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FIELD VERIFICATION OF THE NELSON DEAD FUEL MOISTURE MODEL AND COMPARISONS WITH NATIONAL FIRE DANGER RATING SYSTEM (NFDRS) PREDICTIONS

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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 (Bradshaw *et al.*, 1983). 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 many automated weather stations today, but because of variations between manufacturers, the NWCG Fire Danger Working Team has recommended that NFDRS algorithms be used for consistency.

With the increasing number of automated weather monitoring stations and networks, the calculation of dead fuel moisture need not be limited to once-a-day weather data. The next-generation fire danger rating 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 for dead fuel moisture (DFM) 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 data set of DFM observations made during a 21-month period at Slapout, Oklahoma in the Oklahoma panhandle. We also compare the corresponding DFM predictions of NFDRS to the observed and Nelson model DFM values.

2. THE NELSON DEAD FUEL MOISTURE MODEL

The Nelson model for dead fuel moisture is a physically based model which contains the equations for heat and moisture 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 original mathematical model was converted into a finite-difference numerical model, so as to be usable in practice.

The original Nelson model was developed and tested by the USDA Forest Service using 1-hour weather data inputs. However, in the Research Joint Venture Agreement with the Forest Service which

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funded this research, we tested the model not only using 1-hour weather data, but also using 15-minute weather data. Because the Nelson model was targeted for eventual incorporation into the Oklahoma Fire Danger Model (Carlson *et al.*, 2002; Carlson *et al.*, 2003), we wished to test the Nelson model with the 15-minute weather data that is readily available from the Oklahoma Mesonet, Oklahoma's automated weather station monitoring network (Brock *et al.*, 1995).

Early in the research it was discovered that weather data time steps less than one hour led to numerical instability when one used the computational time steps developed for the "1-hour" Nelson model. Upon reducing these computational time steps, the instability was eliminated.

It was also seen that the results using 15-minute weather data were not as good (especially for 100- and 1000-hour DFM) than when using 1-hour weather data. This led to a series of computational experiments in which various model parameters were altered to try to improve the results for the 15-minute model. In addition, the treatment of rainfall within the model code was changed from rainfall amount to rainfall rate, in order to handle weather-data time steps different from one hour.

Finally, the original numerical code for the Nelson model was written for use with only one weather station. We adapted the code to work with the entire Mesonet weather station network of 116 sites in an operational environment.

Table 1 below presents the "optimal" Nelson model parameters for use with 15-minute and 1-hour weather data inputs. These values were based on several months of experimentation and comparison of the Nelson model DFM to the 21-month observational DFM data set to be later described. Aside from different moisture and diffusivity computational time steps, the "15-minute" and "1-hour" Nelson model parameter sets are nearly identical (the adsorption coefficients for 100-hour fuels being different). These were the model parameters used in the analysis to be presented in this paper.

Note that the Nelson model has built-in maximum limits for dead fuel moisture in rainy conditions ("maximum moisture due to rain" in Table 1). The limits are 85% for 1-hour fuels, 60% for 10-hour fuels, 40% for 100-hour fuels, and 32% for 1000-hour fuels. In the comparisons later in this paper, it will be seen that there were some observed DFM values, albeit a small number, that exceeded these limits, especially in the case of 1-hour fuels.

3. OKLAHOMA FIELD OBSERVATIONS

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).

The following sets of dowels 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, and to the nearest gram for the 1000-hour logs.

Table 1. Nelson model parameters for different size fuels using 1-hour weather data inputs. If different, parameters for use with 15-minute weather data are in parentheses.

MODEL PARAMETER	1-HOUR	10-HOUR	100-HOUR	1000-HOUR
Number of calculation nodes	11	11	11	11
Stick radius (cm)	0.20	0.64	2.00	6.40
Stick length (cm)	41	41	41	20
Stick density (gm/cm3)	0.40	0.40	0.40	0.40
Moisture computation time step (hr)	0.004 (0.000833)	0.02 (0.00417)	0.05 (0.01)	0.20 (0.0417)
Diffusivity computation time step (hr)	0.05 (0.01)	0.25 (0.05)	0.25 (0.05)	0.25 (0.05)
Barometric pressure (cal/cm3)	0.0218	0.0218	0.0218	0.0218
Maximum moisture due to rain (g/g)	0.85	0.60	0.40	0.32
Planar heat transfer (cal/cm2-hr-C)	2.50	0.38	0.30	0.12
Surface mass transfer - adsorption (cm3/cm2-hr)	0.065	0.02	0.012 (0.006)	0.00001
Surface mass transfer - desorption (cm3/cm2-hr)	0.08	0.06	0.06	0.06
Initial rainfall factor	5.0	0.55	0.50	0.50
Subsequent rainfall factor	10.0	0.15	0.25	0.25
"Storm" transition value (cm/hr)	0.006	0.05	0.05	0.05
Water film contribution (g/g)	0.10	0.05	0.016	0.005

Figure 1. *Arrangement of ponderosa pine dowels in the field study at Slapout. Observer Randall Bensch is standing in the background near the rotatable wooden shelter housing the balances.*

The 1- and 10-hour dowels 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 to 1145 local time and the afternoon times from 1530 to 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; 100-hour dowels, every 6 months; but the original 1000-hour logs were kept in the field for the 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 weight divided by the oven-dry weight.

In the results 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. The 10-hour DFM is from the standard set of connected 10-hour fuel sticks. In addition, observations where fuel sticks had obvious 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 0.2C (32F) to 26.6C (80F), and monthly precipitation from 0.5 mm (0.02") to 173.7 mm (6.84"), so a wide range of weather conditions was encountered with which to test the Nelson model.

This 21-month DFM observational data base constitutes the longest continuous data base of DFM observations on which the Nelson model has heretofore been tested.

4. ANALYSIS METHODOLOGY

In the model output to be discussed, the Nelson model was run using weather data from the Slapout weather monitoring station of the Oklahoma Mesonet. This station is only 0.7 km distant from the DFM study site. 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 the 21-month period using both 15-minute and hourly weather data from Slapout. For the 15-minute runs, the "15-minute" parameter set was utilized, while for the hourly runs, the "hourly" parameter set was used (Table 1).

The NFDRS algorithms for DFM were also run during this period (as part of the Oklahoma Fire Danger Model). In our operational model, NFDRS dead fuel moisture is updated hourly for 1- and 10-hour fuels, while 100-hour and 1000-hour DFM are updated once a day at 2200 GMT (1600 CST) using hourly data from the past 24-hour period. In the NFDRS DFM calculations, described in more detail in Carlson *et al.* (2002), 1- and 10-hour DFM are functions of equilibrium moisture content (EMC), which utilizes fuel-level temperature and relative humidity, as well as solar radiation. Change in 100-hour DFM is a function of the average EMC over the past 24 hours as well as the duration of precipitation. Change in 1000-hour DFM is a function of the average EMC over the past 7 days as well as the duration of precipitation over that period.

With respect to the field observations, all valid fuel stick measurements were converted to 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 Nelson model and NFDRS output, which used the GMT day.

In the results to follow, we will qualitatively compare observed, Nelson model, and NFDRS dead fuel moisture to each other (for each size fuel class) during the period of field observations (late March 1996 through 1997). However, to facilitate a statistical analysis, Nelson model and NFDRS DFM values were interpolated to the exact times of the observations. Linear interpolation in time was utilized between surrounding Nelson model and NFDRS DFM output. We will conclude our discussion by observing the detailed behavior of the Nelson model and NFDRS during July 1996, a month that featured both the highest monthly average temperature and greatest monthly rainfall of the 21-month period.

5. RESULTS

5.1 Dead Fuel Moisture over the 21-Month Period

Using the interpolated DFM data bases for the Nelson model and NFDRS, we begin our analysis with some descriptive statistics of dead fuel moisture over the 21-month period. Table 2 presents these statistics for the observed DFM, the "15-minute" and "hourly" Nelson DFM, and the NFDRS DFM.

Table 2. Descriptive statistics for observed dead fuel moisture (DFM), "15-minute" and "hourly" Nelson model DFM, and NFDRS DFM over the 21-month period of observations.

OBSERVED DEAD FUEL MOISTURE (DFM)	FM1	FM10	FM100	FM1000
Mean (%)	15.3	15.0	13.4	11.4
Median (%)	10.7	11.9	12.5	10.9
Maximum (%)	109.2	64.3	35.7	27.9
Minimum (%)	0	1.6	5.4	4.7
Range (%)	109.2	62.7	30.3	23.2
Standard deviation (%)	15.4	10.2	4.8	3.5
Skewness	2.7	2.2	1.4	1.1
"15-MINUTE" NELSON MODEL DFM	**FM1**	**FM10**	**FM100**	**FM1000**
Mean (%)	16.8	15.1	14.0	11.1
Median (%)	14.6	12.6	13.3	11.3
Maximum (%)	85.0	60.0	34.5	16.3
Minimum (%)	1.8	4.0	5.7	6.5
Range (%)	83.2	56.0	28.8	9.8
Standard deviation (%)	12.2	9.0	4.6	1.8
Skewness	3.1	2.3	1.0	-0.1
"HOURLY" NELSON MODEL DFM	**FM1**	**FM10**	**FM100**	**FM1000**
Mean (%)	18.0	15.9	15.6	12.4
Median (%)	14.7	12.9	14.5	12.5
Maximum (%)	85.0	60.0	36.6	18.0
Minimum (%)	1.8	4.3	6.5	7.1
Range (%)	83.2	55.7	30.1	10.9
Standard deviation (%)	15.5	10.1	4.9	2.1
Skewness	3.0	2.3	1.0	-0.1
NFDRS DFM	**FM1**	**FM10**	**FM100**	**FM1000**
Mean (%)	13.1	13.3	14.1	16.2
Median (%)	11.9	12.4	13.4	16.1
Maximum (%)	27.0	26.2	30.3	23.9
Minimum (%)	1.4	2.4	4.7	8.0
Range (%)	25.6	23.8	25.6	15.9
Standard deviation (%)	5.8	5.2	4.0	3.0
Skewness	0.5	0.4	0.6	-0.2

Looking first at the observed DFM, one finds that over the 21-month period 1-hour DFM (FM1) ranged from 0.0% to 109.2%; 10-hour DFM (FM10), from 1.6% to 64.3%; 100-hour DFM (FM100), from 5.4% to 35.7%; and 1000-hour DFM (FM1000), from 4.7% to 27.9%. Thus, a wide range of DFM was encountered over which to test the Nelson model and NFDRS DFM algorithms.

With respect to the maximum DFM values within each fuel class, it is clear that the Nelson model does a much better model capturing the observed maxima than does NFDRS. The model limits of 85% (FM1) and 60% (FM10) were reached in both the 15-minute and hourly Nelson models, and values as high as 36.6% (FM100) and 18.0% (FM1000) were modeled. NFDRS, on the other hand, recorded maxima of only 27% (FM1), 26.2% (FM10), 30.3% (FM100), and 23.9% (FM1000) during the same period.

With respect to minimum DFM values, NFDRS was able to predict lower values for FM1 (1.4%), FM10 (2.4%), and FM100 (4.7%) during the period than the two Nelson models. The NFDRS FM1000 minimum, however, was higher.

The Nelson model does a much better job than NFDRS of reproducing the observed DFM standard deviations and skewness for FM1, FM10, and FM100. In the case of FM1000, the Nelson model means and medians are much closer to the observed than are those of NFDRS, which are about 5% higher than the observed (Nelson mean and median values are within 1% and 2%, respectively).

5.2 Analysis of Nelson and NFDRS Dead Fuel Moisture

a. <u>1-hour dead fuel moisture</u>

We begin by qualitatively comparing the behavior of the Nelson model (1-hour weather data input) and NFDRS against the observations for the 21-month period. Figure 2 presents these plots for 1996 (a) and 1997 (b). What is readily apparent is the inability of the NFDRS to capture 1-hour DFM values above 25% or so, while the Nelson model is able to do so. One can see the built-in maximum of 85% for this model is frequently reached during the 21-month period. Note the existence

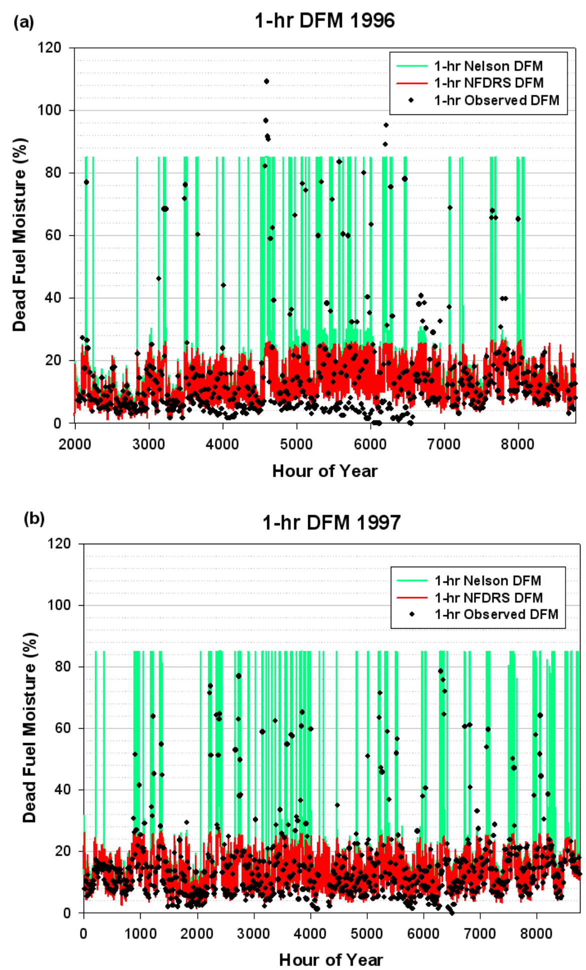

Figure 2. *Comparison of Nelson model (green) and NFDRS (red) 1-hour DFM against field observations (black dots) for 1996 (a) and 1997 (b).*

of several DFM observations above that 85% level, however. Also, note that the Nelson and NFDRS plots are based on hourly DFM output, while the observations of 1-hr DFM are only twice per day. Thus, it is should not be unexpected that many Nelson DFM predictions of high DFM (above 25%) are not corroborated by observations.

We now turn to the interpolated Nelson and NFDRS data sets, which are suitable for statistical comparison to the observational data set. Figure 3 presents a scatterplot of Nelson model 1-hour DFM and NFDRS 1-hour DFM (y-axes) against the observational values (x-axis) for these "paired" data sets. The Nelson model output using 1-hour weather data is presented.

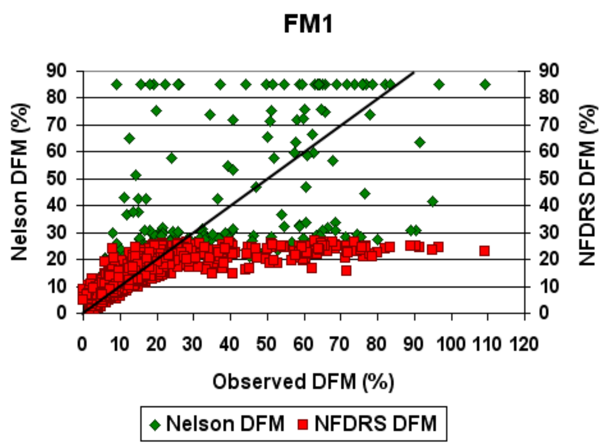

Figure 3. *Scatterplot of Nelson model (green) and NFDRS (red) 1-hour DFM (y-axes) versus observed DFM (x-axis) for the 21-month paired data sets. The x=y line is included for reference.*

The NFDRS algorithm clearly underestimates 1-hour DFM (FM1) for observed DFMs > 25%. The Nelson model, for these higher values, underestimates some observed values and overestimates other values. The larger deviations (both negative and positive) of the Nelson model are largely rainfall related, as the observations do not always coincide with the whole hours at which the model output occurs. For example, there could be rain reported (on the whole hours) just before and after a given DFM observation, while at the observation time itself no rain was falling, leading to a lower DFM measurement; or there could be rain at observation time, but none at the surrounding whole hours. Nevertheless, consistent with Figure 2, the Nelson model is able to model higher DFM values, while NFDRS does not.

Finally, Table 3 presents a statistical analysis of the paired data sets. Both the "15-minute" and "1-hour" Nelson models are included, as is NFDRS. R2 values between the various models and the observed DFM are first presented, followed by some descriptive statistics of the "error" of each model (i.e., of [Model DFM - Observed DFM]).

Table 3. Statistics for 1-hour dead fuel moisture (FM1) for the "15-minute" and "1-hour" Nelson models and NFDRS. Comparisons of each of these "models" to the observed FM1 data set are presented.

FM1	MODEL		
Model vs Observed	Nelson (15 min)	Nelson (1 hour)	NFDRS
R2	0.64	0.64	0.55
Model Error (%) [Model - Observed]			
Mean	1.4	2.7	-2.2
Median	2.5	2.6	0.6
Std. Deviation	9.3	9.8	11.7
Skewness	-2.3	0.4	-3.4
Maximum	65.9	76.1	16.1
Minimum	-61.6	-59.9	-86.3

The r2 value for both Nelson models is 0.64 and is significantly better than the NFDRS r2 value of 0.55. Turning to "model error", one can see that the failure of NFDRS to predict higher DFM values (Figure 3) leads to a negative mean error of -2.2%. Standard deviations of model error for the two Nelson models are less than that for NFDRS, which is consistent with the higher r2 values for the Nelson models. With respect to FM1, the "15-minute" Nelson model may have a slight advantage over the "1-hour" model due to more timely rainfall incorporation. Means and standard deviations of model error are slightly less in magnitude for the 15-minute model. Mean and median model errors on the order of 1-3% (overprediction) are indicated for the Nelson models, while NFDRS has a mean error around -2% (underprediction).

b. <u>10-hour dead fuel moisture</u>

Figure 4 compares the Nelson model (1-hour version) and NFDRS 10-hour dead fuel moisture (FM10) outputs against the FM10 observations for 1996 (a) and 1997 (b). Here, as with 1-hour fuel moisture, one sees the inability of NFDRS to model dead fuel moisture above 25% or so, while the Nelson model is able to do so. The built-in maximum of 60% for the Nelson model is frequently reached during the 21-month period. Only three DFM observations exceeded this maximum and all were below 65%.

As before, we now turn to the interpolated Nelson and NFDRS data sets, which are suitable for statistical comparison to the FM10 observations. Figure 5 presents a scatterplot of Nelson model 10-hour DFM and NFDRS 10-hour DFM (y-axes) against the observational values (x-axis) for these "paired" data sets. Again, the Nelson model output using 1-hour weather data is presented.

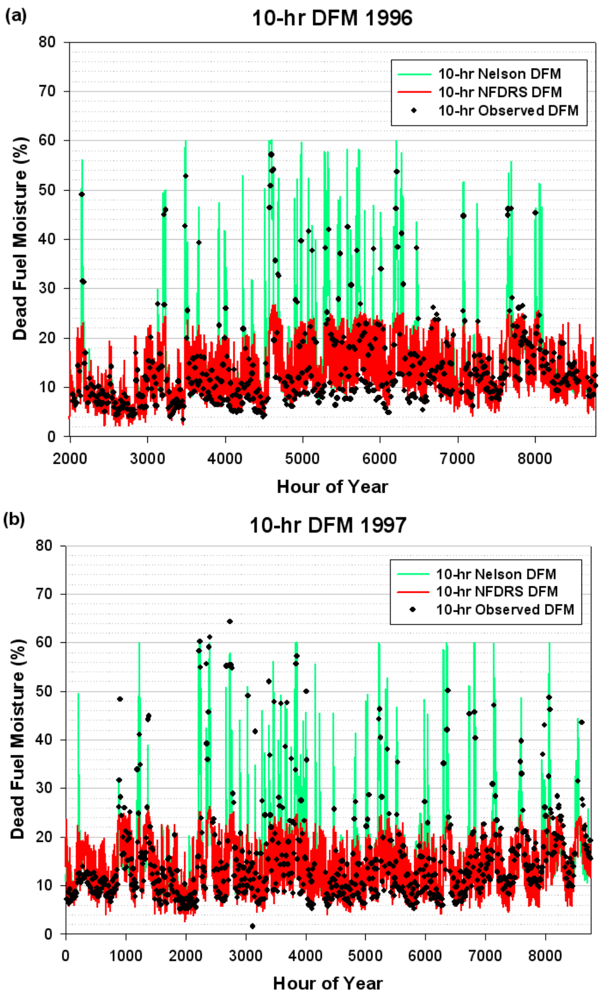

Figure 4. *Comparison of Nelson model (green) and NFDRS (red) 10-hour DFM against field observations (black dots) for 1996 (a) and 1997 (b).*

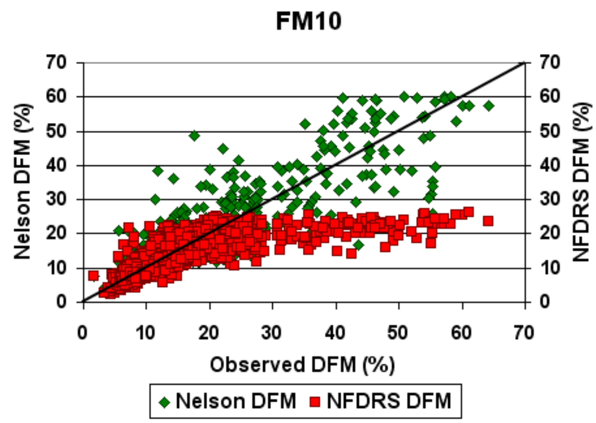

Figure 5. *Scatterplot of Nelson model (green) and NFDRS (red) 10-hour DFM (y-axes) versus observed DFM (x-axis) for the 21-month paired data sets. The x=y line is included for reference.*

As with 1-hour DFM, the NFDRS algorithm clearly underestimates 10-hour DFM (FM10) for observed DFMs > 25%. While many Nelson model green markers are obscured by the red NFDRS markers (as with the continuous plots of Figures 2 and 4), it is readily apparent that the Nelson model is able to predict higher DFM values and that deviations appear to be evenly scattered above the x=y line for this range of values.

Finally, Table 4 presents a statistical analysis of the paired data sets. For FM10 the improvement of the Nelson model over NFDRS is even more marked. Nelson r2 values rise from 0.64 (FM1) to 0.79, which exceeds the r2 value of NFDRS (0.58) by more than 0.2. Moving to "model error", one sees that the mean model errors and standard deviations for the Nelson models are smaller than those of NFDRS. The "15-minute" model may have a slight advantage over the "1-hour" model due to more timely incorporation of rainfall (note the mean and median model errors are lower for the 15-minute model). Mean and median model errors on the order of 1% or less (overprediction) are indicated for the Nelson models, while NFDRS has a mean error around -2% (underprediction).

Table 4. Statistics for 10-hour dead fuel moisture (FM10) for the "15-minute" and "1-hour" Nelson models and NFDRS. Comparisons of each of these "models" to the observed FM10 data set are presented.

FM10	MODEL		
Model vs Observed	**Nelson (15 min)**	**Nelson (1 hour)**	**NFDRS**
R2	**0.79**	**0.79**	**0.58**
Model Error (%) [Model - Observed]			
Mean	**0.1**	**0.9**	**-1.8**
Median	**0.5**	**0.9**	**0.1**
Std. Deviation	**4.7**	**4.7**	**7.1**
Skewness	**-1.7**	**-0.4**	**-2.6**
Maximum	**19.3**	**31.0**	**14.6**
Minimum	**-28.0**	**-29.5**	**-40.7**

c. 100-hour dead fuel moisture

The comparisons of Nelson and NFDRS 100-hour dead fuel moisture (FM100) against observed FM100 for the 21-month period are presented in Figure 6. These plots show the Nelson model continues to be better at simulating higher DFM values than NFDRS. A significant number of observations on the high end are modeled by Nelson, but underestimated by NFDRS. It is also apparent that there are a number of DFM

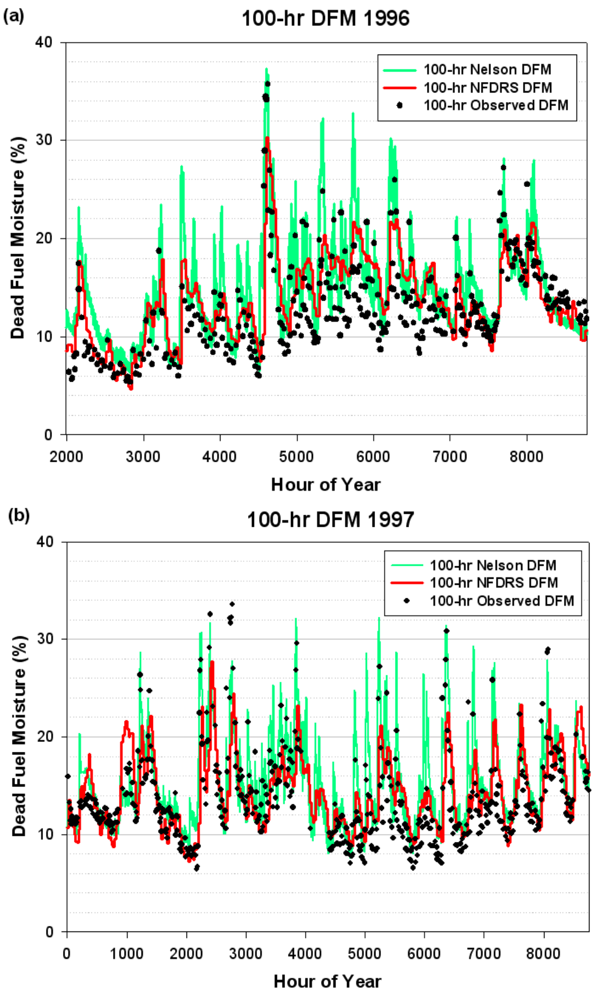

Figure 6. *Comparison of Nelson model (green) and NFDRS (red) 100-hour DFM against field observations (black dots) for 1996 (a) and 1997 (b).*

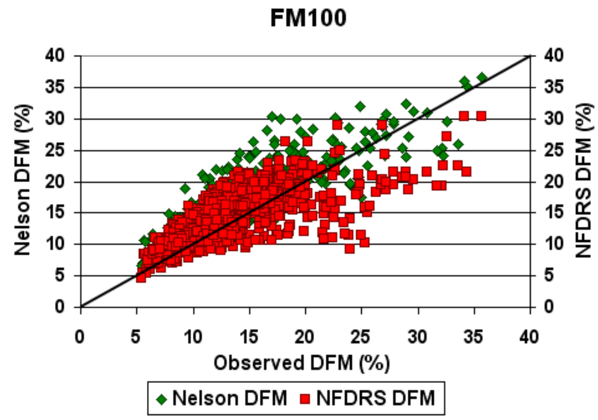

Figure 7. *Scatterplot of Nelson model (green) and NFDRS (red) 100-hour DFM (y-axes) versus observed DFM (x-axis) for the 21-month paired data sets. The x=y line is included for reference.*

observations on the low end which are not adequately modeled by either Nelson or NFDRS.

We now turn to the interpolated Nelson and NFDRS data sets, which are suitable for statistical comparison to the FM100 observations. Figure 7 presents the scatterplot of Nelson model 100-hour DFM and NFDRS 100-hour DFM (y-axes) against the observational values (x-axis) for these "paired" data sets. Again, the Nelson model output using 1-hour weather data is presented.

It is clear that the NFDRS algorithm clearly underestimates 100-hour DFM (FM100) for observed DFM values above about 20%. Again, while many Nelson model green markers are obscured by the red NFDRS markers, it is readily apparent that the Nelson model is able to predict higher DFM values and that deviations appear to be more or less evenly scattered above the x=y line for this range of values.

Finally, Table 5 presents a statistical analysis of the paired data sets. It is for this size fuel that the Nelson model shows the greatest improvement over NFDRS, with an r2 increase of about 0.25 as compared to NFDRS. Nelson model FM100 r2 values (0.75-0.77) are the same order of magnitude as those for the Nelson FM10 model (0.79). Moving to "model error", one sees that the standard deviations are smaller for the Nelson model than NFDRS, while mean and median errors are positive (overprediction) and on the order of 1-2% for all models. The "15-minute" Nelson model again shows a slight advantage over the "1-hour" model in that its mean and median errors are smaller, while its r2 value is slightly higher.

Table 5. Statistics for 100-hour dead fuel moisture (FM100) for the "15-minute" and "1-hour" Nelson models and NFDRS. Comparisons of each of these "models" to the observed FM100 data set are presented.

FM100	MODEL		
Model vs Observed	**Nelson (15 min)**	**Nelson (1 hour)**	**NFDRS**
R2	**0.77**	**0.75**	**0.51**
Model Error (%) [Model - Observed]			
Mean	**0.6**	**2.1**	**0.7**
Median	**0.5**	**1.9**	**1.1**
Std. Deviation	**2.3**	**2.5**	**3.4**
Skewness	**-0.1**	**0.4**	**-1.3**
Maximum	**9.2**	**13.3**	**8.1**
Minimum	**-10.2**	**-8.2**	**-15.1**

d. 1000-hour dead fuel moisture

The comparisons of Nelson and NFDRS 1000-hour dead fuel moisture (FM1000) against observed FM1000 for the 21-month period are presented in Figure 8. For this size fuel, the Nelson model shows a clear advantage. The NFDRS predictions consistently overpredict the majority of the observed FM1000 values by about 5%. While Nelson is not able to model the highest FM1000 values, it does stick closer to the bulk of the observations than does NFDRS. It is also apparent the Nelson is not able to model some of the lower values, especially during 1997; even then, however, it does a much better job than NFDRS.

We now turn to the interpolated Nelson and NFDRS data sets, which are suitable for statistical comparison to the FM1000 observations. Figure 9 presents the scatterplot of Nelson model 1000-hour DFM sets. Again, the Nelson model output using 1-hour weather data is presented.

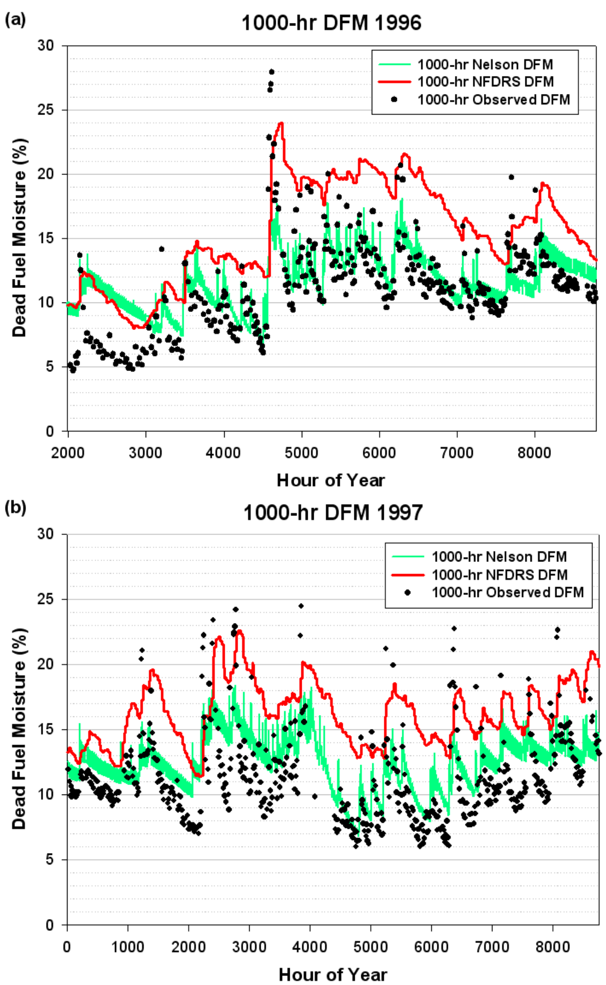

Figure 8. *Comparison of Nelson model (green) and NFDRS (red) 1000-hour DFM against field observations (black dots) for 1996 (a) and 1997 (b).*

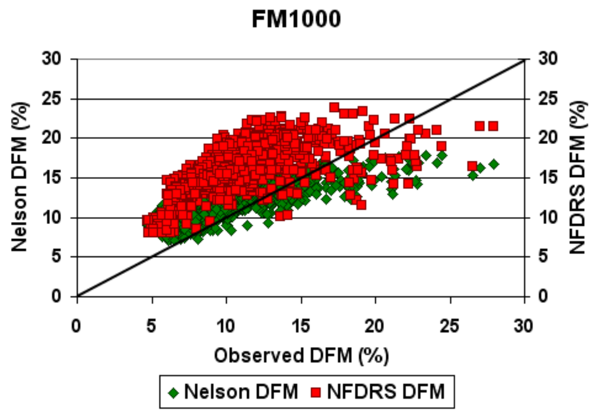

Figure 9. *Scatterplot of Nelson model (green) and NFDRS (red) 1000-hour DFM (y-axes) versus observed DFM (x-axis) for the 21-month paired data sets. The x=y line is included for reference.*

This scatterplot clearly reflects what is seen in the plots of Figure 8, namely, the tendency of the NFDRS FM1000 algorithm to overestimate the actual FM1000 values. This tendency is most pronounced in the 5-15% DFM range, where overestimates of 5-10% are common. The inability of Nelson to capture the higher DFM values (above 20% or so) is also indicated.

Finally, Table 6 presents the statistical analysis for the paired Nelson and NFDRS data sets. The Nelson r2 values for FM1000 (0.51-0.56), although the lowest Nelson r2s of any size fuel, are still significantly better than NFDRS (0.39). The tendency of NFDRS to overpredict FM1000 values is easily seen in the mean and median errors, which are both on the order of 5%. Nelson mean and median errors are much smaller, on the order of 0% for the 15-minute model and 1% for the hourly model. Standard deviations are similar between all models.

Table 6. Statistics for 1000-hour dead fuel moisture (FM1000) for the "15-minute" and "1-hour" Nelson models and NFDRS. Comparisons of each of these "models" to the observed FM1000 data set are presented.

FM1000	MODEL		
Model vs Observed	Nelson (15 min)	Nelson (1 hour)	NFDRS
R2	0.51	0.56	0.39
Model Error (%) [Model - Observed]			
Mean	-0.2	1.0	4.8
Median	0.2	1.4	5.1
Std. Deviation	2.5	2.4	2.9
Skewness	-1.6	-1.3	-1.4
Maximum	3.9	6.1	10.6
Minimum	-13.5	-11.3	-10.1

e. Comparisons between dead fuel classes

Table 7 presents a summary comparison of the Nelson model and NFDRS performance over the 21-month observational period for the four different fuel size classes. Again, the comparison is of the "model" based dead fuel moisture (DFM) against the observed DFM.

With respect to r2 values, the Nelson model (using either time step for weather data input) is the superior model. The improvements in r2 over NFDRS are 0.09 (FM1), 0.21 (FM10), 0.24-0.26 (FM100), and 0.12-0.17 (FM1000). The Nelson model does best for the 10- and 100-hour fuels (r2 values of 0.75-0.79), followed by 1-hour fuels (r2 values of 0.64), and then 1000-hour fuels (r2 values of 0.51-0.56).

The inability of NFDRS to predict higher values of DFM for FM1 and FM10 is seen in the negative mean model errors around -2%. In contrast, the tendency of the NFDRS to overpredict FM1000 is seen by the large mean model error around +5%.

Mean errors for the 15-minute Nelson model are lower in magnitude than the 1-hour Nelson model and NFDRS across all size fuels. Standard deviations in model error are lower (and of the same order of magnitude) for both Nelson models as compared to NFDRS.

Table 7. Nelson model and NFDRS dead fuel moisture performance over the 21-month observational period for the four different fuel size classes.

Model vs Observed	MODEL		
	Nelson (15 min)	Nelson (1 hour)	NFDRS
R2			
FM1	0.64	0.64	0.55
FM10	0.79	0.79	0.58
FM100	0.77	0.75	0.51
FM1000	0.51	0.56	0.39
Model Error (%) [Model - Observed]			
Mean			
FM1	1.4	2.7	-2.2
FM10	0.1	0.9	-1.8
FM100	0.6	2.1	0.7
FM1000	-0.2	1.0	4.8
Standard Deviation			
FM1	9.3	9.8	11.7
FM10	4.7	4.7	7.1
FM100	2.3	2.5	3.4
FM1000	2.5	2.4	2.9

5.3 Model Behavior during July 1996

The weather encountered during the 21-month observation period had wide ranges of temperature and precipitation. The highest temperature recorded was 42.2C (108F) in July 1996 and the lowest was -17.8C (0F) in December 1996. Average monthly temperatures ranged from only 0.2C (32F) in December 1997 to as high as 26.6C (80F) in July 1996. Monthly precipitation totals ranged from only 0.5 mm (0.02") in April 1996 to as much as 173.7 mm (6.84") in July 1996.

Because of the extremes of July 1996 (highest temperature and monthly average temperature, and greatest monthly rainfall), we conclude by showing plots of Nelson and NFDRS DFM behavior during this month. The 1-hour Nelson model is plotted here (the 15-minute plots are similar but with more temporal variation due to greater sensitivity to rainfall). The observed DFM is shown as before, and, in addition, hourly rainfall is plotted below the DFM.

Figure 10 shows the 1-hour dead fuel moisture (FM1) during the month of July 1996. Both the Nelson and NFDRS do a good job in capturing the diurnal cycle in FM1 during dry periods, but during rainy periods (note, not all rain can be depicted using such a large scale on the rainfall axis) the Nelson model responds greatly, often hitting its maximum of 85%. With only two DFM observations per day, it is not surprising that many Nelson model predictions of high DFM are not corroborated by observations. But it is clear that the Nelson model does a much better job during such events, with NFDRS DFM not able to rise above 25%.

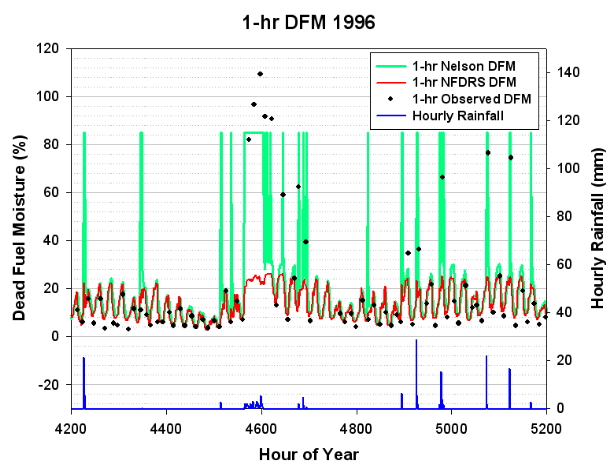

Figure 10. *Comparison of Nelson model (green) and NFDRS (red) 1-hour DFM against field observations (black dots) for July 1996. Hourly rainfall is also depicted.*

Next, Figure 11 shows the 10-hour dead fuel moisture (FM10) during July 1996. As with FM1, both models do a good job in capturing the diurnal cycle in FM10 during dry conditions, but during rainy conditions the Nelson model is able to respond much better. The built-in maximum of 60% is reached a number of times during the month. In contrast, the NFDRS DFM is not able to go much above 25% during the entire month.

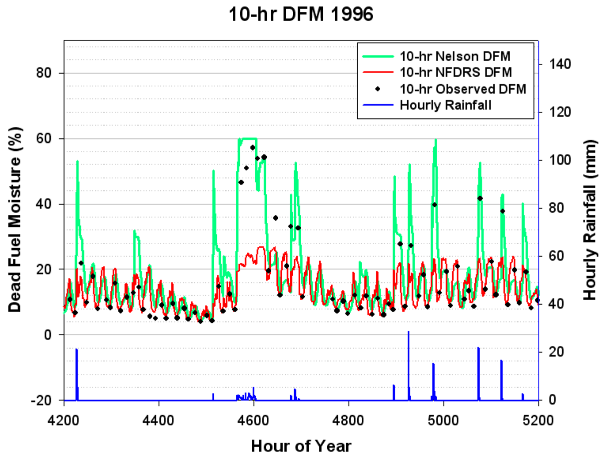

Figure 11. *Comparison of Nelson model (green) and NFDRS (red) 10-hour DFM against field observations (black dots) for July 1996. Hourly rainfall is also depicted.*

Moving to 100-hour dead fuel moisture (FM100), Figure 12 shows the behavior of the Nelson model and NFDRS during the same month of July 1996. The Nelson model is better able to capture the dynamics of FM100 during this month, modeling both the higher and lower DFM values better than NFDRS. The second peak in the Nelson model DFM is actually caused by a rain event too small to plot on the rainfall scale being used. The biggest peak during the month (and largest rise in DFM) occurs with a rain event of low intensity but of greater duration than the others. This shows, at least for FM100 (and FM1000), that it is not the intensity or amount of rainfall that matters, rather, the duration.

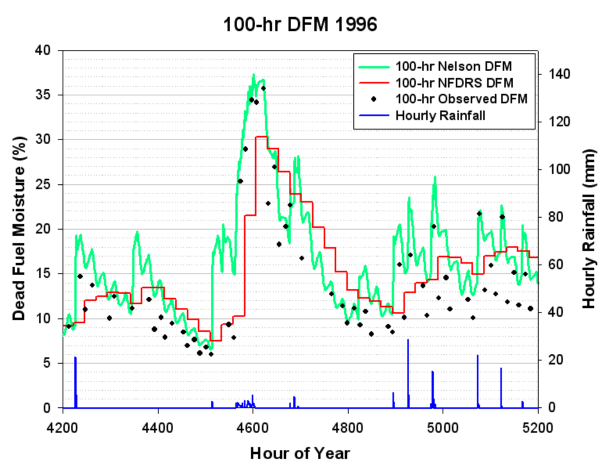

Figure 12. *Comparison of Nelson model (green) and NFDRS (red) 100-hour DFM against field observations (black dots) for July 1996. Hourly rainfall is also depicted.*

Finally, Figure 13 shows the behavior of the Nelson model and NFDRS for 1000-hour dead fuel moisture (FM1000) during July 1996. As with all size fuels, the Nelson model is better able to capture the dynamics of FM1000 during this month. While not able to model the higher DFM values during the middle of the month, it is able to model the bulk of the observations in the 5-20% range in a much better fashion than NFDRS. The tendency of NFDRS to overpredict FM1000 (as was seen earlier) is readily seen, with typical deviations of + 5-10% over observed values. Like the plot for FM100, the largest values (and rise) of FM1000 occur during and after a rain event of low intensity but of greater duration than any of the others.

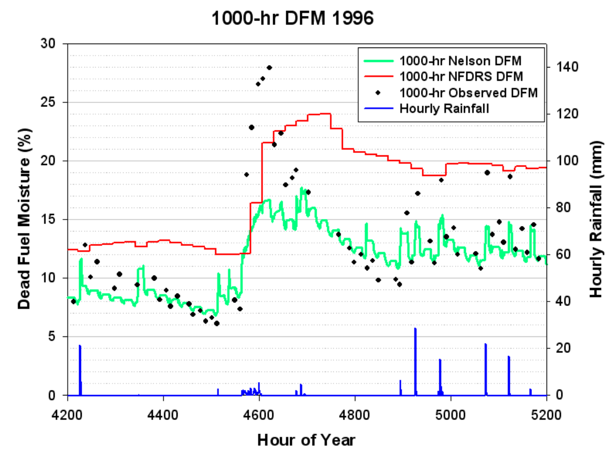

Figure 13. *Comparison of Nelson model (green) and NFDRS (red) 1000-hour DFM against field observations (black dots) for July 1996. Hourly rainfall is also depicted.*

6. SUMMARY

In this study the Nelson model for dead fuel moisture (DFM) was evaluated against field observations of DFM from Slapout, Oklahoma over a 21-month period lasting from late March 1996 through December 1997. All four fuel classes (1-, 10-, 100-, and 1000-hour) were included in the study. In addition, the corresponding DFM output from existing National Fire Danger Rating System (NFDRS) algorithms was used in the comparisons.

The observational data set from Slapout constitutes the longest continuous data base of DFM observations used for Nelson model development and testing. The model parameters used in this study (Table 1) were developed in conjunction with this observational data base. In addition, a wide range of weather conditions under which to test the model occurred during this period, with monthly average temperatures ranging from 0.2C (32F) to 26.6C (80F) and monthly precipitation, from 0.5 mm (0.02") to 173.7 mm (6.84").

Two “versions” of the Nelson numerical model were tested in this study - one using 15-minute weather data input (referred to as the “15-minute” model) and one using hourly weather data input (“1-hour” model). The weather data for input into the model (temperature, relative humidity, solar radiation, and rainfall) came from the Slapout weather station of the Oklahoma Mesonet. The same weather data source was used for the NFDRS DFM calculations.

Over the 21-month period, the Nelson model (both versions) outperformed NFDRS for each size fuel class, with improvements in r2 values ranging from 0.09 in the case of 1-hour fuels to 0.24-0.26 in the case of 100-hour fuels when compared against the observational data (Table 7).

The Nelson model has a built-in advantage for 1-hour (FM1) and 10-hour (FM10) fuels, since the NFDRS algorithms for these size fuels do not include the effects of rainfall. Thus, the Nelson model is able to reproduce the higher values of DFM for 1- and 10-hour fuels, while NFDRS DFM routinely stays below about 25%. This results in higher values of r2 (0.64 for FM1, 0.79 for FM10) for the Nelson model as compared to NFDRS (0.55 for FM1, 0.58 for FM10). With respect to “model error” (Table 7), the inability of NFDRS to model higher values of DFM results in negative mean errors in DFM of around -2% during the 21-month period. The Nelson model shows a slight tendency to overpredict, with positive mean errors for FM1 of + 1.4-2.7% and for FM10, + 0.1-0.9%. Standard deviations of model error are less for the Nelson model than NFDRS for these two size fuels.

With respect to 100-hour (FM100) and 1000-hour (FM1000) fuels, the Nelson model also outperforms NFDRS. The r2 analysis for FM100 shows the Nelson model with r2 values of 0.75-0.77, in contrast with the NFDRS r2 value of 0.51. For FM1000, despite a drop in r2, the Nelson model (r2 from 0.51-0.56) still outperforms NFDRS (r2 of 0.39). At least for this 21-month period and location, NFDRS consistently overpredicted the bulk of observed FM1000 values by up to 5-10%. This resulted in an average positive mean error of around +5%.

In summary, the Nelson model for dead fuel moisture (either with 15-minute or 1-hour weather data) constitutes an improvement over existing NFDRS dead fuel moisture algorithms, which are essentially the same ones developed in the 1970s. This improvement is seen for all four fuel sizes. Not only is the Nelson model more accurate in modeling dead fuel moisture, but being a numerical model, can easily be incorporated into fire-related models utilizing frequent, regularly spaced weather observations from automated weather station networks.

The Nelson model is targeted for inclusion in the next-generation NFDRS, which will utilize weather data from automated weather monitoring stations. In addition, a mid-range forecast component will be utilized in conjunction with the Nelson model to forecast DFM over the next 2-3 days. For this purpose, a companion research study was conducted to evaluate the Nelson model in such a forecast environment. The results of this study are reported in a companion symposium paper 7.3 (Carlson *et al.*, 2005).

Finally, by the end of 2005, the Nelson model is targeted for incorporation into the Oklahoma Fire Danger Model (Carlson *et al.*, 2003; Carlson *et al.*, 2002), Oklahoma’s operational fire danger model based on the National Fire Danger Rating System. In addition, a mid-range forecast component will be added to the fire danger model through incorporation of 84-hour weather forecast output from the NCEP Eta model. Thus, the Nelson model described in this paper, will be utilized in an operational setting using both observational weather data from the Oklahoma Mesonet and forecast data covering an 84-hour period.

7. ACKNOWLEDGEMENTS

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