J11.5

INDEPENDENT FIELD VERIFICATION OF A NEXT-GENERATION MODEL FOR DEAD FUEL MOISTURE

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1. INTRODUCTION

Dead fuels represent a category of wildland fuels whose moisture content is controlled exclusively by environmental conditions. Accurate assessment of fuel moisture in dead fuels is critical since these fuels are typically involved in the start and initial spread of wildland fires. In the National Fire Danger Rating System (NFDRS) of the USA (Deeming *et al*., 1977; Bradshaw *et al*., 1983), dead fuels are separated into four "timelag" classes: 1-hour, 10-hour, 100-hour, and 1000-hour. These four fuel classes are typically associated with fuels ranging from less than 0.64 cm to 20.3 cm in diameter. The timelag is a measure of the time it takes for the fuel to reach 63% of the difference between initial and equilibrium moisture contents given constant environmental conditions.

The algorithms used operationally today to calculate dead fuel moisture in NFDRS are essentially the same ones developed in the 1970s. They use once-a-day weather information (typically around 1400 local time) and require human intervention, every day, to enter a state-of-the-weather code, which triggers solar radiation estimates to calculate fuel temperature from the ambient temperature. Observed 10-hour fuel moisture from a standard set of fuel sticks (four connected, 1.27 cm diameter ponderosa pine dowels) can also be included as input to NFDRS. Electronic fuel moisture sticks are on a number of automated weather stations today, but because of variations between manufacturers, the National Wildfire Coordinating Group's (NWCG) Fire Danger Working Team has recommended that NFDRS algorithms be used for consistency.

With the increasing number of automated weather stations and networks, the calculation of dead fuel moisture need not be limited to once-a-day weather data. The next-generation fire danger system of the USDA Forest Service calls for the inclusion of new dead fuel moisture models which can take advantage of the frequent weather observations available from such automated weather stations.

During the 1990s, Ralph Nelson, Jr., formerly of the USDA Forest Service, developed a theoretical model to take advantage of frequent observations which come from such automated weather stations. The model as originally developed and published (Nelson, 2000) was only for 10-hour dead fuels. Since 2000, however, Nelson developed fuel stick parameters to allow the model to be run for the three other size fuel classes.

This paper compares the performance of the "Nelson" model for all dead fuel classes against an extensive measured data set during a 21-month period from Slapout, Oklahoma, in the Oklahoma panhandle.

2. THE NELSON DEAD FUEL MOISTURE MODEL

The Nelson model for dead fuel moisture is a physically based model which contains the equations for moisture and heat transfer (Nelson, 2000). Besides internal water, it also takes into account water at the surface through the processes of adsorption, desorption, rainfall, condensation, and evaporation. Inputs to the Nelson model include air temperature, relative humidity, solar radiation, and rainfall amount since the last observation. Outputs include moisture content and temperature of the fuel stick at the times corresponding to the weather data inputs.

The model, so as to be usable in practice, has been converted into a finite-difference numerical model. Separate time steps for moisture and heat diffusivity are used. In the model runs to be discussed (using hourly weather data), the moisture time steps for 1-, 10-, 100-, and 1000-hour fuels were 0.004 hour, 0.02 hour, 0.05 hour, and 0.20 hour, respectively. The heat time steps were 0.05 hour, 0.25 hour, 0.25 hour, and 0.25 hour, respectively. When more frequent weather data than hourly are used, these time steps need to be reduced to prevent numerical instability.

The model also has maximum limits for dead fuel moisture in rainy conditions; these are 85% for 1-hour

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fuels, 60% for 10-hour fuels, 40% for 100-hour fuels, and 32% for 1000-hour fuels. In the comparisons to follow, it will be seen that some observations exceed these thresholds, especially in the case of 1-hour fuels.

For the model output to be discussed, the Nelson model was run using hourly weather data from the nearby (0.7 km away) Slapout weather monitoring station of the Oklahoma Mesonet. The Oklahoma Mesonet, operational since 1994, consists currently of 115 remote automated weather and soil monitoring stations throughout Oklahoma with an average spacing of 30 km that relay observations every 15 minutes by radio signal (Elliott *et al*., 1994; Brock *et al*., 1995). The Nelson model, for each size fuel, was initialized using the appropriate Mesonet weather data and a dead fuel moisture of 5%, and then run consecutively for 21 months using hourly Mesonet weather data.

3. OKLAHOMA FIELD STUDY

Field weighings of ponderosa pine dowels of four different diameters (0.4, 1.27, 4.0, and 12.8 cm), representing the four timelag fuel classes, were regularly made by Randall Bensch on his property in Slapout, Oklahoma during a 21-month period lasting from March 25, 1996 through December 31, 1997. The dowels, 41 cm long (except for a standard 10-hour set, which was also weighed), were fully exposed to the atmosphere in a horizontal mode 30 cm above the ground cover (Figure 1).

Figure 1. *Arrangement of ponderosa pine dowels in a similar field study to that of Slapout.*

The following sets of fuel sticks were weighed using two battery-powered balances enclosed in a nearby rotatable wooden shelter (for wind shielding): ten 1-hour and four 10-hour dowels, each weighed as a group; a "standard" set of 10-hour fuel sticks; three 100-hour dowels, weighed individually; and three 1000-hour logs, weighed individually. During periods of rain or dew, the surface water was not shaken off before weighing. Weights were taken to the nearest tenth of a gram for the 1-, 10-, and 100-hour dowels (one balance), and to the nearest gram for the 1000-hour logs (the other balance).

The 1- and 10-hour fuel sticks were weighed twice daily (in the morning and in the afternoon). The 100- and 1000-hour dowels were weighed once per day during the first three months of the study, and approximately twice daily thereafter. The morning observation times varied from 0500-1145 local time, and the afternoon times from 1530-2315 local time - depending on time of year and the work schedule of the producer.

To minimize loss of wood material that would affect dead fuel moisture calculations, the fuel sticks were replaced in the field as follows: 1- and 10-hour dowels, every 3 months; and 100-hour dowels, every 6 months. The original 1000-hour logs were kept in the field for the entire duration of the study. Oven-dry weights of all sets of fuel sticks were obtained before placement in the field. Dead fuel moisture (DFM) was calculated as the difference in field and oven-dry weights divided by the oven-dry weight.

In the comparative study to follow, the observed 100-hour dead fuel moisture represents the average DFM of the three separate 100-hr dowels, and the same is true of the observed 1000-hr DFM. In addition, observations which noted that fuel sticks had accumulations of ice/snow on them were discarded in the analysis, since the Nelson model does not handle such situations.

During the period of fuel stick observations, monthly average temperatures at Slapout ranged from 0C to 27C, and monthly precipitation from 0.25 mm to 174 mm, so a wide range of weather conditions was encountered with which to test the Nelson model.

4. MODEL TO FIELD COMPARISONS

All valid field observations were converted to dead fuel moisture (DFM) in % using the appropriate oven-dry weights. Observation times were converted to Julian day and GMT, and, from there, to "Hour of Year" for comparison to model output, which used the GMT day.

4.1 *1-Hour Fuels*

For illustration we have chosen a very dry month (April 1996) and the wettest/warmest month of the period (July 1996). April 1996 had a monthly rainfall total of 0.5 mm and an average temperature of 14.8C; July 1996 had a monthly rainfall total of 174 mm and an average temperature of 26.6C.

Looking first at April 1996 (Figure 2), one sees that the diurnal pattern of higher and lower observed dead fuel moisture (DFM) is captured well by the Nelson model. This close agreement is typical of dry weather periods - when there is rain, as with the model DFM peaks over 80%, if the observation doesn't exactly coincide with the rain event, there won't be close agreement - but this is not a problem of the model.

Looking at July 1996 (Figure 3), one sees some patterns that are typical of rainy periods. Note that there are frequent instances when model DFMs exceed the observed DFMs, but this is largely a function of the observation not coinciding exactly with the rain events.

Also observe how the model peaks at 85% during many of these rain events. Finally, note that there are a number of observed DFM values (around hour 4600) which exceed the model peak values of 85%.

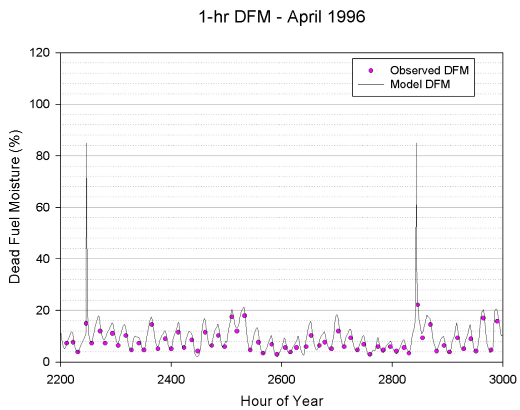

Figure 2. *Observed versus model 1-hour dead fuel moisture (DFM) for April 1996.*

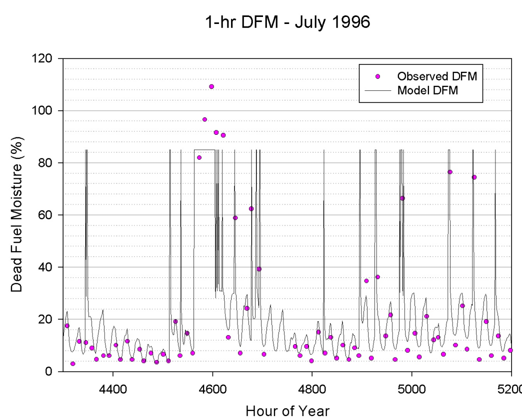

Figure 3. *Observed versus model 1-hour dead fuel moisture (DFM) for July 1996.*

4.2 *10-Hour Fuels*

The same two months are chosen for illustration. Figure 4 shows the model versus observation 10-hour DFMs for April 1996. Here the 10-hr standard set of fuel sticks was used for the observation DFM values. Note how the diurnal behavior is again captured by the Nelson model. Figure 5 shows the 10-hour behavior during a rainy month. Observe that there are a number of instances when the model DFM maximum of 60% is reached.

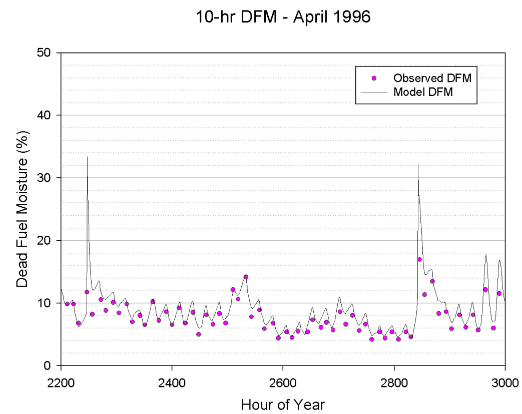

Figure 4. *Observed versus model 10-hour dead fuel moisture (DFM) for April 1996.*

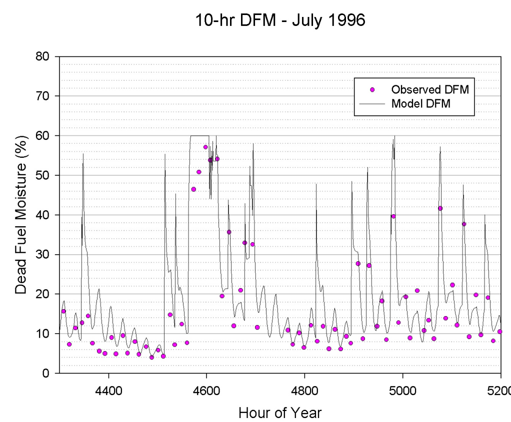

Figure 5. *Observed versus model 10-hour dead fuel moisture (DFM) for July 1996.*

4.3 *100-Hour Fuels*

As an example of model behavior, we choose to present the entire period of 1996 for which observations were taken (late March through December). Figure 6 shows the comparisons. The Nelson model does an admirable job of estimating 100-hour DFM, although it seems to consistently overestimate the low end by a few percent. The 1997 graph (not shown) also shows instances where the model underestimates the high peaks by up to 6% at times.

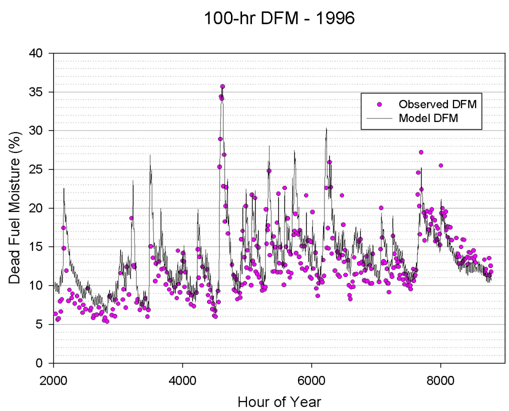

Figure 6. *Observed versus model 100-hour dead fuel moisture (DFM) for 1996.*

4.4 *1000-Hour Fuels*

The Nelson model does the poorest job with 1000-hour fuels, as shown by Figure 7, which presents the comparisons for the entire year 1997. Similar to the 100-hour, the low values of DFM are frequently overestimated by several percent, but, in contrast with the 100-hour, the high values of DFM during rainy periods are greatly underestimated. It appears that the Nelson model, in its current parameterization for 1000-hour DFM, does not have sufficient amplitude of variation to properly model the observed 1000-hour behavior. On the other hand, the 1000-hour logs possessed several lateral cracks into which water could move and reside during rain events and thus lead to higher DFM than the model would predict. Finally, since fire managers are more concerned about the low side of DFM, the model may be more than adequate to meet those needs, since overestimation is only by a few percent.

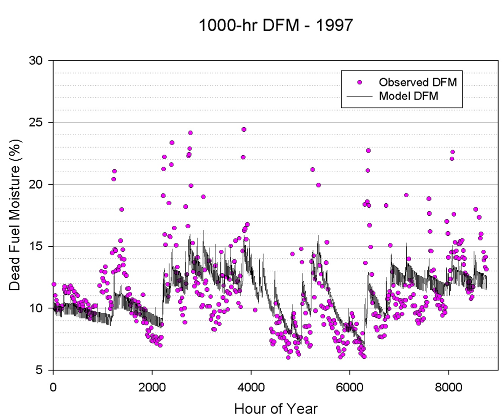

Figure 7. *Observed versus model 1000-hour dead fuel moisture (DFM) for 1997*

5. PAIRED MODEL TO FIELD COMPARISONS

To be better able to assess the performance of the Nelson model, however, one really needs to compare the model output only occurring at the exact times of the observations. Only then can one do a proper statistical analysis to compare the two, including regression. The model output DFMs were thus interpolated to the exact times of the observations for such analyses.

Table 1 gives some simple statistics for the four fuel sizes. First, the highest and lowest DFMs produced by the observed data set are given, followed by the mean, standard deviation, skewness, and kurtosis of the distribution. Next, for comparison, follows the same set of information for the model in the reduced data set.

Overall, these results are encouraging. Means between observed and model DFMs differ by less than 3% in the case of 1-hour, falling to only 0.2% difference for the 1000-hour. Standard deviations are even closer, the maximum difference being 1.2% for the 1000-hour. The fact that skewness and kurtosis are of the same sign (except in the case of the 1000-hour) show the distributions of both observed and model DFM are shaped similarly.

Table 2 gives results from a linear regression analysis. The r-square value (r2) is given, as is the standard error of estimate (%), followed by the linear equation linking the model DFM to observed DFM.

The r2 values are best for the 10-hour and 100-hour model (0.78 and 0.77, respectively), followed by the 1-hour (0.65) and then the 1000-hour, which is by far the worst at 0.50. As one might expect for the fuel size under consideration, the standard error of estimate is highest for 1-hour fuels (9.2%) falling to 1.6% for 1000-hour fuels.

Looking at the regression equations for all four fuel classes can indicate for what moisture regimes the Nelson model tends to overestimate and underestimate dead fuel moisture. With the aid of some algebra, the 1-hour equation indicates that below observed DFM values of 29.8%, the model tends to overestimate the actual values while underestimating them above 29.8%. The “break-even” point for the 10-hour (85%) is above the maximum model DFM of 60%, indicating that for all observed DFMs below 85%, the model tends to overestimate the actual values. For the 100-hour case, the Nelson model overestimates observed DFM values below 17.5%, while underestimating them above this value. Finally, for the 1000-hour fuels, the model overestimates observed values below 11.1%, while underestimating them above. Of course, these results are based on linear regression, which may not be the best fit for these data sets.

6. SUMMARY

This paper has compared 1-, 10-, 100-, and 1000-hour dead fuel moistures from the Nelson model using hourly weather data from a nearby automated weather station against a 21-month independent data set from Slapout, Oklahoma. In contrast with current National

Table 1. *Statistics of dead fuel moisture for the entire 21-month study period. The Nelson model analysis considers only model output at the same times as the Slapout observations.*

FUEL SIZE	OBSERVED DEAD FUEL MOISTURE						NELSON MODEL DEAD FUEL MOISTURE					
	MaxImum value	Minimum value	Mean	Standard deviation	Skewness	Kurtosis	Maximum value	Minimum value	Mean	Standard deviation	Skewness	Kurtosis
1-Hour	109.2 %	0.0 %	15.3	15.4	2.7	7.8	85 %	1.8 %	18.1	15.5	3.0	9.7
10-Hour	64.3 %	1.6 %	15.0	10.2	2.2	5.0	60.0 %	3.7 %	17.0	11.3	2.1	4.2
100-Hour	35.7 %	5.4 %	13.4	4.8	1.4	2.9	35.7 %	6.4 %	14.4	4.1	1.4	3.2
1000-Hour	27.9 %	4.7 %	11.4	3.5	1.1	2.3	18.3 %	4.9 %	11.2	2.3	-0.1	-0.1

Table 2. *Linear regression results for the paired model-observation data set for the 21-month study period.*

FUEL SIZE	r2	Standard Error	Linear Regression Equation for Nelson Model Dead Fuel Moisture (DFM) in Percent
1-Hour	0.65	9.2 %	DFM (model) = 0.812 * DFM (observed) + 5.6
10-Hour	0.78	5.3 %	DFM (model) = 0.972 * DFM (observed) + 2.4
100-Hour	0.77	2.0 %	DFM (model) = 0.760 * DFM (observed) + 4.2
1000-Hour	0.50	1.6 %	DFM (model) = 0.460 * DFM (observed) + 6.0

Fire Danger Rating System (NFDRS) algorithms for dead fuel moisture, which were developed in the 1970s for use with once-a-day weather observations, the Nelson model represents a next-generation model for fuel moisture to take advantage of frequent weather observations taken by automated weather stations.

The 21-month comparison presented here shows the Nelson model does an excellent job in modeling dead fuel moisture (DFM) of 10- and 100-hour fuels (with r2 values of 0.78 and 0.77, respectively). In the case of 1-hour fuels, the model does a good job, with an r2 value of 0.65. In the case of 1000-hour fuels, the model does an adequate job (r2 of 0.50), but not to the level of success with the smaller size fuels. On the other hand, since fire managers are more concerned with the lower range of DFM values, the 1000-hour model may prove more than adequate over that range of DFM (as a regression analysis limited to the lower range of DFM might show).

In addition, the Nelson model has shown itself to be responsive to diurnal variations in temperature, solar radiation, and relative humidity, as well as to rainfall events - although not to the extent in the 1000-hour fuels as one might like. Since it doesn't require manual intervention and can take advantage of automated weather station networks, the Nelson model is an appropriate model to calculate dead fuel moisture in next-generation fire danger rating systems such as NFDRS.

The Rocky Mountain Research Station of the USDA Forest Service currently has a Research Joint Venture Agreement with Oklahoma State University to investigate how the Nelson model performs in a near-real-time data stream environment. Plans are moving forward to integrate the Nelson model into the Oklahoma Fire Danger Model (Carlson *et al.*, 2002; Carlson and Burgan, 2003) and, thereby, into the near-real-time Oklahoma Mesonet of 115 automated weather monitoring stations. Instead of hourly data, 15-minute data will be used. In addition, to see how the Nelson model performs in a forecast environment, output from the National Weather Service's Eta model will be integrated into the Oklahoma Fire Danger Model. After the completion of this project, it is anticipated that the Nelson model will become a keystone element in the "next generation" NFDRS.

5. REFERENCES

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