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

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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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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.

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

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

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

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

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,