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International Journal of Wildland Fire

Scientific Journal of IAWF

VOLUME 11, 2002

Editor-in-Chief
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IJWF is published for the International Association of Wildland Fire by:

International Association of Wildland Fire

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International Journal of Wildland Fire, 2002, **11**, 267–279

Measuring moisture dynamics to predict fire severity in longleaf pine forests*

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This paper is derived from a presentation at the 4th Fire and Forest Meteorology Conference, Reno, NV, USA, held 13–15 November 2001

Abstract. To understand the combustion limit of biomass fuels in a longleaf pine (*Pinus palustris*) forest, an experiment was conducted to monitor the moisture content of potentially flammable forest floor materials (litter and duff) at Eglin Air Force Base in the Florida Panhandle. While longleaf pine forests are fire dependent ecosystems, a long history of fire exclusion has allowed large amounts of pine litter and duff to accumulate. Reintroducing fire to remove excess fuel without killing the longleaf pine trees requires care to burn under litter and duff moisture conditions that alternately allow fire to carry while preventing root exposure or stem girdle. The study site was divided into four blocks that were burned under litter and duff moisture conditions of wet, moist, dry, and very dry. Throughout the 4-month experiment, portable weather stations continuously collected meteorological data, which included continuous measurements of water content in the forest floor material from *in situ*, time-domain reflectometers. In addition, volumetric moisture samples were collected almost weekly, and pre-burn fuel load and subsequent consumption were measured for each burn. Meteorological variables from the weather stations compared with trends in fuel moisture showed the influence of relative humidity and precipitation on the drying and wetting rates of the litter and duff. Fuel moisture conditions showed significant influence on patterns of fuel consumption and could lead to an understanding of processes that govern longleaf pine mortality.

Introduction

As fire is used more frequently to help restore natural patterns of vegetation, it is becoming increasingly important to understand the environmental conditions that control the initiation and extent of combustion in a variety of potential fuel elements. While the influence of weather on fuel condition is well known for woody fuel types, most relationships are designed to quantify potential behavior in wildfire and are poorly applied to prescribed fire for determining desired effects. Applying such relations to combustion processes that lead to more benign goals, such as reducing litter (needles and bark slough with no evidence of decay) and duff layers (decomposed organic matter) to enhance seed germination, is not straightforward. In addition, most fuel moisture algorithms are embedded in fire danger rating systems and consider only daily-varying conditions (McArthur 1966; Deeming *et al.* 1978; Bradshaw *et al.* 1983; Van Wagner 1987; Stocks *et al.* 1989; Viney and Hatton 1989; Viegas *et al.* 1999). This inhibits their use for planning fire at different times of the day. Although time-lag functions have been developed to determine diurnal variation of fuel moisture (e.g. Catchpole *et al.* 2001), they do not consider the effect of precipitation or wind.

Knowing a threshold of moisture that fosters combustion could help define the extent of consumption and subsequent effects of fire at resolutions that are important for prescribing the use of fire. The moisture of extinction, the moisture content above which a fuel element cannot sustain fire, is known for some Australian fuel types (Tolhurst and Cheney 1999), but the extinction moisture is not well known in other fuel types. Also, the spatial and temporal variability of extinction moisture is poorly understood.

10.1071/WF02010 1049-8001/02/030267

We have undertaken a series of experiments to help define the extinction moisture in a variety of fuel types. In doing so, we hope to quantify the moisture values that lead to different stages of combustion and resulting consumption. In addition, we are developing methods of continuously monitoring water content in non-traditional fuel elements, such as litter, duff, and moss, with the hopes of developing new relationships between readily available weather observations and moisture in the forest floor. This paper describes results from one of our first experiments in longleaf pine [*Pinus palustris*] of the south-eastern United States.

A management goal in the longleaf pine region is to reintroduce fire to remove excess fuel without killing the longleaf pine trees. This requires knowledge to burn under fuel moisture and weather conditions that alternately allow fire to carry while preventing deleterious fire effects, such as extensive consumption of the duff and exposure to heat that could lead to root exposure or stem girdle and eventual mortality.

To help understand the effects of fuel moisture on combustion of biomass fuels in a longleaf pine forest, we continuously monitored weather and the water content of litter and duff throughout a series of controlled burns that occurred in late winter, early spring, and autumn of 2001. We measured fuel loading before and after each burn from which consumption was calculated. The sequence allowed observations of combustion processes and fire effects in wet, moist, dry, and very dry conditions.

Methods

The study site was located on Eglin Air Force Base in the Florida Panhandle (N 30° 38′ latitude, W 86° 24′ longitude). Terrain in the region is within a few meters of mean sea level and relatively flat. The site was divided into four adjacent units of about 25 ha each (Fig. 1) that were burned in 2001 on 18 February 1 (unit A), 27 March (unit B), 26 April (unit C), and 21 September (unit D).

Each burn was timed to fall within a controllable range of moisture conditions that tested the limits of consumption. The first burn on 18 February was considered relatively wet by local standards, the second burn on 27 March was moist, the third burn on 26 April was dry, and the fourth burn on 21 September was very dry. All burns were hand ignited using a strip-head ignition pattern. The fire behavior for the wet and moist burn units had average flame length of less than 0.50–0.75 m and rates of spread approximately 1–3 m per minute. The flame lengths of the dry burn were approximately 1 m with rates of spread at 3–5 m/min. No flame length or rate of spread information were available for the fourth, very dry burn.

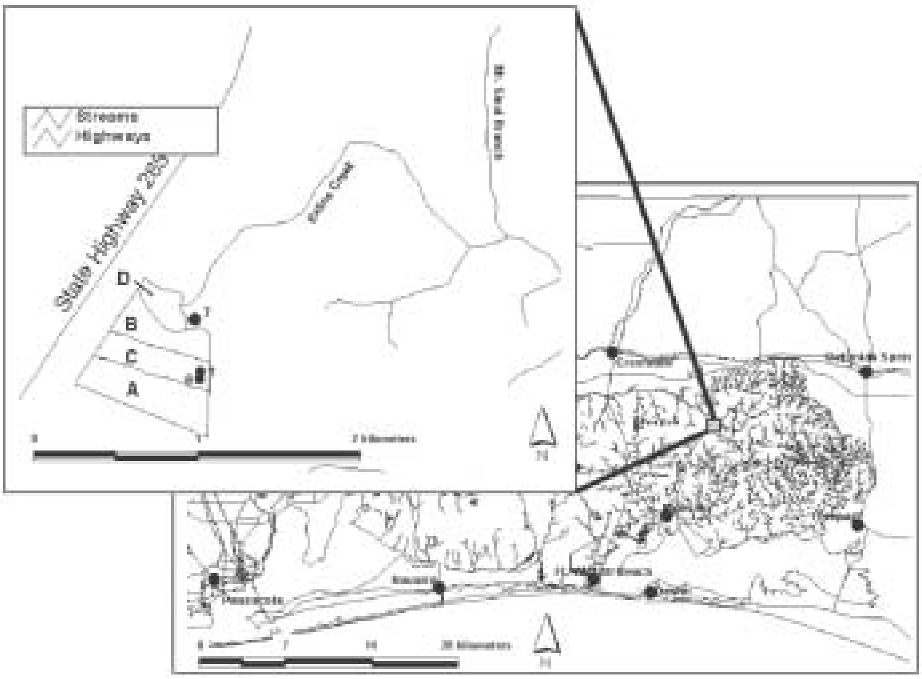

Fig. 1. Location of burn units and weather stations at Eglin Air Force Base in Florida during the 2001 experiment. Unit A was burned on 18 February in a wet regime, unit B was burned on 27 March in a moist regime, unit C was burned on 26 April in a dry regime, and unit D was burned on 21 September in a very dry regime. Stations 1 and 6 were installed on 14 February and removed on 26 April. Station 7 was installed on 21 March and left in place.

Weather

To monitor below-canopy weather conditions and forest floor moisture conditions, we selected sites that represented general characteristics of all units. Two weather stations were established on 14 February (day number 45), one next to a large longleaf pine (Station 6) and one in a nearby opening (Station 1). We thought we could keep these stations in place throughout the experiment but last-minute changes in the burn plan required Stations 6 and 1 to be removed on 26 April (day number 116) just before unit C was burned. Another station (Station 7) was established next to a large longleaf pine on 21 March (day number 80) and ran until the end of the experiment. All of the weather stations measured wind speed, wind direction, air temperature, and relative humidity. In addition, precipitation, barometric pressure, and 10-hour fuel stick temperature and moisture were measured at a base station, which transmitted its weather and moisture data back to our office via cell phone. The base station equipment began at Station 1, then was moved the morning before the unit C burn (26 April) to an opening near Station 7 for the remainder of the experiment.

Sensors at the monitoring stations were sampled every 10 s and averaged every 15 min. The anemometers were mounted 2 m above ground level (agl), air temperature and relative humidity sensors were 1 m agl, and fuel-stick temperature and moisture sensors were 30 cm agl. The placement of litter and duff probes is discussed in the next section.

In situ moisture

The continuously monitoring weather stations recorded measurements of water content in litter, duff, and sand from *in situ*, time-domain reflectometer (TDR) probes (CS–615, Campbell Scientific, Inc), consisting of two parallel wave guides, 3.2 mm in diameter, 30 cm long, and 3.2 cm apart. Changes in water content of a surrounding material affect the transmit time of electromagnetic signals traveling along the wave guides. Therefore, fluctuations in water content can be represented by changes in the period of the signal (inverse of the oscillation frequency). The period of CS–615 TDR probes ranges from 0.7 to 1.6 ms. In mineral soil with low salt content, this corresponds to volumetric water contents of about 0.0–0.5, respectively (Bilskie 1997). We refer to the uncalibrated period output of the TDR probes as a moisture index (*MI*).

TDR instruments commonly are used for measuring water content in mineral soils (e.g. Topp *et al.* 1980; Stein and Kane 1983; Topp and Davis 1985; Herkelrath *et al.* 1991). It is difficult to measure water content in litter and duff with TDR instruments because the structure and composition of the organic material is highly heterogeneous, preventing consistent contact between the probe and the material it is trying to measure. Ferguson *et al.* (2001), however, found value in placing TDR instruments in organic soils, especially if each probe can be inserted with minor disturbance, remain in place, and be calibrated *in situ.* We followed such guidelines in this study.

Placement of the TDR probes at each weather station required some care. TDR instruments have an area of influence surrounding each probe that decreases with distance from the probe to a distance that is about the width of spacing between wave guides (3.2 cm). Therefore, it is important to place the probes in layers that are sufficiently thick to be representative of the material within the layer and not of material surrounding the layer.

There was little to no litter and only shallow layers (up to 6 cm) of duff in the open areas, where two probes measured water content in the shallow duff and underlying sand. Deep layers of litter (5–15 cm thick) and humic duff (well decomposed organic material), which was 10–20 cm thick, surrounded most longleaf pine trees, where three sets of TDR probes measured water content of litter, duff, and underlying sand. A fermentation layer of duff (partially decomposed litter) between the litter and humic duff was too thin to capture with TDR instruments. Where possible, probes in the organic material were inserted near mid-depth and parallel to the layering. Every effort was made to locate TDR instruments in layers that had consistent thickness and composition over the length of the probes. Probes in sand were inserted vertically.

Table 1 summarizes TDR probe locations at each station along with the average bulk density within the study area. Station 1 was in a small opening in the forest. It recorded data from two TDR probes; probe 1A was inserted horizontally about 3 cm from the surface in a humic duff layer that was about 6 cm thick. Probe 1B was oriented

Table 1. Locations of TDR probes at stations 1, 6, and 7 and average bulk density (± standard error) within the study area

Material type	Station 1 (in opening)	Station 6 (near tree)	Station 7 (near tree)	Bulk density (gm/cm^3)
	Probe No.: depth (cm)			
Litter	—	6A : 7	7A : 3	0.042 ± 0.003
Duff (humic)	1A : 3	6B : 17	7B : 7	0.123 ± 0.005
Sand	1B : 4–34	6C : 22–52	7C : 7–37	—

vertically in the sand at 4–34 cm from the surface. Because the TDR instrument is influenced by conditions within about 3.2 cm of its probes, 1A may have been affected slightly by the overlying atmosphere and moisture of the underlying sand.

Station 6 was next to a nearby longleaf pine. It recorded data from three TDR probes; probe 6A was placed horizontally 7 cm from the surface in the litter layer of about 12 cm thick, 6B was placed horizontally at 17 cm from the surface in the middle of a humic duff layer of about 10 cm thick, and 6C was inserted vertically in the sand at 22–52 cm from the surface.

Station 7 was located next to a large longleaf pine tree in a nearby unit. TDR probe 7A was located horizontally at 3 cm from the surface in a litter layer of about 6 cm thick, 7B was placed horizontally at 7 cm in the middle of a humic duff layer of about 8 cm thick, and 7C was inserted vertically from 7 cm to 37 cm in the sand. Like probe 1A, the shallowness of litter at Station 7 may have caused probe 7A to be slightly influenced by the overlying atmosphere and underlying duff layer.

Moisture sampling

To help calibrate the TDR probes, samples of known volume in litter and duff were collected almost weekly following a method that was adapted from Wilmore (2000). Samples were collected from around the bases of large longleaf pine trees from the surface down to the sand. All the material within a 12.7 cm × 12.7 cm square was collected. The samples were broken up into the three layer types: litter, fermentation duff layer, and humic duff layer. The depth of each layer was recorded and the volume calculated. The samples were collected in airtight bags and weighed wet. Later, they were dried in an oven at 70°C to remove all the moisture and then weighed dry. The volumetric moisture content was then calculated as a ratio of the weight of water lost during drying to the volume of the sample as:

$$VMC_s = \frac{M_i - M_f}{V} \times 100, \qquad (1)$$

where VMC_s = volumetric moisture content of the sample, M_i = initial mass of the sample, M_F = final mass of the sample, and V = volume.

Calibration of TDR Probes

To convert the moisture indexes (*MI*) from TDR probes in the litter and duff layers to values of volumetric moisture content (VMC_{tdr}), we compared the period response output of each probe to the VMC_s from samples. A best fit was derived between the probe output and VMC_s through simple regression, following techniques described in Ferguson *et al.* (2001). Applying a natural logarithm transformation to the *VMC* linearized the relationship. Also, the variance of *VMC* was positively correlated with the mean (i.e. as the moisture levels increase, the variability of the volumetric moisture content increases). The log-transformation of *VMC* helped stabilize this variance.

The r^2 values and the regression equations for TDR probes in litter and duff at stations 1, 6, and 7 are summarized in Table 2. The r^2 values are somewhat low, primarily because the single point measurement of an individual probe does not reflect the spatial variability captured in the samples, which were gathered in many places throughout each burn unit. For example, Fig. 2*a* shows the VMC_s of litter samples taken from around the bases of longleaf pine trees and the moisture index readings from TDR probe 6A located in the litter. While the variance among samples appears large, when the time series of moisture index is calibrated against the samples, the resulting curve (Fig. 2*b*) shows magnitudes and trends that are consistent with qualitative observations of moisture conditions during and between sampling periods. That is, the magnitude and trend of the resulting moisture curve become physically reasonable.

No volumetric moisture samples were taken in sand. While there are a number of different ways to calibrate soil moisture from TDR instruments (e.g. Ledieu *et al.* 1986), we felt that the manufacturer's conversion equation was sufficient: $VMC = -0.187 + 0.037(MI) + 0.335(MI)^2$, where *VMC* is the volumetric moisture content and *MI* is the moisture index. This does not consider the effect of salinity (Atkins *et al.* 1998), which could be a factor in Florida. The conversion to volumetric moisture in the sand did not significantly change its range of values, only absolute magnitude.

Fuel consumption

Pre- and post-burn fuel loadings were measured at a set of 30 plots on each unit following procedures outlined in Brown (1974). While all potential fuel elements (above ground, dead and down woody debris, and forest floor organic material) were measured, only effects on forest floor fuels are discussed in this work. Forest floor materials were measured with eight steel pins that were placed 0.5 m apart in an orthogonal cross grid from the center of each plot. While

Table 2. Calibration equations and r^2 values for TDR probes at stations 1, 6, and 7, where VMC_{tdr} is the volumetric moisture content derived from the TDR probes and *MI* is the probe's moisture index (output period in milliseconds)

Probe No.	Material type	Depth (cm)	Calibration equation $\ln(VMC_{tdr})$ =	r^2
1A	Duff in opening	3	6.49(MI)–2.76	0.176
6A	Litter near tree	7	48.9(MI)–37.6	0.558
6B	Duff near tree	17	20.6(MI)–14.0	0.129
7A	Litter near tree	3	19.0(MI)–15.7	0.488
7B	Duff near tree	7	8.27(MI)–4.35	0.513

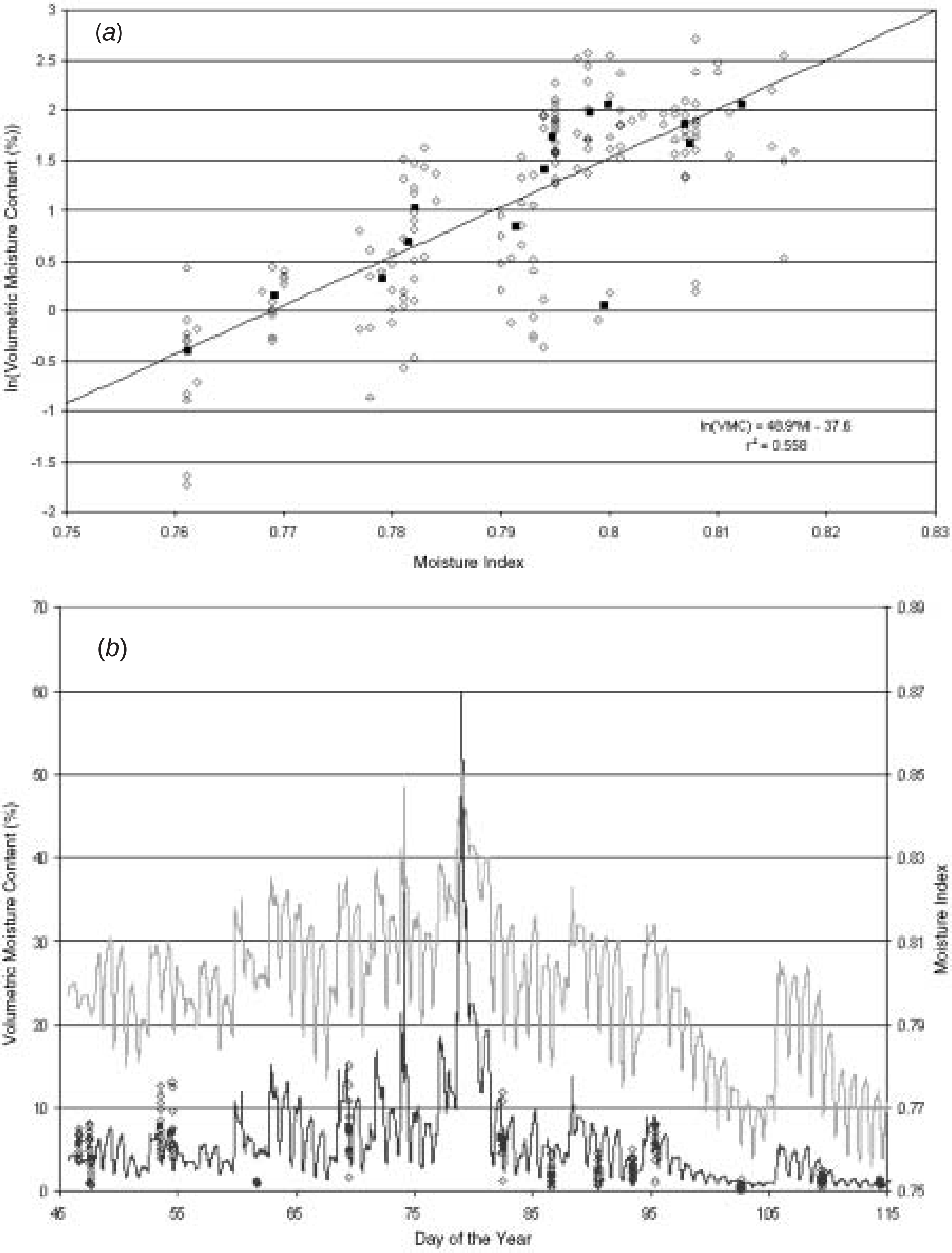

Fig. 2. (*a*) Calibration curve for TDR probe 6A (litter at the base of tree). The open diamonds are the moisture index (*MI*) at the time of a sample plotted against the volumetric moisture content of the litter sample (VMC_s). The filled squares are the average volumetric moisture content of litter samples for a day.
(*b*) A time series of calibrated volumetric moisture content (VMC_{tdr}) and moisture index (*MI*) from TDR probe 6A (litter at base of tree). Shown are volumetric moisture content (VMC_s) in samples of litter (open diamonds), daily sample averages (filled squares), *MI* (gray line), and VMC_{tdr} (black line).

plots were located in a variety of vegetation types in each burn unit, only pins in areas of longleaf pine vegetation were compared with TDR measurements. To complement the plot pins, which were mostly in open areas between trees, groups of eight, equally spaced pins were placed around the bases of 20 randomly selected longleaf pine trees.

Both plot and tree pins were inserted through the organic forest floor material and well into the sand until they were flush with the top of the litter. The depth of the litter layer was determined prior to the burns by carefully measuring (with minimal disturbance) the distance from the top of the pin to the bottom of the litter layer. After each burn, two measurements were taken: one from the top of the pin to the top of the remaining forest floor and one from the top of the pin to the surface of the sand. From this information the pre-burn and post-burn depth of litter and duff were calculated. Consumption is calculated as percentage consumed by depth.

Observations

Moisture trends

Because TDR probes are difficult to calibrate in heterogeneous landscapes with heterogeneous material, illustrated by low r^2 values in Table 2, it is helpful to demonstrate some value in the uncalibrated measurements. Indeed, burn managers successfully used uncalibrated *MI* values during the experiment to help make decisions about whether moisture conditions fit into wet, moist, dry, or very dry categories. Such usage is possible only with probes that are fixed in place and undisturbed throughout the recording period. The output of one probe cannot be compared with another because each probe is inserted in material of structure and composition that may be quite different from another, which influences the contact surface area along the probes and the resulting frequency response.

Figure 3 shows the uncalibrated trend of moisture from Station 1. The sand layer's moisture index at 07:00 LST (Local Standard Time) was similar for the first burn on 18 February and second burn on 27 March (0.862 and 0.863, respectively) but clearly drier (0.836) for the third burn on 26 April. While 07:00 LST duff moisture index values were lowest for the third burn (0.798), the index suggested that wetter conditions existed in the duff during the second burn (0.850) than during the first burn (0.839). The second burn had been expected to be drier than the first because the surface litter layer appeared significantly drier to the burn crew. In fact, measurements from Station 6 near a longleaf pine (Fig. 4) showed slightly drier moisture conditions (0.807) in litter at 7 cm below the surface during the second burn than during the first burn (0.811). Deeper layers of duff and sand at Station 6 followed the same trends as those at Station 1. Between the second and third burns, the duff moisture index at 07:00 LST fell from 0.823 to 0.809 at Station 6 and from 0.865 to 0.805 at Station 7 (Fig. 5). The

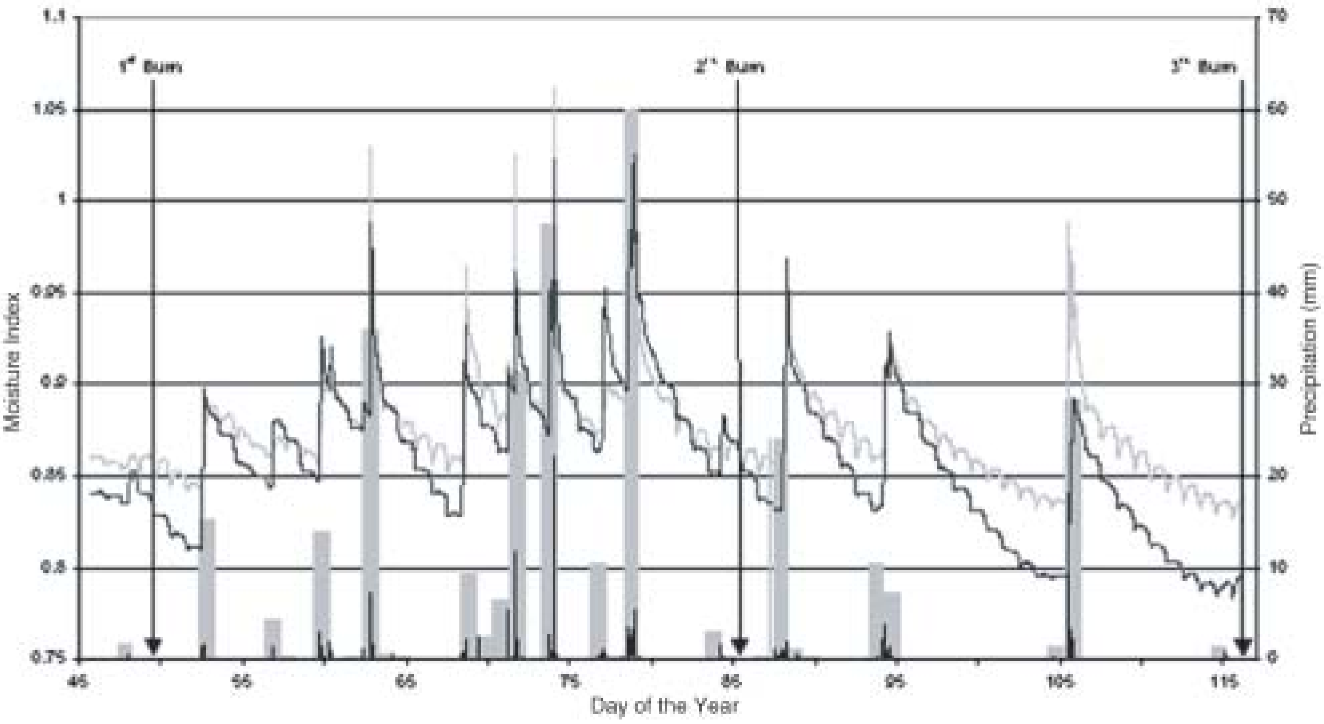

Fig. 3. Time series of uncalibrated moisture index (*MI*) from Station 1 in a small clearing: 1A (black line) is placed horizontally in duff at 3 cm and 1B (light gray line) is placed vertically in sand from 4 to 34 cm. Gray bars indicate 24-h precipitation totals in millimeters and thin black bars show15-min totals. Arrows indicate the date of each experimental burn.

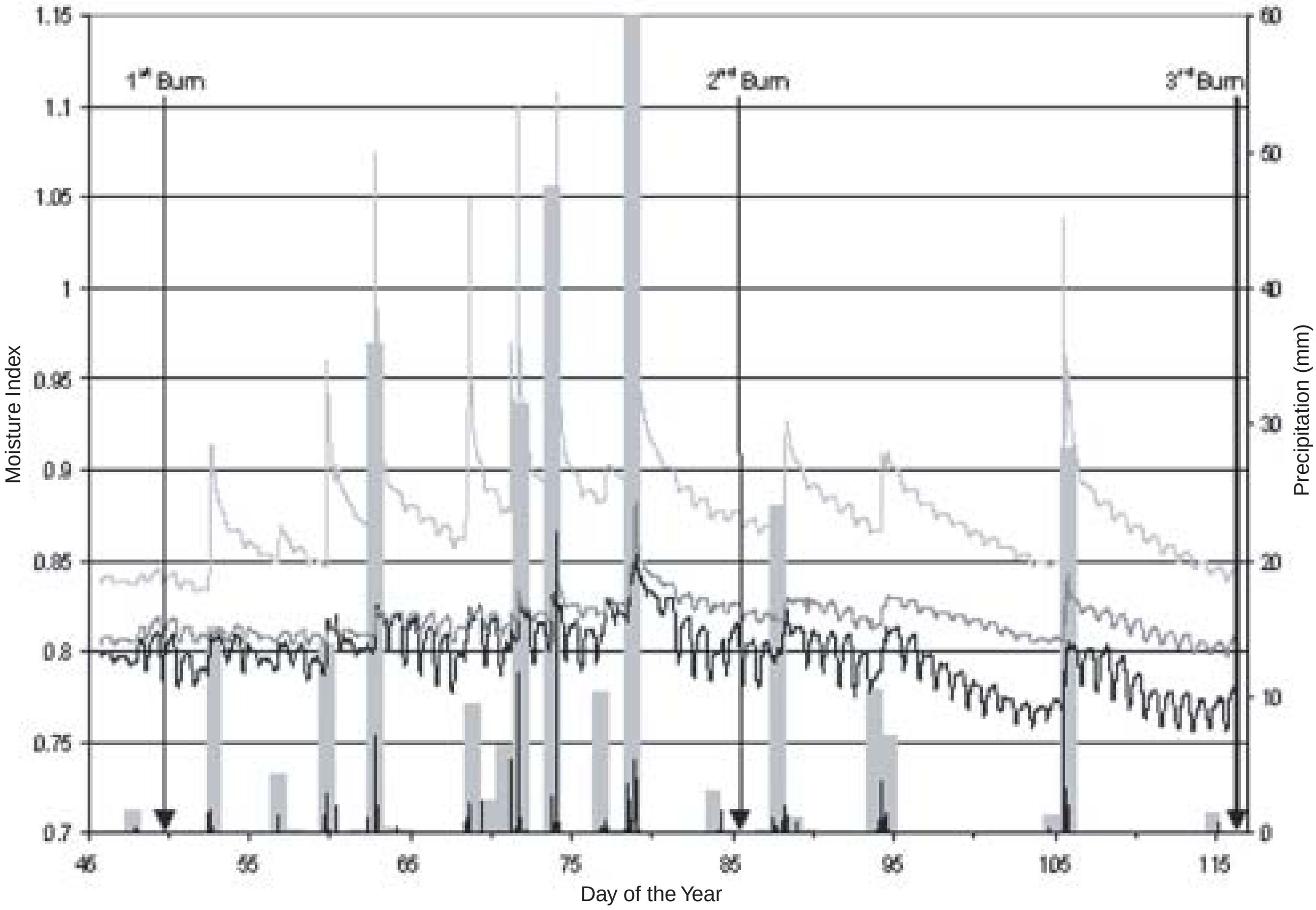

Fig. 4. Time series of uncalibrated moisture index (*MI*) from Station 6 near a large longleaf pine: 6A (black line) is in litter at 7 cm, 6B (dark gray line) is in duff at 17 cm and 6C (light gray line) is in sand from 22 to 52 cm. Gray bars indicate 24-h precipitation totals in millimeters and thin black bars 15-min totals. Arrows indicate the date of each experimental burn.

fourth burn on September 21 was the driest of all, with a duff moisture index at Station 7 of 0.778.

We see similar trends in relative dryness after the probes are calibrated. Table 3 summarizes the moisture index (*MI*) and calibrated volumetric moisture content (VMC_{tdr}) at 07:00 LST on the day of each burn in litter and duff layers at Stations 1, 6, and 7. Note that we use VMC_{tdr} data here instead of VMC_s because samples were not always available at consistent times near ignition and the spatial location of samples were not recorded. While uncalibrated *MI* values can show trends over time, the calibrated values of VMC_{tdr} help show moisture trends between sites. For example, the deep litter and duff layers at site 6 held more water content than the shallow litter and duff layers at site 7. The water content in shallow duff within a small clearing (probe 1A) was similar to the water content of shallow duff layers near trees (probe 7B).

Effect of rain on moisture content

The amount and duration of rain affected how deeply into the forest floor the moisture penetrated and how much moisture the organic material absorbed. Sharp increases in moisture content occur in shallow duff layers after each rain event. Deep layers, however, respond only to heavy and sustained rain events. For, example, Fig. 6 shows time series of calibrated volumetric moisture from litter (probe 6A), shallow duff (probe 1A), and deep duff (probe 6B). Between days 50 (19 February) and 60 (1 March), three moderate rain events occurred. The TDR probe in the shallow duff of a small clearing (1A) spiked noticeably after each event. The same rain events were barely noticeable at the deeper duff probe by the tree (6B) and it appears that about 20 mm in 24 h is needed to have a substantial impact on the duff moisture at 17 cm.

The volumetric moisture content (VMC_{tdr}) of the litter reaches levels comparable to the duff only during the heaviest of rain events and then drops quickly (probe 6A in Fig. 6). The litter wets and dries more quickly than the other components of the forest floor. A large diurnal variation can be seen in the time series of VMC_{tdr} in litter, reflecting its high porosity, which allows air to circulate through the litter.

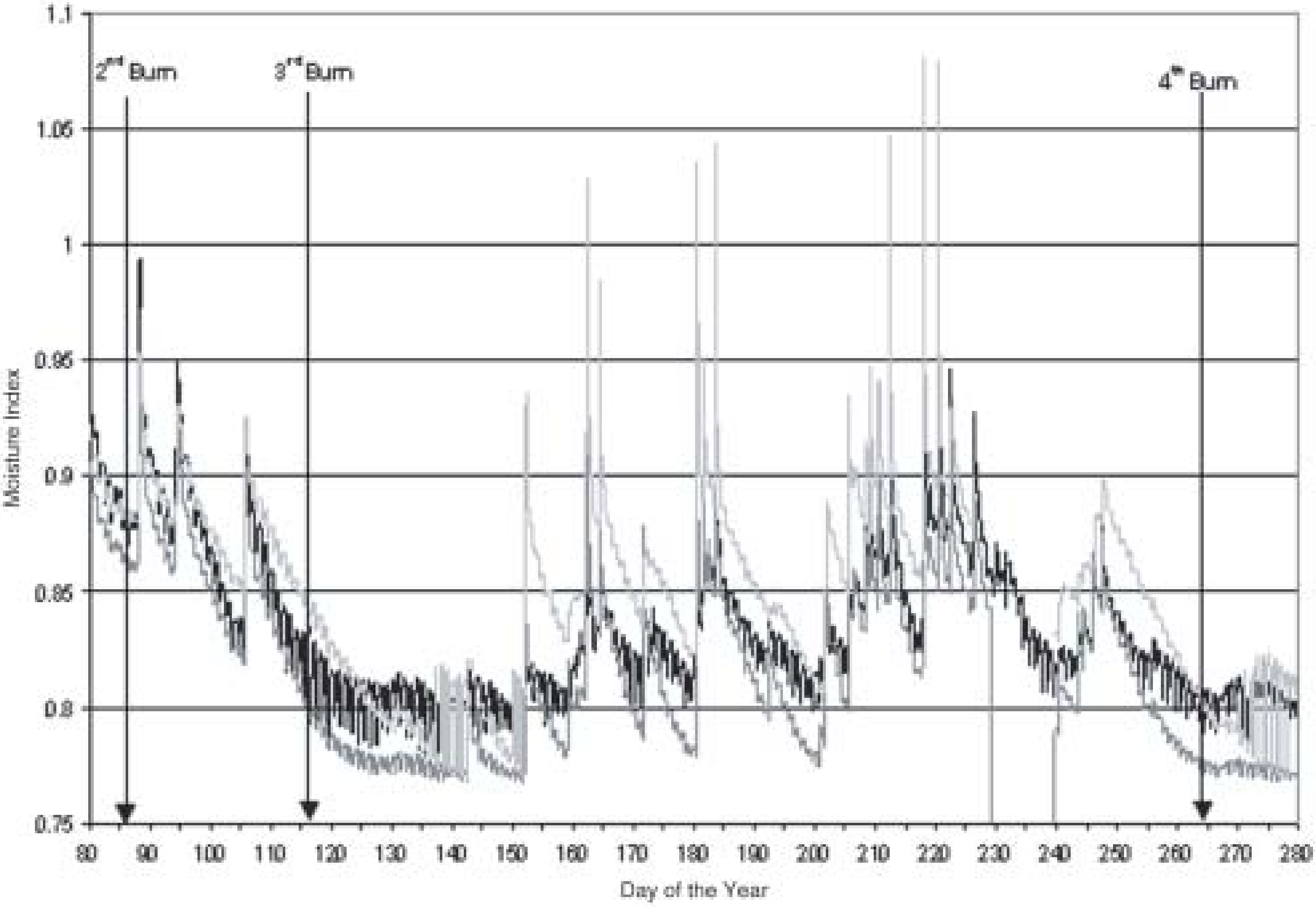

Fig. 5. Time series of uncalibrated moisture index (*MI*) from Station 7 near a large longleaf pine: 7A is in litter at 3 cm (black line), 7B is in duff at 7 cm (dark gray line), and 7C is in sand from 7 to 37 cm (light gray line). Arrows indicate the date of the each experimental burn. Sand and duff measurements were missed for a period from days 229 to 240.

Other aspects of weather, such as wind, temperature and relative humidity affect drying rates of the forest floor material. In longleaf pine forests of the Florida Panhandle, however, the deep sand layer keeps the forest floor exceedingly well drained even after very heavy rains. This allows the litter and duff to dry at a relatively constant rate.

By comparing the uncalibrated TDR measurements (*MI*) to wind, temperature, relative humidity, and precipitation, it was found that nearly all of the variability in *MI* could be explained by the previous day's *MI* and precipitation. For example, a multiple linear regression of the moisture index at time t (MI_t) from probe 7A with the previous day's moisture index (MI_{t-1}), the square root of the most current 24-h precipitation (P_t) and the previous 24-h precipitation total (P_{t-1}) yields:

$$MI_t = 0.9957 \times MI_{t-1} + 0.023 \times \sqrt{P_t} - 0.013 \times \sqrt{P_{t-1}}, \quad (2)$$

with an r^2 value of 0.9997. The moisture values at 13:00 LST and the 13:15–13:00 LST precipitation totals from days 55 through 219 were used to derive the regression. Figure 7 shows how the model compares with observations. Pearson's product-moment correlation between the observed and modeled moisture index for the model-development time period (days 55–219) yielded a correlation value of 0.9533. For days 220–335, which were omitted from the model development, the correlation value was 0.9212.

These results may have useful applications. For example, the moisture content of the forest floor material could be predicted a number of days in advance during a rain-free period or at least 24 h in advance after precipitation. The amount of rain necessary to increase the moisture content to a given level also could be estimated, which may be useful for land and fire managers.

Effect of moisture on consumption

The relatively moist conditions under trees during the first two burns (16% to 19% VMC_{tdr} in duff and 3% to 8% in litter) coincide with very small amounts of duff consumption (2% to 7%) and only moderate amounts of litter consumption (60% to 69%) around the trees (Table 4). Drier conditions during the last two burns (8% to 14% VMC_{tdr} in duff and less

Table 3. Moisture values at 07:00 LST on the day of each burn of litter and duff probes at stations 1, 6, and 7, where *MI* is the moisture index (frequency output of the probe) and VMC_{tdr} is the calibrated volumetric moisture content

Probe location	1st Burn		2nd Burn		3rd Burn		4th Burn	
	MI	VMC_{tdr}	*MI*	VMC_{tdr}	*MI*	VMC_{tdr}	*MI*	VMC_{tdr}
1A: 3 cm duff in clearing	0.839	14.6%	0.850	15.8%	0.789	11.3%		
6A: 7 cm litter near tree	0.811	7.7%	0.807	6.3%	0.779	1.6%		
6B: 17 cm duff near tree	0.819	17.5%	0.823	19.0%	0.809	14.3%		
7A: 3 cm litter near tree			0.886	3.0%	0.835	1.2%	0.808	0.7%
7B: 7 cm duff near tree			0.865	16.5%	0.805	10.0%	0.778	8.0%

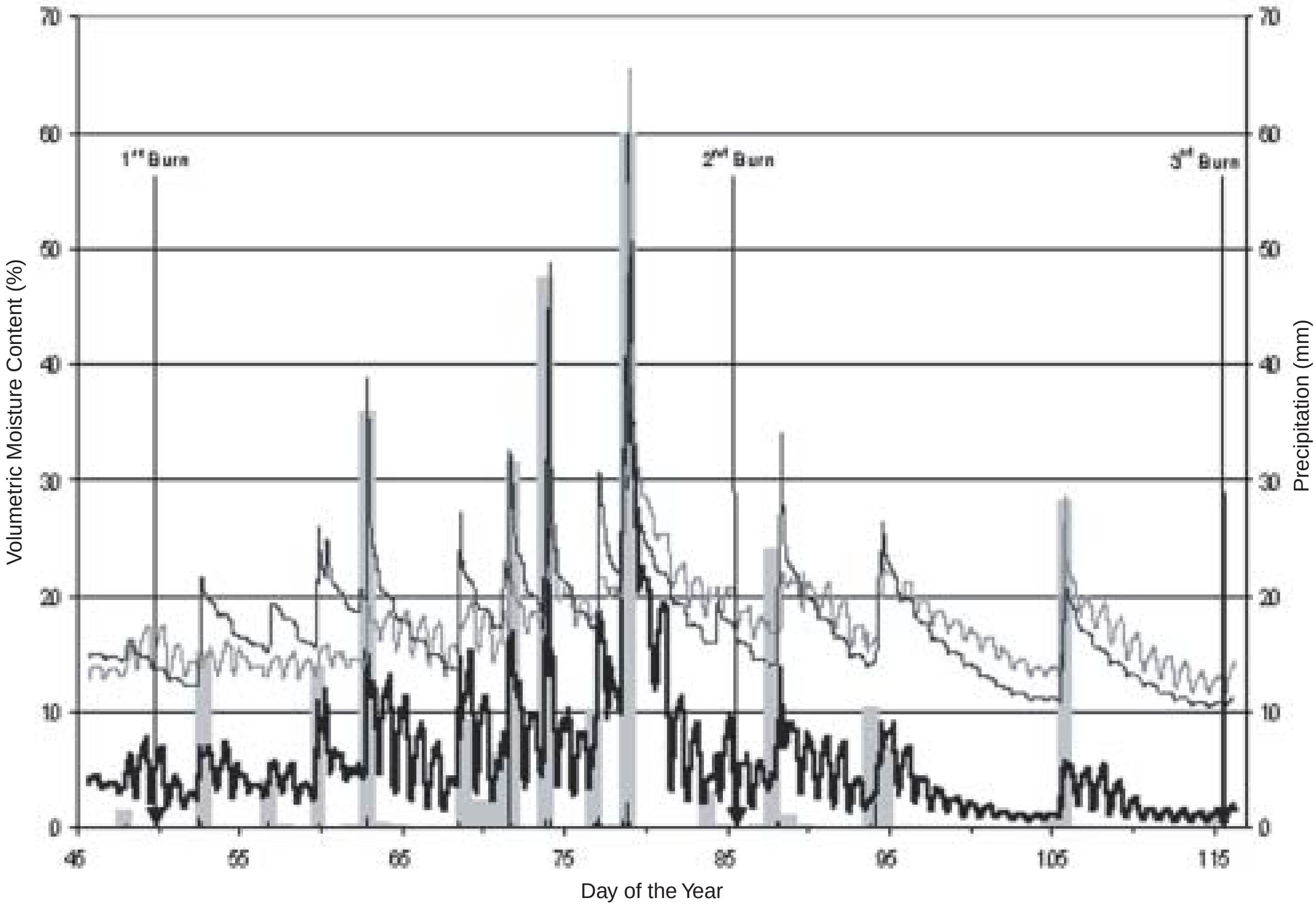

Fig. 6. Time series of calibrated volumetric moisture content (VMC_{tdr}) from duff and litter at Station 6 and Station 1: 6A is in litter at 7 cm (thick black line), 6B is in deep duff at 17 cm (gray line), and 1A is in shallow duff at 3 cm (thin black line). Gray bars indicate 24-h precipitation totals in millimeters and thin black bars are 15-min totals. Arrows indicate the date of each experimental burn.

than 2% in litter) were associated with significant duff consumption (50% to 65%) and litter (90% to 95%). Figure 8 combines VMC_{tdr} of litter and duff (Table 3) with consumption (Table 4) to more clearly illustrate the effect of fuel moisture on consumption.

While trends in moisture and consumption between the first two (wet and moist) and last two (dry and very dry) burns appear physically consistent, there is a discrepancy between the first and second burns. Greater duff consumption occurred during the second burn when duff moisture was greater, which seems to be caused by the timing of ignition related to the diurnal recovery of relative humidity. The first burn was ignited from 13:15 to 16:45 LST, whereas the second ignition happened from 10:00 to 13:00 LST (Fig. 9). Because the first burn occurred late in the day, relative humidity and fuel moisture rose quickly shortly after ignition and helped suppress subsequent smoldering. The second burn occurred earlier in the day, which allowed smoldering to persist all afternoon. On both days, the relative humidity followed very similar diurnal patterns and reached minimum levels of approximately 25% from about 10:00 to 16:00 LST.

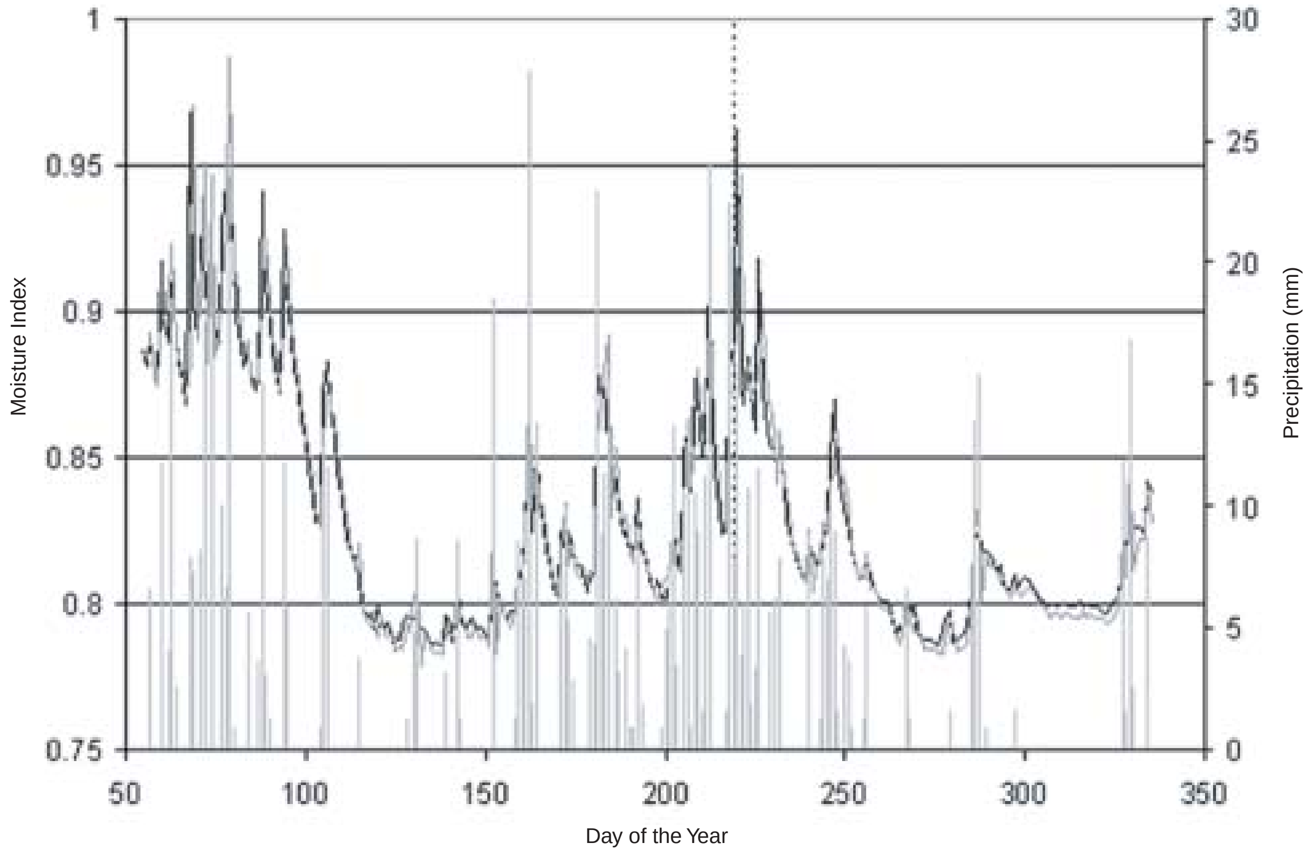

Fig. 7. Observed (black line) and modeled (gray line) moisture index for probe 7A at 13:00 LST. The light gray bars indicate 24-h total precipitation. The dotted vertical line marks the division between the model development period (days 55–219) and the model validation period (days 220–235).

Table 4. Depth of pre-burn fuel load and post-burn fuel consumption (percentage of depth) in litter and duff among plot pins, tree pins, and all pins. Depth values are mean ± standard error

	Litter			Duff		
	Pre-burn depth (mm)	Post-burn depth (mm)	% consumed	Pre-burn depth (mm)	Post-burn depth (mm)	% consumed
Plot pins						
A. Wet burn (*n* = 47)	23.7 ± 1.05	9.2 ± 1.12	61.3	19.4 ± 4.32	18.3 ± 4.15	5.6
B. Moist burn (*n* = 51)	24.4 ± 1.51	9.0 ± 0.85	63.0	12.3 ± 2.39	12.1 ± 2.37	1.9
C. Dry burn (*n* = 36)	16.6 ± 0.90	3.4 ± 0.65	79.5	13.6 ± 3.98	11.4 ± 2.72	16.3
D. Very dry burn (*n* = 46)	25.1 ± 1.45	3.6 ± 0.85	85.7	39.8 ± 4.07	20.1 ± 2.76	49.5
Tree pins						
A. Wet burn (*n* = 158)	33.3 ± 1.33	12.9 ± 0.63	61.2	59.8 ± 2.54	58.1 ± 2.54	2.8
B. Moist burn (*n* = 159)	36.6 ± 1.44	11.3 ± 0.83	69.1	73.0 ± 2.76	67.8 ± 2.78	7.1
C. Dry burn (*n* = 156)	31.8 ± 0.71	3.4 ± 0.57	89.2	66.1 ± 3.01	33.2 ± 2.52	49.8
D. Very dry burn (*n* = 155)	43.2 ± 1.15	2.2 ± 0.42	94.9	92.6 ± 2.91	32.2 ± 2.87	65.2
All pins						
A. Wet burn (*n* = 205)	31.1 ± 1.09	12.1 ± 0.55	61.2	50.6 ± 2.49	49.0 ± 2.47	3.1
B. Moist burn (*n* = 210)	33.7 ± 1.20	10.8 ± 0.67	68.1	58.3 ± 2.81	54.3 ± 2.73	6.8
C. Dry burn (*n* = 192)	28.9 ± 0.74	3.4 ± 0.48	88.2	56.2 ± 2.95	29.1 ± 2.19	48.3
D. Very dry burn (*n* = 201)	39.1 ± 1.09	2.5 ± 0.38	93.5	80.5 ± 2.89	29.5 ± 2.33	63.4

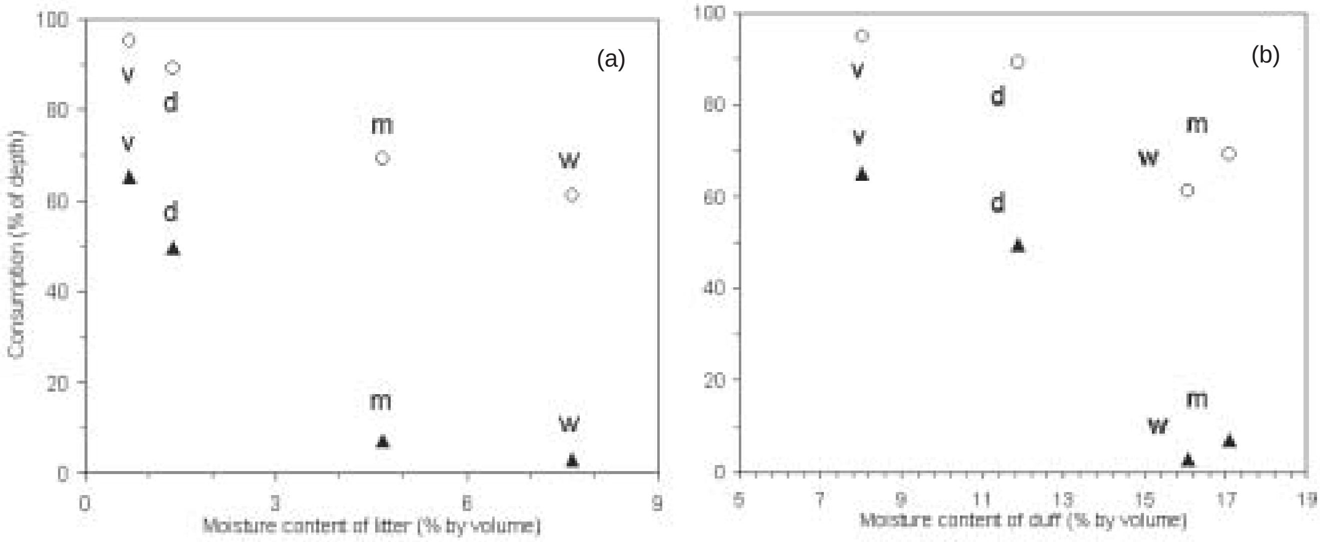

Fig. 8. Consumption of litter (○) and duff (▲) from tree pins and volumetric moisture content of (*a*) litter and (*b*) duff from calibrated TDR probes (VMC_{tdr}) at 07:00 LST for each fire event (w = wet, m = moist, d = dry, and v = very dry).

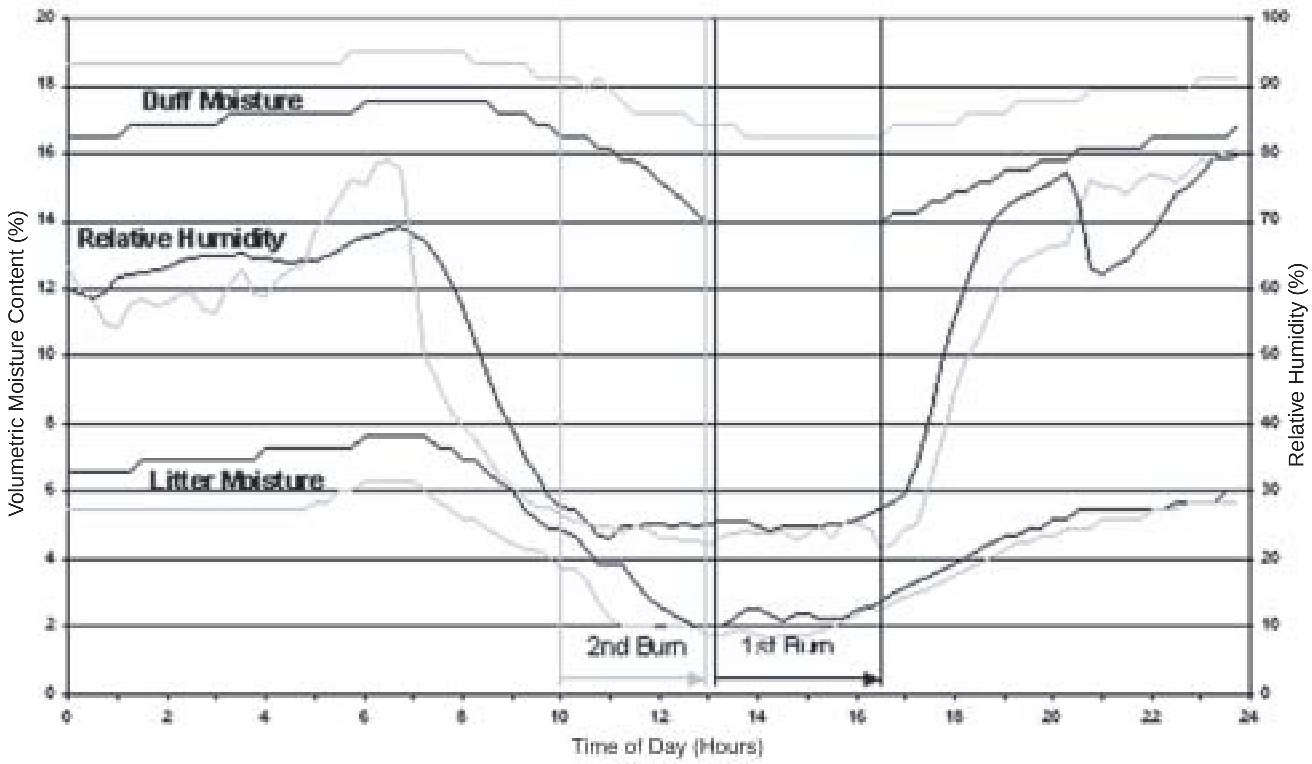

Fig. 9. Hourly values of litter moisture (VMC_{tdr} at probe 6A), duff moisture (VMC_{tdr} at probe 6B), and relative humidity on the day of the first burn (black lines) and second burn (gray lines). Arrows above the *x*-axis indicate the times of each ignition period.

Because smoldering was so easily suppressed in these early burns by rising relative humidity of the night-time atmosphere, the moisture of extinction in longleaf pine duff can be approximated from Fig. 9 as near 16% to 19% *VMC* and near 3% to 8% *VMC* in litter. More detailed observations of the duration of combustion are needed to precisely determine extinction moisture.

The influence from diurnal recovery of the relative humidity on consumption was less apparent during the third and fourth burns, which were ignited between 10:00 and 13:00 LST, and 12:00 and 16:00 LST, respectively. The fuel began significantly drier than the first two burns and, even though relative humidity rose from 22% to 95% after the third ignition and from 35% to 100% after the fourth ignition, fuel moistures remained low enough to maintain combustion. Smoldering continued after the fourth ignition for up to 3 days. We might expect from these results that the moisture of extinction in longleaf pine duff is well above the 8% to 14% *VMC* in duff and 2% in litter.

Conclusions

Subtle variations in water content between layers of the forest floor were clearly observed by *in situ* monitoring of moisture with TDR sensors. The variations in water content explained differences in consumption patterns in four distinct burn environments. While follow-up at the site is needed to determine the extent of longleaf pine mortality, the range of consumption observed by just a few percent changes in fuel moisture is noteworthy.

A simple model of afternoon fuel moisture can be derived from 24-h precipitation and previous day's fuel moisture for longleaf pine litter. While this model is specific to pine litter overlying porous sand, such as in the Florida Panhandle, it provides a useful tool for fire managers in the area who must predict drying rates to maximize the efficiency of prescribed fire.

By calibrating the TDR sensors, values of moisture critical to the combustion process began to emerge. The moisture of extinction was approached quite closely, especially in the longleaf pine duff during the first two burns, which were defined as having wet and moist conditions. Because of last-minute changes in the burn plan, stations were displaced, which prevented a precise definition of moisture extinction values. With *in situ*, continuously monitoring sensors, however, precise timing of ignition to achieve desired results becomes possible.

While we only reported results from three weather and moisture monitoring stations and we averaged consumption over the entire burn unit of about 25 ha, there is much information about the large spatial variability of fuel elements, its moisture, and associated consumption that remains to be analysed. As we replicate these experiments in other fuel types, we hope to clearly define the magnitude, trend, and spatial variability of fuel conditions that support combustion.

Acknowledgements

Many thanks to Kevin Hiers and the rest of the Jackson Guard fire crew for coordinating the burns and providing a map of the area. A special thanks to Pete Jerkins for helping set up and maintain the weather stations as well as coordinating the collection of the volumetric moisture samples and to volunteers Trisha Dall and James Morrison for taking the many volumetric litter and duff moisture samples necessary to calibrate the moisture probes. The collection of the consumption data by the Fuels crew at the Seattle Forestry Sciences Lab was very much appreciated, as was help with the data analysis from Casey Anderson and Jenny McCormick. The thoughtful suggestions from two anonymous reviewers were greatly appreciated. This project was partly funded by the U.S. Department of Agriculture and U.S. Department of Interior, Joint Fire Science Program.

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