J11.6 A COMPARISON OF 3 MODELS OF 1-HR TIME LAG FUEL MOISTURE IN HAWAII

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ABSTRACT

Fosberg developed a model of moisture diffusion in wood that is currently used in the National Fire Danger Rating System to predict fine fuel moisture. Nelson (2000) recently developed a fuel moisture model that includes functions for both heat and moisture transfer. Fuel moisture samples were collected in Hawaii hourly for up to 96 hours for an herbaceous plant near mean sea level (MSL), pine needles and eucalyptus leaves at 700 m MSL, pine needles at 1500 m MSL, and a native grass at 2500 m MSL. Weather data were collected every five minutes. Weather variables necessary to predict fuel moisture were also predicted using a mesoscale model. Fuel moisture predictions from each physical model are compared with the observed fuel moistures. Predictions from a time series model using equilibrium moisture content are also presented. Results of the comparisons will be presented and implications for application of fire danger rating in Hawaii are discussed.

1. INTRODUCTION

Prediction of the moisture content of small diameter wildland fuels has been a key component of wildland fire behavior and danger research programs throughout the world since the early 1900s. Various approaches and models have been developed and applied over the years (e.g., Jemison 1935; Gisborne 1936; Byram and Jemison 1943; Simard 1968; Van Wagner 1982; Viney 1991; Catchpole et al. 2001; Nelson 2001). With the advent of the National Fire Danger Rating System in the United States a set of equations to predict fuel moisture content throughout the range of climatic zones in the U.S. was implemented (Deeming et al. 1972; Deeming et al. 1977; Fosberg and Deeming 1971). A review of the NFDRS in the eastern U.S. highlighted a weakness in the system in terms of fuel moisture response in the humid eastern U.S.

The following equations are used in the 1978 National Fire Danger Rating System to calculate fuel moistures for 1-hr time lag fuels (Bradshaw et al. 1983). The preferred equation (1) was developed for the California wildland fire danger system. An alternative equation (2) can also be used if 10-hr stick fuel moisture is not available.

$$m_1 = 0.2(4M_e + m_{10}) \qquad (1)$$

where m_1, m_{10}, M_e are the time-dependent 1-hr and 10-hr stick moisture content and equilibrium moisture content, respectively.

$$\begin{aligned} m_t &= m_{t-1} + (M_e - m_{t-1})(1 - \zeta e^{-\delta t/\tau}) \\ &= M_e - M_e \zeta e^{-\delta t/\tau} + m_{t-1}\zeta e^{-\delta t/\tau} \end{aligned} \qquad (2)$$

where $m_t, m_{t-1}, t, \zeta, \tau, \delta t$ are 1-hr moisture content at time *t* and *t-1*, a similarity coefficient, the fuel particle moisture time lag, and the time increment, respectively (Fosberg and Deeming 1971). For 1-hr fuels, $\tau = 1$. Fosberg and Deeming (1971) solved eq.2 to estimate 1-hr fuel moisture content for a mid-afternoon observation resulting in eq. 3.

$$m_1 = 1.03M_e \qquad (3)$$

Nelson (2000) developed a new physical model to predict fuel moisture in wooden cylinders. The model included processes for heat transfer and moisture movement within the wooden cylinder as well as between the atmosphere and the surface of the cylinder. Several differential equations are solved iteratively along a radial cross-section of the cylinder. The cylinder's moisture content is determined by calculating the volume-weighted average moisture content along the radial cross-section.

While the physical model is theoretically valid for all cylindrical wooden fuels, the diameter of the largest size class modeled in the National Fire Danger Rating System is 20 cm (8 in.) (1000-hr time lag). Model predictions have been compared with moisture content data for 1.27 cm diameter wooden sticks at several locations in the continental U.S. These sites included Michigan and North Carolina, at locations with a continental climate, in contrast to a marine climate. The Nelson model provided accurate predictions for these cases. We are not aware of other comparisons of model predictions with observed moisture content.

The NFDRS was designed to predict fire danger for large areas (>100 km^2). Weather data from a single weather station are assumed to represent conditions within these fire weather zones which are also characterized by one or more fuel types. This approach yields coarse-scale fire danger information that is useful for strategic planning. However, fine-scale knowledge of fire danger is desirable when dealing with small land areas or special resources that occur within larger areas. For example, it may be desirable to know what the fire danger is in a specific valley because a population of threatened flora occurs in the valley. The Hawaii Fire Danger Rating System is a high resolution modification of the National Fire Danger Rating System that combines fuel information

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with fine-scale modeled weather*. With fine-scale weather, it may be possible to predict dead fuel moisture using either the current NFDRS equations or the new Nelson model.

2. METHODS

2.1 *Fuel Sampling*

The Hawaiian Islands have a wide variety of native and introduced vegetation. Several non-native tree species were planted about 50 years ago to determine their suitability for biomass production. The tree species planted included various pines (*Pinus* sp.) and eucalyptus (*Eucalyptus* sp.). Numerous non-native grasses have been introduced throughout the islands for a variety of reasons including cattle forage. Fire occurrence in these grasses is common. Given the wide variety of species available, we asked fire management personnel from the Hawaii Division of Forestry and Wildlife within the Department of Lands and Natural Resources and from the National Park Service at Hawaii Volcanoes National Park to identify the fine fuels that concerned them most. The sampling locations were located on 4 of the major islands and ranged from near sea level to over 2000 m elevation (Table 1, Fig. 1). Of the 11 sites sampled, results for Polihale Ridge, Kauai; Haleakala, Maui; Keanae, Maui; and Mauna Kea, Hawaii are presented. Standing grass, leaf and needle litter were the fuel components sampled; fuel bed depths ranged from 5 cm to over 150 cm (Table 2). Loblolly (*Pinus taeda*), slash (*P. elliottii*), and Monterey (*P. radiata*) pine needles, and eucalyptus leaves (*Eucalyptus robustus*) comprised the litter fuels. The 2 grass fuels were velvet grass (*Holcus lanatus*) and alpine hairgrass (*Deschampsia nubigena*). A native Hawaiian plant uluhe (Old World forked fern, *Dicranopteris linearis*) was the only vine/forb fuel sampled.

Two fuel moisture content samples were either clipped (for grasses and uluhe) or collected from the surface litter hourly. Each sample was placed in a plastic bottle that was closed to prevent moisture loss. Samples were then transported to a lab in Hawaii where they were weighed, dried at 95°C to a constant weight, and then weighed to determine dry mass. Moisture content was calculated on a dry mass basis. Mean sample dry mass ranged from 15 to 65 g. Because of wet fuels, the original plan to sample 96 hours of fuel moisture continuously at each site was modified (Table 2).

2.2 *Weather Data*

At each sampling site, a portable weather station was established for the duration of the sampling period. Sensors on the station included the following: Dacom* RH45 (air temperature and relative humidity), FM505 (10-hr fuel moisture stick), FM507 (fuel temperature of a 10-hr stick), WS034A (wind speed and direction), two SR300 (pyranometer for incoming and outgoing radiation). Precipitation was not measured by the weather station. Data were collected by the weather station and recorded every 5 minutes. In addition to the weather station, manual observations of air temperature (web bulb, dry bulb), state of weather (SOW) wind speed and direction were made hourly at the time of fuel moisture sample collection (Cohen and Deeming 1985).

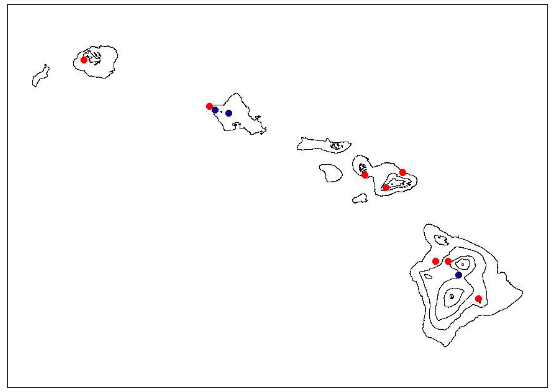

Figure 1. Approximate locations of fuel moisture sampling sites in Hawaii. Blue sites were sampled in 2000, red sites in 2001.

A composite weather record was created from the 3 sources of weather information available to us. The 5-minute weather data from the portable weather station (air and fuel temperature, incoming solar radiation, relative humidity) were combined with precipitation estimated from the hourly observation of SOW (Table 4) using a simple heuristic. The estimated precipitation was compared with hourly or daily weather observations from nearby weather stations when available.

The Regional Spectral Model (RSM) was used to predict weather variables on a 2-4 km grid spacing for each of the major islands. Temperature, relative humidity, cloud cover, and precipitation (kg/m^2) were predicted for each sampling period. Precipitation was converted using eq. 4. The RSM did not predict solar radiation so observed solar radiation was used. Predicted weather at the grid point(s) closest to each sample location were combined with observed solar radiation and used to predict fuel moisture.

$$\left(\frac{kg}{m^2}\right)\left(\frac{1000g}{kg}\right)\left(\frac{cm^3}{g}\right)\left(\frac{m^2}{10^4 cm^2}\right) = 0.1cm \qquad (4)$$

2.3 *Fuel Moisture Prediction*

Three different models were used to predict m_1. The simplified form of Fosberg's equation (eq. 3) was used to calculate fuel moisture. This model used air temperature, relative humidity, and state of weather (SOW) to adjust temperature and relative humidity (Byram and Jemison 1943). The adjusted values were then used to predict M_e. If precipitation was observed, then m_1 was set equal to 35%.

The Nelson model differs from the Fosberg model appreciably. The initial fuel moisture content used by the Nelson model was set equal to the 1st mean measured moisture content for the species. Fuel moisture predictions were made using computer code

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* For more information, see http://ecpc.ucsd.edu/projects/pdc/pdc_user_manual/A3.burganUserManual.htm.

* The use of trade names is provided for information purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

provided by Larry Bradshaw, U.S.D.A. Forest Service, Missoula, MT that had been developed by Colin Bevins, Systems for Environmental Management, Missoula, MT. Every fuel was assumed to be identical in terms of physical properties. The code contains parameters for an idealized 1-hr response time wooden fuel that is cylindrical in shape. Some parameters are based on measured physical properties and others are "tuning" parameters that can be used to improve the fit of the predicted fuel moistures. For this paper, no "tuning" parameters or physical properties were changed from the original code. The assumed radius, length, and density for the 1-hr stick were 2 mm, 25 cm, and 0.40 g cm^{-3}, respectively. The stem radii for the various cylindrical fuels we sampled have not been determined.

Predicted weather data for the grid point closest to each sampling location were extracted from the 2-4 km grids produced for each major island. While the RSM was run with a time step less than 1 second, the predicted data (air temperature, specific humidity, and precipitation) used in this study had a 3-hour time step. Gridded weather forecasts were only available for Polihale Ridge and Haleakala. The RSM did not predict solar radiation at the surface so observed solar radiation was combined with the predicted variables to create weather data sets which were then used to predict fuel moisture content using the Fosberg and Nelson models.

The 3rd model, a time series model, was developed from the observed weather and fuel moisture data. From eq. 2, for the 1-hr time lag $(\tau = 1)$ fuel moisture data that was collected at 1-hour intervals $(\delta t = 1)$,

$$m_t = (1 - \beta_1) M_e + \beta_1 m_{t-1} \tag{5}$$

2.4 *Statistical Analysis*

The coefficient in eq. 5 was estimated using ordinary least squares (OLS) for each of the 5 fuel moisture data sets. We used the OLS algorithm in the PROC MODEL procedure (SAS Institute 1999) to estimate β_1 temporarily assuming no autocorrelation between observed fuel moistures. The similarity coefficient (ζ) can be estimated using $\hat{\zeta} = \frac{\hat{\beta}_1}{e}$. The difference between predicted and observed fuel moistures was calculated for each of the 3 moisture models (Nelson, eq. 3, eq. 5). The differences were plotted against time and observed fuel moisture to identify any obvious trends in the errors. Using Fosberg's simple fuel moisture model (eq. 3) as a basis for comparison, the percentage of predictions from Nelson's model and eq. 5 that fell closer to the observed fuel moisture than predictions from eq. 3 was determined. The squared coherency, the power spectra analog of the r^2 statistic (Taylor et al 1998), will be used in future analyses to determine which of the prediction equations fit best with the observed data. No coherency data will be presented here.

Table 1. Description of fine fuel sampling sites in Hawaii.

Name	Island	Latitude*	Longitude	Elev. (m)	T** (°C)		RH (%)		Srad (w m^{-2})
Polihale Ridge	Kauai	22.096N	-159.683W	700	17.1	25.6	45.7	93.5	455
Haleakala	Maui	20.675N	-156.333W	1890	6.5	23.6	29.6	99.0	1481
Keanae	Maui	20.854N	-156.150W	135	20.2	27.6	69.7	97.9	1376
Mauna Kea	Hawaii	19.833N	-155.600W	2256	8.8	22.1	15.2	79.6	1279

Table 2. Description of 1-hr time lag fuels sampled in Hawaii in 2001.

Location	Species*	Component	Depth (cm)	Sampled Dry Mass			
				N**	Mean	Min.	Max.
Polihale Ridge	*Pinus taeda, P. elliottii*	needles	7.7	191	26.69	11.97	51.89
	Eucalyptus robustus	leaves	2.5	157	63.44	25.28	122.46
Haleakala	*Pinus radiata*	needles	5.6	159	51.62	19.33	91.41
	Holcus lanatus	stems, leaves	107.0	158	31.77	9.14	55.09
Keanae	*Dicranopteris linearis*	leaves	161.2	110	23.92	2.35	43.42
Mauna Kea	*Deschampsia nubigena*	stems, leaves	53.6	138	15.81	6.10	37.41

* Estimated from map, not a GPS unit.

** Minimum and maximum temperature, minimum and maximum relative humidity, and maximum solar radiation recorded during sampling period.

* USDA Plants Database (http://plants.usda.gov/), Wagner et al. 1999.

** N=number of fuel moisture samples collected, not number of hours of sampling.

3. RESULTS

3.1 *General Weather Conditions*

In Hawaii, the trade wind inversion caps the marine layer at about 1900 m (Loope 2000), creating a much drier environment at higher altitudes. The Mauna Kea and Haleakala sites were located above the inversion. The Keanae site was closest to MSL and exhibited the highest minimum relative humidity since it was located on the windward or moist side of Maui.

In some instances, fuels became too wet for sampling because of precipitation so a break occurred in the sampling. Observed fuel moistures ranged from 2% on Mauna Kea to over 60% at Polihale Ridge. The fuel beds varied greatly for the various fuels. The litter fuel beds were relatively shallow in depth (< 15 cm) while the uluhe (*Dicranopteris linearis*) fuel bed was 1.6 m tall. Other grass fuel beds (not reported here) were over 2 m in depth. Vegetation cover was >95% at all 4 locations.

All sites except the Mauna Kea site received precipitation (Table 3). The heuristics estimated precipitation from 0.8 to 14 mm for the sampling period. The precipitation predicted by the RSM was 0 and 70 mm for the grid point closest to the Polihale Ridge and Haleakala sampling sites, respectively. RSM values were not available for the sampling times at Keanae and Mauna Kea. Observed precipitation from nearby stations ranged from 0 to nearly 40 mm. Temperature and relative humidity exhibited typical diurnal trends (Fig. 2). The heuristics used to estimate precipitation amount from SOW did not match the observed precipitation from nearby stations very well. In most cases the nearest weather station was several kilometers away.

Fuel moisture exhibited a strong diurnal pattern (Fig. 3). However, the amplitude of the diurnal cycle (maximum – minimum) varied appreciably between fuel types. For example, the pine litter at Haleakala changed by less than 10% early in the sampling period while some of the grasses changed by up to 20%. Precipitation increased the amplitude of the diurnal cycle.

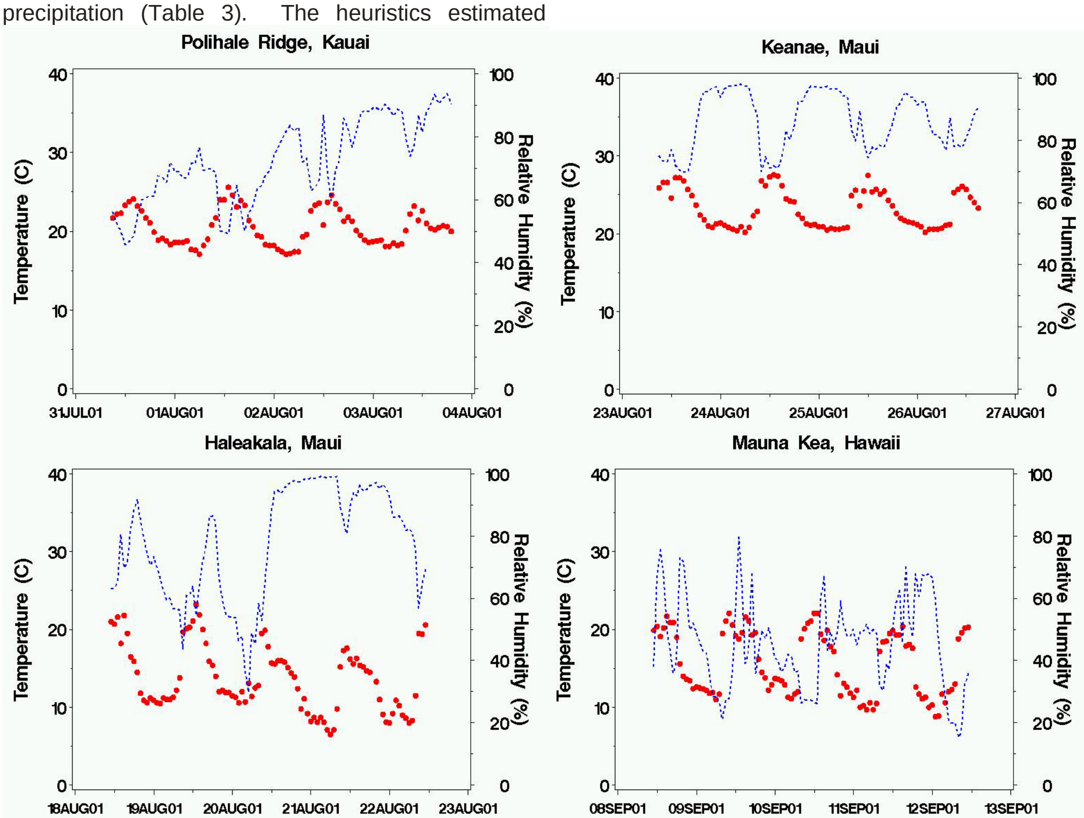

Figure 2. Observed diurnal trends in temperature (●) and relative humidity (-----) for fuel moisture sampling locations in Hawaii.

3.2 *Predicted Fuel Moisture*

The Fosberg model (eq. 5) was fit to each fuel type with varying degrees of success. Estimated values for $\hat{\beta}_1, \hat{\zeta}$ were remarkably consistent for the 1-hr fine fuels in Hawaii (Table 4). The model for uluhe, while significant, accounted for little of the observed variation. In contrast, the model for eucalyptus leaves explained over 90% of the observed variation. Averaging the 6 estimates of $\hat{\beta}_1$ yields a value of 0.93 that resulted in an average $\hat{\zeta} = 0.34$ for the 6 fine fuels. This value differs appreciably from the value (1) Fosberg assumed when deriving eq. 3. This difference in $\hat{\zeta}$ may explain the performance of eq. 3 as described below.

Predictions from the fuel moisture models varied considerably. Eq. 3, the NFDRS equation used when fuel sticks are not present, tended to underestimate 1-hr fuel moisture content (S, Fig. 3). In the NFDRS, fuel moisture content was set to 35% when precipitation occurred. Nelson's 1-hr fuel moisture model was very sensitive to rainfall. Predicted fuel moisture content increased by 30 to 50% for precipitation amounts ranging from 1 to 3 mm. Predicted fuel moistures using the Nelson model and observed weather data generally fit the data (N). The Nelson model coupled with the gridded weather data captured diurnal trends in fuel moisture. At Polihale Ridge, no precipitation was predicted for the grid cell closest to the sampling site so no dramatic increase in fuel moisture was predicted for either eucalyptus leaves or loblolly pine needles (Fig. 4). Precipitation was predicted by the RSM at Haleakala and fuel moisture was predicted to increase accordingly.

In all 6 cases, predictions from the Nelson model and the fitted Fosberg model (eq. 5) were closer to the observed fuel moisture than the simple Fosberg model (eq. 3) (Table 4). The percentage of Nelson model predictions that were closer to the observed fuel moisture ranged from 67 to 97%. Almost every prediction from the fitted Fosberg models was closer to the observed fuel moisture.

Results were similar when only the observations with gridded weather data were considered. The percentage of predictions from the Nelson model with weather station data closer to observed fuel moisture ranged from 76 to 100% and from the Nelson model with RSM data—46 to 81%. All of the fitted Fosberg model predictions were closest (Table 5).

Table 3. Description of sources of precipitation data used to estimate fuel moisture of 1-hr time lag fuels in Hawaii.

Location	Weather Station*	Heuristic**	Precipitation (mm)		
			Observed	Estimated	Gridded***
Polihale	Kanalohuluhulu 1075	H1	14.7	3.0	0.0
Haleakala	Haleakala R S 338	H1	1.5	5.6	70.0
Keanae	Kailua 446	H1	38.8	14.0	
Mauna Kea	No precipitation		0.0		

*Source of non-RAWS weather station data is the U.S. Weather Service Coop station network. Data graciously provided by Dr. John Roads, Scripps Institute of Oceanography, La Jolla, CA.

**Heuristic 1: $P_{i+1} = P_i + \Delta P, \begin{Bmatrix} for\ SOW < 4, \Delta P = 0 \\ for\ SOW = 4, \Delta P = 0.1\,mm \\ for\ SOW = 5, \Delta P = 0.5\,mm \\ for\ SOW = 6, \Delta P = 1.0\,mm \end{Bmatrix}$

Heuristic 2: $P_{i+1} = P_i + \Delta P, \begin{Bmatrix} for\ SOW < 4, \Delta P = 0 \\ for\ SOW < 6, \Delta P = 0.1\,mm \\ for\ SOW = 6, \Delta P = 0.5\,mm \end{Bmatrix}$

***RSM model runs not available for Keanae and Mauna Kea sampling dates.

Table 4. Parameter estimates for fitted Fosberg model for selected Hawaiian 1-hr time lag fuels.

Location	Species	$\hat{\beta}_1$	$\hat{\zeta}$	R^2
Mauna Kea	*Deschampsia nubigena*	0.891	0.328	0.71
Polihale	*Eucalyptus robustus*	0.938	0.345	0.94
	Pinus taeda, P. elliottii	0.883	0.325	0.66
Keanae	*Dicranopteris linearis*	0.970	0.357	0.09
Haleakala	*Pinus radiata*	0.884	0.325	0.65
	Holcus lanatus	0.901	0.331	0.76

Table 5. Performance of fuel moisture models for selected Hawaiian fine fuels.

Location	Species	Percentage*		Number of observations
		Nelson	Fitted Fosberg	
Mauna Kea	*Deschampsia nubigena*	67	98	96
Polihale	*Eucalyptus robustus*	85	100	80
	Pinus taeda, P. elliottii	97	100	78
Keanae	*Dicranopteris linearis*	80	100	55
Haleakala	*Pinus radiata*	96	100	76
	Holcus lanatus	79	100	62

* Percentage of predicted moisture contents closer to observed fuel moisture than simple Fosberg prediction (eq. 3).

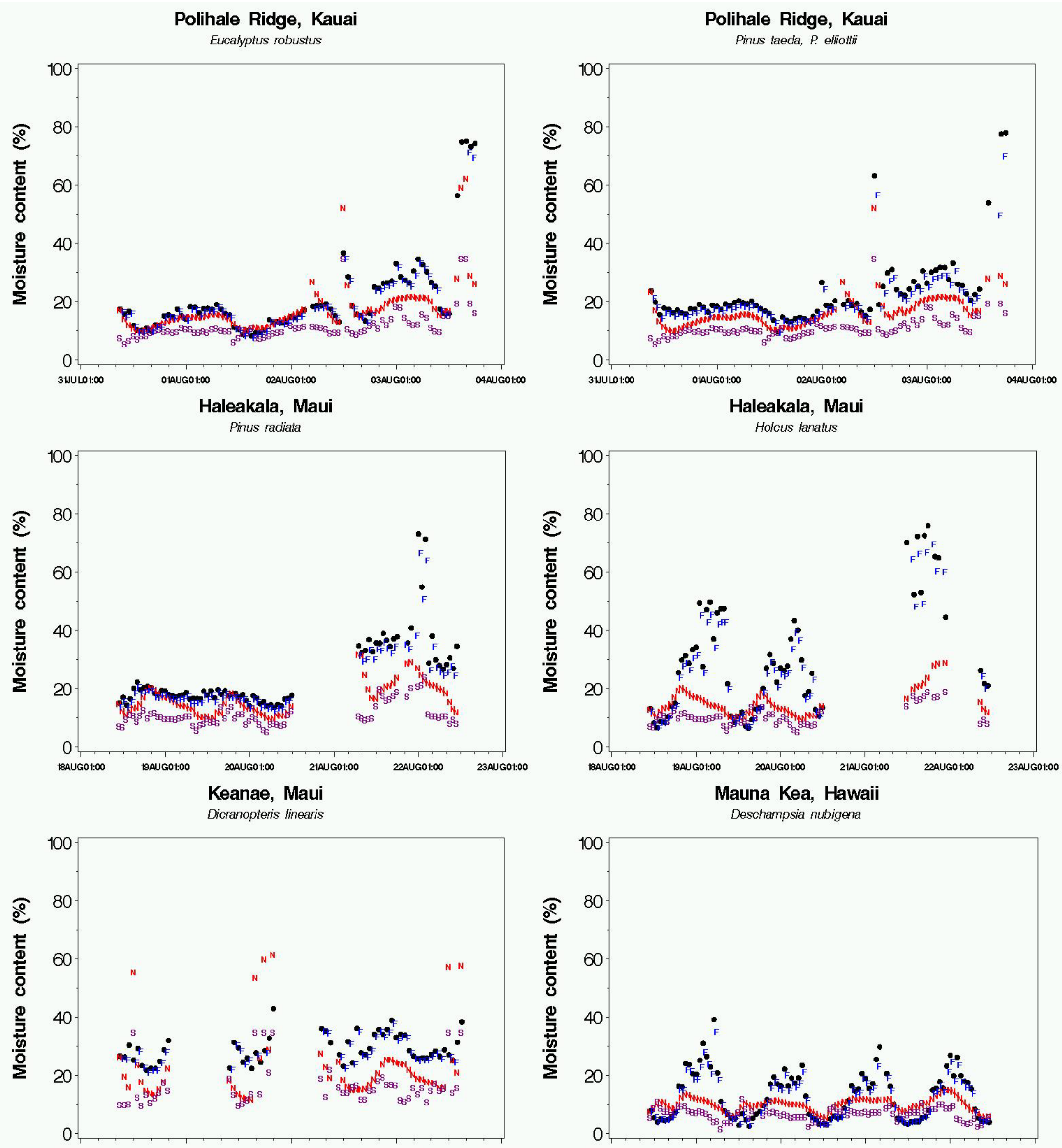

Figure 3. Examples of predicted 1-hr and observed fuel moisture content for a variety of fine fuel types in Hawaii, USA. ● – observed, S – current fuel moisture model (eq. 3), N – Nelson physical model, F – fitted Fosberg model (eq. 5).

Table 6. Performance of fuel moisture models using only gridded weather predictions for selected Hawaiian fine fuels. Percentage defined in Table 4.

Location	Species	Percentage			Number of observations
		Nelson	Nelson w/ gridded Wx	Fitted Fosberg	
Polihale	*Eucalyptus robustus*	77	46	100	26
	Pinus taeda, P. elliottii	92	81	100	26
Haleakala	*Pinus radiata*	100	71	100	17
	Holcus lanatus	76	59	100	17

While both the Nelson and the fitted Fosberg models predicted fuel moistures that were closer to the observed data than the simple Fosberg model, both models were inaccurate. The mean difference (eq. 6) indicated that the simple Fosberg, the fitted Fosberg, and the Nelson model generally underestimated fuel moisture content (Table 7). The Nelson model combined with the RSM forecasted weather overestimated fuel moisture for 3 of 4 fuel types. The average deviation of the simple Fosberg model ranged from 7.6 to 19.2% (eq. 6, Table 7). The models had the greatest differences between observed and predicted fuel moisture for velvet grass at Haleakala. The smallest differences occurred in eucalyptus leaves at Polihale and alpine hairgrass on Mauna Kea. Of the 4 models examined, the fitted Fosberg model had the smallest range of average deviation.

$$\text{Mean difference}=\frac{\sum_{n} P_i - Obs_i}{n}$$

$$\text{Average deviation} = \frac{\sum_{n} P_i - Obs_i}{n} \qquad (6)$$

where P = predicted value, and Obs = observed fuel moisture.

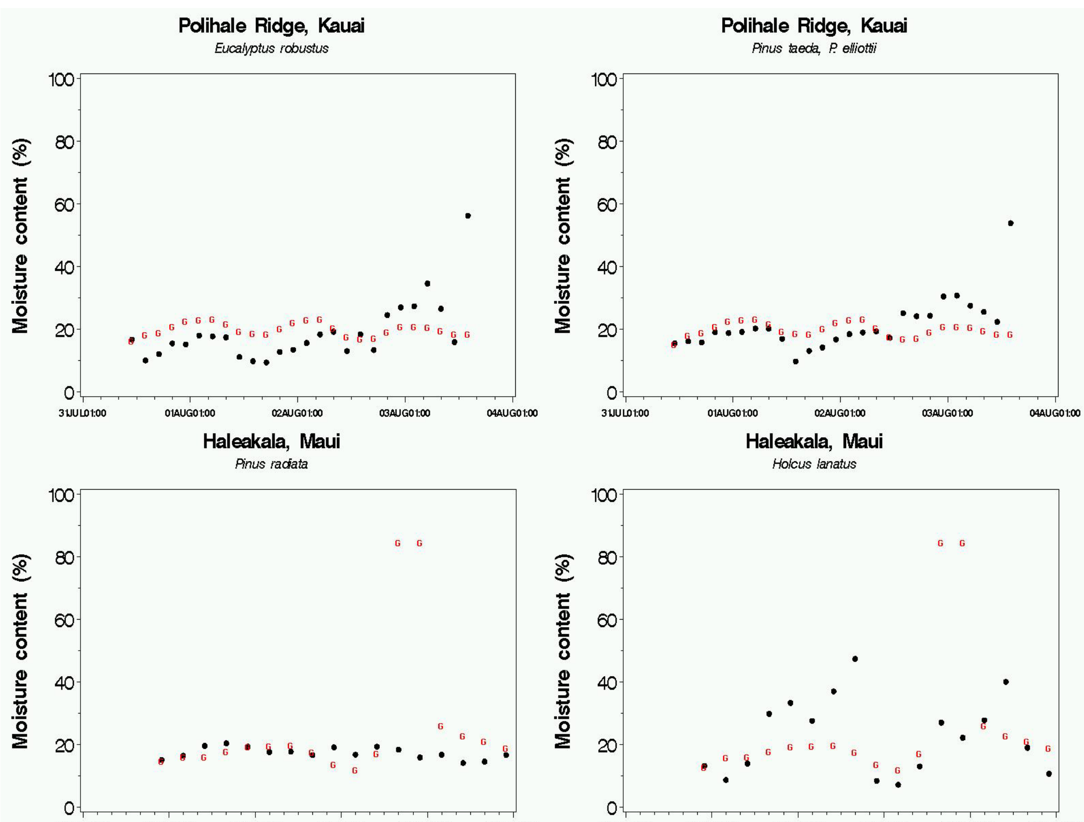

Figure 4. Examples of predicted 1-hr and observed fuel moisture content for 4 fine fuel types in Hawaii, USA. ● – observed, G – Nelson physical model with RSM gridded weather.

There was a strong correlation between the prediction errors (predicted – observed) and the observed fuel moisture for the simple Fosberg model and for Nelson's model (Table 8, Fig. 5) for most fuels. For both models, the correlation exceeded 0.9. There was little evidence of strong correlation between the observed fuel moistures and the prediction errors of the fitted Fosberg model. Of the 6 fuels examined, uluhe had the smallest correlations between model predictions and prediction errors. In many cases, there was a strong negative linear relationship between the error and the observed value. As observed fuel moisture increased, the error became more negative.

4. DISCUSSION

Observed fuel moisture of vertical fuels (grasses) in Hawaii responded more dramatically to diurnal changes in temperature and relative humidity than horizontal (litter) fuels did. Fuel moisture increased dramatically in response to precipitation and then decreased rapidly after the precipitation ended. The fuel moisture models responded dramatically to precipitation and essentially captured the observed trends of fuel moisture. Of the 4 prediction models tested, the current NFDRS model that relies solely on equilibrium moisture content to predict 1-hr fuel moisture content exhibited the greatest errors. However, the average deviation of the Nelson model was at least 6% for the 6 fuels examined here. The model that fit the data best was the empirical form of Fosberg's general moisture model equation that we fit. The Nelson model predictions were closer to observed fuel moisture than the simple Fosberg model.

The current fuel moisture model in the NFDRS uses equilibrium moisture content and empirically derived constants to estimate fuel moisture content. The derivation of these empirical constants is not clear. The Nelson model is a physical model that uses weather variables to estimate moisture content. However, the Nelson model does have parameters that can be used to adjust the accuracy of the predictions. These include both physical properties of the fuels as well as "tuning" parameters that affect the iterative numerical solution of the differential equations.

Based on the performance of eq. 3 in this study, alternative fuel moisture prediction models should be used to predict 1-hr time lag fuel moisture in Hawaii. The "preferred" model, eq. 1, requires the moisture content of a 10-hr time lag fuel stick to predict 1-hr fuel moisture content. Most fire danger weather stations either include an actual 10-hr stick or estimate 10-hr fuel moisture. The weather station used in this study had a 10-hr fuel moisture stick that we can use to test eq. 1. One possible approach to predicting 1-hr fuel moisture is to predict 10-hr fuel moisture using the Nelson model and then use eq. 1 to estimate 1-hr fuel moisture. This approach will also be tested in the near future. We will also attempt to improve the fit of the 1-hr model by "tuning" it.

For the 6 fuels in this study, the parameter estimates were similar. It may be possible to use the general fitted model (eq. 7) to estimate 1-hr fuel moisture.

$$m_t = 0.07M_e + 0.93m_{t-1} \qquad (7)$$

This equation can be used to predict fuel moisture for the remaining fuels in this study. For all 6 fuels, the moisture content at time *t-1* contributed more to the estimate at time *t* than did the equilibrium moisture content. This contradicts Fosberg's solution (Fosberg and Deeming 1971).

Current meteorological research is seeking to develop models that can be used to predict weather variables of interest to fire managers. Output from these gridded weather models can be coupled with a physically-based fuel moisture model such as the Nelson model to forecast fuel moisture across landscapes if the weather models predict the necessary variables. If these weather forecasts are reliable and the moisture prediction equations are accurate, they should be used in fire danger rating.

Table 7. Mean difference (predicted – observed fuel moisture) and average deviation for several prediction models of 1-hr fuel moisture content in Hawaii.

Location	Species	Model							
		Simple Fosberg		Fitted Fosberg		Nelson		Nelson w/ Gridded Wx	
		Mean	Average Deviation	Mean	A. D.	Mean	A. D.	Mean	A. D.
Mauna Kea	*D. nubigena*	-5.8	7.6	-0.7	3.0	-2.3	5.6		
Polihale	*E. robustus*	-9.1	9.2	-0.2	1.9	-3.1	4.7	1.5	7.4
	P. taeda, P. elliottii	-11.3	11.3	-1.1	3.1	-5.7	6.3	-1.0	5.9
Haleakala	*P. radiata*	-12.9	12.9	-1.6	3.4	-7.5	7.5	9.0	11.0
	H. lanatus	-18.6	19.2	-1.4	6.7	-14.1	15.6	3.5	15.0
Keanae	*D. linearis*	-12.2	13.4	-0.7	3.2	-5.3	11.1		

Table 8. Correlation between prediction model errors and observed fuel moisture for selected 1-hr time lag fuels in Hawaii.

Location	Species	Model			
		Simple Fosberg	Fitted Fosberg	Nelson	
				Station Data	RSM Gridded
Mauna Kea	*D. nubigena*	-0.98	-0.50	-0.97	
Polihale	*E. robustus*	-0.98	-0.26	-0.96	-0.98
	P. taeda, P. elliottii	-0.98	-0.49	-0.94	-0.97
Haleakala	*P. radiata*	-0.96	-0.44	-0.92	-0.16
	H. lanatus	-0.99	-0.36	-0.98	-0.37
Keanae	*D. linearis*	-0.77	-0.49	-0.50	

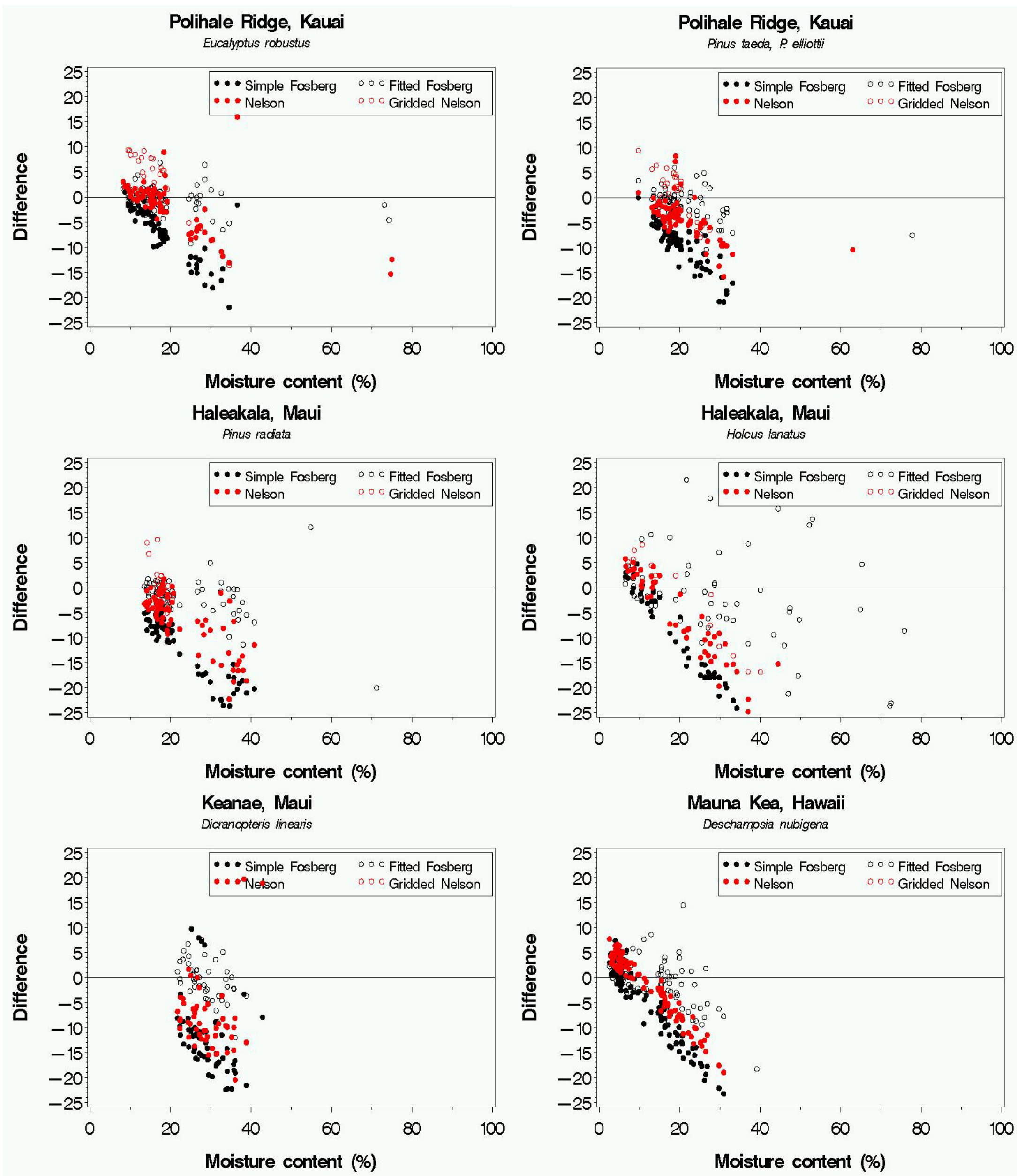

Figure 5. Relationships between model prediction errors (predicted-observed) and observed fuel moisture content for selected 1-hr time lag fuels in Hawaii.

5. SUMMARY

Fuel moisture data were collected for 6 different grass and litter fuels at 4 locations in Hawaii. Weather data (except precipitation) were measured on site. Precipitation was estimated using a heuristic or directly measured at weather stations near the sample sites. Observed fuel moistures were compared to predicted fuel moistures. In general, the Nelson model and a fitted Fosberg model predicted fuel moistures that were closer to the observed data than the simple form of the Fosberg model currently used in the NFDRS. The causes of underestimation by the Nelson model are currently unknown. Future work will compare the Nelson model to additional Hawaii fuel moisture data and to other fuel moisture equations used in the National Fire Danger Rating System.

6. ACKNOWLEDGEMENTS

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