J6E.2   THE INFLUENCE OF WEATHER ON COMBUSTION LIMITS IN A LONGLEAF PINE FOREST

Casey Anderson[A]*, Sue Ferguson[A], Miriam Rorig[A], Kevin Hiers[B], Steve McKay[A], Mark Moore[A], Diana Olson[A], David Wright[A], Clint Wright[A], Bob Vihnanek[A], Roger Ottmar[A]

[A] USDA Forest Service, Pacific Northwest Research Station, Seattle Forestry Sciences Laboratory
[B] Jackson Guard, Eglin Air Force Base, FL

1.0 INTRODUCTION

While the benefits of prescribed fire are generally understood, the environmental conditions needed to accurately achieve desired consumption values are not well quantified. The influence of weather on the moisture of woody fuel has been studied extensively, yet much of the research has focused on the conditions required for wildfire initiation and is less appropriate for the combustion processes in prescribed fire.

In order to better quantify the effects of weather on moisture dynamics and associated consumption values in a longleaf pine (*Pinus palustris* Mill.) forest, a series of experiments were set up in both 2001 and 2002. During both years, controlled burns were conducted under a variety of moisture conditions and an array of portable weather stations monitored both meteorological conditions and forest floor moisture levels.

2.0 SITE DESCRIPTION

The two study areas used were located on Eglin Air Force Base in the Florida Panhandle. Prescribed burns were conducted at the Ramer Tower study area in 2001, and at both the Ramer Tower study area and the Ranger Camp study area in 2002. These sites lie approximately 20 miles apart and contain sets of individual units roughly 25 ha each. In addition to longleaf pine, the overstory vegetation consisted of turkey oak (*Quercus laevis*), sand live oak (*Quercus geminata*), and sand pine (*Pinus clausa*). Yaupon (*Ilex vomitoria*) and Palmetto (*Serenoa repens*) were common understory shrubs. The terrain in the area is relatively flat and 200 feet above sea level.

At the Ramer Tower study area, 4 units were burned in 2001 and three units were burned in 2002. The Ranger Camp study area contained two adjacent blocks of units, labeled mesic and xeric, each containing three units which burned in 2002. The mesic and xeric units were labeled based upon slight differences in the vegetation structure and an elevation difference of a few meters.

2.1 *Data Collection*

Six weather stations were set up in 2001 for varying lengths of time to monitor conditions at the Ramer Tower site. One of these stations, Eglin 1, was left in place to monitor the 2002 burns and as of August 2003 is still collecting data. Two weather stations (Eglin 12 and 13) were set up at Ranger Camp in January of 2002 and collected data until May 2003. For the purposes of this paper, only the data from Eglin 1, 12, and 13 will be presented as these three stations provide the longest and most complete data record available.

All weather stations measured air temperature, relative humidity, wind speed, and wind direction. Additionally, stations 1, 12 and 13 measured 10 hour fuel temperature, 10 hour fuel moisture, barometric pressure, and precipitation. Sensors at all stations had a sampling interval of 10 seconds and logged data averages every 15 minutes.

Forest floor moisture was monitored at all stations using Campbell Scientific model CS-615 time-domain reflectometer (TDR) probes. These TDRs consisted of two parallel wave guides 3.2 mm in diameter, 30 cm long, and 3.2 cm apart. The period of the electromagnetic signal traveling down the wave guides is influenced by the moisture level of the surrounding material. Therefore, varying moisture conditions are represented by changes in the signal's period. The CS-615 probes have an operational period range from 0.7 to 1.6 ms. All weather stations sampled and logged the raw period output from the CS-615 probes. We refer to this uncalibrated output as the moisture index (MI).

Two to four moisture probes were inserted either horizontally or vertically into the forest floor organic layer at each station, at varying depths. Litter (needles and bark slough with no evidence of decay) and duff (decomposing organic material) layers were highly variable across the landscape, with shallow layers (1-5 cm litter, 1-5 cm duff) in open areas and significantly thicker layers (5-10 cm litter, 5-10 cm duff) surrounding the base of most large longleaf pine trees. In all locations, the underlying mineral soil was well drained sand.

2.2 *Burn Thresholds*

For each prescribed fire, pre- and post-burn fuel loadings were measured at a set of 30 plots per unit set in a 1 chain (66-foot) grid. The fuel loadings in the

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* *Corresponding author address*: Casey Anderson, USDA Forest Service, PNW Research Station, Seattle Forestry Sciences Lab, 400 N 34th St Ste 201, Seattle, WA 98103; email: canderson@fs.fed.us

Unit Name	Date of Burn	Time of Ignition	Duff MI	Plot Pin Duff Consumption (percentage by depth)	Tree Pin Duff Consumption (percentage by depth)
Ramer Tower Inner North	2/18/2001	1200	*	2	3
Ramer Tower Outer South	3/27/2001	1000	0.863	2	7
Ramer Tower Inner South	4/26/2001	1000	0.800**	9	50
Ramer Tower Outer North	9/21/2001	1200	0.772	27	66
Ramer Tower East	2/22/2002	1030	0.848	2	15
Ramer Tower West	3/5/2002	930	0.857	5	4
Ramer Tower Mid	3/24/2002	1100	0.824	13	30
Ranger Camp Xeric NW	3/8/2002	1100	0.894	18	26
Ranger Camp Xeric NE	3/14/2002	1300	0.922	3	6
Ranger Camp Xeric Mid	4/7/2002	1700	0.867	24	52
Ranger Camp Mesic Mid	2/22/2002	1400	0.882	9	24
Ranger Camp Mesic SE	3/4/2002	1400	0.906	2	17
Ranger Camp Mesic SW	4/24/2002	1320	0.828	25	57

Table 1. List of the 2001 and 2002 prescribed fires used in this study.
* Weather station not installed for this burn.
** Estimated value, weather station offline from 0800 to 1130 on day of burn

forest floor organic layer are the only ones used in this study. By conducting prescribed burns on adjacent units under differing moisture conditions, a range in forest floor consumption was achieved. The consumption values in table 1 show good correspondence between duff consumption amount and relative TDR duff moisture level at the time of ignition. Using this relationship, burn thresholds were defined at the upper and lower limits of the TDR-measured moisture indexes. These thresholds correspond to the wettest (least overall consumption) and driest (most overall consumption) fires at the Ramer Tower site in 2001 and at the Ranger Camp site in 2002. These thresholds do not however represent the full range within which prescribed burning occurs. Figure 1 shows the wet and dry thresholds superimposed upon a time series of moisture index for the duff layer from Eglin 1. The wet and dry thresholds correspond to the moisture indexes at the time of ignition for the burns on days 86 and 264, respectively. Observed data are posted to the website www.fs.fed.us/PNW/AIRFIRE/fm each day so that burn managers in the area can track the moisture index as it relates to these thresholds and anticipate whether maximum or minimum consumption may occur based upon observed moisture levels.

3.0 DEVELOPMENT OF A LITTER MODEL

As is described in Ferguson et al. (2002), a study of the relationship between the Eglin 1 litter layer moisture index and wind, relative humidity, temperature and precipitation found that nearly all of the variability in the moisture index could be explained by the previous day's MI and precipitation. A multiple linear regression of the moisture index for probe 1A at time t ($MI1A_t$) with the previous day's moisture index ($MI1A_{t-1}$), the square root of the past 24 hour precipitation (P_t) and the square root of the precipitation from the previous 24 hour period (P_{t-1}) yields the equation:

$$MI1A_t = 0.9957 \times MI1A_{t-1} + 0.0023 \times \sqrt{P_t} - 0.0013 \times \sqrt{P_{t-1}} \quad (1)$$

This regression has a multiple r^2 value of 0.9997 and a correlation value of 0.9533. Moisture index values and 24 hour precipitation totals (in 0.01 mm) at 1300 LST from days 55 through 219 2001 were used to derive the regression. When tested on days 220 through 335 2001, the correlation value was 0.9212.

This type of equation could be very helpful in trying to determine future moisture levels in the forest floor organic layer. When coupled with defined burn thresholds, a prediction can be made of the number of days following a rain event needed to sufficiently dry the forest floor below the wettest burn threshold. An estimate can also be made for the amount of rain needed to lift the forest floor moisture above the dry threshold to avoid a prescribed fire of high intensity.

4.0 DEVELOPMENT OF A DUFF MODEL

Given the high correlation values for the litter layer prediction in Ferguson et al. 2002, the same approach was used to fit a model to the duff layer at the same location for the same time period. Again, 1300 LST values were used to filter out the diurnal cycle and to create a model consistent with the National Fire Danger Rating System, which uses 1300 LST observations to calculate its indexes. Many predictors, including past 24-hour average relative humidity, past 24-hour average 10 hour fuel moisture, past 24-hour precipitation duration, and past 48-hour precipitation were tested in multiple linear regressions. Once again it was found that the three predictors used in the litter equation yielded the highest r^2 and correlation values for a prediction of the duff layer moisture. Some predictors, such as past 24-hour precipitation duration, also fit quite well, but

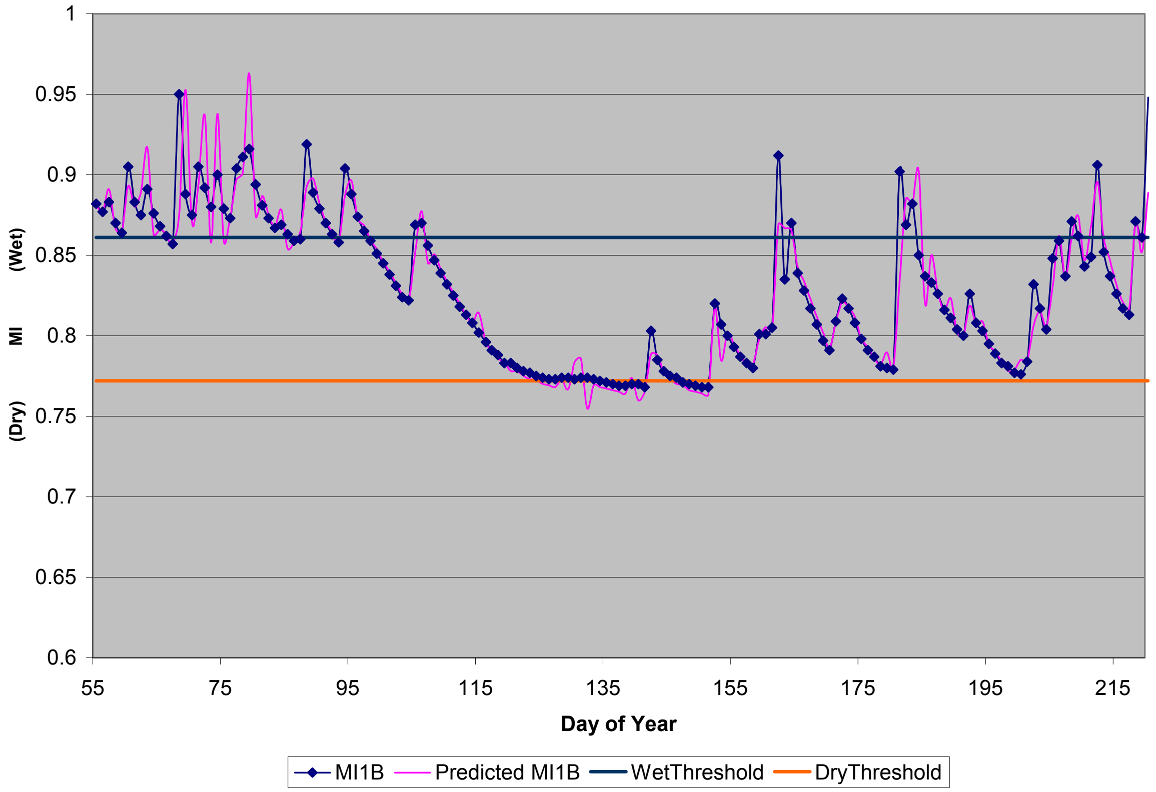

Fig. 1. A time series of moisture index for probe 1B (MI1B), the predicted MI for probe 1B and the wet and dry thresholds.

the correlation values were not as high as for the total past 24-hour precipitation amount.

A multiple linear regression of the moisture index 1B with the previous day's moisture index ($MI1B_{t-1}$), the square root of the past 24 hour precipitation (P_t) and the square root of the precipitation from the previous 24 hour period (P_{t-1}) gives the equation:

$$MI1B_t = 0.9938 \times MI1B_{t-1} + 0.0029 \times \sqrt{P_t} - 0.0016 \times \sqrt{P_{t-1}} \quad (2)$$

with an r^2 value of 0.9997 and a correlation value of 0.95.

Figure 1 shows a time series of the 1300 LST moisture index 1B prediction as well as the actual values for the development period in 2001. The plot shows that the prediction works well during dry periods but has some trouble accurately capturing wetting periods. Overall, the mean absolute error for the model is 0.0080. Separating the days with rain from the days without rain gives an idea of the differing model performance for the two phases. Mean absolute error is 0.0037 for days without rain and 0.0135 for days with rain.

Visual inspection of the time series of the moisture index and precipitation indicates that for any given amount of rain, the moisture index response is not consistent. We hypothesize that a short intense rainfall is less effective at wetting the forest floor than a longer, less intense rain event of the same magnitude. Additionally, it appears that the forest floor organic layers are somewhat hydrophobic when the moisture index drops to very low levels. When the forest floor is very dry, it appears to require an as-of-yet unquantified volume of rain for the moisture index to noticeably respond.

These differing trends in forest floor wetting are likely to be the cause of the poorer model performance on days with rain as opposed to rainless days.

To further test the application of this type of predictive model, multiple linear regressions were performed using data from weather stations Eglin 12 and Eglin 13. These regressions are based upon data from 2002 and 2003. Again predictive equations were developed that were consistent in accuracy with the Eglin 1 predictions. Some of the same patterns were also found. The same predictive variables yielded the highest correlation, and drying was better predicted then wetting.

5.0 A DRYING CALCULATOR

To best utilize the predictive equation developed for the duff layer at Eglin 1 in an easy to use format, a

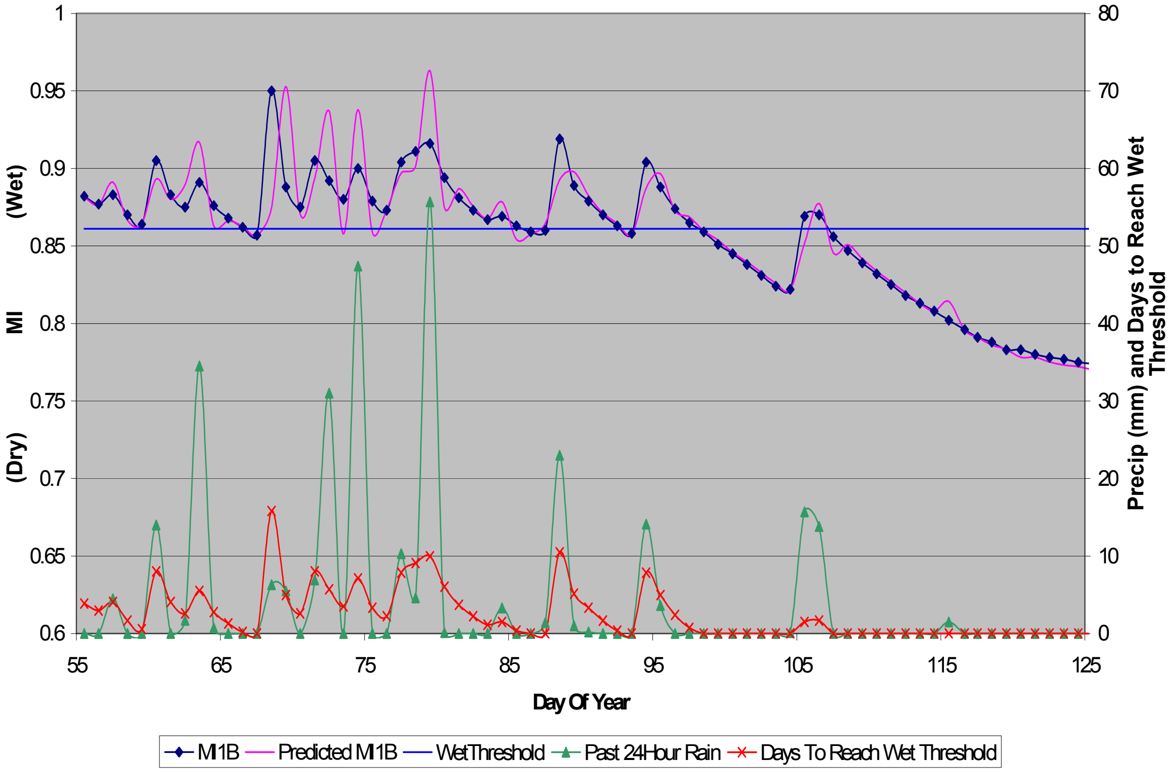

Fig. 2. A time series of moisture index for probe 1B (MI_{1B}), predicted moisture index, rain, and the number of dry days need for the MI to reach wet threshold.

website will be created that employs a calculator to predict future moisture index values. Using the current moisture index and past precipitation totals, equation 2 is used to calculate the number of dry days needed to reach either the wet or the dry burn threshold. This provides a quick forecast that can be used to anticipate the timing for fuel conditions to reach a desirable level for prescribed fire operations.

The accuracy of the moisture index prediction degrades with time. Mean absolute error increases from 0.0082 to 0.0188 as the prediction extends from 1 to 7 days out. The accuracy of the drying calculator's prediction can be examined in Figure 2. Notice the rain event on day 88 of 2001 and the dry period that followed. On day 88, the past 24 hour rain amount totaled 23 mm and the 1pm MI of probe 1B (MI_{1B}) had peaked at 0.919. Given this MI value, the drying calculator predicts that 10 dry days are required for the MI_{1B} to drop below the wet burn threshold. The MI_{1B} actually dropped below the threshold in 4 days, significantly faster than the predicted 10 days. However, on day 89, after 24 hours of drying, the drying calculator predicts 5 dry days are needed to drop the MI_{1B} below the wet burn threshold. This is much closer to the 3 days actually needed for the drying to occur. The same pattern is found for the rain events on day 63 and 94. The predicted number of drying days are much more accurate after one day of drying has already occurred. Therefore, it appears that the drying calculator performs significantly better 24 hours after a rain event then directly after a rain event.

6.0 CONCLUSIONS

A simple model developed from a multiple linear regression of past moisture index and past precipitation can provide a useful tool for predicting the evolution of future moisture conditions. By using a long time series of continuous data in 2001 to derive the equation, correlation values remain high when tested against data in 2002 and 2003.

7.0 REFERENCE

Ferguson SA, Ruthford JE, McKay SJ, Wright D, Wright C, Ottmar R (2002) Measuring moisture dynamics to predict fire severity in longleaf pine forests. *International Journal of Wildland Fire*, **11**, 1-14.