

Application of the Nelson model to four timelag fuel classes using Oklahoma field observations: model evaluation and comparison with National Fire Danger Rating System algorithms

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Abstract. The application of a next-generation dead-fuel moisture model, the ‘Nelson model’, to four timelag fuel classes using an extensive 21-month dataset of dead-fuel moisture observations is described. Developed by Ralph Nelson in the 1990s, the Nelson model is a dead-fuel moisture model designed to take advantage of frequent automated weather observations. Originally developed for 10-h fuels, the model is adaptable to other fuel size classes through modification of the model’s fuel stick parameters. The algorithms for dead-fuel moisture in the National Fire Danger Rating System (NFDRS), on the other hand, were originally developed in the 1970s, utilise once-a-day weather information, and were designed to estimate dead-fuel moisture for mid-afternoon conditions. Including all field observations over the 21-month period, the Nelson model showed improvement over NFDRS for each size fuel size class, with r^2 values ranging from 0.51 (1000-h fuels) to 0.79 (10-h fuels). However, for observed fuel moisture at or below 30%, the NFDRS performed better than the Nelson model for 1-h fuels and was about the same accuracy as the Nelson for 10-h fuels. The Nelson model is targeted for inclusion in the next-generation NFDRS.

Additional keywords: dead-fuel moisture, modelling.

Introduction

Dead fuels represent a category of wildland fuels whose moisture content is controlled exclusively by environmental conditions. An 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, 10, 100, and 1000 h. These four fuel classes are typically associated with dead fuels having diameters ranging from less than 0.64 cm (0.25”) in the case of 1-h fuels to as high as 20.3 cm (8.0”) in the case of 1000-h fuels. 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 (DFM) 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 manual entry of a ‘state-of-the-weather’ code, which is used to calculate fuel-level relative humidity and temperature

from the corresponding shelter height values. Observed 10-h 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. If weighed 10-h sticks are not used, and the state-of-the-weather code indicates steady rain (or snow), the 1 and 10-h DFM values are set to 35%. 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 DFM 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 DFM models that 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 DFM, which can utilise the frequent observations made by automated weather stations. The model as originally developed and published (Nelson

2000) was only for 10-h dead fuels. Since then, however, Nelson has modified the values of the original fuel-stick parameters to allow modelling of other fuel size classes.

This paper describes the application of the 'Nelson model' to four timelag fuel classes using an extensive set of DFM field observations made during a 21-month period at Slapout, Oklahoma in the Oklahoma panhandle. The paper subsequently evaluates the performance of the Nelson model for all fuel size classes against this observational database, and compares model output with corresponding DFM estimates made by NFDRS DFM algorithms for each fuel size class.

The Nelson dead-fuel moisture model

The 'Nelson model' for DFM is a physically based model that contains 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 amount of rainfall since the last observation. Outputs include moisture content and temperature of the fuel stick at the times corresponding to the weather data inputs. The theoretical 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 hourly weather data inputs. However, in the Research Joint Venture Agreement with the Forest Service that funded this research, the model was tested not only with hourly weather data, but also with 15-min weather data. Since the Nelson model was targeted for eventual incorporation into the Oklahoma Fire Danger Model (Carlson *et al.* 2002; Carlson and Burgan 2003), it was desirable to test the Nelson model with the 15-min weather observations that are readily available from the Oklahoma Mesonet, Oklahoma's automated weather station monitoring network (Elliott *et al.* 1994; Brock *et al.* 1995; McPherson *et al.* 2007).

Early in the research it was discovered that weather data time steps of less than one hour (e.g. 15-min weather data) led to numerical instability when one used the computational time steps developed for the 'hourly' Nelson model. Upon reducing these computational time steps, the instability was eliminated.

It was also seen, through comparison with the 21-month observational database, that model results using 15-min weather data were not as good for 100 and 1000-h fuels as when using hourly weather data. This led to a series of computational experiments in which various model parameters were altered in an attempt to optimise results for these two fuel sizes in both the '15-min' and 'hourly' models. 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.

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

Table 1 presents the 'optimal' Nelson model parameters for use with 15-min and hourly weather data inputs. Aside from different stick lengths and smaller computational time steps for use with 15-min data, the parameters for 1 and 10-h fuels are identical to those originally developed by Nelson. Parameter values for the 100 and 1000-h fuels were based on several months of experimentation and comparison of the Nelson model DFM predictions to the 21-month observational DFM dataset to be described later. Aside from different moisture and diffusivity computational time steps, the '15-min' and 'hourly' Nelson model parameter sets are nearly identical (the adsorption coefficients for 100-h fuels being different). Additional experimentation with model parameters might have led to improved performance with respect to the DFM field observations, but given the time constraints of the project, the model parameters in Table 1 were the ones chosen for the analysis to be presented in this paper.

Note that the Nelson model has built-in maximum limits for DFM in rainy conditions (cf. 'maximum moisture due to rain' in Table 1). The limits are 85% for 1-h fuels, 60% for 10-h

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

Nelson model parameter	1-h fuels	10-h fuels	100-h fuels	1000-h fuels
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 (g cm^{-3})	0.40	0.40	0.40	0.40
Moisture computation time step (h)	0.004 (0.000833)	0.02 (0.00417)	0.05 (0.01)	0.20 (0.0417)
Diffusivity computation time step (h)	0.05 (0.01)	0.25 (0.05)	0.25 (0.05)	0.25 (0.05)
Barometric pressure (cal cm^{-3})	0.0218	0.0218	0.0218	0.0218
Maximum moisture due to rain (g g^{-1})	0.85	0.60	0.40	0.32
Planar heat transfer ($\text{cal cm}^{-2} \text{h}^{-1} \text{ } ^\circ\text{C}^{-1}$)	2.50	0.38	0.30	0.12
Surface mass transfer: adsorption ($\text{cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$)	0.065	0.02	0.012 (0.006)	0.00001
Surface mass transfer: desorption ($\text{cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$)	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 h^{-1})	0.006	0.05	0.05	0.05
Water film contribution (g g^{-1})	0.10	0.05	0.016	0.005

fuels, 40% for 100-h fuels, and 32% for 1000-h 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-h fuels.

Finally, the stick lengths (Table 1) of 41 cm for 1, 10, and 100-h fuels are, with the exception of the standard 10-h set (50-cm long), the lengths of the dowels used in the field study and differ from the 'default' lengths provided with the model (25 cm for 1-h fuels, 50 cm for 10-h, 100 cm for 100-h, and 200 cm for 1000-h). Using these default lengths resulted in the same r^2 values as with the 41-cm lengths for 1, 10, and 100-h fuels (hourly weather data used), but produced a much lower r^2 (0.31 vs 0.46) for 1000-h DFM. Further experimentation found that reducing the length even further (to 20 cm) for this size fuel gave even better results ($r^2 = 0.56$ with hourly weather data) with respect to the 21-month set of 1000-h DFM field observations (a length of 30 cm produced an only slightly lower r^2 of 0.55). For this reason, and no other, a stick length of 20 cm was selected for the 1000-h model, even though 41 cm was the actual length of the 1000-h fuels in the field study. The authors feel the sensitivity to stick length in the case of 1000-h fuels does not indicate a problem with the physical model, but rather a need for further experimentation in modifying fuel-stick parameters for this size fuel.

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 25 March 1996 to 31 December 1997. The dowels, 41-cm long (except for a standard 10-h set, 50-cm long, which was also weighed), were fully exposed to the atmosphere in a horizontal mode 30 cm above the ground (Fig. 1).

Two battery-powered balances enclosed in a nearby rotatable wooden shelter (for wind shielding) were used to weigh the dowels. The ten 1-h and four 10-h dowels were each weighed as a group, while the standard set of 10-h fuel sticks, three 100-h dowels, and three 1000-h logs were 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-h dowels, and to the nearest gram for the 1000-h logs.

The 1 and 10-h dowels were weighed twice daily (in the morning and in the afternoon). The 100 and 1000-h 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 minimise the loss of wood material that could affect DFM measurements, the 1 and 10-h dowels were replaced every 3 months, and the 100-h dowels were replaced every 6 months. The original 1000-h logs were kept in the field for the duration of the study. Before placement in the field, the ends of the 100 and 1000-h dowels were sealed with wax to prevent lateral moisture loss (a process not modelled by Nelson). Oven-dry weights for all sets of fuel sticks were also obtained. DFM (%) was calculated



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

as 100 times the difference in field and oven-dry weight divided by the oven-dry weight.

In the results to follow, the observed 100-h DFM represents the average DFM of the three separate 100-h dowels, and the same is true of the observed 1000-h DFM. The 10-h DFM is from the standard set of connected 10-h fuel sticks. 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 0.2°C (32°F) to 26.6°C (80°F), and monthly precipitation from 0.5 mm (0.02") to 173.7 mm (6.84"), so a wide range of weather conditions was encountered during the study period. This 21-month DFM observational database constitutes the longest continuous database of DFM observations used for development and testing of the Nelson model.

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 (0.4-mile) distant from the DFM study site. The Nelson model, for each fuel size, was initialised on 1 January 1996 using the appropriate Mesonet weather data and a DFM of 5%, and then run continuously until the end of the 21-month observational period (31 December 1997) using both 15-min and hourly weather data from the Slapout Mesonet site. For the 15-min runs, the '15-min' parameter set was utilised, 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 DFM is updated hourly for 1 and 10-h fuels, while 100 and 1000-h DFM values are updated once a day at 2200 GMT (1600 local standard time) using hourly data from the past 24-h period. In the NFDRS DFM calculations, described in more detail in Carlson *et al.* (2002), 1 and 10-h DFM are functions of equilibrium moisture

content (EMC), which utilises fuel-level temperature and relative humidity. Solar radiation is used in conjunction with 1.5 m temperature and relative humidity to estimate the corresponding fuel-level values. Since the Oklahoma system is automated and uses no state-of-the-weather code, the 1 and 10-h DFM values are calculated using the algorithms described and not set to 35% by rule during times of rain or snow as in the national system. Thus, NFDRS performance for 1 and 10-h fuels in this paper may be slightly different than if the national system were used; the evaluation for these size fuels is of the 'Oklahoma NFDRS'. The larger size fuel classes more closely follow the national methodology. Changes in 100-h DFM are a function of the average EMC over the past 24 h as well as the duration of precipitation. Changes in 1000-h DFM are 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 weights were converted into DFM (%) using the appropriate oven-dry weights. Observation times were converted into Julian Day and GMT, and, from there, to 'hour of year' for comparison to Nelson model and NFDRS output, which used the GMT day.

For each dead-fuel class, the datasets available for analysis include Nelson model DFM output in 15-min or hourly increments; NFDRS DFM output in hourly increments; and field observations of DFM with at most a resolution of twice a day. To facilitate a statistical analysis among these three datasets, Nelson model and NFDRS DFM values were interpolated to the exact times of the field observations. Linear interpolation was utilised between surrounding hourly or 15-min DFM values in the case of the Nelson model and between surrounding hourly DFM values in the case of NFDRS output. These datasets will be referred to as the 'interpolated' or 'paired' DFM datasets.

In the results to follow, we first offer some descriptive statistics of the observed DFM dataset and the interpolated Nelson model and NFDRS datasets. For each fuel size class, we then begin by qualitatively comparing the observed DFM values to the hourly output of the Nelson model and NFDRS datasets, and finish with a statistical analysis comparing the interpolated Nelson model and NFDRS DFM values to the field observations. We conclude our discussion by observing the detailed behaviour 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.

Results

Dead-fuel moisture over the 21-month period

Using the interpolated DFM databases for the Nelson model and NFDRS, the analysis begins with some descriptive statistics of DFM over the 21-month period. Table 2 presents these statistics for the observed DFM, the '15-min' and 'hourly' Nelson DFM, and the NFDRS DFM.

With respect to observed DFM over the 21-month period, 1-h DFM (FM1) ranged from 0.0 to 109.2%; 10-h DFM (FM10), from 1.6 to 64.3%; 100-h DFM (FM100), from 5.4 to 35.7%; and 1000-h DFM (FM1000), from 4.7 to 27.9%. Thus, the observational period featured a wide range of DFM against which to evaluate the Nelson model and NFDRS DFM algorithms.

Table 2. Descriptive statistics for observed dead-fuel moisture (DFM), '15-min' and 'hourly' Nelson model DFM, and National Fire Danger Rating System (NFDRS) DFM over the 21-month period of observations

	FM1	FM10	FM100	FM1000
Observed DFM				
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-min' Nelson model DFM				
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				
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				
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

It is clear from Table 2 that the Nelson model does a much better job capturing the observed DFM maxima within the 1, 10, and 100-h fuel size classes than does NFDRS. The model limits of 85% (FM1) and 60% (FM10) were reached in both the '15-min' and 'hourly' Nelson models, with maxima of 36.6% for FM100 and 18.0% for FM1000. NFDRS, on the other hand, calculated maxima of 27% (FM1), 26.2% (FM10), 30.3% (FM100), and 23.9% (FM1000) during the same period. This behaviour, however, is not unexpected, since the Oklahoma NFDRS algorithms do not take into account rainfall for 1 and 10-h fuels, and were developed to model mid-afternoon conditions, when fuel moisture values are typically at their lowest levels.

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 versions of the Nelson model. 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, while NFDRS shows a closer standard deviation for FM1000 as compared to the observed value. On the other hand, for FM1000, the Nelson models' means

and medians are much closer to the observed than are those of NFDRS, which are ~5% higher than the observed (the Nelson mean and median values are within 1 and 2%, respectively).

Evaluation of Nelson model and NFDRS dead-fuel moisture calculations

At the outset, it should be noted that for 1 and 10-h fuels, comparison of the Nelson model output to field observations constitutes a true evaluation (or verification) since model parameters for these size fuels were not altered from the original values (aside from different stick lengths and smaller computational time steps for use with the ‘15-min’ model). However, for 100 and 1000-h fuels, the 21-month observational dataset was utilised in modifying model parameters to achieve optimal results in the limited time frame available. So for these size fuels, the Nelson model comparison is not a true independent evaluation. However, it should also be mentioned that the r^2 value for the 100-h ‘hourly’ Nelson model is virtually the same as that tested earlier in Missoula before our parameter testing began, so that even the 100-h analysis could be considered an independent evaluation.

1-h dead-fuel moisture

The analysis for 1-h DFM (FM1) begins with a qualitative comparison of the behaviour of the ‘hourly’ Nelson model and NFDRS against the observations for the 21-month period. Fig. 2 presents these plots for 1996 (Fig. 2a) and 1997 (Fig. 2b). What is readily apparent is the inability of NFDRS to capture 1-h DFM values above 25% or so, while the Nelson model is able to do so. The built-in maximum of 85% for this model is frequently reached during the 21-month period. There are a small number of DFM observations above the 85% level, however. Also, note that the Nelson and NFDRS plots are based on hourly DFM output, while the observations of 1-h DFM are only twice per day. Thus, it should come as no surprise that many Nelson DFM predictions of high DFM are not corroborated by observations.

Utilising next the interpolated Nelson and NFDRS datasets, which are suitable for statistical comparison to the 1-h DFM observations ($n = 1237$, where n is the number of field observations utilised in the analysis), Fig. 3 presents a scatterplot of the Nelson model and NFDRS 1-h DFM (y axis) against the observational values (x axis) for these paired datasets. The interpolated output from the ‘hourly’ Nelson model is presented.

The NFDRS algorithm clearly underestimates FM1 for observed DFM values greater than 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 DFM 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, which leads to a lower DFM measurement; or there could be rain at the observation time, but none at the surrounding whole hours. Nevertheless, consistent with Fig. 2, the Nelson model is able to calculate higher DFM values, while NFDRS is not.

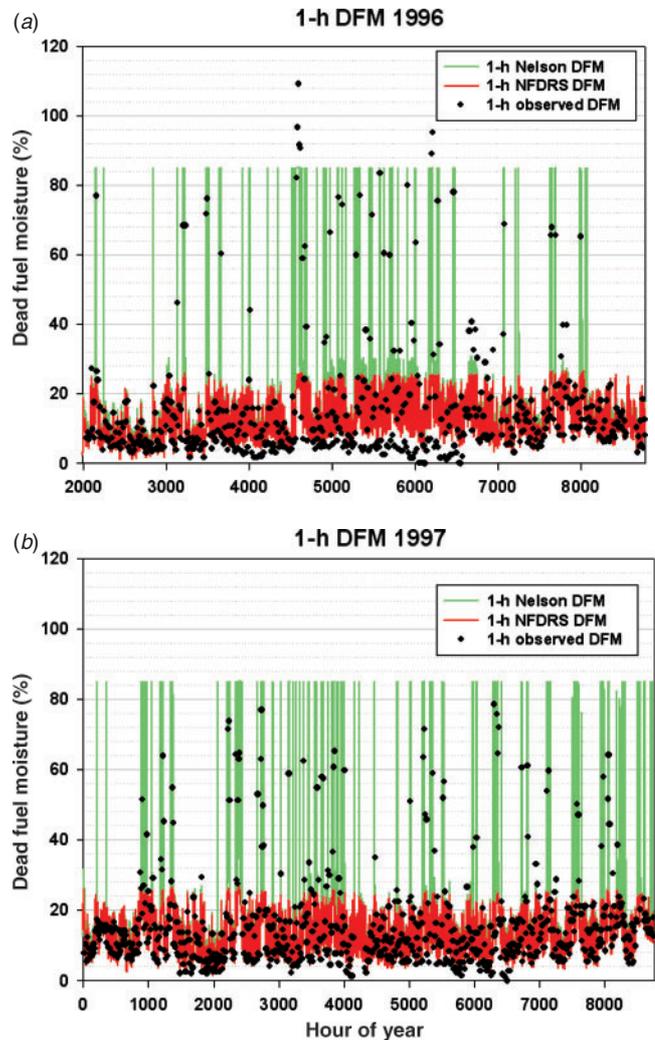


Fig. 2. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1-h dead-fuel moisture (DFM) against field observations (black dots) for 1996 (a) and 1997 (b).

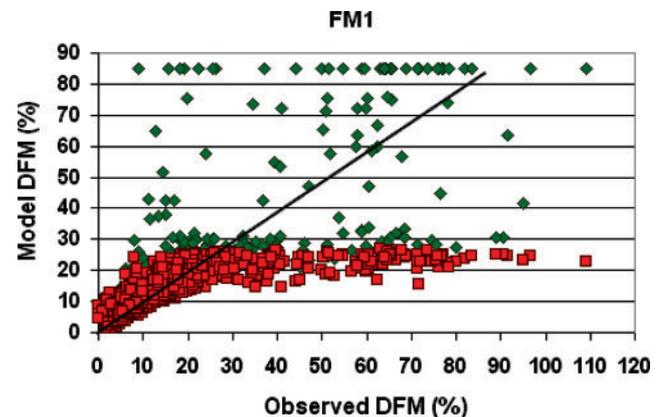


Fig. 3. Scatterplot of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1-h dead-fuel moisture (DFM) (y -axis) vs observed DFM (x -axis) for the 21-month paired datasets. The $x = y$ line is included for reference.

Finally, Table 3 presents a statistical analysis of all paired 1-h DFM datasets for two scenarios. The first scenario includes all observed FM1 values, while the second is a subset that includes only those observed FM1 values less than or equal to 30%, which is the generally accepted value for fibre saturation point. For purposes of fire-danger modelling, it is useful to see how models perform in the lower ranges of fuel moisture (especially for 1 and 10-h fuels), so this analysis was also included in Table 3. Both the ‘15-min’ and ‘hourly’ Nelson models are included, as is NFDRS. r^2 values among the various models and the observed FM1 values are included, as are some descriptive statistics of model error, where ‘model error’ = [model DFM – observed DFM].

Looking at the analysis for all FM1 observations ($n = 1237$), the r^2 value for both Nelson models is 0.64, which is substantially higher than the NFDRS value of 0.55. With respect to model error, the failure of NFDRS to predict higher DFM values (Fig. 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 r^2 values for the Nelson models. With respect to FM1, the ‘15-min’ Nelson model may have a slight advantage over the ‘hourly’ model because of more timely rainfall incorporation. Means and standard deviations of model error are slightly less in magnitude for the ‘15-min’ 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 of around -2% (underprediction).

Turning to the analysis that includes only observed FM1 values less than or equal to 30% ($n = 1116$), the results are quite different. NFDRS shows an r^2 value of 0.73, which is much higher than that of the ‘hourly’ Nelson model with an r^2 of 0.46. The ‘15-min’ Nelson model does much better, with an r^2 of 0.64, but is still less than NFDRS. NFDRS has a mean and median

Table 3. Statistics for 1-h dead-fuel moisture (FM1) for the ‘15-min’ and ‘hourly’ Nelson models and National Fire Danger Rating System (NFDRS)

Comparisons of each of these models to the observed FM1 dataset are presented for all observed FM1 values ($n = 1237$) and for observed FM1 $\leq 30\%$ ($n = 1116$)

FM1 statistic	All observed FM1		Model			
	Nelson (15-min)	Nelson (hourly)	NFDRS	Nelson (15-min)	Nelson (hourly)	NFDRS
Model vs observed R^2	0.64	0.64	0.55	0.64	0.46	0.73
Model error (%) (model – observed)						
Mean	1.4	2.7	-2.2	3.2	3.6	1.1
Median	2.5	2.6	0.6	2.7	2.7	1.0
Standard deviation	9.3	9.8	11.7	4.3	6.5	3.1
Skewness	-2.3	0.4	-3.4	5.8	6.9	-0.1
Maximum	65.9	76.1	16.1	65.9	76.1	16.1
Minimum	-61.6	-59.9	-86.3	-8.4	-8.5	-11.8

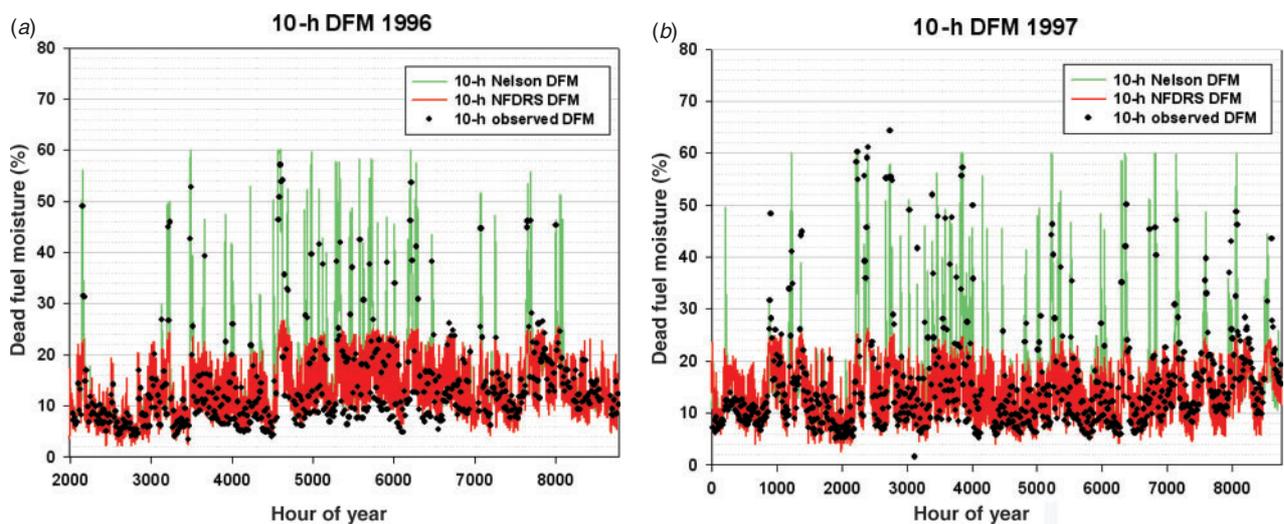


Fig. 4. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 10-h dead-fuel moisture (DFM) against field observations (black dots) for 1996 (a) and 1997 (b).

bias of around +1% over the observed FM1, while the Nelson model biases are in the range of +3 to 4%. Standard deviation of model error is also higher for both Nelson models.

10-h dead-fuel moisture

Fig. 4 compares the ‘hourly’ Nelson model and NFDRS 10-h DFM (FM10) outputs against the FM10 observations for 1996 (Fig. 4a) and 1997 (Fig. 4b). Here, as with the 1-h fuel moisture, the inability of NFDRS to model DFM above 25% or so is easily seen, 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%.

Turning next to the interpolated Nelson and NFDRS datasets, which can be statistically compared to the FM10 observations ($n = 1237$), Fig. 5 presents a scatterplot of the Nelson model and NFDRS 10-h DFM against the observational values for these ‘paired’ datasets. Again, the interpolated output from the ‘hourly’ Nelson model is presented.

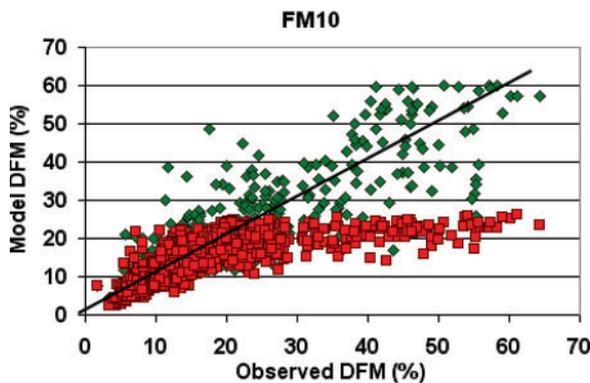


Fig. 5. Scatterplot of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 10-h dead-fuel moisture (DFM) (y-axis) vs observed DFM (x-axis) for the 21-month paired datasets. The $x = y$ line is included for reference.

As with 1-h DFM, the NFDRS algorithm clearly underestimates 10-h DFM (FM10) for observed DFM greater than 25%. While many Nelson model green markers are obscured by the red NFDRS markers (as with the continuous plots of Figs 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.

As with 1-h fuels, Table 4 presents a statistical analysis of all paired 10-h DFM datasets for two scenarios. The first scenario includes all observed FM10 values, while the second is a subset that includes only those observed FM10 values less than or equal to 30%.

Looking at the analysis for all FM10 observations ($n = 1237$), the improvement of the Nelson 10-h model over NFDRS is even more marked. The Nelson r^2 value of 0.79 exceeds the r^2 value of NFDRS (0.58) by more than 0.2. With respect to model error, note that the mean model errors and standard deviations for the Nelson models are smaller than those of NFDRS. The ‘15-min’ model may have a slight advantage over the ‘hourly’ model because of more timely incorporation of rainfall (note the mean and median model errors are lower for the ‘15-min’ 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 of around -2% (underprediction).

Turning to the analysis that includes only FM10 values less than or equal to 30% ($n = 1139$), one sees similar results between NFDRS and the two Nelson models. All r^2 values lie between 0.61 and 0.67, with the ‘15-min’ Nelson model being a bit better than NFDRS and the ‘hourly’ model a bit worse. Mean and median biases are near zero for NFDRS, and are slightly positive (up to +1%) for both Nelson models.

100-h dead-fuel moisture

The comparisons of the ‘hourly’ Nelson model and NFDRS 100-h DFM (FM100) against observed FM100 for the 21-month period are presented in Fig. 6. These plots show that the Nelson model continues to be better at simulating higher DFM values

Table 4. Statistics for 10-h dead-fuel moisture (FM10) for the ‘15-min’ and ‘hourly’ Nelson models and National Fire Danger Rating System (NFDRS)

Comparisons of each of these models to the observed FM10 dataset are presented for all observed FM10 values ($n = 1237$) and for observed FM10 $\leq 30\%$ ($n = 1139$)

FM10 statistic	Model					
	All observed FM10			Observed FM10 $\leq 30\%$		
	Nelson (15-min)	Nelson (hourly)	NFDRS	Nelson (15-min)	Nelson (hourly)	NFDRS
Model vs observed						
R^2	0.79	0.79	0.58	0.67	0.61	0.64
Model error (%)						
(model - observed)						
Mean	0.1	0.9	-1.8	0.6	1.1	0.0
Median	0.5	0.9	0.1	0.6	1.0	0.3
Standard deviation	4.7	4.7	7.1	3.2	3.8	3.3
Skewness	-1.7	-0.4	-2.6	0.2	1.3	-0.7
Maximum	19.3	31.0	14.6	19.3	31.0	14.6
Minimum	-28.0	-29.5	-40.7	-11.5	-13.0	-15.7

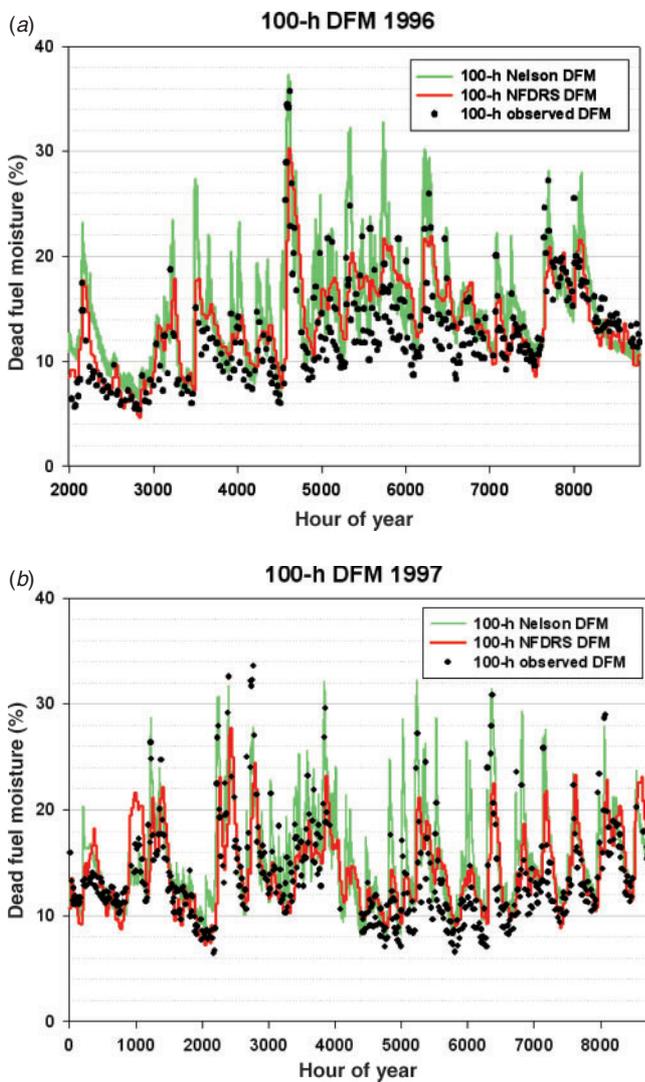


Fig. 6. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 100-h dead-fuel moisture (DFM) against field observations (black dots) for 1996 (a) and 1997 (b).

than NFDRS. A significant number of observations on the high end are modelled by Nelson, but underestimated by NFDRS. It is also apparent that there are several DFM observations on the low end that are not adequately modelled by either Nelson or NFDRS.

Proceeding next to the interpolated Nelson and NFDRS datasets, which are suitable for statistical comparison to the FM100 observations ($n = 874$), Fig. 7 presents the scatterplot of the Nelson model and NFDRS 100-h DFM against the observational values for these ‘paired’ datasets. As before, the interpolated output from the ‘hourly’ Nelson model is presented.

The NFDRS algorithm clearly underestimates 100-h DFM (FM100) for most observed DFM values above $\sim 20\%$. 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.

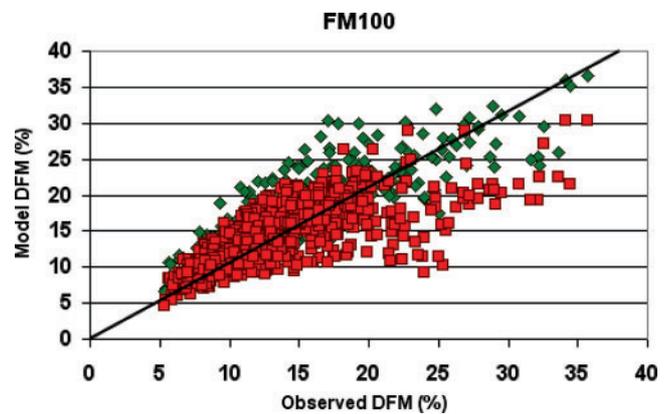


Fig. 7. Scatterplot of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 100-h dead-fuel moisture (DFM) (y-axis) vs observed DFM (x-axis) for the 21-month paired datasets. The $x = y$ line is included for reference.

Table 5. Statistics for 100-h dead-fuel moisture (FM100) for the ‘15-min’ and ‘hourly’ Nelson models and National Fire Danger Rating System (NFDRS)

Comparisons of each of these models to the observed FM100 dataset ($n = 874$) are presented

FM100 statistic	Model		
	Nelson (15-min)	Nelson (hourly)	NFDRS
Model vs observed R^2	0.77	0.75	0.51
Model error (%) (model – observed)			
Mean	0.6	2.1	0.7
Median	0.5	1.9	1.1
Standard 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

Finally, Table 5 presents a statistical analysis of all paired 100-h DFM datasets (using all observed FM100 values). It is for this size fuel that the Nelson model shows the greatest improvement over NFDRS, with an r^2 advantage of ~ 0.25 over NFDRS. Nelson model FM100 r^2 values (0.75–0.77) are the same order of magnitude as those for the Nelson FM10 model (0.79). With regard to model error, note that the standard deviations are smaller for the Nelson model than for NFDRS, while mean and median errors are positive (overprediction) and on the order of 1–2% for all models. The ‘15-min’ Nelson model again shows a slight advantage over the ‘hourly’ model in that its mean and median errors are smaller, while its r^2 value is slightly higher. Analysis of results for observed FM100 values less than or equal to 30% was not included, because (1) there were relatively few observations over 30% to throw out and (2) it is largely for 1 and 10-h fuels that fuel moisture values under 30% are most critical for fire behaviour. For similar reasons, no such analysis for 1000-h fuels was performed.

1000-h dead-fuel moisture

The comparisons of the ‘hourly’ Nelson model and NFDRS 1000-h DFM (FM1000) against observed FM1000 for the 21-month period are presented in Fig. 8. Recall that for this size fuel (and 100-h fuels), the Nelson model parameters were estimated using field observations so comparisons are not truly independent. Given this caveat, the 1000-h Nelson model for this dataset is clearly superior. The NFDRS algorithm consistently overpredicts the majority of the observed FM1000 values by ~5%. While Nelson is not able to model the highest FM1000 values, it does stay closer to the bulk of the observations than does NFDRS. It is also apparent that 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.

Switching to the interpolated Nelson and NFDRS datasets, which can be statistically compared to the FM1000 observations ($n = 877$), Fig. 9 presents the scatterplot of the Nelson model and NFDRS 1000-h DFM against the observational values.

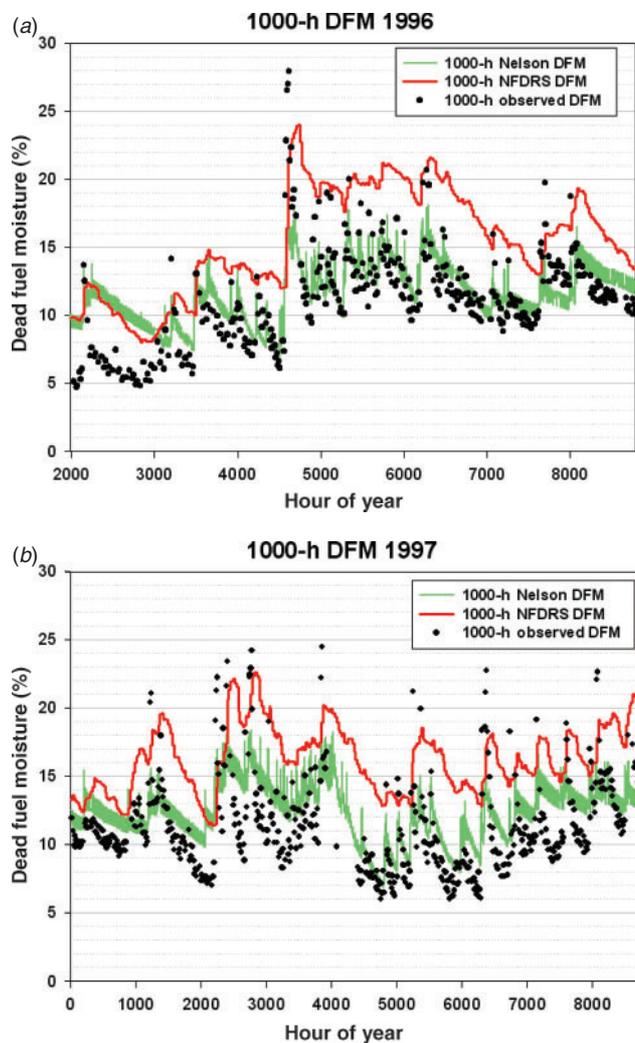


Fig. 8. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1000-h dead-fuel moisture (DFM) against field observations (black dots) for 1996 (a) and 1997 (b).

Again, the interpolated output from the ‘hourly’ Nelson model is presented.

This scatterplot clearly reflects what is seen in the plots of Fig. 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 18% or so) is also indicated.

Table 6 presents the statistical analysis for all paired 1000-h DFM datasets. The Nelson r^2 values for FM1000 (0.51–0.56), although the lowest Nelson r^2 values of any size fuel, are still much higher than NFDRS (0.39). The tendency of NFDRS to overpredict FM1000 values is easily seen in the mean and median errors, both of which are on the order of 5%. Nelson mean and median errors are much smaller, on the order of 0% for the ‘15-min’ model and 1% for the ‘hourly’ model. Standard deviations are similar among all models.

Finally, it should be mentioned that in another research study, the NFDRS 1000-h algorithm displayed similar behaviour with respect to the 1000-h Nelson model. In studies of eleven

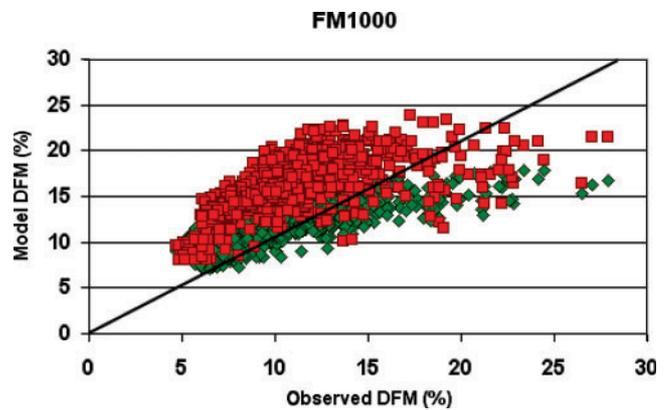


Fig. 9. Scatterplot of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1000-h dead-fuel moisture (DFM) vs observed DFM (x-axis) for the 21-month paired datasets. The $x = y$ line is included for reference.

Table 6. Statistics for 1000-h dead-fuel moisture (FM1000) for the ‘15-min’ and ‘hourly’ Nelson models and National Fire Danger Rating System (NFDRS)

Comparisons of each of these models to the observed FM1000 dataset ($n = 877$) are presented

FM1000 statistic	Model		
	Nelson (15-min)	Nelson (hourly)	NFDRS
Model vs observed			
R^2	0.51	0.56	0.39
Model error (%)			
(model – observed)			
Mean	–0.2	1.0	4.8
Median	0.2	1.4	5.1
Standard 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

Mesonet sites during 2003, NFDRS estimates of 1000-h DFM were routinely 5–10% higher than corresponding Nelson values (Carlson 2004). There were no field observations of DFM in 2003, however, against which to compare model output.

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 DFM against the observed DFM. All field observations are included in these analyses.

With respect to r^2 values, the Nelson model (using either time step for weather data input) is the superior model over the entire range of fuel moisture. The improvements in r^2 over NFDRS are 0.09 (FM1), 0.21 (FM10), 0.24–0.26 (FM100), and 0.12–0.17 (FM1000). The Nelson model performs best for the 10 and 100-h fuels (r^2 values of 0.75–0.79), followed by 1-h fuels (r^2 values of 0.64), and finally by 1000-h fuels (r^2 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 of around –2%. In contrast, the tendency of the NFDRS to overpredict FM1000 is seen by the large mean model error of around +5%.

Mean errors for the ‘15-min’ Nelson model are lower in magnitude than the ‘hourly’ Nelson model and NFDRS across all size fuels. Standard deviations in model error are lower (and numerically similar) for both Nelson models as compared to NFDRS.

Model behaviour during July 1996

The weather encountered during the 21-month observation period had wide ranges of temperature and precipitation. The highest temperature recorded was 42.2°C (108°F) in July 1996 and the lowest was –17.8°C (0°F) in December 1996. Average monthly temperatures ranged from only 0.2°C (32°F) in

December 1997 to as high as 26.6°C (80°F) 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, highest monthly average temperature, and greatest monthly rainfall), it is instructive to show plots of Nelson model and NFDRS DFM behaviour during this month. The ‘hourly’ Nelson model is plotted here (the ‘15-min’ model plots are similar but with more temporal variation because of greater sensitivity to rainfall). The observed DFM is shown as before, and, in addition, hourly rainfall is plotted below DFM.

Fig. 10 shows the 1-h DFM (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 the Nelson model responds greatly, often hitting its maximum of 85% (note, not all rain can be depicted using such a large scale on the rainfall axis). With only two DFM observations per day, it is not surprising that many Nelson model predictions of high DFM are not corroborated by observations. Clearly, the Nelson model does a much better job during such events, with the NFDRS DFM not able to rise above 26%.

Next, Fig. 11 shows the 10-h DFM (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 responds much better. The built-in maximum of 60% is reached several times during the month. In contrast, the NFDRS DFM is not able to rise above 27% during the entire month.

Moving to 100-h DFM (FM100), Fig. 12 shows the behaviour 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, modelling 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 confirms, at least

Table 7. Nelson model and National Fire Danger Rating System (NFDRS) dead-fuel moisture performance over the 21-month observational period for the four different fuel size classes

Statistic	Model		
	Nelson (15-min)	Nelson (hourly)	NFDRS
Model vs observed			
R^2			
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

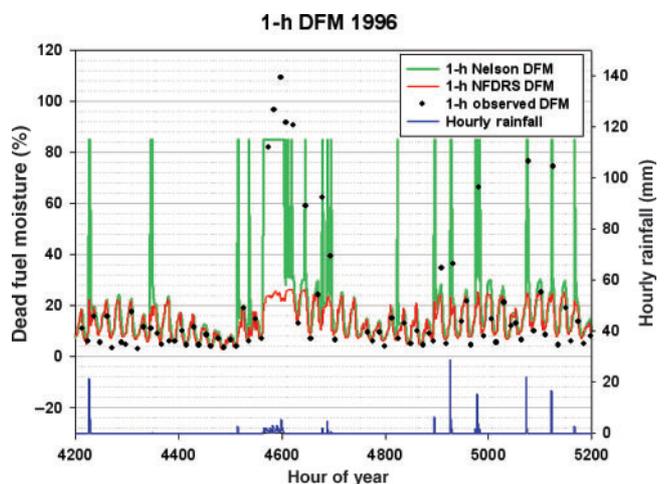


Fig. 10. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1-h dead-fuel moisture (DFM) against field observations (black dots) for July 1996. Hourly rainfall is also depicted.

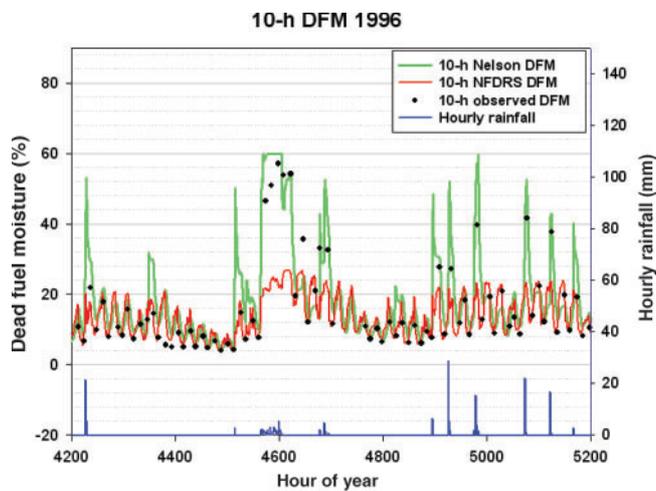


Fig. 11. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 10-h dead-fuel moisture (DFM) against field observations (black dots) for July 1996. Hourly rainfall is also depicted.

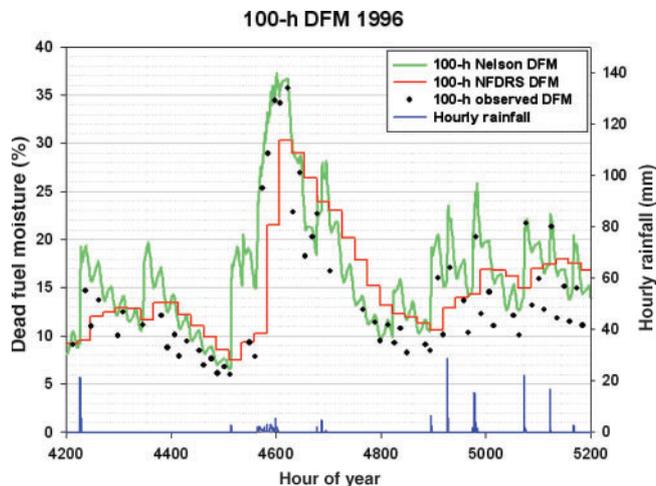


Fig. 12. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 100-h dead-fuel moisture (DFM) against field observations (black dots) for July 1996. Hourly rainfall is also depicted.

for FM100 (and, as will be seen, for FM1000), that it is not the intensity or amount of rainfall that matters, rather, the duration.

Finally, Fig. 13 shows the behaviour of the Nelson model and NFDRS for 1000-h DFM (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 noted earlier) is readily seen, with typical deviations of +5 to 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.

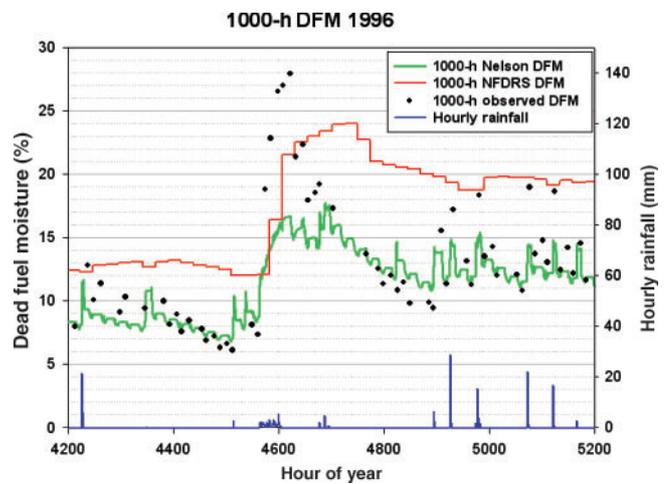


Fig. 13. Comparison of Nelson model (green) and National Fire Danger Rating System (NFDRS) (red) 1000-h dead-fuel moisture (DFM) against field observations (black dots) for July 1996. Hourly rainfall is also depicted.

Summary

In this study the ‘Nelson model’ for dead-fuel moisture (DFM) was adapted to all four timelag fuel classes (1, 10, 100, and 1000 h) using field observations of DFM from Slapout, Oklahoma over a 21-month period lasting from late March 1996 to December 1997. The Nelson model was evaluated against this observational dataset, which as discussed earlier, constitutes an independent evaluation for 1 and 10-h fuels, and arguably for 100-h fuels as well. In addition, comparison was made to the corresponding DFM output from existing Oklahoma National Fire Danger Rating System (NFDRS) algorithms.

The observational dataset from Slapout constitutes the longest continuous database of DFM observations used for Nelson model development and testing. The model parameters for 100 and 1000-h fuels used in this study (Table 1) were developed in conjunction with this observational database. In addition, a wide range of weather conditions under which to test the model occurred during this period, with monthly average temperatures ranging from 0.2°C (32°F) to 26.6°C (80°F) 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-min weather data input (referred to as the ‘15-min’ model) and one using hourly weather data input (‘hourly’ 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 statewide automated weather station monitoring network. The same weather data source was used for the NFDRS DFM calculations.

Over the 21-month period and including the entire range of observed fuel moisture, the Nelson model (both versions) showed improved performance over NFDRS for each fuel size class, with improvements in r^2 values ranging from 0.09 in the case of 1-h fuels to 0.24–0.26 in the case of 100-h fuels when compared against the observational data (Table 7). However, as was seen in the ‘Results’ section, when field observations were restricted to DFM values of less than or equal to 30%, the NFDRS

algorithm for 1-h fuels outperformed both versions of the Nelson model and gave about the same level of accuracy for 10-h fuels in this lower range of fuel moisture.

With respect to the calculation of 1-h (FM1) and 10-h (FM10) DFM, the Oklahoma implementation of NFDRS does not include any effects of precipitation, while the national system sets DFM to 35% for these two fuel sizes when it is raining or snowing. Because the Nelson model calculates the influence of rainfall directly, it is able to reproduce the higher values of DFM for 1 and 10-h fuels, while DFM as calculated by NFDRS routinely stays at or below 27% in the Oklahoma system and at or below 35% in the national system. As a result, when all levels of fuel moisture are considered, higher values of r^2 (0.64 for FM1, 0.79 for FM10) occur 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 to 2.7% and for FM10 of 0.1 to 0.9%. Standard deviations of model error are less for the Nelson model than NFDRS for these two sized fuels.

As was seen earlier, the NFDRS outperforms both the 'hourly' and the '15-min' Nelson model for 1-h fuels when fuel moistures are at or under 30%, a range considered crucial for fire danger modelling. The bias of both Nelson models is around +3% as compared to field observations, whereas NFDRS has a bias of about +1%. Several comments can be made at this point. First, one approach for users of the Nelson model might be to adjust model output of the 1-h model by subtracting 3% when DFM values are at or below 30%. Another approach would be to utilise 15-min data if available (the r^2 for the '15-min' model was 0.64 as opposed to 0.46 for the 'hourly' model), although the bias for the '15-min' model is still around +3%. Finally, further experimentation with parameter modification in the 1-h Nelson model could conceivably reduce this bias and more accurately reproduce DFM values in the lower ranges.

With respect to 100-h (FM100) and 1000-h (FM1000) fuels, the Nelson model also does a better job of reproducing observed fuel moistures than NFDRS. The analysis for FM100 shows the Nelson model with r^2 values of 0.75–0.77, in contrast with the NFDRS value of 0.51. For FM1000, despite a drop in r^2 , the Nelson model ($r^2 = 0.51–0.56$) still outperforms NFDRS ($r^2 = 0.39$). At least for this 21-month period and location, NFDRS consistently overpredicted the bulk of observed FM1000 values, with an average positive mean error of around +5%. The authors believe that with further parameter modification of the 1000-h Nelson model, r^2 values could be further improved.

In summary, considering the entire range of DFM, the Nelson model (either with 15-min or hourly weather data) constitutes an improvement over existing NFDRS DFM algorithms, which are essentially the same ones as developed in the 1970s. This improvement is seen for all four fuel sizes. The ability of the Nelson model to predict higher levels of fuel moisture (e.g. >30%) is useful, for it is important to know when fuel moisture climbs above moisture of extinction levels as well as when it returns to levels below. Not only is the Nelson model more accurate in modelling DFM over the entire range of fuel moisture, but

being a numerical model, it can easily be incorporated into fire-related models that utilise frequent, regularly spaced weather observations from automated weather station networks.

The Nelson model is targeted for inclusion in the next-generation NFDRS. In addition, a mid-range forecast component may be utilised in conjunction with the Nelson model to forecast DFM over the next 2 to 3 days. For this purpose, a companion research study was conducted to evaluate the Nelson model in such a forecast environment (Carlson *et al.* 2005).

The Nelson DFM model has already been incorporated into the Oklahoma Fire Danger Model (Carlson *et al.* 2002; Carlson and Burgan 2003), Oklahoma's operational fire danger model, which runs on weather observations from the Oklahoma Mesonet. A mid-range forecast component has also been added to the fire danger model through integration of 84-h weather forecast output from the new WRF-NMM model (Weather Research and Forecasting Nonhydrostatic Mesoscale Model) of the National Centers for Environmental Prediction; this model is also known now as the North American Model (NAM). Thus, the Nelson model described in this paper is now being utilised in an operational setting using both observational weather data from the Oklahoma Mesonet and forecast data covering an 84-h period. In this setting the '15-min' Nelson model is used in conjunction with 15-min weather observations from the Oklahoma Mesonet and the 'hourly' Nelson model is used with interpolated hourly forecast output from the WRF-NMM model.

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