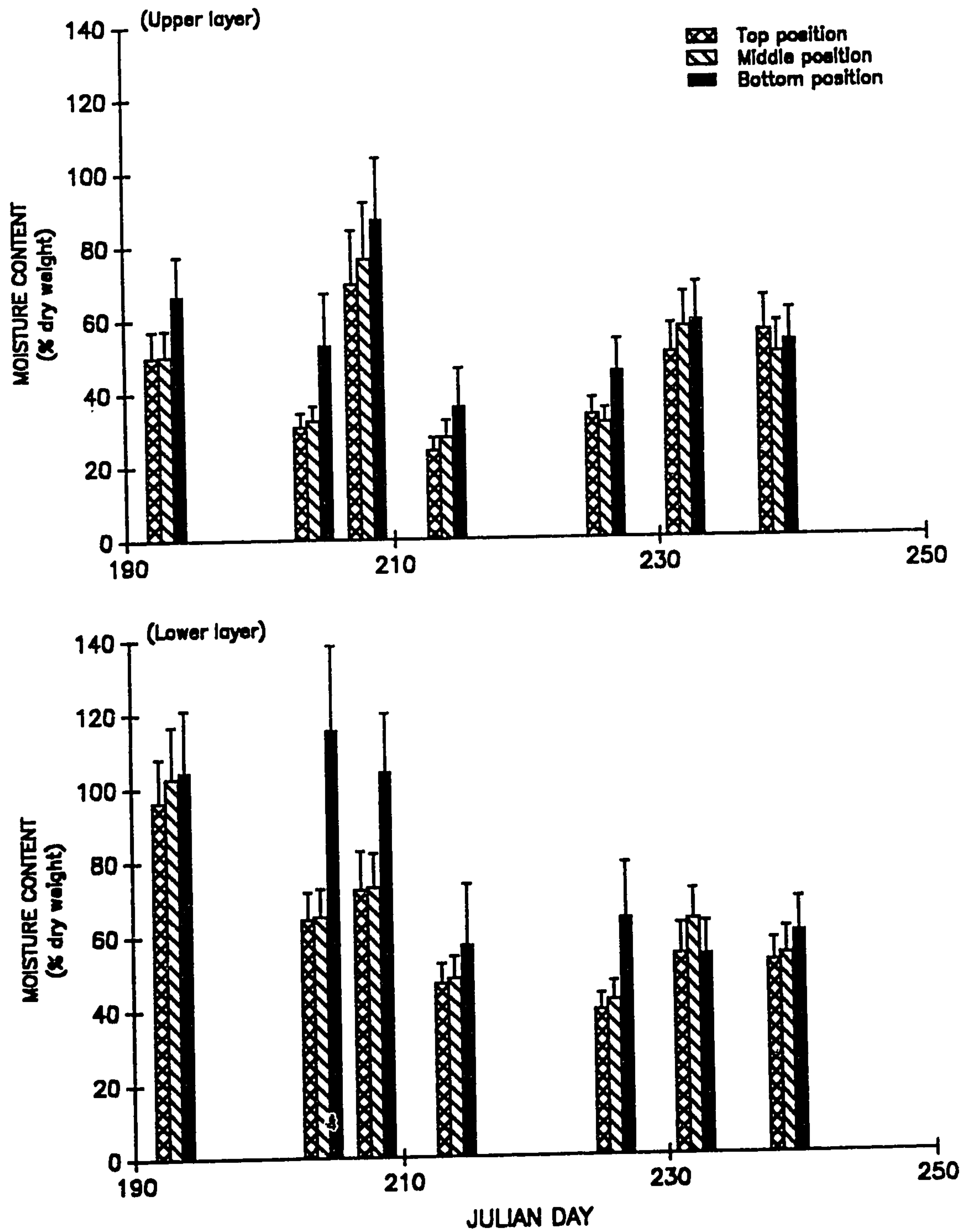


FIGURE 7. Average gravimetric ground fuel moisture contents with standard error bars for the upper and lower layers among slope positions regardless of treatments over 7 sampling times (n =18).

11%, or 13% higher than at the middle and top positions, respectively (Table 6). The average moisture content of the lower layer at the bottom position was 16%, or 19% higher than at middle and top positions.

4.4 Ground fuel moisture contents among treatments

Ground fuel moisture contents were significantly different among the three treatments, $p<0.0001$ (Table 5). Multiple comparisons indicated the moisture contents of each treatment were significantly different from each other. Average moisture contents of the control regardless of fuel layers and slope positions were always higher than those for the other two treatments because they were fully exposed to the effects of precipitation and/or soil water (Figure 8). The moisture contents for the control were more variable than those for T_1 and T_2. The moisture contents for the control varied from a maximum of 156% to a minimum of 47%.

The moisture contents for T_1 were always less than those for the control but greater than those for T_2, where all hydration was prevented. Changes in moisture content of T_1 always paralleled those of the control, which suggested some other sources of hydration existed. The moisture contents for T_1 ranged from minimum of 29% to maximum of 106%, respectively.

The moisture contents for T_2 were always less than those for the control and T_1, and showed a steady decreasing trend from the start to the end of sampling period (Figure 9). This trend was especially strong for the lower layer, which

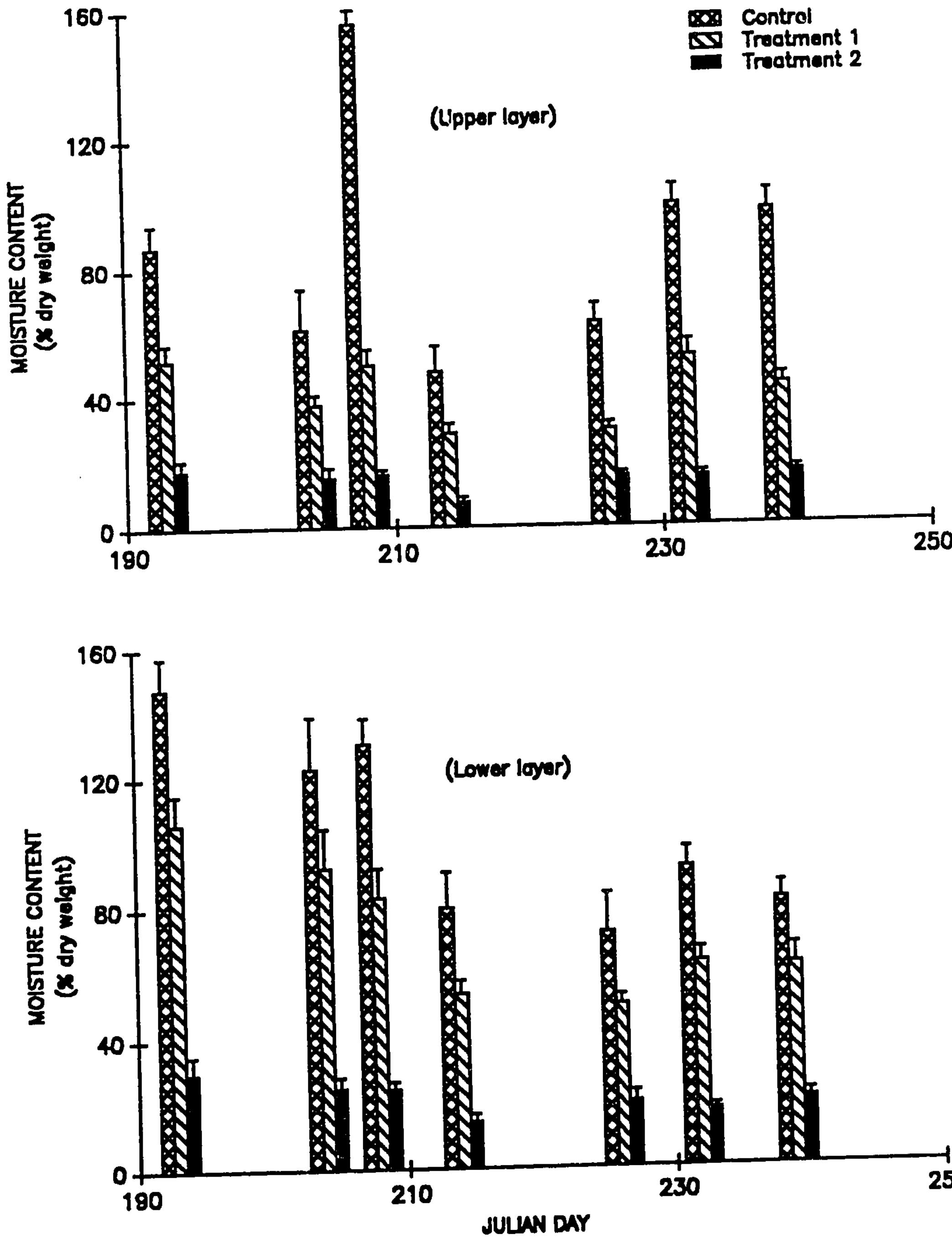


FIGURE 8. Average gravimetric ground fuel moisture contents with standard error bars for the upper and lower layers among treatments regardless of slope positions over 7 sampling times (n =18).

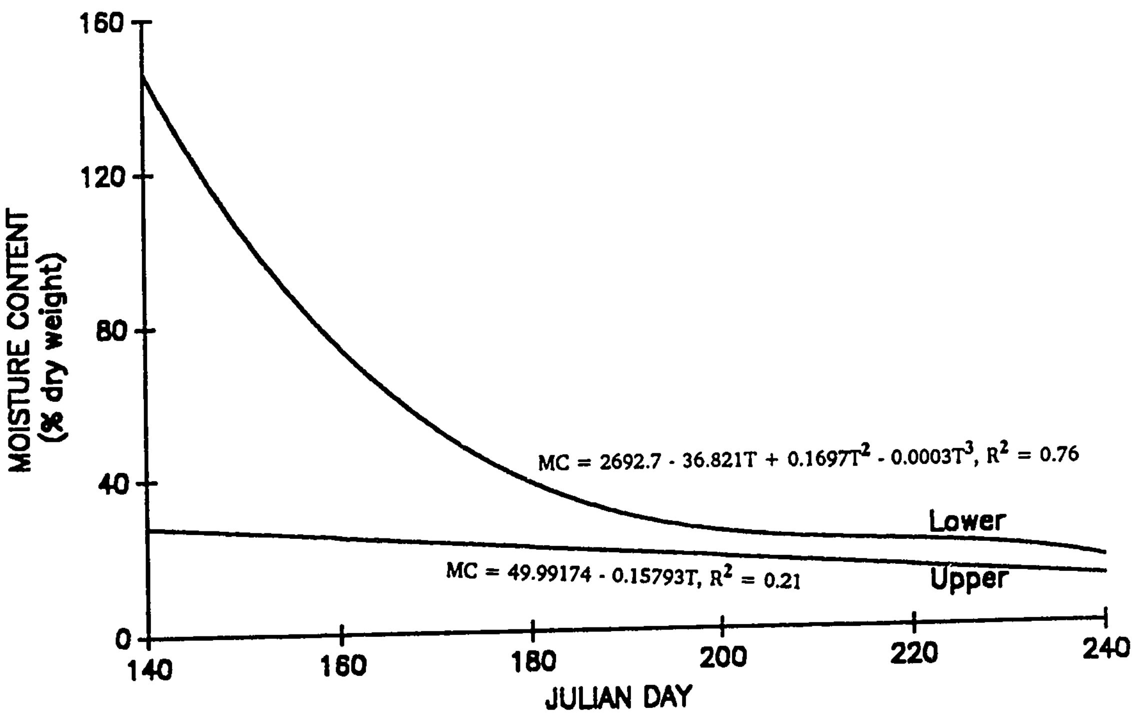


FIGURE 9. Drying trends of ground fuels for upper and lower layers which indicated by Treatment 2 during study period (May 24 to Aug 27, 1990) (n=180).

was protected from precipitation and atmospheric wetting (ie. high RH could possibly cause condensation). By Julian day 193 fuel moisture contents in T_2 decreased to a more or less a constant value or equilibrium (ie. air dry moisture content). From Julian days 193-239 moisture contents in the lower layer for T_2 averaged 21.7% compared to equivalent values of 103.6% and 73.6% in the control and T_1, respectively.

The effects of treatments on fuel moisture were evaluated during this time period because of the strong drying conditions and limited precipitation. This drying period was well illustrated by moisture contents in the lower fuel layers. In addition, the moisture contents for T_2 had stabilized. It had been 55 days since the experiment was initiated. The steady state moisture status of T_2 was used as a measure of the unaccountable moisture, which averaged 13% and 21.7% for the upper and lower layers, respectively.

An examination of the differences between moisture contents on each sample date illustrated the effectiveness and probable sources of hydration. Moisture contents for the control and treatments were assumed equal to the inputs (+) and outputs (-) as shown in the following equations:

$$\text{Control} = Ppt^{+} + SW^{+} + ET^{-} = C \quad [3]$$

$$\text{Treatment 1} = SW^{+} + ET^{-} = T_1 \quad [4]$$

$$\text{Treatment 2} = ET^{-} = T_2 \quad [5]$$

In these comparisons, the moisture content of T_2 was used to identify and separate the contributions of precipitation and soil water in hydrating fuels. The following equations show how these effects were isolated:

$$C - T_2 = Ppt + SW = \text{Total inputs} \quad [6]$$

$$T_1 - T_2 = \text{SW-input only} \quad [7]$$

$$C - T_1 = \text{Ppt-input only} \quad [8]$$

where: Ppt, SW, and ET are abbreviations for precipitation, soil water, and evapotranspiration, respectively.

In the upper layer, the difference in moisture content between the control and T_1 (Ppt) was always greater (45% vs 27%) than the difference between T_1 and T_2 (SW). In the lower layer, however, the reverse was true, with the difference in moisture content between T_1 and T_2 (SW) was greater (52% vs 30%) than the difference between the control and T_1 (Ppt). These results suggested soil water may be more important as a source of hydration in the lower than upper fuel layers.

4.5 Proportion of water contribution to ground fuels

Analysis of water contribution by equations 1 and 2 showed that overall precipitation was relatively more important to ground fuel hydration than soil water (Table 7). This was especially true for the upper layer where precipitation accounted for 64% of fuel moisture, which is almost twice that contributed by soil water. Contributions by precipitation to the upper fuel layer were similar at all slope positions. Moisture contribution by precipitation, hence, was not significantly different among slope positions for the upper layer (Table 7).

TABLE 7. Percent contribution of precipitation (Ppt) and soil water (SW) to ground fuels on different slope positions

Fuel layer	Water source	Slope position			Average
		Top	Mid	Bot	
Upper	Ppt	65(±21.2)a	65(±21.2)a	62(±16.7)a	64(±11.4)
	SW	35(±5.9)b	35(±5.9)b	38(±4.5)b	36(±3.2)
Lower	Ppt	44(±8.5)c	44(±8.5)c	35(±8.3)c	41(±5.0)
	SW	56(±4.9)d	56(±4.9)d	65(±7.8)d	59(±3.6)

NOTE: Values in each row are mean (± SE). Means followed by the same letter in the same row are not significantly different by Duncan's multiple-range test ($p>0.05$).

Sample size (n) = 7 fcr the three slope positions and 21 for the average of these three positions.

Soil water, in contrast, was more effective in hydrating the lower layer than the upper one. Overall, soil water contributed slightly higher moisture to the lower layer than did precipitation. Soil water contributions to the lower layer averaged 59% compared to 41% for precipitation. Contributions were greatest at the bottom positions, possibly because of drainage and proximity to water table and open water body. However, analysis indicated contributions by soil water were not significantly different between slope positions.

4.6 Moisture indices and desorption curves

The moisture indices were different between ground fuel and underlying soil layers (Figure 10a). Continuous monitoring by the fiberglass moisture sensors showed soil water contents underlying the fuel layer were slightly greater through the end of summer months, except for short (1-3 days) periods following rainfall. During these events moisture contents were higher in the fuel than in underlying soil. However, the wetter moisture contents on the fuel layer during and immediately after precipitation were rapidly dried. The moisture contents in fuel layer 1-2 days after rainfall were lower than those in the underlying soil. These results corresponded well with periodic measurements of volumetric moisture contents of ground fuel layers and underlying mineral soil (Figure 10b). Moisture contents of underlying soil were generally higher than those of ground fuels.

An examination of desorption curves for paired samples of humus layer (H)

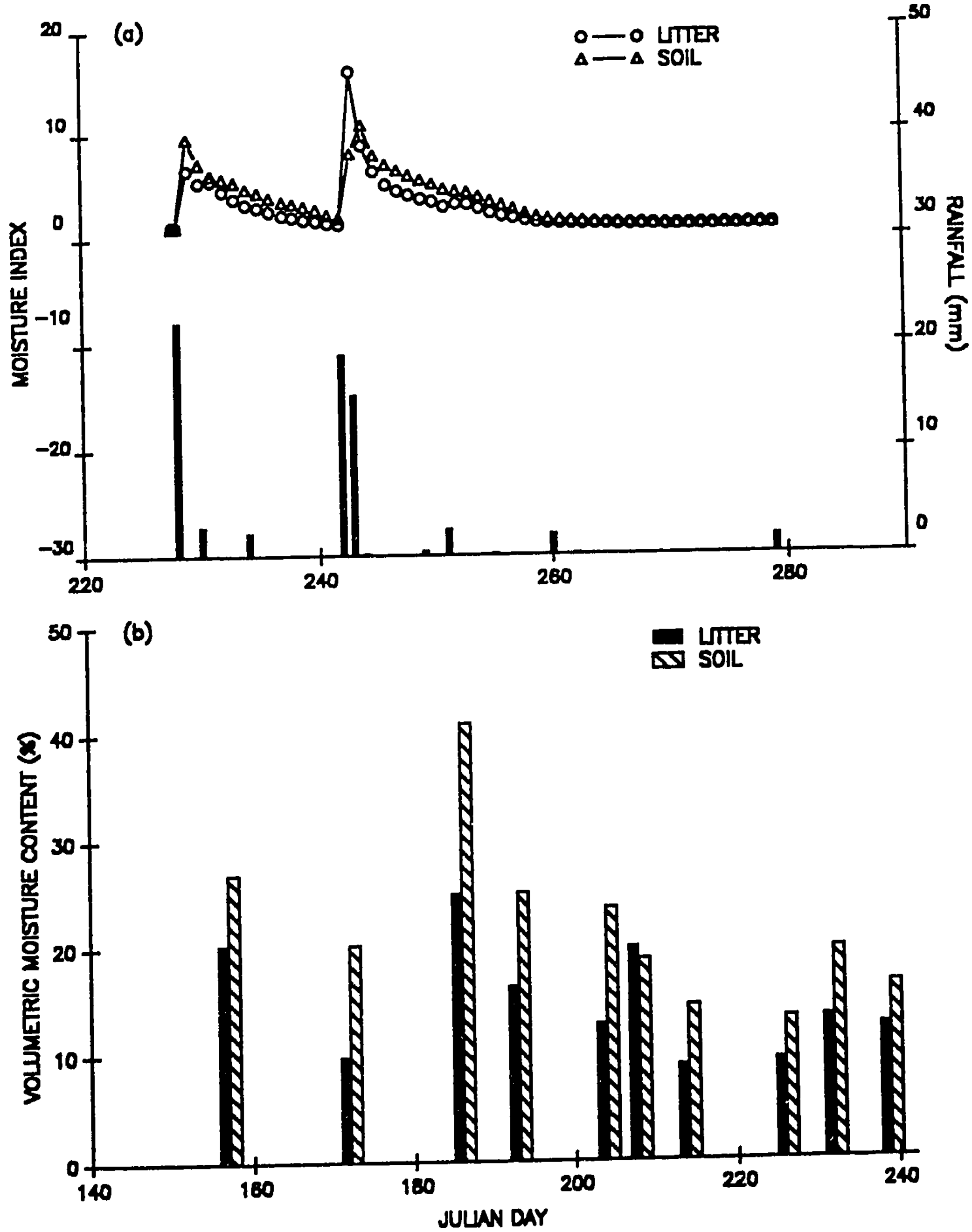


FIGURE 10. (a) Moisture indices for aspen litter and underlying soil over time at the end of summer, 1990 (Aug 15 to Oct 7). (b) Comparing of volumetric moisture contents between litter and underlying soil throughout the study season.

and underlying soil showed the soil had greater water retention characteristics than the litter (Figure 11). Air intrusion values (ie. inflection point describing change in water content from partially saturated to fully unsaturated) for soil and litter occurred at volumetric water content of 35% and 40%, respectively. Water potentials of the soil were greater than those of the litter at any given water content, which suggested the direction of water flow would be from soil to litter (ie. upwards). This was especially true for lower water contents. For example, the water potential difference between soil and litter at a water content of 35% was 25 cm H_2O compared to 6 cm at a water content of 60% (Figure 11).

4.7 The drying trends of ground fuels

All ground fuel conditions followed seasonal drying patterns, characterized initially by wet conditions in May, slowly decreasing to low relatively constant values in late summer and fall. The drying patterns for the control and T_1 were highly variable because of periodic hydration from precipitation and/or soil water. This was especially the case for the control which was fully exposed to all hydration sources. The fluctuations in moisture content for T_1 were similar to the control, but smaller in magnitude because of the interception of precipitation.

The drying pattern for T_2, where all hydration was prevented, followed that of a "typical drying curve". Moisture contents steadily decreased, with no signs of rehydration, to a constant or equilibrium value (air dry moisture content) by

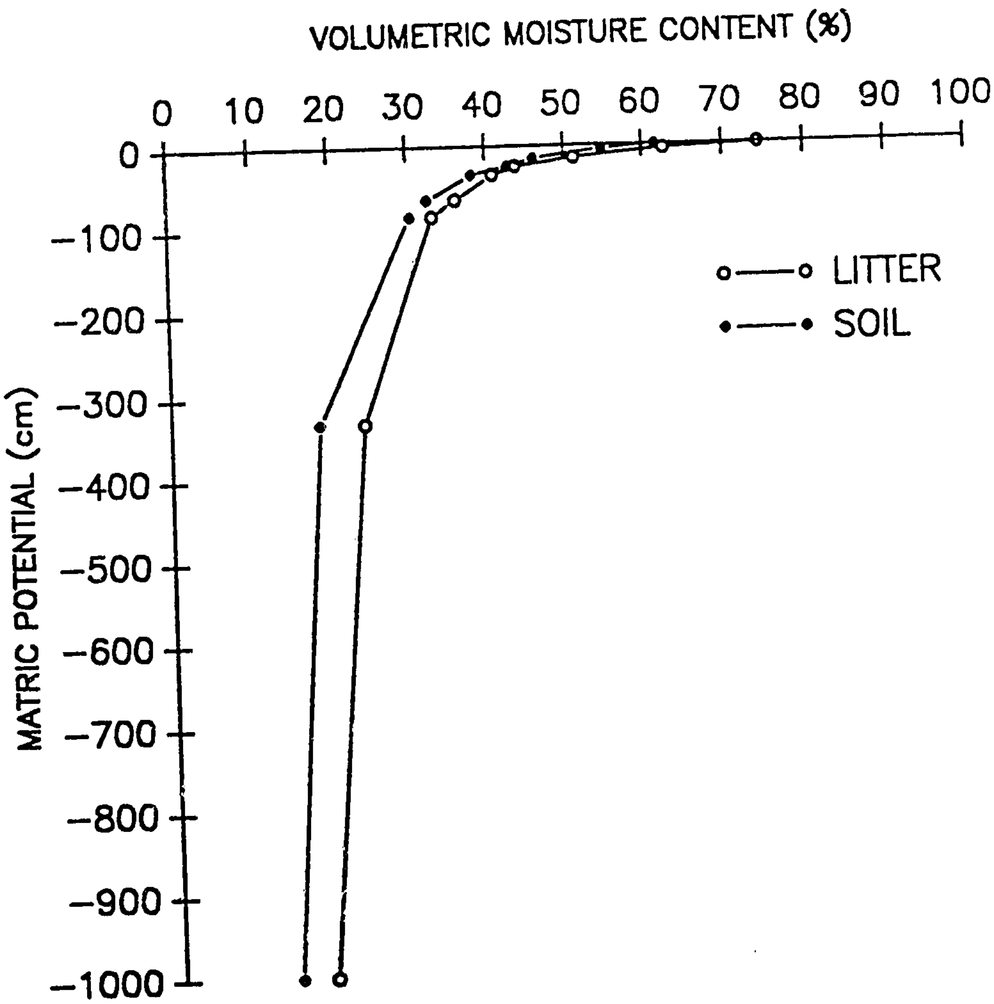


FIGURE 11. Desorption curves for aspen humus and underlying soil at Elk Island National Park.

early July (ie. Julian day 190). The average equilibrium values for T_2 were 15% and 21.7% for the upper and lower layer, respectively. The drying rates for all treatments by mid to late summer (Julian days 190-240), during periods of no or little precipitation, were similar. The differences in moisture content between the treatments were ostensibly due to differences in rehydration.

Drying rates for the upper fuel layer were greater and more variable than for the lower layer because of direct exposure to radiation and air movement. This appeared to be the case for all conditions but could not be confirmed for the control and T_1 because of point measurements in time and periodic rehydration.

Drying curves for T_2, where hydration was controlled, were best described by fitting polynomial curves of moisture content on time (Figure 9). Best fit for the upper layer was obtained with a first degree or linear polynomial, while the lower layer was best fit by a third degree or cubic polynomial. The equation fit for the lower layer was better than that for the upper (R^2 of .76 vs R^2 of .21) probably because of its less variability and sensitivity to climatic parameters. The lower layer dried at an exponential rate at the beginning and then slowed as it reached equilibrium. Curves fitted to data from each slope position indicated no significant differences in drying rates due to position (Appendix 1). As with the other curves initial moisture contents and drying rates were high, rapidly decreasing with time to a constant, equilibrium value.

Stepwise regression analysis of moisture contents by slope position and fuel layers showed drying of ground fuels were dependent on several weather parameters. Moisture contents for both layers were significantly correlated with soil temperature, air temperature, relative humidity and daily wind speed (Table 8). Soil temperature was the most important variable to dry ground fuel for both the upper and lower layers, but was not highly correlated. Soil temperature was responsible on average for only 23% and 41% of the variability in drying moisture contents for the upper and lower fuel layers, respectively.

TABLE 8. The importance of weather parameters[1/] (as measured by % increases in R^2) which influenced ground fuel drying when there was no hydration (Treatment 2) on different slope positions

Layer	Slope position: Top		Middle		Bottom		Average	
	Factors	R^2	Factors	R^2	Factors	R^2	Factors	R^2
Upper	ST,WS	.36	ST,RH,AT,FT	.54	ST	.17	ST,WS,RH,AT	.33
	ST	.28	ST,RH,AT	.50			ST,WS,RH	.30
			ST,RH	.42			ST,WS	.28
			ST	.32			ST	.23
Lower	ST,AT,RH	.77	ST,AT,FT	.69	ST,AT,FT	.63	ST,AT,FT,RH	.69
	ST,AT	.72	ST,AT	.61	ST,AT	.58	ST,AT,FT	.67
	ST	.55	ST	.34	ST	.36	ST,AT	.62
							ST	.41

1/: ST is daily soil temperature on the sampling date at 10 cm deep (°C).
WS is daily windspeed on the sampling date at 90 cm high (m/sec).
RH is daily relative humidity on the sampling date at 30 cm high (%).
AT is daily air temperature on the sampling date at 30 cm high (°C).
FT is daily fuel temperature on the sampling date at 2 cm deep (°C).

5. DISCUSSION

5.1 Sources of water contribution to ground fuels

It is well known that moisture content of surface and ground fuels is highly influenced by the amount and timing of rainfall events (Wright 1932, Deeming et al. 1974, Van Wagner 1987, Burgan 1988). Thus, there was never any doubt that precipitation was of primary importance in hydrating ground fuels of aspen stands in central Alberta. This was most evident from the large and immediate increases in fuel moisture contents for the control following precipitation events.

However, speculation of high ground fuel moisture content during dry periods (Johnston and Woodard 1985) and the difficulty of prescribed burning in these stands (Fechner and Barrows 1976, Brown and Simmerman 1986, Alexander and Sando 1989) suggested other sources of hydration or other processes were influencing ground fuel availability in aspen stands. The results of this study further confirmed and supported these observations.

Natural ground fuel moisture contents throughout most of the summer of 1990 were at levels (>30%) that would not allow ignition or support combustion (Wright 1932, Beall 1967). The average lowest moisture contents for upper and lower fuel layers from May 24 to September 20 were 48% and 72%, respectively. The probability that ground fuels were affected by higher soil water content resulting from the removal of the shrub layer on the study sites was considered to be small. The amount of vegetation removed within the study plots was small relative to the photosynthetic and evapo-transpiration surface area within the study area. Possible increases in streamflow with canopy reduction of less than 20% are not detectable (Bosch and Hewlett 1982). In this study less than 0.1% of the evapo-transpiration area was removed.

Assuming that precipitation was the only source of hydration, the moisture contents of T_1 should have followed a drying trend similar to that of T_2 where no hydration was allowed. Instead, moisture contents of T_1 showed periods of rehydration that were correlated with precipitation events, but the magnitude of change was always less than that for the control. Moisture contents of T_1 were on average 38% less than that for the control, and 40% greater than that for T_2. The differences in moisture content also appeared to be independent of evapotranspiration. The rates of evaporation inferred from T_2 were similar among slope positions.

The differences in moisture content between the control and T_1 were considered indicative of another source of hydration, possibly soil water. Precipitation not only hydrates fuel directly, it also recharges soil water levels by infiltration (Rothwell 1978, Hewlett 1982). In the absence of slope, ground water levels can rise toward the soil surface and capillary soil water flow can contribute water to hydrate downed fuels (Rivard, unpublished Ph.D. work at the University of Alberta, Edmonton). Results of this study suggested soil water significantly contributed to ground fuel moisture contents in the Aspen Parklands of Alberta. Even though the sample was small, only one field season, these results were considered valid as a full range of fuel conditions were sampled.

Moisture indices and moisture contents of mineral soil under the litter layer in late summer showed water contents were consistently greater than the overlying litter layer, except during and shortly following precipitation. During these times litter moisture contents exceeded soil water contents for 1-2 days at most, and then rapidly dried to values less than the soil. This suggested water flowed from the higher concentrations in the soil layer to the lower concentrations in the litter (Hillel 1982). This indicated soil water flow from the soil to ground fuels was theoretically possible.

Construction of desorption curves for the humus and soil indicated that under these conditions, the matric potential of the soil exceeded that of the humus making it possible for upward unsaturated soil water flow. The upward movement of water from underlying soil to litter layer can be explained by the capillary flow of water (Paavilainen and Virrankoski 1967, Hanks and Ashcroft 1980). Unsaturated flow, assuming it occurred, was probably very slow because of low soil and litter water contents in late summer. Soil water flows, however, probably would be greater and more important earlier in the year when soil was wetter.

The Canadian Forest Fire Weather Index System does not account for the influence of soil water when predicting fuel availability (Canadian Forestry Service 1970, Muraro and Lawson 1970, Van Wagner 1970, Lawson 1977, Alexander _et al._ 1984). In well-drained red pine sites, where this system was first developed (Wright 1932), soil water probably was not a significant factor. Hence, fuel availability could be fully accounted for by precipitation only. The speculations of high ground fuel moisture content made by Johnston and Woodard (1985) were substantiated by the findings of this study.

Soil water flows to ground fuels would be most significant for the humus layer because of its greater bulk density and direct contact with mineral soil. Soil water contribution to the upper layer would be less important, or more difficult to detect because of greater evaporation and less favorable condition for capillary water flow. The importance of water contribution to the upper and lower layers was illustrated by the proportion of precipitation and soil water contributing to each layer. For the upper layer, precipitation accounted for 64% of fuel moisture compared to 36% of soil water. For the lower layer, precipitation accounted for only 41% compared to 59% for soil water.

5.2 The effect of relative slope positions on ground fuel moisture contents

Fuel moisture levels did vary by slope positions. Fuels at bottom slope positions for the control and T_1 were significantly wetter than fuels at middle or top slope positions. Fuels subjected to T_2 were very similar in moisture content among all slope positions. However, fuel moisture contents regardless of treatments at bottom position were significantly greater at the 90% confidence level than at the middle and upper positions.

It was expected that fuel moisture contents would be greater at slope bottoms because of drainage and proximity to water table and nearby open water bodies. At this position soil moisture content is usually greater than the upper positions (Dunne 1978). Capillary water movement was perhaps more effective in hydrating surface fuels at the bottom slope position due to higher soil moisture content (Moore 1939). Higher fuel moisture contents may also have been influenced by greater root growth stimulated by the wetter conditions of slope bottoms. Live vegetation, as a part of ground fuels, contains more moisture than dead fuels (Van Wagner 1967) causing higher moisture contents.

In addition, The study area has a lot of permanent and temporary water bodies. Permanent water bodies are lakes and ponds, while temporary water bodies are depressions that have been flooded. Most temporary water bodies contained water for most of the study season. This suggests a relatively high water table or plentiful soil water at low elevations in the area. Thus, soil water could contribute more moisture to the ground fuel at the bottom positions.

Ground fuel moisture contents at the top and middle positions were not different perhaps because of the short topographic relief of the landscape. In addition, the physical characteristics of ground fuels and environment were not significantly different. The bottom position should have similar characteristics to the upper position also, but the wet conditions around water bodies made it different.

Contributions of water to the upper fuel layers among the slope positions were not significantly different. Hydration of the upper layer was primarily due to precipitation, and was similar at all slope positions. Average differences in summer precipitation between the study plots were very small, 2-3%. The physical characteristics of ground fuels were also very similar, with very small differences among the slope positions.

Contributions of water to the lower layer were not significantly different either, although, the percent contribution by soil water at the bottom position was 9% higher than that at other positions. This was probably due to the proximity of the bottom position to water table and open water body where fuels were more effective to receive the soil water. Therefore, soil water contributions to fuel appeared to be greater at the lower slope position than at the upper ones.

5.3 The drying trends of ground fuels

Sampling clearly showed that ground fuels in natural or control conditions frequently rehydrated and dehydrated during the study period. The rehydration occurred following precipitation events. This was normal because of the importance of precipitation in hydrating ground fuels. Moisture contents for the lower fuel layer were normally greater than for the upper layer. However, a few exceptions of greater moisture contents for the upper fuel layer occurred in late summer after rainfall. This is because of the absorption characteristics of ground fuels (Simard 1968). In late summer the fuels were so dry, most of rainfall was intercepted and retained by the upper layer, which was directly exposed to atmosphere.

Dehydration generally occurred in the absence of precipitation. The rate of drying was fast when fuels were wet and slow after fuels dried (Britton et al. 1973). The steady drying trends of natural ground fuels were easier to describe for the lower layer because there was smaller fluctuations in moisture contents in the lower layer. The trends of gain and loss of moisture contents for T_1 were similar to those of the control, because T_1 also rehydrated after rainfall. However, the moisture contents for both the control and T_1 never reached an equilibrium moisture content of 20% (ie. theoretical an air dry moisture content for aspen litter in a laboratory environment of 27 °C temperature and 70% relative humidity) (Van Wagne [illegible] rson 1990). The minimum moisture contents during the study season [illegible] ntrol and T_1 were 47% and 29%, respectively.

T_2 illustrated a continuous drying trend through the summer for both the upper and lower layers. This was as expected, because T_2 received no hydration. The drying trend for the lower layer was best described by a typical exponential drying curve (Van Wagner 1970, Van Wagner 1972, Anderson 1990). Its moisture content decreased exponentially until it reached equilibrium.

The differences in drying trends between the fuel layers of T_2 were attributed to differences in drying rates and different moisture contents at the start of sampling. Theoretically the drying curves for the upper and lower layers should be similar, except for the upper layer which would have a faster rate (ie. greater slope) and shorter time to reach equilibrium moisture content because of its direct exposure to radiation and air movement. This was the case in this study where the upper layer in T_2 dried rapidly and was at an equilibrium moisture content 7 days after the treatments were established. The lower moisture contents of the upper fuel layer indicated it was farther advanced along its drying curve. Drying of the lower curve was slower requiring upwards of 50 days for equilibrium moisture content to occur. The drying curve for the lower layer was more representative of a complete drying cycle.

The overall drying trends for the lower layer were close to the ideal. The drying rate for T_2 was fast in the beginning and slowed afterwards until reaching equilibrium. The equilibrium moisture contents of 15% and 21.7% for the upper and lower layers of T_2 were similar to controlled laboratory values reported by Van Wagner (1972) and Anderson (1990). The drying rates for the lower layer of the control and T_1 were also quite homogeneous throughout the dry period or late summer, after an extreme rainfall event. Theoretically, the moisture contents for all treatments should reach the same equilibrium moisture content if the drying period was long enough, as illustrated by Figure 12.

The relationships between drying of ground fuels and weather parameters in this study were different from reports. Generally, the drying of fuel moisture is highly related to relative humidity and air temperature (Forsberg et al. 1970, Van Wagner 1972, Britton et al. 1973, Anderson et al. 1978). The moisture content of ground fuels usually decreases with decreasing relative humidity and increasing air temperature. Drying of ground fuels in this study was weakly

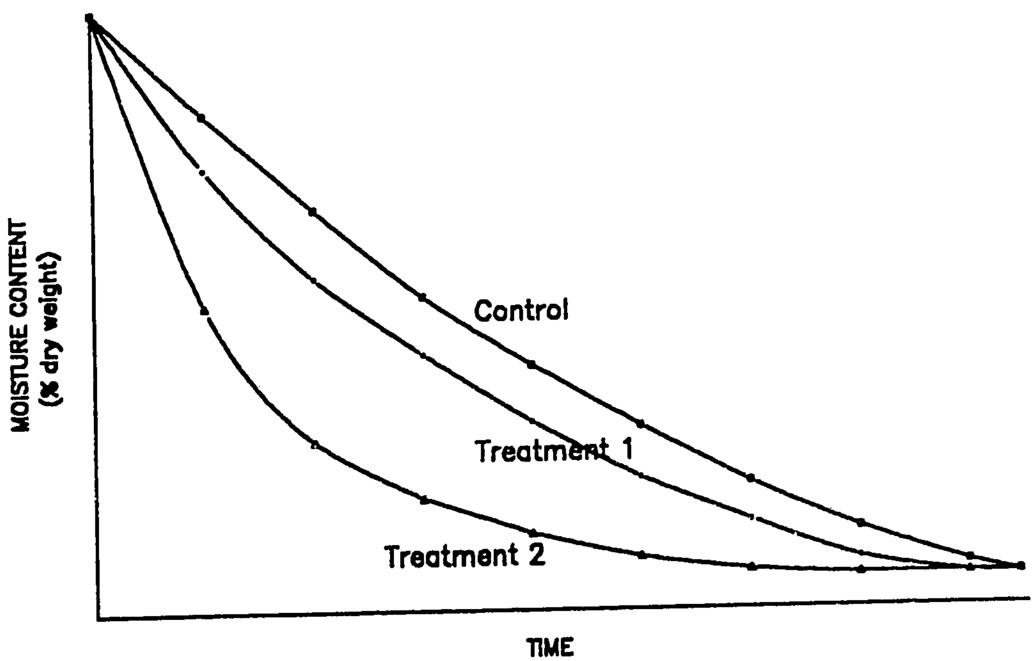


FIGURE 12. Theoretical drying curves for ground fuels among different treatments.

correlated to relative humidity and air temperature. Drying was more sensitive to soil temperature, which has not been previously reported. The poor relationship between relative humidity and ground fuel drying as measured in this study was attributed to the use of average daily relative humidity, which high and showed little variability and correlation with fuel moisture contents. Better results would have been obtained if minimum day-time of relative humidity a 1200 noon had been used as an independent variable in regression analysis.

5.4 Fuel availability

Ground fuels never completely dried during the study season. Fuel moisture contents during most of the sampling period were at levels greater than 30%, thus ignition would not be possible (Atmospheric Environment Service 1982, Brown and DeByle 1989, Wright and Bailey 1982). This was especially true for the lower fuel layer and for all fuels at the bottom of slopes where soil water was more effective in rehydrating fuels.

Ground fuels were occasionally available for ignition in the absence of rain as described by T_1. The average moisture contents for T_1 at occasional given times were lower than the ignition level. However, this was the case only for the upper layer and the upper slope positions. The moisture contents of the lower layer were still too wet for burning. Thus, burning would be still difficult under non-precipitation period because of the effect soil water had on ground fuel moisture content.

However, there may have been times suitable for burning earlier in the year just after snowmelt, before trees leafed out, when radiation and low humidity could dry fuels. Wright and Bailey (1982) state usually there are about two weeks of suitable spring weather after snowmelt every second or third year for burning aspen forests. In addition, ground fuels could be ignited after very long dry periods at the end of summer. Occasionally fall burning can be done after leaf fall (Wright and Bailey 1982). The trends of drying curves for the control showed ground fuels were getting drier and drier in late summer that there was less rainfall than in the spring. Unfortunately, the absence of sampling during the early spring and fall prevented to verify these observations.

Ground fuels could be dried out to the ignition point under the normal climatic conditions of the area, if they were not recharged by precipitation or soil water. Based on the drying trends of T_2 the upper fuel layer would reach to the ignition point in about 7 days with no any hydration, while 50 days or more would be required for the lower fuel layer. This was because the upper fuel layer was directly exposed to atmosphere, while the drying of the lower layer was retarded by the upper one. The evaporative energy did not easily penetrate to the lower layer. Unfortunately, such conditions did not occur because natural ground fuels were periodically recharged by precipitation that kept the moisture content high over the study season.

Fuel moisture level is not the only prescription variable that must be satisfied for burning to occur. The ambient air temperature and relative humidity to include windspeed and days since rain must also be within prescription (Pyne 1984). Perala (1974) suggested a successful burning prescription for aspen slash would be: air temperature > 18°C, relative humidity < 35%, windspeed 2.5- 5 m/sec, and number of days with less than 2.5 mm rain > 5 days. This prescription is similar to the burning conditions suggested by Bailey (1978), Bartos (1979), Weber (1990), Wright and Bailey (1982). These prescriptions were rarely met at the study area of Elk Island National Park during the 1990 field season. The daily relative humidity was never lower than 35%, and windspeeds were always less than 1.51 m/sec. However, even the prescription was met, fuel consumption of the lower layer would be still very small due to its high soil moisture content (Norum 1977).

6. CONCLUSIONS

6.1 The moisture content of ground fuel in aspen stands of central Alberta was maintained by two major sources: precipitation and soil water. As a result, fuel moisture contents were relatively high throughout the study season, even during the driest period due to the amount of soil water present in the study area.

6.2 Generally, precipitation was the primary water source in the study area. It rehydrated ground fuels and maintained soil water levels. Precipitation had a greater direct effect on the upper fuel layer (< 2.5 cm deep) than on the lower fuel layer (> 2.5 cm deep). During the study season, it contributed an overall average of about 64% of fuel moisture content for the upper layer, while the remaining 36% was attributed to soil water.

6.3 Soil water was a secondary source of water for rehydrating ground fuels in the study area. This water source had the greatest effect on the moisture status of the lower fuel layer. An average about 59% of all water in the lower fuel layers were due to soil water inputs, while precipitation contributed the remaining of 41%.

6.4 Slope positions had a significant effect on ground fuel hydration. Only the fuels hydrated at bottom slope positions, which were closet to a permanent water sources, were always wetter than those at the upper positions. Fuels with no hydration were not significantly affected by slope position.

6.5 Fuel hydration by either precipitation or soil water was similar at all slope positions. This may be due to the small topographic relief of the area, similar physical characteristics of the area, similar precipitation distribution, and small sample size. Although, the lower slope position showed higher soil water contribution for the lower layer, the difference in moisture content was still not significant.

6.6 In the absence of water from any source, ground fuels dried steadily over time. The moisture contents decreased exponentially to equilibrium moisture contents of 21.7% for the lower layers. Drying of the upper layer was more advanced at the start of the experiment, and therefore decreased linearly and reached the equilibrium moisture content of 15% earlier than the lower layer because of less moisture and direct exposure to atmosphere.

6.7 Ground fuels under natural conditions were rarely below an optimum level of 30% required for ignition during the study season because of periodic rehydration. The ignition moisture level of ground fuel occasionally occurred under conditions of no hydration, but it was restricted only to the upper layer on the upper slope positions. This is the reason ground fuels in aspen stands of central Alberta are difficult to burn.

7. MANAGEMENT APPLICATION AND FUTURE RESEARCH

The results indicated ground fuels in Aspen Parklands are rarely available for burning because of the frequency and magnitude of precipitation as well as soil water. However, the results implied ground fuels could be available if non-precipitation periods were long enough to reduce the effect of soil water on ground fuel. However, the availability of ground fuels under those situations was restricted only to the upper layer and at the upper slope positions where soil water is less effective. This information will help the forest manager to carefully and properly consider the possibility of time and place to burn in Aspen Parklands. Also, the results suggested soil water should be incorporated into the Fire Weather Index in Aspen Parklands. Currently, this variable is not used when calculating the Fire Weather Index.

In the process of answering a question, it is not uncommon to discover new one. This was true of this study. The following list for further study will enable scientists and managers to better understand the water relations and fuel availability in the Aspen Parklands of Alberta.

7.1 The study should be replicated in time and space. The study should be carried out for more than one year to determine the effect of climatic parameters on fuel moisture contents. Furthermore, the study period should include from early spring after snowmelt to the start of winter (ie. permanent snow pack) because ground fuel at those times may be more available than that observed in this study period. Ground fuel should be sampled more frequently to increase the continuity of moisture data because fuel moisture contents are generally related to day-to-day climatic conditions. In addition, the study should be conducted in other areas besides Elk Island National Park, especially areas with no disturbance by animals and areas with high slope and elevation, to compare and determine the reliability of the results. Also, the study should be conducted in other soil types.

7.2 The hydrological characteristics of ground fuel and underlying soil layers in the study area which may influence the contribution of precipitation and soil water should be well understood. Those characteristics consist of water table level, precipitation characteristics, soil and fuel moisture storage capacities, soil and fuel infiltration, evaporative fluxes, water potential, etc. These kinds of information will further clarify the characteristics of ground fuel moisture contents, the amount of precipitation and soil water contributions to ground fuels, and the relationship between ground fuel and sources of hydration.

7.3 The relationship between fire and ground fuel moisture contents should be well understood. The critical moisture level that prohibits ignition of ground fuels will give information on how well ground fuels can be burned in this specific area. In addition, the fire behaviour, such as rate of spread, fuel consumption, and heat of combustion of this specific fuel will further indicate the advantage and disadvantage of using fire to manage the aspen stands. Therefore, the burning characteristics of ground fuel should be determined either in the laboratory or field.

7.4 The Fire Weather Index should be tested to determine its reliability as an index to predict moisture content of surface fuels in Aspen Parklands of Alberta.

7.5 Effects of canopy cover on fuel moisture content should be considered. The moisture content of ground fuels may be either increased or decreased after full leaf out.

7.6 The study of desorption curves of fuel and soil layers and the monitoring moisture indices by fiberglass moisture sensors should be continued over a longer time period to fully evaluate the dynamics of fuel and soil water contents.

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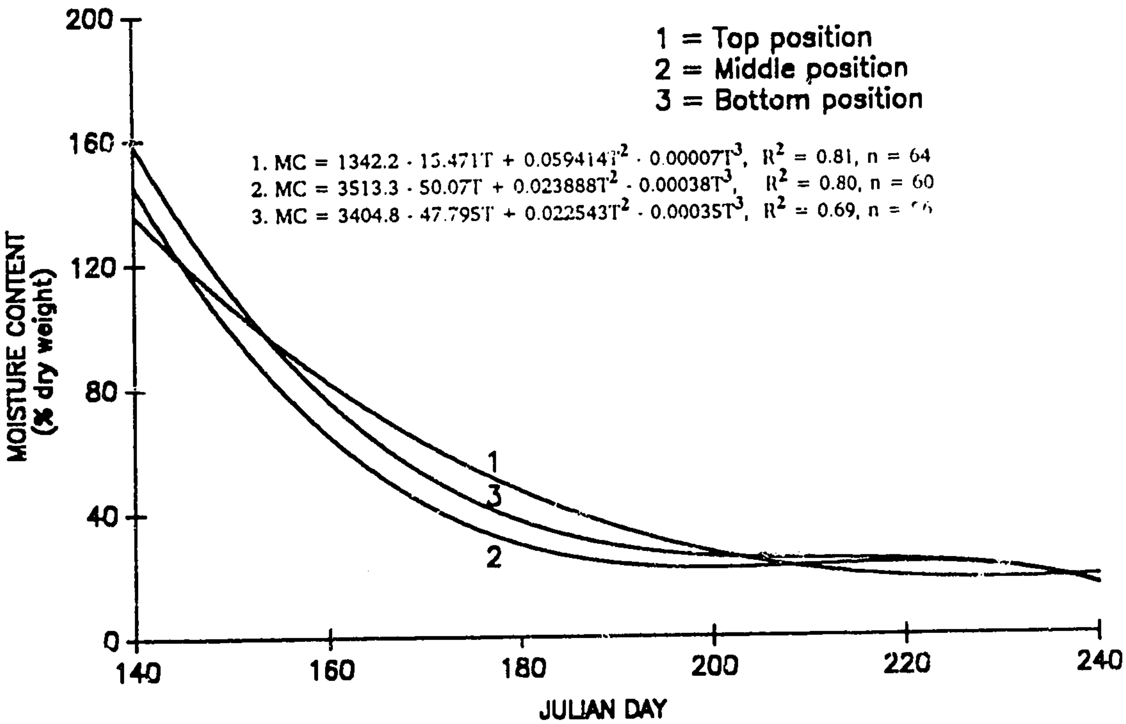
APPENDIX 1. Drying trends for lower layer for Treatment 2 among different slope positions.



APPENDIX 2. Multiple regression equations between ground fuel moisture contents of treatment 2 and weather parameters on different layers and slope positions developed by stepwise method

Layer	Slope position	Regresstion equation	R^2	F	P
Upper	Top	MC = 46.646269 - 2.432432ST + 8.924143WS	.36	17.08	<.0001
	Middle	MC = 12.420353 - 1.586111ST + 0.360544RH + 3.457551AT - 3.3[illegible]19FT	.54	16.27	<.0001
	Bottom	MC = 47.419110 - 2.103658ST	[illegible]	10.76	.0008
	Average	MC = 15.78137 - 3.014045ST + 4.540880WS - 0.325065RH + 1.047793AT	.33	21.16	<.0001
Lower	Top	MC = 82.775587 - 20.861952ST + 9.538806AT + 1.233717RH	.77	68.25	<.0001
	Middle	MC = 149.641047 - 7.875983ST + 22.674130AT - 24.338169FT	.69	41.92	<.0001
	Bottom	MC = 183.859389 - 10.716915ST + 24.817697AT - 24.931918FT	.63	30.11	<.0001
	Average	MC = 107.237166 - 13.319359ST + 21.545920AT - 18.383931FT + 0.818553RH	.69	98.07	<.0001

NOTE: MC is moisture content (% oven dry weight).
ST is daily soil temperature on the sampling date at 10 cm deep (^oC).
AT is daily air temperature on the sampling date at 30 cm high (^oC).
RH is daily relative humidity on the sampling date at 30 cm high (%).
WS is daily windspeed on the sampling date at 90 cm high ([illegible]).