Forest Science, Vol 41, No 2, pp 255–267

The Effect of Soil Water on Ground Fuel Availability

SUPPARAT SAMRAN
PAUL M. WOODARD
RICHARD L. ROTHWELL

ABSTRACT. A determination of ground fuel hydration was carried out in an aspen forest in Alberta, Canada. 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 moisture status of these layers was affected by slope position (bottom, mid, and top) or distance to a water body, and (3) to determine the drying rates for these two fuel layers. Results showed that upper and lower downed and dead fuels were hydrated by soil water as well as precipitation and that both sources contributed significantly to fuel moisture. During the period May 20 to September 20, 1990, precipitation and soil water contributed about 64% and 36% of the water to fuel moisture contents to the upper layer, and 41% and 59% to the lower layer, respectively. Fuel moisture contents varied significantly by slope position. The bottom slope position was always the wettest, while the fuel moisture contents in the other two positions were similar. In the absence of hydration, the upper and lower litter layers reached equilibrium moisture contents of 15% and almost 22%, respectively, but never dried out completely. FOR. SCI. 41(2):255–267.

ADDITIONAL KEY WORDS. Fuel moisture, Aspen Parkland, Alberta, Boreal Forest, fire danger rating, Canadian Fire Weather Index.

THE CANADIAN FOREST FIRE WEATHER INDEX (CFFWI) system (Van Wagner 1987) is used throughout Canada, Australia, New Zealand, and in some United States National Forests in Alaska to predict downed and dead fuel availability in forest stands. Available fuel is defined as the amount of fuel that would be consumed under specific burning conditions (Merrill and Alexander 1987), and fuel consumption is strongly influenced by fuel moisture (Chandler et al. 1983).

In general, precipitation is considered the primary source of hydration in downed and dead organic material above and below the soil-surface interface (Van Wagner 1987). Fuel dehydration is mostly affected by evaporation, which is largely controlled by relative humidity, wind, and air temperature. All of these climatic parameters are used in the CFFWI system to estimate fuel availability. Specifically, the CFFWI uses noon (1200 hr) readings of temperature, relative humidity, wind speed, and the total amount of rain over the previous 24-hr period (noon to noon), and season 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 fire behavior if ignition occurs (Burgan 1988).

Soil water, which is not considered in fuel availability models, may also affect the moisture status of downed and dead woody fuels. This is particularly true in the Aspen Parklands of central Alberta, where soil water is generally plentiful, high water tables are common, soils are shallow and fine textured, and the physiography is undulating (Crown 1977). Further, work by Johnston and Woodard (1985) suggests precipitation may not be the only factor affecting fuel availability and fire behavior in these forests. They found aspen duff was still moist enough to inhibit burning even though the weather conditions were extremely dry prior to and during burning.

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 upper and lower ground fuel moisture contents were affected by elevation from the nearest known water body, which might result in differential drying related to slope position and (3) to determine the drying rate for upper and lower ground fuel layers in aspen stands of central Alberta.

STUDY AREA

The study was conducted in Elk Island National Park, which is approximately 37 km east of Edmonton, Alberta, Canada. The Park is situated in a region of morainal deposits known as the Cooking Lake Moraine, and is elevated some 30–60 m above the surrounding lacustrine plain (Crown 1977). The local topography is characterized by hummocks and hollows with slopes that range from 5 to 15%. The elevation within most of the Park lies between 710 and 740 m above sea level (Crown 1977).

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). 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). Snowfall accounts for 30% of the annual precipitation.

Three sampling locations were located in the east-central part of Elk Island National Park (Samran 1991). All selected sampling locations were within 300 m of each other, but each was on a separate hummock-hollow sequence. All locations were similar, and had the following site characteristics: (1) slope, (2) a water body at the foot of the slope, (3) similar forest vegetation as determined visually, and (4) similar slope aspect. The physical characteristics of the sampling locations are summarized in Table 1. The 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.

The vegetation on the sampling locations fell into the Taraxacum Subtype of the *Corylus-Rosa* Upland Group (Polster and Watson 1979). The area was dominated by an overstory of trembling aspen. The tree crown cover ranged between 40% and 75% for all three sites. The shrub stratum was 100 cm tall, and consisted mostly of beaked hazelnut (*Corylus cornuta* Marsh.) and prickly rose (*Rosa acicularis* Lindl.). The forest floor was composed mostly of aspen leaf litter under trees and of grass in open spots. The shrub stratum also contributed to the litter complex. Dead and down woody debris contributed very little to the total litter complex, although there were some large downed aspen boles scattered throughout the study site.

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	27.5–42.0	34.7 (±3.4)
Slope height (m)	3	3.8–10.2	7.1 (±1.5)
Aspect	3	S–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)

Soils at the study sites were Brunisolic or Dark Gray Luvisols, which have generally developed under forest vegetation (Crown 1977). These mineral soil types are moderately well to well drained. Adjacent to these sites were low lying areas that contained standing or slow flowing water due to beaver (*Castor canadensis*) dams or in some cases the absence of sufficient slope to assist in drainage.

STUDY DESIGN AND METHODS

The hydration of undisturbed ground fuels was studied by the random application of two treatments and a control among plots (5.5 m × 6.0 m) established at the top, middle, and bottom of hummock-hollow complexes at three sampling locations. The control treatment (*C*) allowed hydration of undisturbed ground fuels by precipitation (*P*) and soil water (*SW*) as under normal conditions. Treatment 1 (T_1) prevented hydration of ground fuels by precipitation. Each sampling site was covered by a 40 × 40 cm wooden frame covered with 4 mil clear plastic and chicken wire, tilted at a 50% slope to allow water to drain easily from the top of the frame. The frames were elevated 7.5–15 cm above the ground to allow air exchange and evaporative fluxs (*ET*) at the ground surface.

Treatment 2 (T_2) prevented hydration of ground fuels by precipitation and soil water flow. The movement of soil water into sample sites was prevented by carefully cutting cylindrical fuel samples from the forest floor, lining the excavated hole with a piece of clear 4 mil plastic sheeting, and replacing the fuel sample into the original hole. A 2 × 7 cm piece of metal flashing was bent into a circle and placed around each sample. This flashing maintained the peripheral integrity of the samples, kept the plastic liner in place, and because it was higher than the mean ground level, it prevented overland water flow from washing into samples. Precipitation input was prevented with the same type of frame used in Treatment 1.

The contributions of precipitation and soil water to ground fuel moisture content were determined from differences in moisture content between the treatments. Hydration by precipitation alone was obtained by subtracting the average moisture content of Treatment 1 from the Control $[(C - T_1) = (P + SW + ET) - (SW + ET) = P]$. Hydration from soil water alone was obtained by subtracting the average moisture content of Treatment 2 from Treatment 1 $[(T_1 - T_2) = (SW + ET) - (ET) = SW]$. These differences were expressed as percentages of total contribution, which was obtained by subtracting the average moisture content of Treatment 2 from the Control $[(T_2 - C) = (P + SW + ET) - (ET) = P + SW]$.

The effects of overland flow over or through the fuel layer were considered negligible for the three study sites. It is possible that overland flow could have affected the ground fuel moisture contents for the Control and Treatment 1, but rainfall events during our sampling period were not of sufficient magnitude or duration for this condition to occur. In the absence of physical evidence to the contrary, we assumed all rainfall infiltrated into the soil (Crown 1977, Hewlett 1982), except for that portion held by matric forces in the litter layer.

Sampling plots were cleared of ground vegetation prior to treatment installation, to allow for access and to reduce variability in the evapotranspiration surface area between plots. Overstory vegetation (plants >3 m) was left intact. The plots were divided into 50 × 50 cm grids to create alternating rows for access and sampling. Each plot had 6 sampling rows, each with 12 sampling sites. Treatments were randomly allocated within each row. Sampling times were randomly assigned to each row.

Sampling of moisture content was scheduled to represent wet and dry fuel conditions. Wet conditions were usually sampled within 1 day after a rainfall event. Dry fuel conditions were sampled 7–17 days after rainfall. The time of sampling for dry conditions was determined using local weather forecasts, and were scheduled to occur 1–2 days before rainfall, to obtain as long a drying period as possible. Intermediate values between wet and dry conditions were obtained by sampling 3–4 days after rainfall. Attempts were made to obtain replicate samples for all time periods following rainfall.

Ground fuel moisture contents were determined gravimetrically using a 15 cm diameter cylinder sampler (Holowaychuk et al. 1965). The cylinder was driven into the ground, after the soil around the perimeter of the cylinder was cut with a serrated knife to minimize compression. Samples were taken to the depth of the A-horizon (6–7 cm). The sample was removed from the sampler and divided into upper and lower layers. The upper layer was recently deposited material that could still be identified as leaves, grass tillers, and dead wood (i.e., L and F Horizons, Brown 1974). The lower layer was fully decomposed material that could not be identified (i.e., H layer), except for some living roots. The depth of each layer was measured before separation, and then sealed in plastic bags. Moisture contents of each layer were expressed on an ovendry weight basis after drying of samples at 70°C to a constant weight.

The water retention characteristics of the ground fuels and the mineral soil were described for each site (Gardner 1965). Paired samples of the humus layer and underlying material soil were obtained using a standard bulk density sampler, 5 cm in diameter by 3.7 cm high. Desorption curves for the undisturbed soil cores were determined in the laboratory. Water retention of matric potentials of 0 to −10 kPa were measured on a tension table following procedures described by Topp and Zebchuk (1979). Water retention at matric potentials of −10 to −1500 kPa were measured on a pressure membrance apparatus similar to that described by Richards (1965).

A temporary weather station was installed near the sampling sites (Samran 1991). Daily and total values of precipitation, fuel temperature (2 cm deep), soil temperature (10 cm deep), wind speed (90 cm high), and relative humidity and air temperature (at 30 cm high) were recorded using a data logger. In addition, a manual rain gauge was installed on each experimental plot.

A split-split plot analysis of variance with three replications was used to test for differences in moisture content among sources of hydration and among slope positions (Anderson and McLean 1974). Duncan's multiple range test (Duncan 1955) was used to identify differences in means for multiple comparisons. 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 (i.e., precipitation and soil water) among the three slope positions.

RESULTS

Ground fuel moisture contents were greatly affected by the magnitude and frequency of precipitation and the duration of rain-free periods (Figure 1b). Maximum fuel moisture contents of 170–200% (odw) occurred in early July (Julian date 180–190) following 200 mm of rainfall (Figure 1a). Minimum fuel moisture contents of 50–80% occurred in late July (Julian date 206–212) following periods of little or no rain. The longest period without rain was 13 days, and the longest period with rainfall less than 1 mm was 19 days. Weather conditions during the study period were judged intermediate to wet because of the high average relative humidity of 73%, and a moderate average air temperature of 14.9°C, even though precipitation was below the long-term average for this area.[1]

Moisture contents were significantly different between the upper and lower fuel layers ($P < 0.0001$; Samran 1991). The moisture content of the lower fuel layer was usually greater than that for the upper layer. 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 between these two layers was 62%, which occurred in late July (Julian day 204), after a 6-day drying period (Figure 1b). Differences in the moisture content between the upper and lower layers were small following heavy rainfall events or frequent, yet small showers, when both layers were fully hydrated.

The moisture content of the upper layer was more variable than the lower layer (note R^2 in Figure 2). It increased and decreased rapidly in moisture due to its direct exposure to precipitation and evaporation. Toward the end of the sampling period, the moisture content of the upper fuel layer following rainfall events was often greater than that for the lower layer. This occurred because most late season rainfall was intercepted and retained by the upper layer due to water deficits in this fuel zone as a result of extended periods of drying (Figure 1a, Julian days 208, 232, and 239). If precipitation during this time period had been great enough and long enough, then full hydration of the total fuel profile would have occurred.

Ground fuel moisture contents were significantly different among the three slope positions ($P = 0.0962$). The greatest differences existed between the

---

[1] Anonymous. Climate of Alberta with data for the Yukon and Northwest Territories. Annual Reports for 1982–1988. Published by Atmos. Environ. Serv., Environ. Canada, Ottawa.

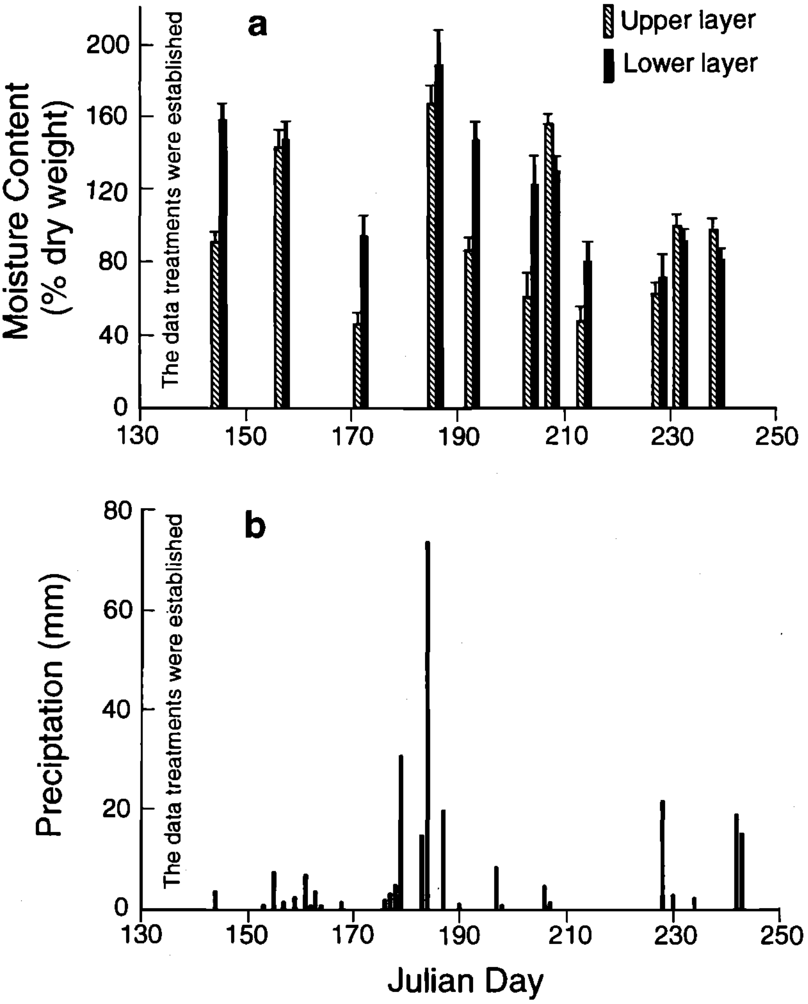

FIGURE 1. (a) Average ground fuel moisture contents with standard error bars for the control treatment ($n = 18$) showing a frequency of sampling over the 1990 study period, and (b) the amount and timing of precipitation throughout that period.

bottom position and the two upper positions for the control and T_1 (Table 2). Average moisture content for the upper layer at the bottom slope position was 102%, or about 22% higher than samples taken from the other two positions (Table 2). Average moisture content of the lower layer at the bottom position was 122%, or 22% higher than the average moisture contents measured at the middle and top positions. The moisture contents of the top and middle positions were similar regardless of fuel layer. As expected, no significant differences in moisture content between slope positions were detected for T_2, where hydration had been prevented (Table 2).

Ground fuel moisture contents were significantly different among the three treatments ($P < 0.0001$). Average moisture contents for the control treatment were always higher and more variable than those for the other two treatments, regardless of fuel layers and slope positions, because they were fully exposed to

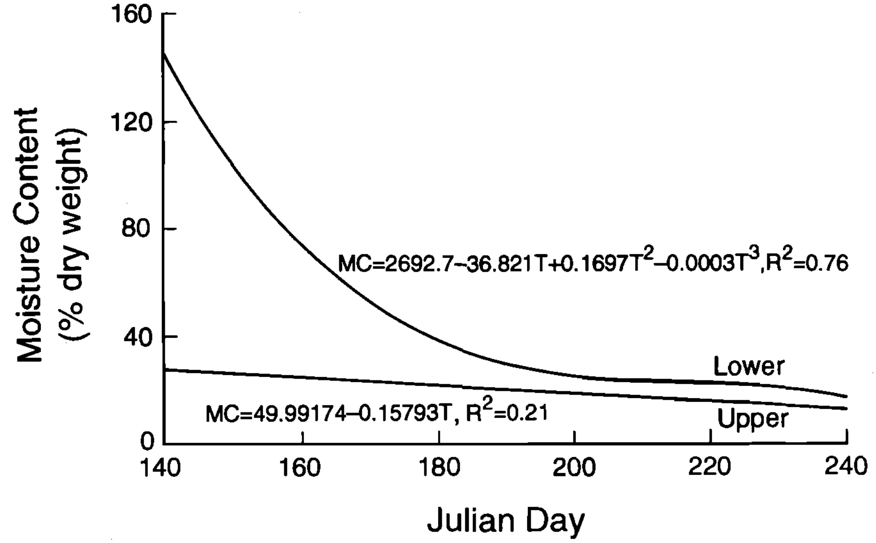

FIGURE 2. The drying curves for upper and lower organic layers of downed and dead fuel in an aspen stand in Alberta. These curves were constructed using fuels from a natural stand where the effects of precipitation and ground water had been eliminated. The study period is May 24 to August 27, 1990 (n = 180).

the full effects of precipitation and soil water. The moisture contents of the control samples varied from a maximum of 156% to a minimum of 47%, whereas the moisture contents for T_1 were on average 38% less than those for the control but 40% greater than those where all hydration was prevented (T_2). The differences

TABLE 2.

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

		Treatment (% odw + SE)			
Layer	Slope position	Control	Treatment 1	Treatment 2	Mean
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 ($P < 0.05$).

in moisture content also appeared to be independent of evapotranspiration. The rates of evaporation inferred from T_2 were similar among slope positions.

Changes in moisture content of T_1 always paralleled those of the control, suggesting the existence of other sources of hydration. The moisture contents for T_1 ranged from a maximum of 106% to a minimum of 29%. The moisture contents for T_2 steadily decreased from the start (Julian day 140) to the end of the sampling period (Julian day 240). This trend was especially strong for the lower layer (Figure 2), which was protected from precipitation and atmospheric wetting (i.e., condensation related to high levels of atmospheric moisture). By July 12 (Julian day 193), the fuel moisture contents for T_2 decreased to a constant value or equilibrium (i.e., air-dry moisture content). Moisture contents averaged 15% and 21.7% for the upper and lower layers, respectively (Table 2).

The effects of the three treatments on fuel moisture were most pronounced from July 12 to October 19 (Julian days 193–239) because of strong ambient drying conditions and limited precipitation. During this period the moisture contents in the lower layer for T_2 averaged 21.7% compared to equivalent values of 103.6% and 73.6% for the control and T_1, respectively.

An examination of the differences between moisture contents on each sample date by water balance calculations illustrated the magnitude of the probable sources of hydration. From this analysis, we determined that precipitation accounted for 64% of fuel moisture content in the upper fuel layer, which was almost twice that contributed by soil water (36%) (Table 3). Contributions by precipitation to the upper fuel layer were similar for all slope positions. Soil water, in contrast, was most effective in hydrating the lower fuel layer. Generally, soil water contributed slightly more moisture to the lower fuel layer than did precipitation (59% vs. 41%). Contributions were greatest at the bottom slope positions (Table 3), possibly because of drainage from up-slope positions and perhaps the proximity of the water table to the ground surface. However, our analysis indicated contributions by soil water were not significantly different between slope positions for either fuel layer.

The desorption curves for paired samples of the humus layer (*H*) and underlying soil (Figure 3) suggest the underlying mineral soil had greater water retention characteristics than the litter. The matric potential for air intrusion (inflection

TABLE 3.

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

		Slope position			
Fuel layer	Water source	Top	Mid	Bottom	Average
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 for the three slope positions and 21 for the average of these three positions.

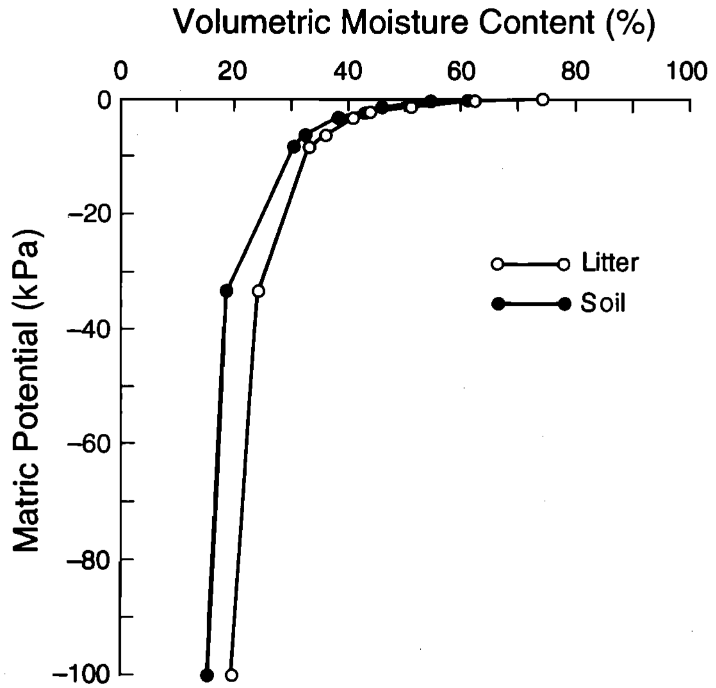

FIGURE 3. Desorption curves for aspen humus (H) and mineral soil at Elk Island National Park (n = 10 each).

point describing change in water content from partially saturated to fully unsaturated) into the litter was greater (−2.5 kPa vs. −5.0 kPa) than that of the soil, which indicated more energy was required to drain water from the soil. Furthermore, water potentials of the soil were greater than those of the litter at any given water content, which suggests the direction of water flow would be upwards from soil to litter, whenever the soil water content was equal to or greater than the litter water content (Paavilainen and Virrankoski 1967, Hanks and Ashcroft 1980). This was especially true for lower soil water contents. For example, the water potential difference between soil and litter at a water content of 35% was −2.5 kPa compared to −6 kPa at a water content of 60%.

The drying pattern for T_2, where all hydration was prevented, followed that of a "typical drying curve" (Fosberg et al. 1970). Its drying rate was fast in the beginning and slowed afterwards until reaching equilibrium (Figure 2). 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 drying period. However, the moisture contents for both the control and T_1 never reached an equilibrium moisture content of 20% (i.e., theoretical air dry moisture content for aspen litter in a laboratory environment of 27°C temperature and 70% relative humidity) (Van Wagner 1972, Anderson 1990). The minimum moisture contents during the study season for the control and T_1 were 47% and 29%, respectively. Theoretically, the moisture contents for all treatments should reach the same equilibrium moisture content if the drying period was long enough.

DISCUSSION

It is well known that the moisture content of surface and ground fuels is highly influenced by the amount and timing of rainfall (Wright 1967, Van Wagner 1987, Burgan 1988). Precipitation not only hydrates fuel directly, it also recharges soil water levels by infiltration (Hewlett 1982). In the absence of slope, the water table can be close to the soil surface and upward capillary soil water flow can occur and possibly contribute water to hydrate downed and dead fuels. Results of our study suggest that 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.

The effect of soil water on ground fuel availability would be most significant for the humus layer because of its greater bulk density and the fact that it is in 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 conditions 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. Therefore, predictions of fire occurrence may be accurate when upper fuel profiles are dry, but managers should not always expect complete consumption of lower organic layers because they may be too wet to burn.

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 slope position, the soil moisture content is usually greater than those at the upper slope 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. Roots and other live vegetation, which are commonly found in deeper organic ground fuels, contain more moisture than dead fuels and might be responsible for the higher moisture contents measured in this layer. 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.

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 evapotranspiration surface area within the study area. Bosch and Hewlett (1982) suggest increases in stream flow (i.e., decreases in evapotranspiration) are not detectable when the reduction in the canopy cover is less than 20%. In this study, we estimate that less than 0.1% of the evapotranspiration surface area was removed.

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 (i.e., greater slope) and shorter time to reach equilibrium moisture content because of its direct exposure to radiation and air movement (Anderson et al. 1978). 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. We believe the drying curve for the lower layer was more representative of a complete drying cycle.

FIRE MANAGEMENT IMPLICATIONS

In this study, the ground fuels never completely dried during the study period. These results may explain why others report difficulty in burning aspen stands (Fechner and Barrows 1976, Brown and Simmerman 1986, Alexander and Sando 1989), even after prolonged drying periods (Johnston and Woodard 1985). 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 hydrating fuels.

It is generally accepted that fuel moisture contents in excess of 30% are too wet for burning (Wright 1967, Bailey 1978, Wright and Bailey 1982, Brown and DeByle 1989). In this study, the average lowest moisture contents for upper and lower fuel layers from May 24 to September 20, 1990, were 48% and 72%, respectively. Occasionally the average moisture contents for T_1 samples were lower than that required for ignition but this occurred only for the upper layer and the upper slope positions. The moisture contents of the lower layer were always too wet for burning. Thus, burning would be still difficult under a nonprecipitation period because of the effect soil water had on ground fuel moisture content.

There may have been times suitable for burning earlier in the year, perhaps just after snowmelt, before the trees leafed out, when solar radiation and low humidity could dry fuels but we did not sample during this time of the year. Wright and Bailey (1982) state there are usually about 2 wk every second or third year when spring weather is suitable for burning in northern aspen forests. They also suggest that ground fuels may also be ignited after very long dry periods at the end of summer. Based on the drying trends of T_2, the upper fuel layer would reach a moisture content capable of ignition in about 7 days without any hydration, while 50 days or more would be required for the lower fuel layer (depending on the initial moisture condition). 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 (and probably do not frequently occur in the Aspen Parklands of Alberta) because natural ground fuels were periodically recharged by precipitation, which kept the moisture content high over the study period, and are shaded by a full canopy.

The Canadian Forest Fire Weather Index system does not use soil water when predicting fuel availability (Muraro and Lawson 1970, Van Wagner 1987). In well-drained red pine sites, where this system was first developed (Wright 1967), soil water probably was not a significant factor as is probably the situation in other areas of the boreal forest where this system is used successfully. In the absence of soil water, fuel availability can be fully accounted for by precipitation only.

Predictions of fuel availability may even be good when soil water is available if the level of the soil water is low. We suspect all of these factors contributed to why soil water was not incorporated in the systems that were designed to predict fuel availability.

LITERATURE CITED

ALEXANDER, M.E., and R.W. SANDO. 1989. Fire behavior and effects in Aspen-Northern hardwood stands. P. 263–274 *in* Proc. 10th Conf. Fire and For. Meteor., MacIver, D.C., H. Auld, and R. Whitwood (eds.). Ottawa, Canada. 471 p.

ANDERSON, H.E. 1990. Predicting equilibrium moisture content of some foliar forest litter in the Northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-429. 10 p.

ANDERSON, H.E., R.D. SCHUETTE, and R.W. MUTCH. 1978. Timelag and equilibrium moisture content of ponderosa pine needles. USDA For. Serv. Res. Pap. INT-202. 28 p.

ANDERSON, V.L., and R.A. MCLEAN. 1974. Design of experiments: A realistic approach. Marcel Decker, Inc., New York. 418 p.

BAILEY, A.W. 1978. Use of fire to manage grasslands of the Great Plains: Northern Great Plains and adjacent forests. P. 691–693 *in* Proc. First Internat. Rangeland Congr., Hyder, D.N. (ed.). 742 p.

BOSCH, J.M., and J.D. HEWLETT. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55:3–23.

BROWN, J.K. 1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16. 24 p.

BROWN, J.K., and N.V. DEBYLE. 1989. Effects of prescribed fire on biomass and plant succession in western aspen. USDA For. Serv. Res. Pap. INT-412. 16 p.

BROWN, J.K., and D.G. SIMMERMAN. 1986. Appraising fuels and flammability in western Aspen: A prescribed fire guide. USDA For. Serv. Gen. Tech. Rep. INT-205. 48 p.

BURGAN, R.E. 1988. 1988 Revisions to the 1978 national fire-danger rating system. USDA For. Serv. Res. Pap. SE-273. 39 p.

CHANDLER, C., P. CHENEY, P. THOMAS, L. TRABAUD, and D. WILLIAMS. 1983. Fire in forestry: Volume II—Forest fire management and organization. Wiley, New York. 298 p.

CROWN, P.H. 1977. Soil survey of Elk Island National Park, Alberta. Alberta Inst. of Pedology. Edmonton, Alberta. Report #S-77-38. 128 p.

DUNCAN, D.B. 1955. Multiple range and multiple F tests. Biom. 11:1–42.

DUNNE, T. 1978. Field studies of hillslope flow process. P. 227–294 *in* Hillslope hydrology, Kirkby, M.J. (ed.). Wiley, Toronto. 389 p.

FECHNER, G.H., and J.S. BARROWS. 1976. Aspen stands as wildfire fuel breaks. Eisenhower Consort. Bull. 4. Rocky Mount. For. and Range Exp. Stn., Fort Collins, CO. 26 p.

FOSBERG, M.A., J.W. LANCASTER, and M.J. SCHROEDER. 1970. Fuel moisture response—Drying relationships under standard and field conditions. For. Sci. 16:121–128.

GARDNER, W.H. 1965. Water content. P. 82–127 *in* Methods of soil analysis: Part 1, Physical and mineralogical properties, including statistic of measurement and sampling. Black, C.A., et al. (eds.). Number 9 in the series Agronomy. Am. Soc. Agron. Inc., Madison, WI. 1572 p.

HANKS, R.J., and G.L. ASHCROFT. 1980. Applied soil physics: Soil water and temperature applications. Springer-Verlag, New York. 159 p.

HEWLETT, J.D. 1982. Principles of forest hydrology. The University of Georgia Press, Athens. 183 p.

HOLOWAYCHUK, N., L.P. WILDING, and P.L. GERSPER. 1965. A core sampler for organic deposits. Can. J. Soil. Sci. 45:108–110.

JOHNSTON, M., and P.M. WOODARD. 1985. The effect of fire severity level on postfire recovery of hazel and raspberry in east-central Alberta. Can. J. Bot. 63:672–677.

MERRILL, D.F., and M.E. ALEXANDER. 1987. Glossary of forest fire management terms. Ed. 4. Publ.

NRCC No. 26516. Nat. Res. Counc. Canada, Can. Comm. on For. Fire Manage., Ottawa, Ontario. 91 p.

MOORE, R.E. 1939. Water conduction from shallow water tables. Hilgardia. 12:383–426.

MURARO, S.J., and B.D. LAWSON. 1970. Prediction of duff moisture distribution for prescribed burning. Fish. Environ. Can., Can. For. Serv., Pacific For. Res. Cent., Info. Rep. BC-X-46. 23 p.

PAAVILAINEN, E., and K. VIRRANKOSKI. 1967. Studies on the capillary rise rate of water in peat. Folia Forestalia. 36:1–6.

PARKS CANADA. 1986. Elk Island National Park: Resource description & analysis. Volume 1. A Park Can. Western region consulting report on file in the Warden's Office, Elk Island National Park, RR#1, Fort Saskatchewan, Alberta. 446 p.

POLSTER, D.F., and L.E. WATSON. 1979. Vegetation classification and evaluation—Elk Island National Park. Prepared by Techman Ltd. Parks Can., West. Reg., Dep. Indian and North. Affairs, Calgary, Alberta.

RICHARDS, L.A. 1965. Physical condition of water in soil. P. 128–152 *in* Methods of soil analysis: Part 1, Physical and mineralogical properties, including statistic of measurement and sampling. Black, C.A., et al. (eds.). Number 9 in the series Agronomy. Am. Soc. of Agronomy, Inc., Madison, WI. 1572 p.

SAMRAN, S. 1991. Ground fuel hydration in aspen stands of central Alberta. M.Sc. thesis, Univ. Alberta, Edmonton. 70 p.

TOPP, G.C., and W. ZEBCHUK. 1979. The determination of soil-water desorption curves for soil cores. Can. J. Soil Sci. 59:19–26.

VAN WAGNER, C.E. 1972. Equilibrium moisture contents of some fine forest fuels in eastern Canada. Petawawa For. Exp. Stn., Info. Rep. PS-X-36. 11 p.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian forest fire weather index system. Can. For. Serv. For. Tech. Rep. 35. 37 p.

WRIGHT, H.A., and A.W. BAILEY. 1982. Fire ecology of the United States and southern Canada. Wiley, New York. 501 p.

WRIGHT, J.G. 1967. Forest-fire hazard research as developed and conducted at the Petawawa Forest Experiment Station. Can. Dep. Forest. Rural Dev. For. Fire Res. Inst. Info. Rep. FF-X-5. 63 p.

Manuscript received July 13, 1993

AUTHORS AND ACKNOWLEDGMENTS

The senior author was a M.Sc. graduate student in the Department of Forest Science, University of Alberta, 751 General Services Building. Edmonton, Alberta T6G 2H1, Canada. P.M. Woodard is the fire scientist, and R.L. Rothwell is the forest hydrologist in that Department. Both served as cosupervisors for Mr. Samran's thesis work. S. Samran has returned to Thailand where he is currently a forester with the Forest Management Division, Royal Forest Department, in Bangkok. We gratefully acknowledge the financial support provided by the Canadian International Development Agency (CIDA) and the funding administration support provided by T.M. Thompson and Associates of Vancouver, B.C. The Department of Forest Science also contributed to the success of this project. We also acknowledge the in-kind assistance provided by wardens at Elk Island National Park, Alberta.