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A comparison of three models of 1-h time lag fuel moisture in Hawaii☆

David R. Weise [a,*], Francis M. Fujioka [a], Ralph M. Nelson Jr. [b]

[a] *Forest Fire Laboratory, Pacific Southwest Research Station, USDA Forest Service, 4955 Canyon Crest Drive, Riverside, CA 92507, USA*
[b] *Rocky Mountain Research Station, USDA Forest Service, Missoula, MT 59807, USA*

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Abstract

The U.S. National Fire Danger Rating System currently uses a moisture diffusion model developed by Fosberg to predict fine fuel moisture in woody fuels. Nelson 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 h for three litter, one herbaceous, and eight grass fuels at sites ranging from near sea level to 2200 m. Weather data were collected every 5 min. Observed fuel moistures were compared to predictions from three models—a simplified form of Fosberg's equation (Simple), the Nelson physical model, and a Markov model fit to the observed data. Mean difference, average deviation, and percentage of predictions closer to the observed data than the Simple model were used to evaluate model performance. Performance of the Markov model was best and of the Simple model was poorest. All models underestimated fuel moisture with the Simple model having the greatest errors and the Markov model having the smallest. The Markov model and the Nelson model predictions were closer to the observed fuel moistures than the Simple model for more than 75% of the observations. Further testing and application of the Nelson physical model is recommended.

Keywords: Moisture; Wildland; Model; Fire; Danger

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; Britton et al., 1973; Van Wagner, 1982; Viney, 1991; Nelson, 2000; Catchpole et al., 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, 1977; Fosberg and Deeming, 1971). This set of equations replaced regional approaches to fuel moisture estimation (Gisborne, 1928; Bickford and Bruce, 1939; Curry et al., 1940; Jemison et al., 1949). The NFDRS was implemented in Hawaii in the late 1970s as a collaborative venture between several agencies, but quickly fell into disuse because all agencies did not continue to support the implementation. The application of mesoscale weather models to fire behavior and danger has lead to a new effort to implement fire danger rating in Hawaii.

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* Corresponding author. Tel.: +1 909 680 1500; fax: +1 909 680 1501.
E-mail address: dweise@fs.fed.us (D.R. Weise).

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A review of the NFDRS highlighted several weaknesses of the system in the humid eastern U.S. (Gale et al., 1986 (cited in Burgan, 1988)). The weaknesses included: (1) NFDRS response to drought in humid environments; (2) lack of flexibility in greening and curing of live fuels; (3) overrating of fire danger in the autumn; (4) fuel model response in humid environments. The following equations are used in the 1978 National Fire Danger Rating System to calculate fuel moistures for 1 h time lag fuels (Bradshaw et al., 1983). The preferred Eq. (1) was developed for the California Wildland Fire Danger System. Equilibrium moisture content is the moisture content that a material (wood, for example) achieves in a constant environment (temperature, humidity) when there is no net exchange of moisture between the environment and the material. For 1 h fuels ($\tau = 1$), Fosberg and Deeming (1971) solved Eq. (2) to estimate moisture content for a mid-afternoon observation resulting in Eq. (3), which can be used if 10 h stick fuel moisture is not available. The use of the Simple model (Eq. (3)) to predict 1 h fuel moisture for times other than mid-afternoon is unknown. Current NFDRS calculations are performed on a daily basis. Fire danger calculation more frequently than daily is being experimented with in Hawaii.

$$m_1 = 0.2(4M_e + m_{10}), \qquad \text{``California''} \tag{1}$$

$$\begin{aligned} m_t &= m_{t-1} + (M_e - m_{t-1})(1 - \zeta e^{-\delta t/\tau}), \qquad \text{``Fosberg''} \\ &= M_e - M_e \zeta e^{-\delta t/\tau} + m_{t-1} \zeta e^{-\delta t/\tau} \end{aligned} \tag{2}$$

$$m_1 = 1.03M_e, \qquad \text{``Simple''} \tag{3}$$

$$m_t = (1 - \beta_1)M_e + \beta_1 m_{t-1}, \qquad \text{``Markov''} \tag{4}$$

where m_1, m_{10}, M_e are the time-dependent 1 and 10 h stick moisture content and equilibrium moisture content, m_t, m_{t-1} the 1 h moisture contents at time t and $t - 1$, ζ the similarity coefficient, τ the fuel particle moisture time lag, and δt is the time increment, respectively. We made Eq. (2) empirical by setting $\zeta e^{-\delta t/\tau} = \beta_1$, a parameter estimated from the data (Eq. (4)).

Nelson (2000) developed a physical model to predict fuel moisture in wooden cylinders. The Nelson 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 (from Nelson, 2000).

> "At its surface, the stick undergoes radiative and convective heat transfer, moisture exchange with the environment due to condensation or evaporation of free water, water vapor diffusion, and adsorption or desorption of bound water. Internal transfers of heat and moisture are considered to be coupled only through stick temperature, but the effects of latent heat associated with gain or loss of free water at the surface are included in the energy equation boundary condition. When free water is held in cell cavities within the stick, most of the liquid flow occurs because of capillary pressure gradients induced by differences in surface tension. Some free water must move by diffusion, however, because permeability of the stick to liquid flow drops to zero (according to the capillary flow model) even though a small amount of liquid remains in the cavities. Water held within cell walls moves by bound water diffusion; vapor diffusion in the cavities contributes significantly to the flow when the moisture content fraction falls below about 0.1. Moisture transfer by capillarity and diffusion is assumed to be much slower than liquid – bound water – water vapor phase interchange, so rates of phase change need not appear in the equations describing liquid, vapor, or bound water transfer."

Several differential equations were 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. The model was tested using data from 10 h fuel moisture sticks. The interested reader is referred to Nelson (2000) for a complete description of the model. The required weather data are air temperature, atmospheric relative humidity, precipitation, and incoming solar radiation; fuel input data required are initial moisture content, fuel surface temperature, and size.

While the Nelson 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 (1000 h time lag). A computer program to predict fuel moisture content by numerically solving the several equations has been developed and parameters for 1, 10, 100, and 1000 h time lag sticks have been derived. Model predictions have been compared with moisture content data for 1.27 cm diameter wooden sticks (10 h) 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. A 21-month study of fuel moisture content for ponderosa pine dowels of 4 diameters (0.4, 1.27, 4.0, and 12.8 cm) was conducted in Oklahoma and results were compared with model predictions. Performance of the Nelson model was generally good and differed by fuel diameter (Carlson et al., 2003). Linear regressions relating observed fuel moisture to measured fuel moisture accounted for 65, 78, 77, and 50% of the variation for 1, 10, 100, and 1000 h fuels, respectively. Anderson (1990) reported that several fine, non-woody fuels had lower values of moisture diffusivity than woody fuels. Diffusivity values for two long-needled pines (*Pinus ponderosa*, *P. monticola*) and four grasses native to the western U.S. were determined. An implication of lower diffusivity values for the NFDRS is that fine fuels would respond to changes in air temperature and relative humidity slower than anticipated in the NFDRS, which was suggested earlier by several authors (see Loomis and Main, 1980, for a summary). In the Nelson model, bound water diffusivity for wood is a function of several variables and is not a constant. The application of the Nelson model to fine non-woody fuels, such as grasses, leaves, and needles is currently unknown.

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 that 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 with fine-scale modeled weather.[1] With fine-scale weather, it may be possible to predict dead fuel moisture using either the current NFDRS equations or the new Nelson model. The objectives of this paper were to test the ability of three models to predict fine fuel moisture content in Hawaii's maritime climate and compare the performance of the models for possible application in the Hawaii Fire Danger Rating System.

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

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 of most concern. The sampling locations were located on four of the major islands and ranged from near sea level to over 2000 m elevation (Table 1, Fig. 1). Loblolly (*Pinus taeda* L.), slash (*P. elliottii* Engelm.), and Monterey (*P. radiata* D. Don) pine needles, and eucalyptus leaves (*Eucalyptus robustus* Sm.) comprised the litter fuels. Eight native and exotic grasses were sampled: velvet grass (*Holcus lanatus* L.), alpine hairgrass (*Deschampsia nubigena* Hbd.), buffelgrass (*Pennisetum ciliare* (L.) Link), guineagrass (*Urochloa maxima* (Jacq.) R. Webster), Hawaiian lovegrass (*Eragrostis atropioides* Hbd.), broomsedge (*Andropogon virginicus L.*), beardgrass (*Schizachyrium condensatum* Kunth (Nees)), and fountaingrass (*Pennisetum setaceum* (Forsk.) Chiov.). A native Hawaiian plant, uluhe (Old World forked fern, *D. linearis* (Burm.) Underwood), was the only herbaceous fuel sampled. All sampled fuels were dead—either cured grass or uluhe fronds, cast leaves or needles on the surface of the litter.

Fuel bed depths ranged from 5 to over 150 cm (Table 2). Two samples were clipped from standing plants (for grasses and uluhe) or collected from the surface (litter) hourly. Only dead material was collected. Each fuel moisture sample was placed in a sealed 500 ml Nalgene[2] plastic bottle to prevent moisture loss. Samples were then transported to a lab on the island of Hawaii, where they were weighed on an electronic balance, dried at 95 °C in a forced convection oven to a constant weight, and then weighed again to

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

Table 1
Description of fine fuel sampling sites in Hawaii

Name	Island	Elevation (m)	T^{a} (°C)	RH (%)	S_{rad} (w m^{-2})
Polihale Ridge	Kauai	700	25.6	43.0	1006
Kaena Point	Oahu	390	29.2	52.8	1336
Makua Valley	Oahu	158	30.6	44.0	1199
Schofield	Oahu	298	30.0	40.0	1341
Kealaloloa Ridge	Maui	100	31.4	37.0	1272
Haleakala	Maui	1890	23.6	22.3	1481
Keanae	Maui	135	28.0	66.7	1376
Pohakuloa	Hawaii	1756	24.4	3.0	1432
Mauna Kea	Hawaii	2256	22.7	14.2	1453
Puuanahulu	Hawaii	830	27.8	39.9	1478
Volcanoes NP	Hawaii	1219	24.4	59.5	1353

[a] Maximum temperature, minimum relative humidity, and maximum solar radiation recorded during sampling period.

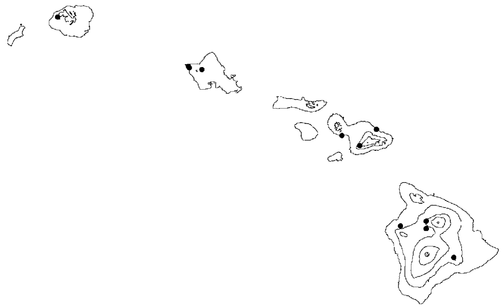

Fig. 1. Approximate locations of fuel moisture sampling sites in Hawaii. Contour interval is 1000 m.

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 h of fuel moisture continuously at each site was modified (Table 3) and the number of hours of sampling ranged from 78 to 101. A total of 15 fuel moisture data sets were available for analysis.

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 h fuel moisture stick), FM507 (fuel temperature of a 10 h 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 min. In addition to the weather station, manual observations of air temperature

Table 2
Description of 1 h time lag fuels sampled in Hawaii in 2000 and 2001

Location	Species[a]	Component	Depth (cm)	Cover (%)
Polihale	*Pinus taeda*, *P. elliottii*	Needles	7.7	100
	Eucalyptus robustus	Leaves	2.5	100
Kaena	*Pennisetum ciliare*	Stems, leaves	60.4	83
Makua	*Urochloa maxima*	Stems, leaves	100.0	
Schofield	*Urochloa maxima*	Stems, leaves	200.0	
Kealaloloa	*Pennisetum ciliare*	Stems, leaves	22.4	23
Haleakala	*Pinus radiata*	Needles	5.6	99
	Holcus lanatus	Stems, leaves	107.0	93
Keanae	*Dicranopteris linearis*	Leaves	161.2	100
Pohakuloa	*Pennisetum setaceum*	Stems, leaves	46.0	
	Eragrostis atropioides	Stems, leaves	36.0	
Mauna Kea	*Deschampsia nubigena*	Stems, leaves	53.6	100
Puuanahulu	*Pennisetum setaceum*	Stems, leaves	98.6	89
Volcano NP	*Andropogon virginicus*	Stems, leaves	90.4	74
	Schizachyrium condensatum	Stems, leaves	128.6	89

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

Fig. 2. Guinea grass (*Urochloa maxima*) fuel bed at Schofield Barracks, Oahu, Hawaii. Fuel bed depth (height) is approximately 2 m.

(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). State of weather is an ordinal-scale variable used in the NFDRS: 0 – clear skies and <0.1 cloud cover; 1 – scattered clouds and 0.1–0.5 cloud cover; 2 – broken clouds and 0.6–0.9 cloud cover; 3 – overcast and 1.0 cloud cover; 4 to 9 – fog, drizzle, rain, snow or sleet, showers, and thunderstorms, respectively. The weather station was moved between the sampling sites on average every 5 days so data from the 10 h stick likely did not reflect actual 10 h fuel moisture content.

A composite weather record was created from the three sources of weather information available to us. The 5 min 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.

2.3. Fuel moisture prediction

Eqs. (1)–(4) all require an estimate of M_e. The Nelson model does not utilize M_e. In the NFDRS, M_e is calculated using polynomial equations developed by Simard (1968) which use air temperature and relative humidity in the boundary layer around a fuel particle. Atmospheric air temperature and relative humidity were adjusted to the air temperature and relative humidity in the boundary layer surrounding a fuel particle using an algorithm based on SOW following Byram and Jemison (1943). In the NFDRS, m_1 was set equal to 35% if precipitation was observed for the Simple model (Eq. (3)).

For the Nelson model, initial fuel moisture content used by the Nelson model was set equal to the 1st mean measured moisture content for the species. The Nelson model used precipitation data differently than the Simple model. Rainfall duration and amount are used to determine which wetting functions and the values of

Table 3
Summary of fuel moisture samples by species

Species	Location	N[a]	Sampled dry mass		
			Mean	Minimum	Maximum
Deschampsia nubigena	Mauna Kea	191	26.7	12.0	51.9
Schizachyrium condensatum	Volcano	166	46.8	23.0	68.2
Andropogon virginicus	Volcano	166	40.6	18.7	60.6
Pennisetum ciliare	Kaena	185	22.2	8.5	37.3
	Kealaloloa	201	30.0	9.9	65.7
Eucalyptus robustus	Polihale	157	63.4	25.3	122.5
Eragrostis atropioides	Pohakuloa	156	59.7	21.4	105.0
Pennisetum setaceum	Puuanahulu	184	33.1	15.6	64.6
	Pohakuloa	155	59.6	20.1	103.4
Urochloa maxima	Makua	187	33.5	14.9	59.6
	Schofield	140	31.5	15.6	54.0
Pinus taeda, Pinus elliottii	Polihale	159	51.6	19.3	91.4
Pinus radiata	Haleakala	158	31.8	9.1	55.1
Dicranopteris linearis	Keanae	110	23.9	2.4	43.4
Holcus lanatus	Haleakala	138	15.8	6.1	37.4

[a] N, number of fuel moisture samples collected, not number of hours of sampling (N/2). N does not apply to the predicted–observed portion of table.

Table 4
Description of sources of precipitation data used to estimate fuel moisture of 1 h time lag fuels in Hawaii

Location	Weather station[a]	Heuristic[b]	Precipitation (mm)	
			Observed	Estimated
Polihale	Kanalohuluhulu 1075	H1	14.7	3.0
Kaena	Makua RAWS	Measured	1.8	
Makua	Makua RAWS	Measured	2.8	
Schofield	Schofield RAWS	Measured	1.3	
Kealaloloa	Kihei 311	H2	0.0	1.4
Haleakala	Haleakala R S 338	H1	1.5	5.6
Keanae	Kailua 446	H1	38.8	14.0
Pohakuloa	PTA portable RAWS	Measured	2.5	
Mauna Kea	No precipitation		0.0	
Puuanahulu	Waikoloa 95.8	H2	0.3	0.8
Volcano NP	Hawaii Volcns NP HQ 54	H1	14.2	11.0

[a] Source of non-RAWS weather station data is the U.S. Weather Service Coop Station Network.

[b] Heuristic 1 $P_{i+1} = P_i + \Delta P$, $\left\{\begin{array}{ll}\text{for SOW} < 4, & \Delta P = 0\,\text{mm}\\ \text{for SOW} = 4, & \Delta P = 0.1\,\text{mm}\\ \text{for SOW} = 5, & \Delta P = 0.5\,\text{mm}\\ \text{for SOW} = 6, & \Delta P = 1.0\,\text{mm}\end{array}\right\}$; heuristic 2 $P_{i+1} = P_i + \Delta P$, $\left\{\begin{array}{ll}\text{for SOW} < 4, & \Delta P = 0\,\text{mm}\\ \text{for } 4 \le \text{SOW} < 6, & \Delta P = 0.1\,\text{mm}\\ \text{for SOW} = 6, & \Delta P = 0.5\,\text{mm}\end{array}\right\}$.

several parameters that are used to predict fuel moisture. Fuel moisture predictions for the Nelson model were made using computer code provided by Larry Bradshaw, USDA, 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 h 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 because physical properties, such as surface area to volume ratio and moisture diffusivity have not been determined for the fuels we tested. The assumed radius, length, and density for the 1 h 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.

2.4. Statistical analysis

The coefficient in Eq. (4) was estimated using nonlinear least squares for each of the 15 fuel moisture data sets. We used the PROC MODEL procedure (SAS Institute Inc., 1999) to estimate β_1 with the constraint $0 \le \beta_1 \le 1$. This condition is necessary to keep m_t finite. Eq. (4) generalizes Eq. (2), in the sense that the similarity coefficient is not held constant. Alternatively, Eq. (4) says the similarity coefficient (ζ) (Eq. (2)) (Fosberg and Deeming, 1971) can be estimated using $\widehat{\zeta} = \hat{\beta}_1 e$. Statistically, Eq. (4) specifies that fuel moisture varies in time as a first-order autoregressive, or Markov, model. Assume that stochastic variations in the model can be represented by including the time-independent zero-mean random variable ε_t:

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

Also assume that the equilibrium moisture content is deterministic but time-dependent, denoted by M_t. Then m_t can be expressed as the sum of the kth past value of fuel moisture and the past k random terms as follows:

$$m_t(k) = \beta_1^k m_{t-k} + \sum_{i=0}^{k-1}[(1 - \beta_1)\beta_1^i M_{t-i} + \beta_1^i \varepsilon_{t-i}] \tag{6}$$

This equation shows that the fuel moistures are autocorrelated, but the condition $0 \le \beta_1 \le 1$ ensures that the stochastic dependency vanishes when k is sufficiently large, except when $\beta_1 = 1$. In that case, the zero-mean condition on ε_t guarantees that $m_t(k)$ converges as k approaches infinity. The difference between predicted and observed fuel moistures was calculated for each of the three moisture models (Nelson, Simple, and Markov). The differences were plotted against time and observed fuel moisture to identify any obvious trends in the errors. Using the Simple model prediction (P_S) as a basis for comparison, a prediction score (P_{Score}, Eq. (7))

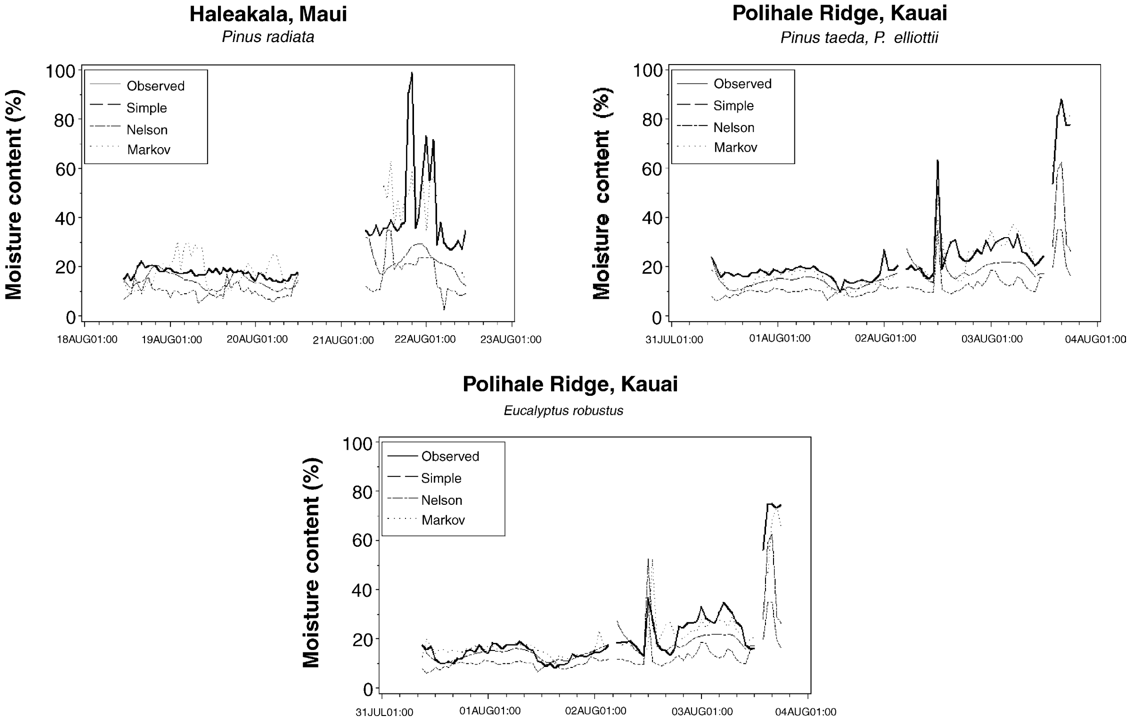

Fig. 3. Predicted 1 h and observed fuel moisture content for various litter fuel types in Hawaii, USA.

was calculated separately for Nelson's model (P_N) and the Markov model (P_L).

$$P_{\text{Score}}(\text{J}) = \frac{100\sum_n X_i}{n}, \quad \left\{ \begin{array}{ll} X_i = 1, & \text{for } |P_\text{J} - \text{Obs}| < |P_\text{S} - \text{Obs}| \\ X_i = 0, & \text{otherwise} \end{array} \right\}, \quad \text{J} = \{\text{N}, \text{L}\} \tag{7}$$

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 Pohakuloa site was sometimes above the inversion. These three sites experienced the lowest relative humidity (Table 1). Minimum relative humidity at the other sites ranged from 37 to nearly 67%. Incoming solar radiation ranged from approximately 1000 to nearly 1500 Wm^{-2} across the sites.

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 bed depths varied greatly. The litter fuel beds were relatively shallow in depth (<15 cm), while some of the grass fuel beds were 2 m in depth (Table 2, Fig. 2). Vegetation cover ranged from a low of 23% at Kealaloloa to 100% at some sites. Bare ground and lava rock comprised 77% of the cover at Kealaloloa.

All sites except the Mauna Kea site received precipitation (Table 4). The heuristics estimated precipitation from 0.8 to 14 mm for the sampling period. Observed precipitation from nearby stations ranged from 0 mm to nearly 40 mm. Temperature and relative humidity exhibited typical diurnal trends. 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 (Figs. 3 and 4). However, the amplitude of the diurnal cycle (maximum–minimum) varied appreciably between fuel types. For example, the *Pinus* 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.

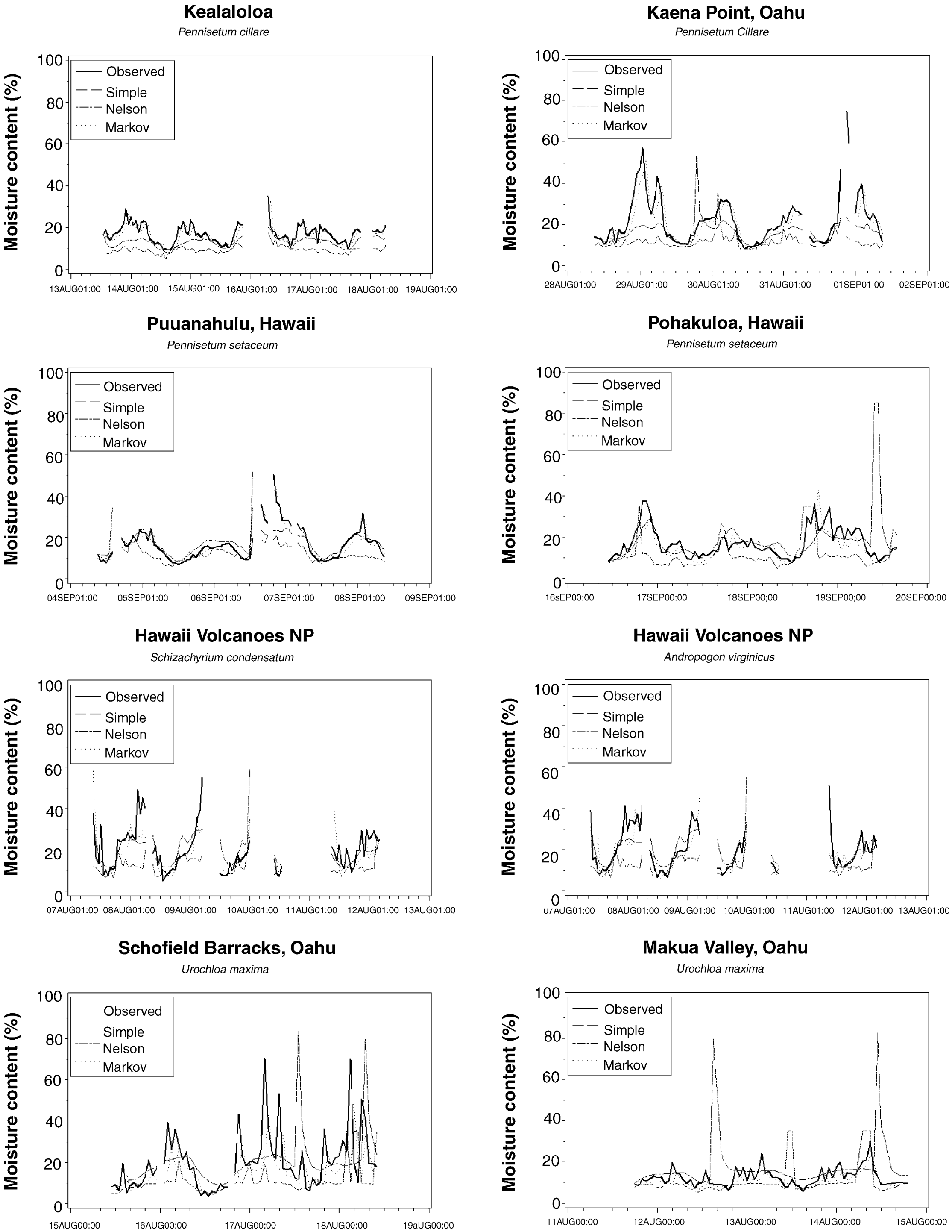

Fig. 4. Predicted 1 h and observed fuel moisture content for grass and herbaceous fuel types in Hawaii, USA.

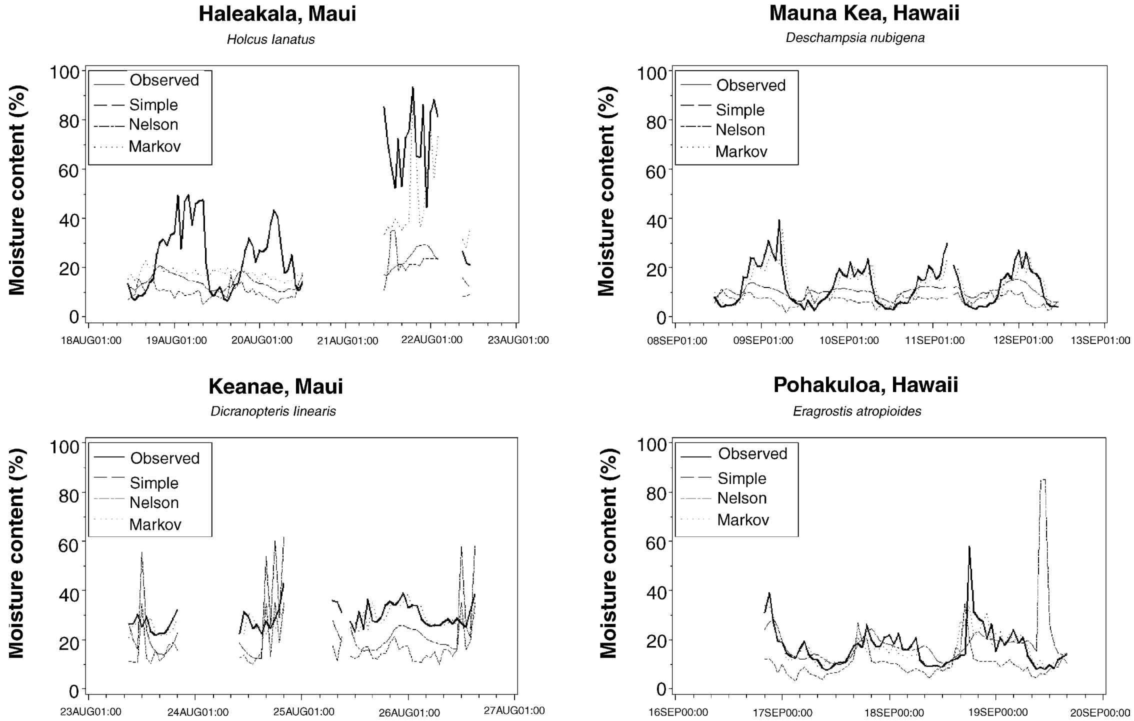

Fig. 4. (*Continued*).

3.2. Predicted fuel moisture

The Markov model (Eq. (4)) was fit for each fuel type with varying degrees of success (Table 5). All models were significant; however, the proportion of explained variance (R^2) ranged from approximately 0.1 (*D. linearis*, Makua *Urochlea maxima*) to 0.8 (Polihale *Eucalyptus robustus*). The solution of the Markov model required that the sum of the coefficients of the lagged moisture content and the equilibrium moisture content equal to 1. Because $0 \le \hat{\beta}_1 \le 1$, then $0 \le \hat{\zeta} \le e$. For all fuels, the coefficient estimate for the lagged moisture content $(\hat{\beta}_1)$ was greater than 0.5 (Table 5). For the *Pinus* species at Polihale and *H.*

Table 5
Parameter estimates for Markov model for selected Hawaiian 1 h time lag fuels

Location	Species	$\hat{\beta}_1$	$\hat{\zeta}$	R^2
Haleakala	*Pinus radiata*	0.520	1.414	0.52
	Holcus lanatus	1.000	2.718	0.20
Volcano NP	*Schizachyrium condensatum*	0.702	1.908	0.44
	Andropogon virginicus	0.754	2.050	0.55
Kaena Point	*Pennisetum ciliare*	0.881	2.396	0.73
Kealaloloa	*Pennisetum ciliare*	0.894	2.429	0.34
Keanae	*Dicranopteris linearis*	0.985	2.678	0.10
Makua	*Urochloa maxima*	0.564	1.532	0.27
Mauna Kea	*Deschampsia nubigena*	0.890	2.418	0.71
Pohakuloa	*Pennisetum setaceum*	0.692	1.880	0.36
	Eragrostis atropioides	0.867	2.356	0.60
Polihale	*Eucalyptus robustus*	0.797	2.168	0.81
	Pinus taeda, P. elliottii	1.000	2.719	0.85
Puuanahulu	*Pennisetum setaceum*	0.762	2.072	0.84
Schofield	*Urochloa maxima*	0.560	1.521	0.01

lanatus at Haleakala, $\hat{\beta}_1$ attained the limiting value of 1, suggesting that the calculated value of equilibrium moisture content for the observed weather conditions provided no additional information for the Markov model. Averaging all estimates of $\hat{\beta}_1$ yielded a value of 0.80 that resulted in an average $\widehat{\zeta} = 2.15$ for the 12 fine fuels. This value differs appreciably from the value of 1 that Fosberg and Deeming (1971) assumed when deriving the Simple model. This difference in $\widehat{\zeta}$ may explain the observed performance of the Simple model.

Predictions from the fuel moisture models varied considerably. All models tended to underestimate fuel moisture, particularly, high fuel moistures. The Simple model, the NFDRS equation used when fuel sticks are not present, tended to underestimate 1 h fuel moisture content (Figs. 3 and 4). In the NFDRS, fuel moisture content was set to 35% when precipitation occurred. Nelson's 1 h fuel moisture model responded quickly to rainfall as shown in Figs. 3 and 4. Predicted fuel moisture content increased by 30–50% for precipitation amounts ranging from 1 to 3 mm. Predicted fuel moistures using the Nelson model with observed weather data generally fit the data.

In all cases, predictions from the Nelson model and the Markov were closer to the observed fuel moisture than the Simple model (Table 6). The percentage of Nelson model predictions (P_{Score}) that were closer to the observed fuel moisture ranged from 67 to 98%; the range of P_{Score} for the Markov model was 68–94%.

Table 6
Performance of fuel moisture models for selected Hawaiian fine fuels

Location	Species	P_{Score}	
		Nelson	Markov
Haleakala	*Pinus radiata*	90[a]	68
	Holcus lanatus	78	71
Volcano NP	*Schizachyrium condensatum*	63	72
	Andropogon virginicus	67	73
Kaena Point	*Pennisetum ciliare*	86	84
Kealaloloa	*Pennisetum ciliare*	98	94
Keanae	*Dicranopteris linearis*	75	96
Makua Valley	*Urochloa maxima*	54	81
Mauna Kea	*Deschampsia nubigena*	67	84
Pohakuloa	*Pennisetum setaceum*	74	86
	Eragrostis atropioides	72	88
Polihale	*Eucalyptus robustus*	85	74
	Pinus taeda, P. elliottii	98	94
Puuanahulu	*Pennisetum setaceum*	68	86
Schofield	*Urochloa maxima*	67	70
	All fuels	77	82

[a] Percentage of predicted moisture contents closer to observed fuel moisture than Simple model prediction.

While both the Nelson and the Markov models predicted fuel moistures that were closer to the observed data than the Simple model, both models were inaccurate. The mean difference (Eq. (6)) indicated that all models generally underestimated fuel moisture

Table 7
Mean difference and average deviation for several prediction models of 1 h fuel moisture content in Hawaii

Location	Species	Simple		Markov		Nelson	
		Mean[a]	A.D.	Mean	A.D.	Mean	A.D.
Haleakala	*Pinus radiata*	−14.7	14.7	−2.0	9.2	−10.0	10.1
	Holcus lanatus	−22.7	23.6	−8.3	16.8	−19.2	20.6
Volcano NP	*Schizachyrium condensatum*	−8.6	9.4	−2.5	5.4	−1.0	6.6
	Andropogon virginicus	−7.9	8.5	−1.5	5.0	−0.3	5.5
Kaena Point	*Pennisetum ciliare*	−10.3	10.4	−1.4	3.8	−5.6	7.0
Kealaloloa	*Pennisetum ciliare*	−7.7	7.7	−0.7	2.4	−4.1	4.1
Keanae	*Dicranopteris linearis*	−12.5	13.6	−0.9	3.5	−5.3	11.1
Makua	*Urochloa maxima*	−2.1	4.7	−1.6	2.7	4.1	5.8
Mauna Kea	*Deschampsia nubigena*	−5.8	7.6	−0.7	3.0	−2.3	5.6
Pohakuloa	*Pennisetum setaceum*	−5.4	7.5	−2.4	3.8	1.2	5.9
	Eragrostis atropioides	−7.0	8.1	−0.6	3.3	2.2	6.2
Polihale	*Eucalyptus robustus*	−9.1	9.2	0.3	3.8	−3.1	4.7
	Pinus taeda, P. elliottii	−12.3	12.3	−2.0	4.0	−6.2	6.7
Puuanahulu	*Pennisetum setaceum*	−4.2	5.7	−0.6	1.8	0.4	3.2
Schofield	*Urochloa maxima*	−9.0	11.4	−4.5	8.2	0.1	9.3
	All fuels	−9.1	10.0	−1.9	4.9	−3.2	7.2

[a] See Eq. (6) for definition of mean difference and average deviation.

content (Table 7). The average deviation (A.D.) of the Simple model ranged from 4.7 to 23.6% (Eq. (6), Table 7). The models had the greatest differences between observed and predicted fuel moisture for *H. lanatus* at Haleakala. The statistical fit of the Markov model for *H. lanatus* was poor. Of the three models examined, the Markov model had the smallest range of average deviation and had the smallest mean differences. This is probably due to the fact that the Markov model was statistically fit to the data. The Nelson model errors and average deviations were generally smaller than the Simple model, but larger than the Markov model.

$$\text{mean difference} = \frac{\sum_n (P_i - \text{Obs}_i)}{n}$$
$$\text{average deviation} = \frac{\sum_n |P_i - \text{Obs}_i|}{n} \tag{8}$$

where P is the predicted value, and Obs is the observed fuel moisture.

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 three prediction models tested, the Simple model exhibited the greatest errors. However, the average deviation of the Nelson model was at least 6% for the fuels examined here. The model that fit the data best was the Markov model. This is not surprising given that the Markov model is a statistical model. The Nelson model predictions were closer to observed fuel moisture than the Simple model. Following the approach of Carlson et al. (2003), we predicted the difference between observed and predicted values as a linear function of the observed fuel moisture, $P_i - \text{Obs}_i = \gamma_0 + \gamma_1\text{Obs}_i$, and used the ratio $-\gamma_0/\gamma_1$ to determine the point at which a model changed from underestimation ($P - \text{Obs} < 0$) to overestimation ($P - \text{Obs} > 0$). The ratios for the Markov model for Polihale *Pinus* and the Nelson model for *D. linearis* were −326 and −52, respectively. Excluding these two values, the mean ratios and standard deviation for the Simple, Markov, and Nelson models were 8 (2), 16 (5), and 16 (4), respectively. This indicated that the Simple model overpredicted moisture content when observed moisture content was greater than 8% and the Markov and Nelson models overpredicted when observed moisture content exceeded 16%. This information is provided only as a general indication of performance of the models—not as an absolute measure of accuracy.

Utility of each of the models tested here is limited. The Simple model in the NFDRS uses equilibrium moisture content and empirically derived constants to estimate fuel moisture content. The equations developed by Simard (1968) to predict equilibrium moisture content for Sitka spruce data are inaccurate and other equations have greater accuracy (Simpson, 1973; Weise and Fujioka, 2002). Fosberg's derivation of the empirical constants in the Simple model is not clear. The similarity coefficient derived by Fosberg did not agree with the similarity coefficient we estimated from the data. The Nelson model is a physical model that uses weather variables to estimate moisture content. However, the Nelson model has 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. The universality of the "tuning" parameters is not yet established. The tuning parameters for the 1 h wooden stick resulted in fuel moisture predictions that were better than the Simple model. Further refinement may yield better results. The applicability of the statistically derived Markov model to other Hawaiian fuels or to the same fuels at other locations is unknown.

Based on the performance of the Simple model in this study, the Simple model should not be used to predict 1 h time lag fuel moisture in Hawaii. The California model, Eq. (1), requires the moisture content of a 10 h time lag fuel stick to predict 1 h fuel moisture content and was not evaluated in this paper due to the lack of 10 h stick data. Most fire danger weather stations either include an actual 10 h stick or estimate 10 h fuel moisture so the California model should be evaluated, where the 10 h data are available and the Nelson model should be reevaluated for 1 h fine fuels when information on physical properties becomes available. Since 1000 h fuels typically are found in the wet forests of the islands and are not a major concern for fire danger, the accuracy of the Nelson model for 10 and 100 h fuels should be evaluated for Hawaiian conditions also before implementing the model as part of the Hawaiian Fire Danger Rating System.

5. Summary

Fuel moisture data were collected for eight grass, three litter, and one herbaceous fuels at 11 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 Markov 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 is needed to tune the Nelson model to additional Hawaii fuel moisture data and to other fuel moisture equations used in the National Fire Danger Rating System.

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