J2.3 MEASURING MOISTURE DYNAMICS TO PREDICT FIRE SEVERITY IN LONGLEAF PINE FORESTS

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1.0 INTRODUCTION

To understand the combustion limit of biomass fuels in a longleaf pine [*Pinus palustris*] forest, an experiment was designed to monitor the moisture content of potentially flammable forest floor materials at Eglin Air Force Base in the Florida Panhandle. While longleaf pine forests are fire dependent ecosystems, a long history of fire suppression has allowed large amounts of pine litter, duff, and woody fuels to accumulate. Reintroducing fire to remove excess fuel without killing the longleaf pine trees requires care to burn under moisture conditions that alternately allow fire to carry while preventing root exposure or stem girdle.

Figure 1: Flames consuming litter and duff at the base of a Longleaf pine during the prescribed burn on February 18, 2001.

2.0 METHODS

The study site was divided into four blocks that were to be burned under wet, moist, dry, and very dry moisture conditions in a period from February to September 2001. Throughout the experiment, portable weather stations continuously collected meteorological data, which included moisture measurements from in-situ, time-domain reflectometers (CS-615, Campbell Scientific, Inc). Two weather stations were set up at each of the burn units, one next to a large longleaf pine and one in a nearby opening. 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 one base station that transmitted its weather and moisture data back to our office via cell phone.

The 9 weather stations established for the experiment show subtle variations in the micro-meteorology within and between each unit. For simplicity, however, we describe results from only 2 sites, which had the most complete records through all burns; Station 1 was in a small opening in the forest, and Station 6 was next to a nearby longleaf pine. Station 1 recorded data from two moisture probes; probe 1A was inserted horizontally in the duff 3 cm from the surface and 1B was oriented vertically from 4 to 34 cm in the sand. Station 6 recorded data from 3 moisture probes; probe 6A was placed horizontally 7 cm from the surface in the litter layer, 6B was located horizontally at 17 cm in the duff layer, and 6C was inserted vertically from 22 to 52 cm in the sand. Table 1 summarizes moisture probe locations at each station.

Table 1. Moisture probe locations at Stations 1 and 6.

Material Type	Station 1 (in opening) Probe Number : Depth (cm)	Station 6 (near longleaf pine) Probe Number : Depth (cm)
litter	N/A	6A : 7
duff	1A : 3	6B : 17
sand	1B : 4-34	6C : 22-52

To help calibrate the moisture probes volumetric moisture samples of litter and duff were collected almost weekly and within an hour before each ignition following a method that was adapted from Wilmore (2000). Pre-burn fuel load and subsequent consumption was measured for each burn to help quantify the combustion limits of each fuel element under different moisture regimes.

The wet, moist, and dry prescribed burns occurred on February 18 (day number 49), March 27 (day number 86), and April 26 (day number 116), respectively. Very dry conditions were not achieved at the time of this report.

2.1 Calibration of Moisture Probes

The CS-615 moisture probes tracked the changes in moisture content of litter and duff well throughout the period. Figure 2 shows the moisture trends at weather station 1, which was in a small clearing. The frequency response of each probe is represented as an index of moisture. High index values correspond to high moisture content. The lowest

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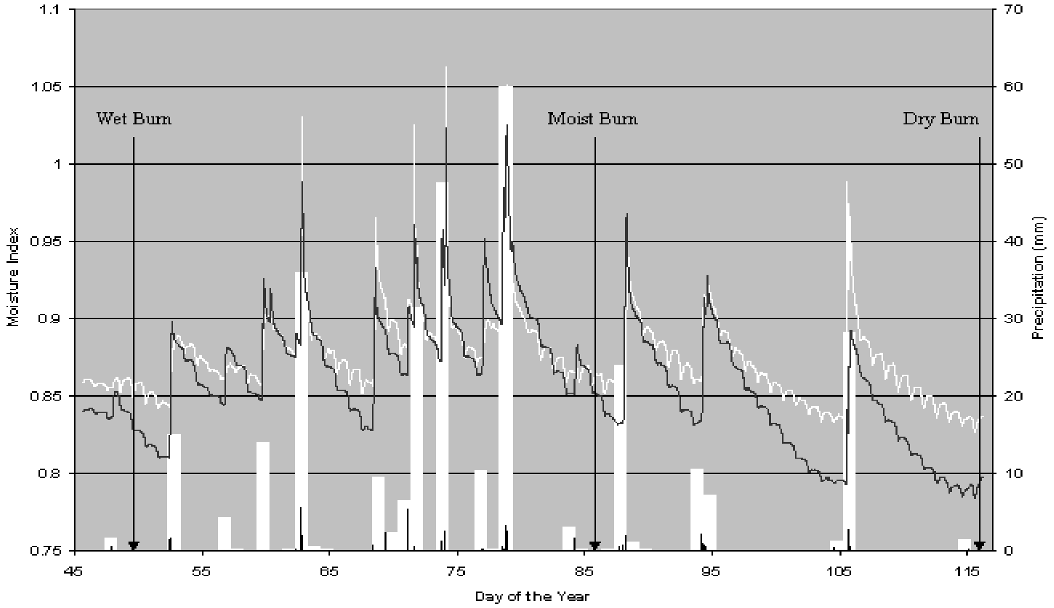

Figure 2. Eglin 1 moisture probe in a small clearing, 1A (black line) is in duff at 3 cm and 1B (white line) is in sand from 4 to 34 cm. White bars indicate 24-hour precipitation totals in millimeters and thin black bars 15-minute totals. Arrows indicate the time of the prescribed burns.

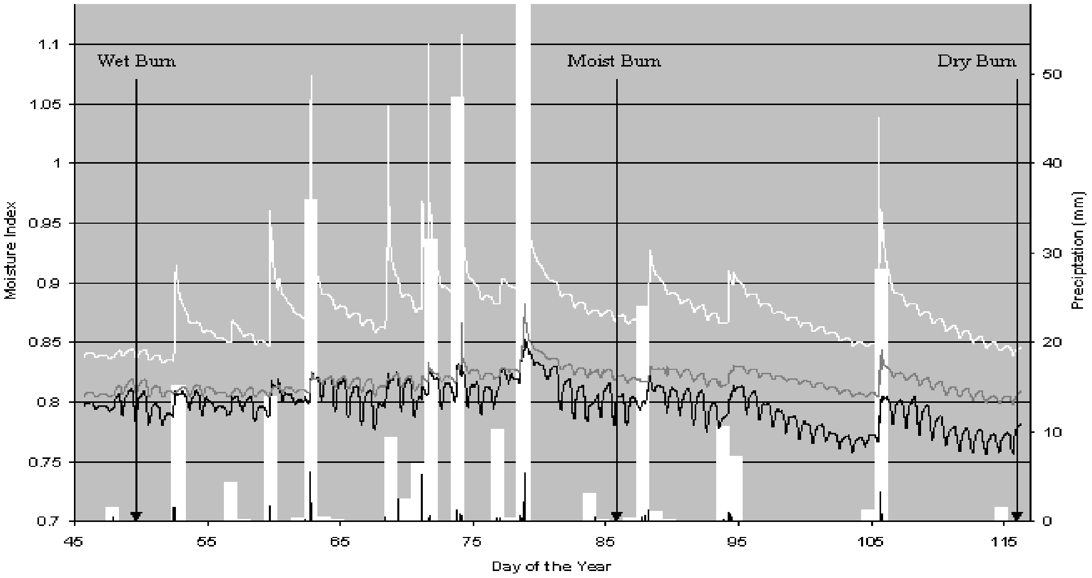

Figure 3. Moisture index values vs. time from station 6, set near a longleaf pine. The probe 6A (black line) is in litter at 7 cm, 6B (gray line) is in duff at 17 cm and 6C (white line) is in sand from 22 to 52 cm. White bars indicate 24-hour precipitation totals in millimeters and thin black bars 15-minute totals. Arrows indicate the time of each prescribed burn.

possible value is 0.7, which corresponds to zero percent moisture content. A vertical arrow indicates the time of each burn. The moisture index of the sand layer was about the same for the wet burn and moist burn (.849 and .852 respectively) but clearly drier for the dry burn (.836). While index values in the duff were clearly driest during the dry burn (.798), the index suggested wetter conditions existed in the duff during the moist burn (.838) than during the wet burn (.829). A burn was conducted on this day because the surface litter layer appeared significantly drier to the field crew. Indeed, the moisture index in litter at 7cm below the surface showed slightly drier conditions (.781) during the moist burn than during the wet burn (.784) as measured station 6 near the longleaf pine (Figure 3). Deeper at layers of duff and sand at station 6 followed the same trends as those at station 1.

To convert the moisture index to volumetric moisture we used the volumetric moisture samples that were collected weekly and before each burn. The index values at the time of the sampling are compared to the volumetric moisture measurements of the same material type as where the probe was located, using methods similar to those reported in Ferguson et al. (2001).

Figure 4a shows the volumetric moisture content of litter samples taken from around the bases of Longleaf Pine trees and the probe readings from moisture probe 6A located in the litter. While we tested a number of curve equations for the regression, the natural logarithm provided the best fit. The R2 value for this regression is 0.558 and the equation of the calibration curve is $\ln(y) = 48.9x-37.6$, where y is the volumetric moisture content and x is the moisture probe output. A time series of the moisture index in litter at Station 6 and the calibrated volumetric moisture content for 6A are shown in Figure 4b. Also shown are the values of volumetric moisture collected from samples that were used in the calibration. Prior to calibration, the moisture index in litter has a relatively large diurnal range but small range between actual peaks. After calibration, its diurnal range is decreased somewhat but its range between peaks is increased.

Similar calibration procedures were used for the probes located in the deep duff near a tree at Eglin 6 (Figure 5) and the shallow duff in a clearing at Eglin 1 in (Figure 6). There is a significantly higher variability in the moisture content of the duff samples than the litter samples so the R2 values for the duff probes are low. While a more complex regression equation may have improved the calibration, we retained the natural logarithm function for simplicity in this preliminary report. For 6B the R2 value is 0.129 and for 1A it is 0.176. The equation calculated to calibrate 6B is $\ln(y) = 20.6x – 14.0$ and for 1A $\ln(y) = 6.49x –2.76$, where y is the volumetric moisture content and x is the moisture index. In each duff layer, calibration appeared to increase the response to wetting; thereby increasing subsequent drying rates.

No volumetric moisture samples were taken in sand. Probes located in the sand were calibrated using the standard soil equation recommended by the manufacturer. This equation is $y = -0.187 + 0.037x + 0.335x2$, where y is the volumetric moisture content and x is the moisture index. Calibration in the sand did not significantly change its range of values, only absolute magnitude.

3.0 RESULTS

While the raw output from the CS-615's was valuable to track moisture conditions over time the actual moisture response is deceiving. For example, prior to calibration the range of moisture probe 6B (Figure 3), which is located in deep duff near a tree, is much smaller than the probes in sand (1B and 6C). After the probes are calibrated, however, it can be seen that the volumetric moisture content in the duff has a much larger range than the sand. This is illustrated during a heavy rain event, which occurred on day 78 (March 19), when 60 mm of precipitation fell on the study site within 14 hours. The volumetric moisture content at the sand probes 6C and 1B (Figure 7) spikes to about 25%, while it increases to 65% at 6B (deep duff near tree) and 55% at 1A (shallow duff in opening) (Figure 8). The results point to an obvious characteristic of organic material, which is more efficient at absorbing water than sand, whose porous structure allows rapid percolation.

Differences can be seen between the shallow, 3-cm duff probe located in the clearing (1A) and the deeper, 17-cm duff probe located at the base of a tree (6B). The calibrated volumetric time series of both are shown in Figure 8. Due to the depth of the litter and duff above the probe, sharp increases in moisture at probe 6B are only noticeable during heavier rain events. Between days 50 (February 19) and 60 (March 1) three moderate rain events occur. The moisture probe in the clearing (1A) spikes noticeably after each event. On the other hand, the same rain events are barely noticeable at the deeper duff probe by the tree (6B).

The volumetric moisture content of the litter only reaches comparable levels to the duff during the heaviest of rain events and then drops quickly (Figure 8). This behavior is consistent with the low bulk density of the litter, which is made up of Longleaf Pine needles and bark. 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 the volumetric moisture content of the litter due to its low density, which allows air to circulate through the litter. The magnitude change in moisture content of the litter is in part driven by changes in the relative humidity. During times of low relative humidity the litter layer dries quickly.

The behavior of moisture probes in sand 1B (4 – 34 cm) and 6C (22 – 52 cm) is quite similar (Figure 7). Both spike to comparable magnitudes shortly after rain events and then dry at similar rates. Moisture probe 6C has a slightly smaller diurnal variation because of its deeper location. The similarity of the moisture probes in the sand is significant because it indicates that the overall flux of moisture through the forest floor near the tree is not greatly different than the flux in the opening.

4.0 DISCUSSION

The moisture content of the litter and duff layers is dependent on a number of weather elements. Precipitation is the main factor in the wetting of the litter and duff. Temperature, relative humidity and wind determine how fast it dries. For much of the summer rain was frequent enough that the previous moisture conditions, amount of precipitation and days since rain explained most of the moisture variability.

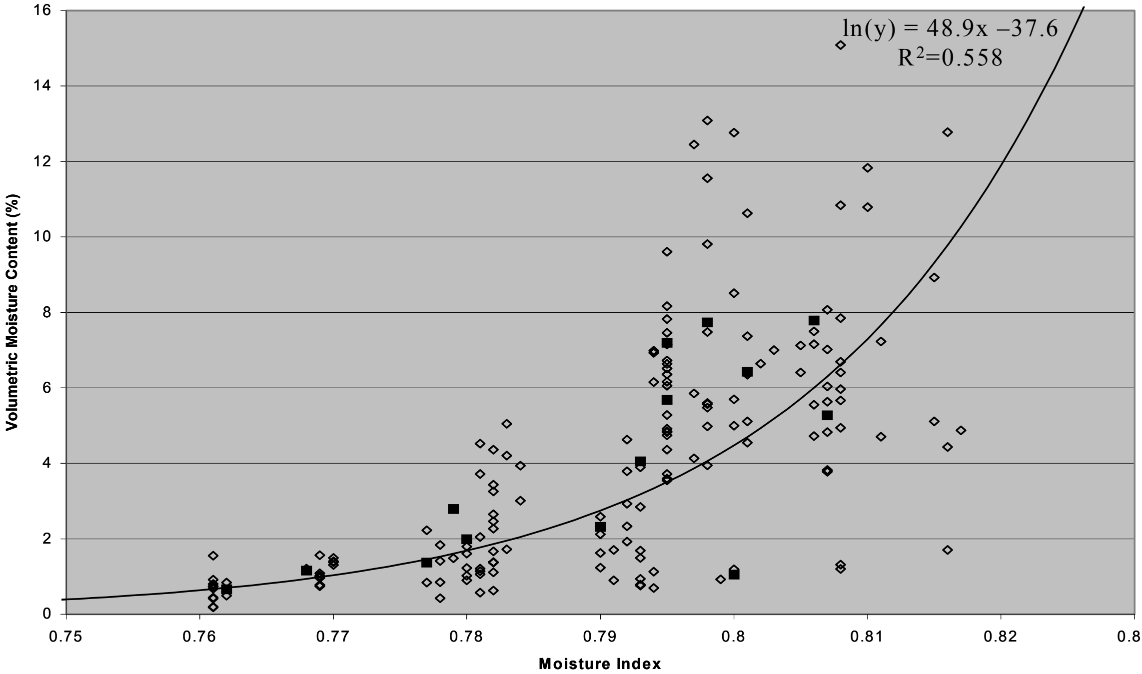

Figure 4a: Calibration curve for moisture probe 6A (litter at base of tree). The diamonds are the moisture index at the time of a sample plotted against the volumetric moisture content of the sample. The filled squares are the average volumetric moisture content of samples for a day.

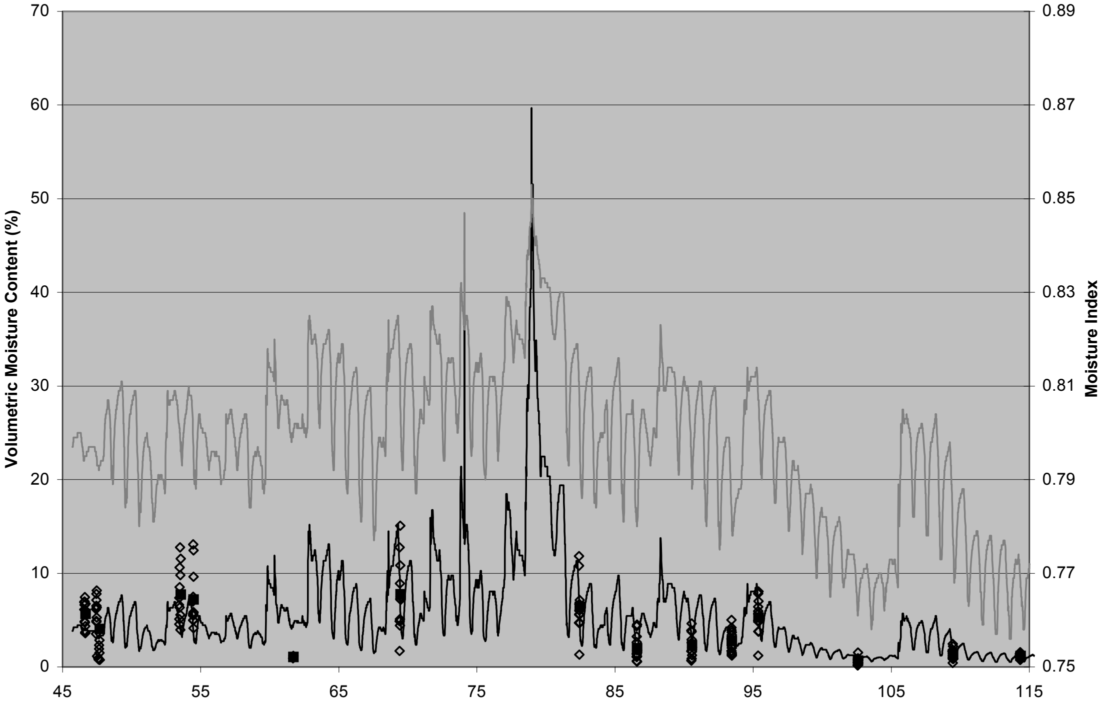

Figure 4b: Eglin 6A (litter at base of tree) moisture probe output (gray line), calibrated volumetric moisture content time series (black line), volumetric moisture content samples of litter (black diamonds) and averages (filled black squares).

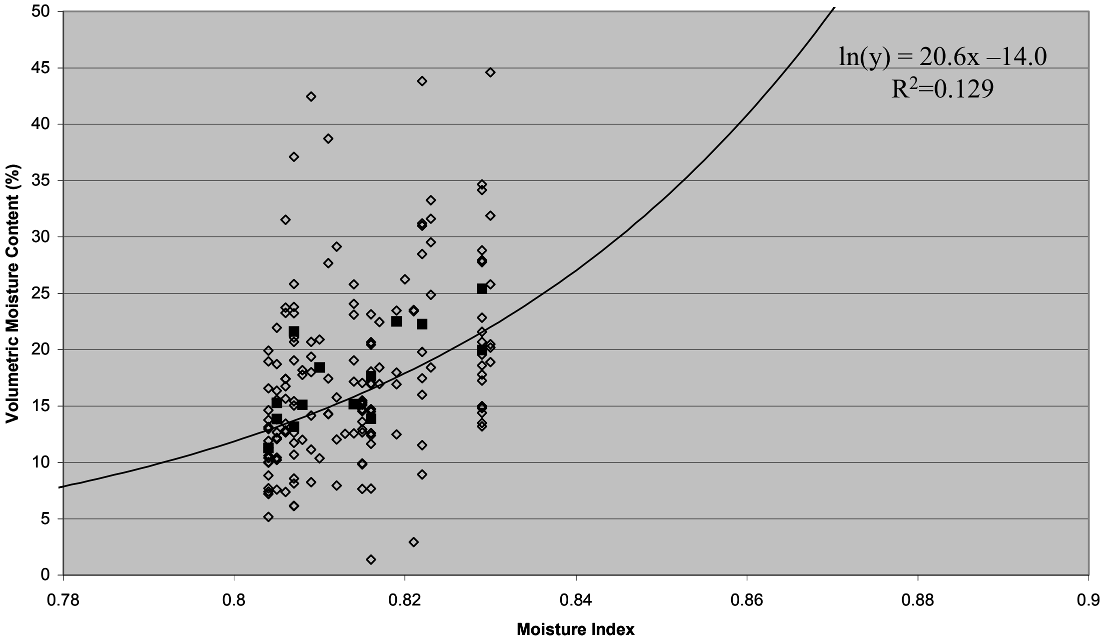

Figure 5a: Calibration curve for moisture probe 6B (deep duff at base of tree). The diamonds are the moisture index at the time of a sample plotted against the volumetric moisture content of the sample. The filled squares at the average volumetric moisture content of the samples for a day.

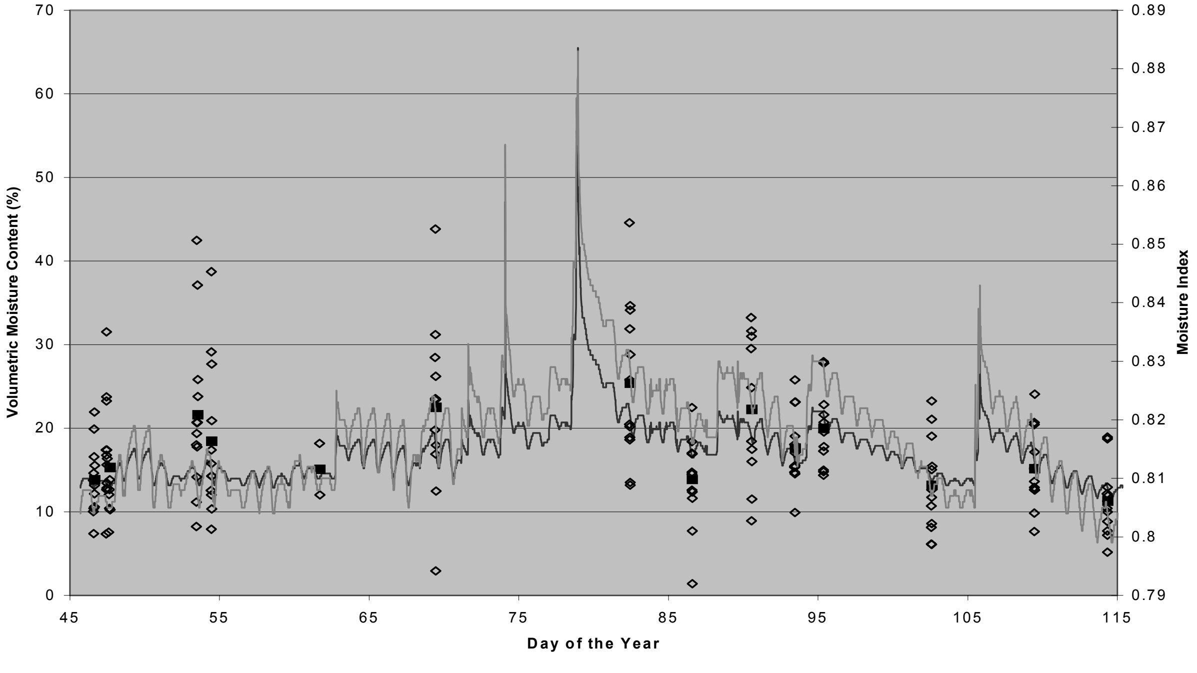

Figure 5b: Eglin 6B (deep duff at base of tree) moisture probe output (gray line), calibrated volumetric moisture content time series (black line), volumetric moisture content samples of litter (black diamonds) and averages (filled black squares).

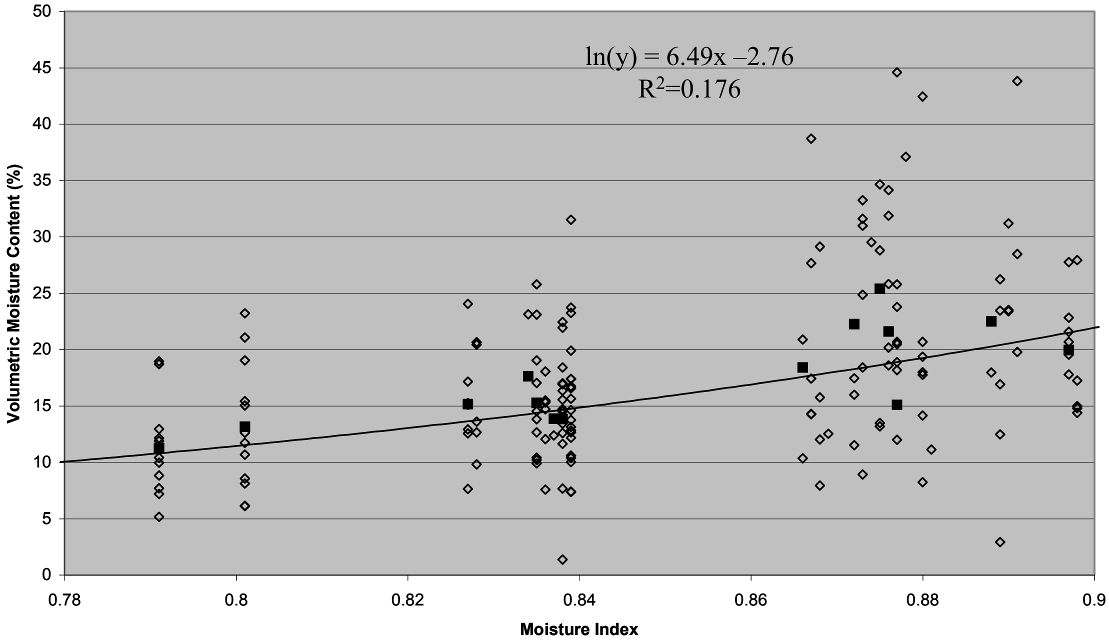

Figure 6a: Calibration curve for moisture probe 1A (shallow duff in clearing). The diamonds are the moisture index at the time of a sample plotted against the volumetric moisture content of the sample. The filled squares at the average volumetric moisture content of the samples for a day.

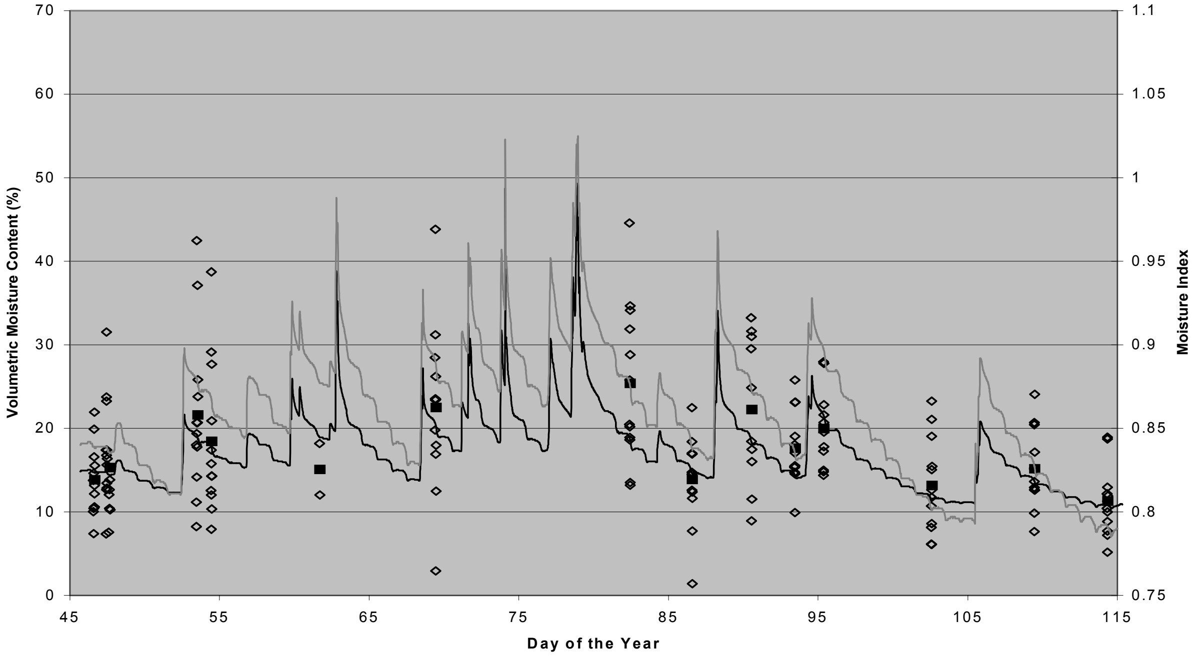

Figure 6b: Eglin 1A (shallow duff in clearing) moisture probe output (gray line), calibrated volumetric moisture content time series (black line), volumetric moisture content samples of litter (black diamonds) and averages (filled black squares).

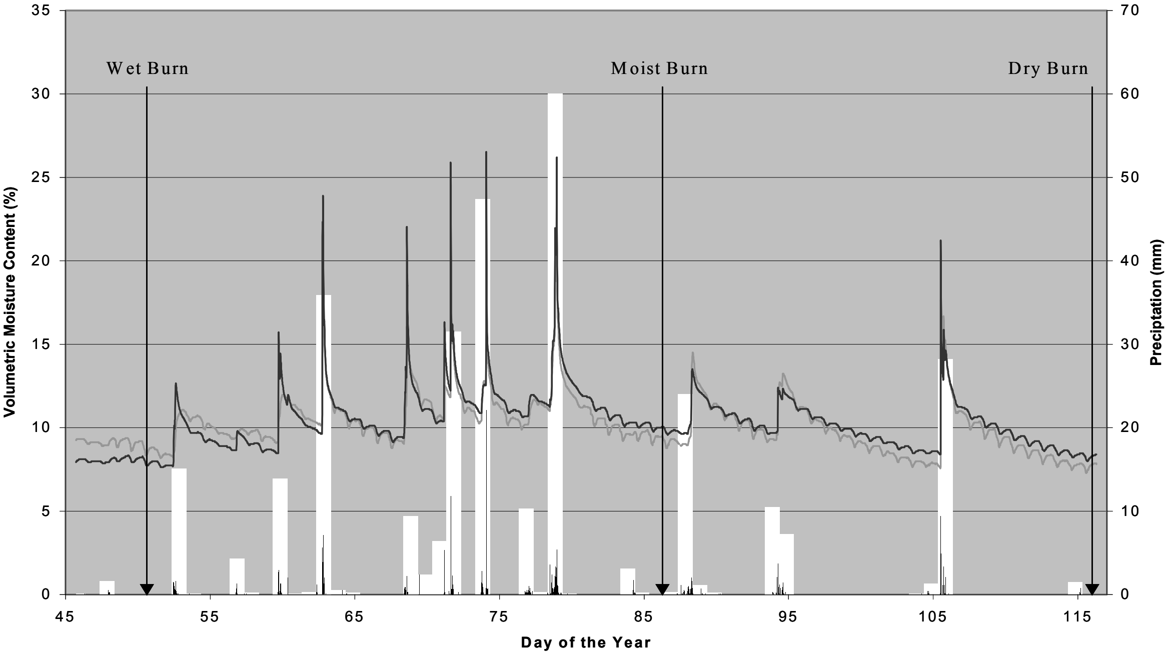

Figure 7: Sand volumetric moisture content time series of moisture probes 6C, sand near tree (black line) and 1B, sand in clearing (gray line). White bars indicate 24-hour precipitation totals in millimeters and thin black bars 15-minute totals. Arrows indicate the time of the prescribed burns.

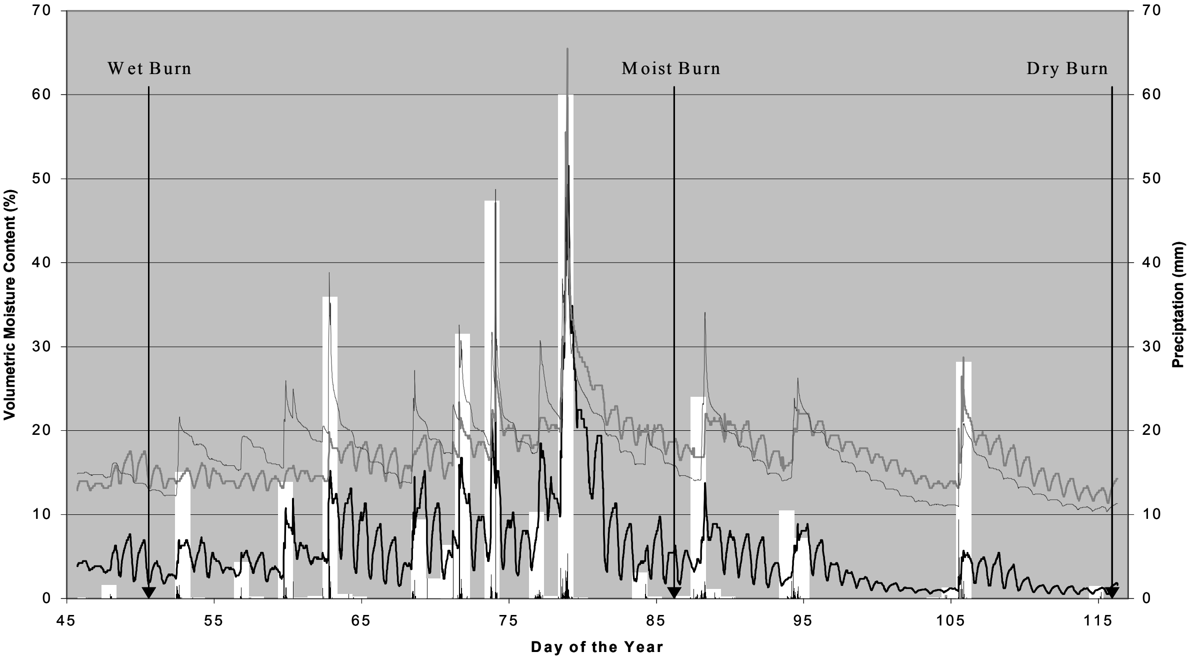

Figure 8: Litter and duff calibrated volumetric moisture content time series of moisture probe 6A, litter near tree (thick black line), 6B, deep duff near tree (thick gray line), and 1A shallow duff in clearing (thin black line). White bars indicate 24-hour precipitation totals in millimeters and thin black bars 15-minute totals. Arrows indicate the time of the prescribed burns.

The amount of rain and duration of the rain affected how deeply in to the forest floor the moisture penetrated. A very light rain might only wet the litter, whereas a slightly heavier rain event would be needed to get the duff wet, and a significantly heavier rain event would be needed to get the deep layer of duff around the base of the Longleaf pine trees thoroughly wet. For the moisture probes at weather station 6 it appears to take a rain event totaling around 20 mm to have a substantial impact on the duff moisture at 17 cm (Figure 7).

The number of days since rain also significantly affected which layers were dry. The litter layer dried very quickly after rain events especially if the relative humidity was low. Many of the rain events during the spring and early summer occurred during frontal passage, after which the relative humidity was quite low. This offers a number of the opportunities for the moisture content of the litter to drop quickly to a flammable level and affords many opportunities for burning if consuming the litter layer but not the duff layer is the management objective. The duff layers took significantly longer to dry following a heavy rain event and the deeper duff layers dried more slowly. Throughout the summer rain was frequent enough that there were significantly fewer opportunities to burn under conditions where the duff layer was dry enough to be consumed. The moisture probes in the litter and duff were able to track the dryness of the litter well and would be a useful management tool to determine when to burn to accomplish a given objective.

Both of the first two prescribed burns that were accomplished occurred during fairly wet conditions (Figure 7) and very little duff was consumed during either burn. While the litter layer was drier during the moist burn, the duff layer was actually wetter. The fire behavior was a bit more intense during the moist burn however the duff was too wet to be consumed. Both the litter and duff layers were significantly drier during the dry burn, which resulted in more intense fire behavior as well as duff being consumed.

5.0 CONCLUSIONS

The CS-615 moisture probes proved useful tools for determining the moisture content at different layers in the forest floor and were quite helpful in determining different moisture regimes in order to plan the prescribed burns. Meteorological variables from the weather stations compared with moisture trends showed the influence of wind, temperature, relative humidity, and precipitation on the drying and wetting rates of the litter and duff. While the analysis of consumption measurements was not completed in time for this report, we hope to show that the magnitude and spatial variability of moisture content in forest floor material significantly influences fire behavior, patterns of consumption, and potential longleaf pine mortality.

6.0 ACKNOWLEDGEMENTS

Many thanks to Kevin Hiers and the rest of the Jackson Guard fire crew for coordinating the burns. A special thanks to Pete Jerkins for helping set up and maintaining 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. Roger Ottmar and Clint Wright were instrumental in establishing the experimental protocol and will be collaborating on results when consumption analysis is complete.

7.0 REFERENCES

Ferguson, Sue A., J. Ruthford, M. Rorig, and D.V. Sandberg. 2001. Measuring moss moisture dynamics to predict fire severity. Tall Timbers. Submitted.

Wilmore, B. 2000. Fuel moisture sampling in Boreal Forest Duff. Alaska Fire Service Report. 11 pp.