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Models to Predict the Moisture Content of Lodgepole Pine Foliage during the Red Stage of Mountain Pine Beetle Attack

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Models were developed and evaluated to predict the moisture content of dead needle foliage of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) trees during the red stage of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) attack. Data for model development were obtained from hourly measurements of moisture content during four 25-hour periods spread across the 2013 fire season at a site in southeastern Wyoming. Calibrated models for two popular operational fine fuel moisture models are presented as well as more complicated bookkeeping-system type models derived from diffusion theory. The models were evaluated against two data sets: one from measurements made in northeastern Utah, and another in British Columbia, Canada. All models generally performed well when compared to the data from northeastern Utah but did not perform as well when compared to the dataset from British Columbia. The calibrated operational fine fuel moisture models appear to be nearly as accurate or more accurate than the more complicated bookkeeping-system type models and are recommended for field use.

Keywords: bark beetle, crown fire, dead foliage, fine fuel moisture

Extensive tree mortality caused by recent outbreaks of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests has prompted debate within the research community as to the importance of dead foliage and its low moisture content on crown fire potential during the red stage of attack (Page and Jenkins 2007, Simard et al. 2011, Jolly et al. 2012a, Moran and Cochrane 2012). The red stage of MPB attack corresponds to the period of time when the majority of "red and dead" needles are retained within the crowns of successfully attacked trees and is usually considered to be a period of 5 to 10 years following initial attack. Based on the data collected by Simard et al. (2011), Moran and Cochrane (2012) proposed that the low moisture contents of the dead needles in the crowns of attacked trees could have considerable impact on crown fire rate of spread through a foliar moisture effect, as originally proposed by Van Wagner (1989). Additionally, both Jolly et al. (2012b) and Page et al. (2012) suggested that the low moisture contents of the dead needles in the crowns could also be important in prompting crown fire initiation due to its effect on foliage ignitibility. The magnitude of the effects on crown fire potential, if any, could be highly dependent on the actual moisture content of the dead foliage and the spatial arrangement of mortality, with the effects possibly strong enough to overwhelm losses in canopy fuel load and continuity (Moran and Cochrane 2012).

Alexander and Cruz (2013) recently reviewed the literature on the effect of foliar moisture content on the rate of spread of crown fires and concluded that the model function proposed by Van Wagner (1989) would overestimate rate of spread at the low moisture contents observed in MPB attacked trees during the red stage of attack but that an increase in rate of spread on the order of two to three times the no tree mortality case was still possible. While seasonal estimates of the changes in the moisture content of the foliage on recently attacked trees are available (Jolly et al. 2012b, Page et al. 2012), a model for predicting the short-term (i.e., hourly) changes in moisture content of the tree foliage during the red stage of MPB attack is lacking. Thus, to improve the validity of crown fire potential

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; millimeters (mm): 1 mm = 0.039 in.; hectares (ha): 1 ha = 2.47 ac; grams (g): 1 g = 0.035 oz.

assessments in lodgepole pine forests recently attacked by the MPB, a model capable of predicting dead foliar moisture content is needed.

Previous work has shown that the moisture content of dead lodgepole pine foliage during the red stage of MPB attack does not follow the typical diurnal variation found in similar fine dead forest fuels (< 0.64 cm in diameter) and that common models of fine fuel moisture do not give accurate predictions (Page et al. 2013). Page et al. (2013) suggested that the dead foliage may have long time lags, which would account for the lack of diurnal variation, as suggested by Anderson (1985). However, the data presented by Page et al. (2013) were limited to only dry periods over two diurnal cycles and did not verify that during drying under laboratory conditions the change in moisture content follows the typical exponential decay seen in other fine forest fuels. Diurnal variation in moisture content has also been investigated in live fuels of ponderosa pine (*P. ponderosa* C. Lawson) in central California (Philpot 1965), pinyon pine (*P. edulis* Engelm.) and various junipers (*Juniperus* spp.) in central Arizona (Jameson 1966), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) in northern New Mexico (Gary 1971). The change in moisture content in these conifers from the peak in the morning to the low point during the afternoon was generally less than 10% of the total needle moisture content and most likely related to physiological changes in the plant during periods of water uptake and loss (Jameson 1966). In fact, in some studies, live fuel moisture contents were seen to increase during the afternoon hours (e.g., Jameson 1966).

To provide fire managers a way to reliably and accurately predict the moisture content of the dead needle foliage on lodgepole pine trees attacked by the MPB, this study was undertaken, which expands on the work of Page et al. (2013). Specifically, the primary objectives of this study were to (1) develop and test models capable of predicting the moisture content of dead needle foliage on lodgepole pine trees during the red stage of MPB attack and (2) verify that the dead needle foliage on lodgepole pine follows an exponential decay during moisture loss under laboratory conditions to confirm the adequacy of models that use diffusion theory (Byram 1963).

Description of Models

Two models often used to predict the moisture content of fine, dead fuels by fire managers include the tables produced by Rothermel (1983) and the Fine Fuel Moisture Code (FFMC) component of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). The tables presented by Rothermel (1983) incorporate the effect of time of year, slope, aspect, and shading on the moisture content of fine fuels using mostly unpublished work by USDA Forest Service fire research (Viney 1991). The FFMC was developed based on empirical correlations obtained from experimental data from lodgepole and jack (*P. banksiana* Lamb.) pine litter for midafternoon conditions using air temperature, relative humidity, wind speed, rainfall, and the previous day's observation (Van Wagner 1987). The FFMC has also been adapted to give hourly predictions (Van Wagner 1977). Previous work has shown that these two models fail to accurately predict the moisture content of lodgepole pine foliage during the red stage of MPB attack, with over- and under-prediction biases during periods of high and low atmospheric moisture respectively (Page et al. 2013). However, calibrated operational models using regression techniques, such as done by Wotton and Beverly (2007), have shown promise in their ability to provide useful and accurate predictions for unique fuel conditions.

Anderson (1985) described changes in the moisture content of fine dead fuels during desorption and adsorption conditions obtained from laboratory testing and in turn reported the resulting time lags (i.e., the time required for a fuel particle to lose 63.2% of its evaporable water content). He found that desorption and adsorption time-lag values for recently cast lodgepole pine litter ranged, respectively, from 20.28 to 24.22 hours and 25.28 to 37.13 hours. Anderson (1985) also speculated on the resulting effect of the long time lags on the diurnal changes in moisture content using a modification of the National Fire Danger Rating System (NFDRS) fine fuel moisture content equation as given by Bradshaw et al. (1984)

$$m_t = m_{t-1} + (EMC - m_{t-1})\left(1 - \delta\left(\exp\left(-\frac{t}{\tau}\right)\right)\right), \quad (1)$$

where m_t is the moisture content (% oven-dry weight) at time t, EMC is the equilibrium moisture content (% oven-dry weight), δ is a dimensionless similarity coefficient assumed to equal 1, t is the time interval (h), and τ is the time lag (h). Page et al. (2013) found that the predictions made using Equation 1 with modifications to the EMC based on the equations developed by Anderson (1990), fit the observed dead foliar moisture contents found on lodgepole pine trees quite well. According to Anderson (1990), EMC can be calculated as follows

$$EMC = MC_v\left(1 - \frac{\ln(\Delta G)}{\ln(\Delta G_0)}\right)100, \quad (2)$$

where EMC is the equilibrium moisture content (% oven-dry weight), $MC_v = -\frac{A}{B}, \Delta G = -\left(\frac{RT}{M}\right)\ln\left(\frac{H}{100}\right), \Delta G_0 = A$, T is air temperature (K), H is relative humidity (%), R is the universal gas constant (1.987 cal mol^{-1} K^{-1}), and M is the molecular weight of water (18.015 g mol^{-1}). The following regression estimates were obtained for recently cast ponderosa pine needles (from Anderson 1990)

$$A(\text{adsorption}) = 26.3 - 0.15758(T) + 0.0002883(T^2), \quad (3)$$

$$B(\text{adsorption}) = -1081.46 + 7.43318(T) - 0.0129658(T^2), \quad (4)$$

$$A(\text{desorption}) = 51.842 - 0.30298(T) + 0.0004933(T^2), \quad (5)$$

$$B(\text{desorption}) = -1000.25 + 6.7543(T) - 0.0116198(T^2), \quad (6)$$

Catchpole et al. (2001) used a different methodology to estimate EMC and time lag from field data based on the governing differential equation for the diffusion of water vapor from the fuel and the semiphysical formulation of EMC by Nelson (1984). Using a centered piecewise approximation of the differential equation of the diffusion equation, Catchpole et al. (2001) suggested the following can be used to estimate moisture content

$$m_t = \left(\exp\frac{-\delta t}{2\tau}\right)^2 m_{t-1} + \left(\exp\frac{-\delta t}{2\tau}\right)\left(1 - \left(\exp\frac{-\delta t}{2\tau}\right)\right) q_{t-1} + \left(1 - \left(\exp\frac{-\delta t}{2\tau}\right)\right) q_t, \quad (7)$$

where m_t is the moisture content (% oven-dry weight) and time t, $\delta t = t_i - t_{i-1}$ (sampling interval), τ is the time lag (h), and q_t is the EMC at time t. Nelson's (1984) model of EMC is

$$q = a + b \ln\left\{-\frac{RT}{M}\ln\left(\frac{H}{100}\right)\right\}, \quad (8)$$

where q is the EMC (% oven-dry weight), R is the universal gas constant (1.987 cal mol^{-1} K^{-1}), T is air temperature (K), M is the molecular weight of water (18.015 g mol^{-1}), H is the relative humidity (%), and a and b are constants. The model does not distinguish between desorption and adsorption conditions and it is assumed that the air temperature is equivalent to the fuel temperature, which has been assumed in the modeling of moisture content in other elevated fuels (e.g., Matthews and McCaw 2006). Catchpole et al. (2001) used nonlinear regression techniques to estimate values for τ, a, and b based on field data collected from mallee shrubland and buttongrass moorland in Australia and found that the fitted values corresponded well to estimates obtained in the laboratory.

Methods

Study Site

Field sampling of lodgepole pine foliage during the red stage of MPB attack was conducted on the Laramie Ranger District of the Medicine Bow-Routt National Forest in southeastern Wyoming (41° 4′ 26′′ N, 106° 7′ 54′′ W) during the summer of 2013. The study site was located adjacent to the Saw Mill Park Remote Automated Weather Station (RAWS) (Weather Information Management System ID 482105) in the Snowy Mountains at an elevation of 2,767 m. The site was comprised of a stand dominated by mature lodgepole pine recently affected by MPB with a basal area and stand density ranging between 20 to 30 m^2 ha^{-1} and 600 to 800 trees ha^{-1}, respectively.

The Saw Mill Park RAWS is designated a year-round NFDRS data collection station with hourly transmissions (52 minutes past the hour) of precipitation duration and amount, a 10-minute average measurement of relative humidity, wind direction and speed (at a 6.1-m open height), a 60-minute average of solar radiation, and an instantaneous air temperature (National Wildfire Coordinating Group 2012).

Field Procedures

A total of 12 MPB-attacked lodgepole pine trees, three trees each period, were sampled hourly over the course of the summer during four different 25-hour periods. Sampling periods were spread throughout the main portion of the fire season as follows: June 3–4 (Period 1), July 1–2 (Period 2), August 5–6 (Period 3), and August 31–September 1 (Period 4). Sample trees were selected based on (1) minimizing the distance from the RAWS, (2) adequacy of lower crown to facilitate repeated sampling, and (3) similarity of size and estimated year of attack. All sample trees were estimated to have been attacked in 2011 with a mean (± standard error [SE]) dbh of 25.4 (±2.8) cm and tree height of 10.8 (±1.0) m, and were located within 305 m of the RAWS.

Every hour at the RAWS transmission time, approximately 5–20 g of dead needle foliage was removed from the lower third of the crown (1–2 m height) on each sample tree, immediately weighed to the nearest 0.01 g, and placed in a bag for transport back to the laboratory. Needle foliage samples were then dried in a forced air-drying oven for 24 hours at a temperature of 105° C and reweighed to obtain a dry weight. Dead foliar moisture content was calculated as a percentage of the oven-dry weight. These sampling procedures were followed during all four periods with the following exceptions. During Period 3, nine samples were discarded as a result of the rainfall that occurred during the time of sampling. During Period 1, the moisture content of dead foliage was also sampled at a height of 5 m on each sample tree every 2 hours during the daylight hours to evaluate differences in moisture content between the two heights. Repeated measures analysis of variance (ANOVA) with a compound symmetry covariance structure and time and sample type as fixed effects were used to assess differences between the mean moisture contents of dead needle foliage at the two heights (i.e., 1–2 and 5 m).

Laboratory Time Lag

Assessment of the desorption time lags of three needle foliage samples collected during Period 4 began with oven drying the samples for 24 hours at 105° C to obtain oven-dry weights and subsequently submerging the samples in water for 24 hours. The wetted samples were then drained and placed in 8.5 cm diameter tins located in a temperature and humidity controlled room with a mean temperature of 22.2° C and relative humidity of 51.4%. The mean initial moisture content and EMC were 103.6% and 12.2%, respectively. The samples were periodically weighed until moisture loss no longer occurred, which took approximately 25 hours. First period time lag (63.2% loss in moisture) was taken to be the inverse of the decay coefficient in the equation

$$\gamma = \gamma_0 e^{-\lambda t}, \quad (9)$$

where γ is relative moisture content, γ_0 is the initial relative moisture content, λ is the decay coefficient, and t is the drying time (Fosberg 1970). The NLIN procedure in SAS (SAS Institute, Inc. 2010) was used to estimate λ based on the collected data. Approximately 1.9 g of oven-dry material was used in each sample equating to a mean loading of 0.33 kg m^{-2} and a fuel-load parameter of 3.8, which is assumed to more closely represent a drying rate controlled by individual particles rather than fuelbed structure—i.e., the fuel-load parameter was < 4 (Nelson and Hiers 2008).

Model Building

Linear regression was used to fit models capable of predicting dead foliar moisture content using the collected data. Specifically, fine dead fuel moisture values obtained from Rothermel's (1983) tables and the hourly FFMC (Van Wagner 1977) were regressed against the observed dead foliar moisture contents (dependent variable) to obtain calibrated or corrected models predicting dead foliar moisture content using the REG procedure in SAS.

In addition to the calibrated operational models, three bookkeeping-system type models were used to predict dead foliar moisture content. The modification of the NFDRS fine fuel moisture and EMC equations as recommended by Anderson (1985, 1990) were used with both the recently cast lodgepole pine litter desorption and adsorption mean time lags of 20.75 and 34.43 hours, respectively, and the mean time lag from the laboratory time lag study. Additionally, the methods proposed by Catchpole et al. (2001) were used to estimate the a and b constants in Equation 8 using the MODEL procedure in SAS with the time lag set to the mean time lag obtained in the laboratory time lag analysis.

Model Evaluation

Evaluation of the five proposed models was undertaken using the data collected in this study and two data sets described by Armitage (2004) and Page et al. (2013). Specifically, the hourly measurements from Page et al. (2013) ($n = 160$) from a site in northeastern Utah

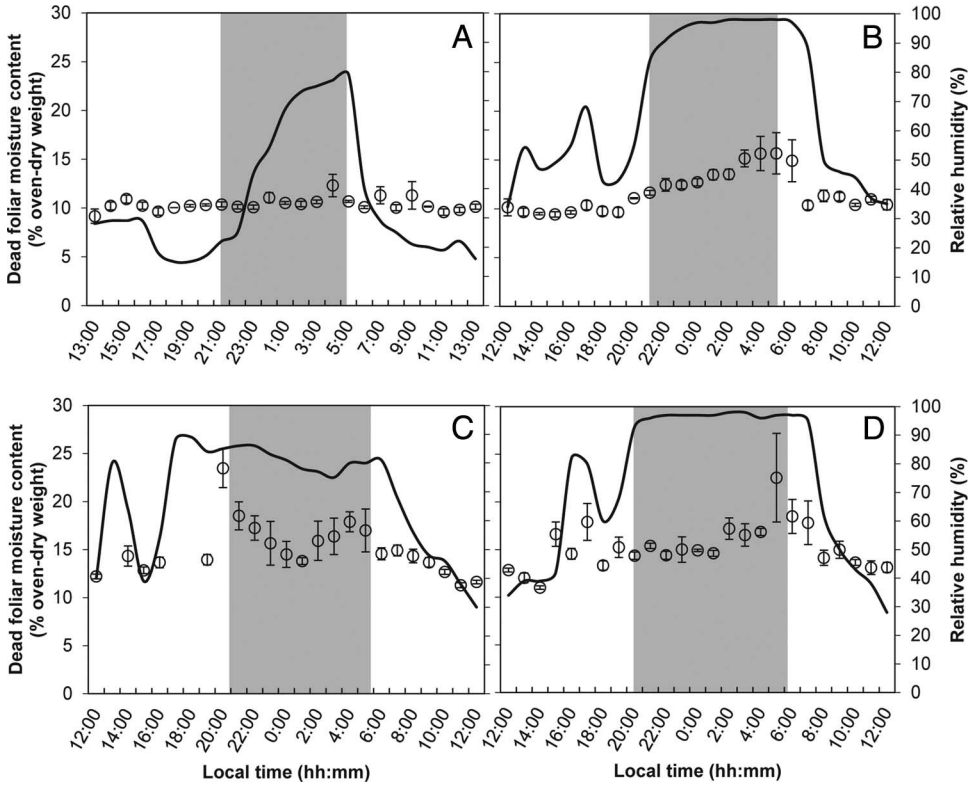

Figure 1. Time series of the mean observed dead foliar moisture contents (± standard error) for Period 1, June 3–4 (A), Period 2, July 1–2 (B), Period 3, August 5–6 (C), and Period 4, August 31–September 1 (D) at the study site in southeastern Wyoming. The measured relative humidity from the Saw Mill Park Remote Automated Weather Station is shown on the secondary axis. The shaded area represents the nighttime period.

Table 1. The observed and historical (1988–2012) mean and 90th percentile Energy Release Component (ERC), Duff Moisture Code (DMC), Drought Code (DC), and Keetch–Byram Drought Index (KBDI) calculated at the Saw Mill Park Remote Automated Weather Station in southeastern Wyoming, for each of the days when sampling was conducted.

	ERC			DMC			DC			KBDI		
Date (2013)	Obs.	Mean ± SD	90th	Obs.	Mean ± SD	90th	Obs.	Mean ± SD	90th	Obs.	Mean ± SD	90th
June 3	43	35 ± 11.9	49	42	39 ± 25.5	67	149	517 ± 196	702	40	67 ± 100	196
June 4	45	34 ± 10.4	46	46	41 ± 23.4	68	155	522 ± 199	708	42	74 ± 105	209
July 1	46	45 ± 11.3	59	81	71 ± 40	119	329	557 ± 230	799	141	124 ± 112	268
July 2	47	45 ± 12.3	58	85	71 ± 42.3	122	337	557 ± 229	806	140	114 ± 112	258
Aug. 5	31	40 ± 8.3	52	13	51 ± 32.1	98	379	601 ± 188	901	100	143 ± 105	278
Aug. 6	34	39 ± 9.3	50	11	50 ± 31.6	91	376	599 ± 181	909	88	147 ± 105	281
Aug. 31	32	41 ± 6.3	51	11	54 ± 25.5	86	333	625 ± 183	791	7	179 ± 117	329
Sept. 1	31	40 ± 6.6	51	10	53 ± 26.6	89	331	619 ± 184	796	4	167 ± 119	319

Note: Obs., observed value; SD, standard deviation; 90th, 90th percentile.

and hourly measurements from a site in central British Columbia reported by Armitage (2004) ($n = 17$) were compared to predictions made using each of the proposed models. For each of the three bookkeeping-system type models, the previous 5 days of air temperature and relative humidity observations were used to initialize the model. Four deviation statistics were calculated for all comparisons with observed data, root mean square error (RMSE), mean absolute error (MAE), percentage mean absolute error (PMAE), and mean bias error (MBE) (Fox 1981, Willmott 1982).

Results

Observed Dead Foliar Moisture Contents

Observed dead foliar moisture contents across all four periods ranged from 8.4 to 32% with a mean (±SE) of 13.0% (±0.19) (Figure 1). Mean moisture contents increased through the summer, starting from 10.4% (Period 1), 11.7% (Period 2), 15.0% (Period 3), and 15.2% (Period 4). Measures of long-term dryness and fire danger tended to decrease through the summer (Table 1). The observed Energy Release Component (ERC) of the NFDRS (Deeming et al. 1977), the Duff Moisture Code (DMC) component of the FWI System (Van Wagner 1987), and the Keetch–Byram Drought Index (KBDI) (Keetch and Byram 1968) decreased through the summer, most likely as a result of increasing amounts of rainfall recorded at the study site (160 mm from June 1 to September 1) generally concentrated in the months of July and August. Compared to historical data (1988–2012) for the study site, the observed 2013 measures of long-term dryness and fire danger started either near or above mean levels (drier than average) but dropped to well below average by sampling Periods 3 and 4.

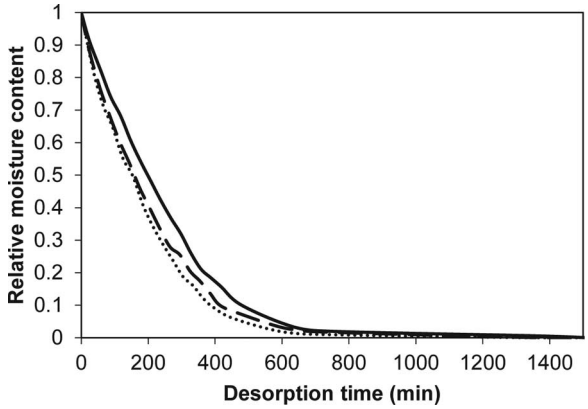

Figure 2. Change in relative moisture content for three lodgepole pine foliage samples during the red stage of mountain pine beetle attack under desorption laboratory conditions (air temperature ~22.2° C and relative humidity 51.4%) using samples obtained from the study site in southeastern Wyoming. The calculated mean (± standard error [SE]) first period time lag is 3.21 (±0.21) h.

Comparisons of the mean dead foliar moisture contents at 1–2 and 5 m heights on the sample trees indicated no significant differences ($F = 02.37$, $P = 0.1982$). The mean (±SE) moisture contents across all sample times were 10.1% (±0.21) at the lower crown and 9.7% (±0.20) at 5 m height.

Laboratory Time Lag

The moisture loss of all three needle foliage samples displayed a typical pattern of exponential decay over time (Figure 2). All samples reached equilibrium within ~25 hours and had time lags that ranged between 2.83 and 3.56 hours with a mean (±SE) of 3.21 (±0.21) hours.

Model Performance

The parameter estimates (±SE) and *r*-square for each of the corrected operational models are shown below. Linear regression of the observed moisture contents with the estimated values from Rothermel's (1983) tables of fine dead fuel moisture produced the following corrected model of dead foliar moisture content with an *r*-square of 0.36

$$m = 9.24(\pm 0.33) + 0.27(\pm 0.02)\, R, \qquad (10)$$

where m is the predicted dead foliar moisture content (% oven-dry weight) and R is the estimated fine dead fuel moisture (% oven-dry weight) from Rothermel (1983).

Linear regression with the hourly FFMC (Van Wagner 1987) values produced the following corrected model with an *r*-square of 0.53

$$m = 17.85(\pm 0.30) - 0.08(\pm 0.004)\, FFMC, \qquad (11)$$

where m is the predicted dead foliar moisture content (% oven-dry weight).

The best fitting model based on Catchpole et al. (2001) as represented by Equations 7 and 8 with the time lag set to 3.21 hours, had parameters a and b estimated (±SE) to be 0.1634 (±0.010) and −0.0143 (±0.004), respectively.

Comparisons of the predictions with the observed values from the study site in southeastern Wyoming, for each of the proposed models are shown in Table 2. The best fitting models were those developed based on the collected data, specifically, the corrected models of Rothermel (1983) and Van Wagner's (1977) hourly FFMC and the equations from Catchpole et al. (2001). The bookkeeping-system type models of Anderson (1985) using both sets of time lags performed similarly with a slight improvement in fit obtained from using the longer adsorption and desorption time lag values reported by Anderson (1985).

Model Evaluation

The evaluation of the models with the data from Page et al. (2013) indicated that most models generally performed well (Table 3). The best-performing models were those of Anderson (1985), based on the modification of the NFDRS fine fuel moisture equations with long time lags and Van Wagner's (1977) corrected hourly FFMC. The two other bookkeeping-system type models using the short time lags had similar but slightly worse performance in terms of overall model fit due to more predicted variation in the change in moisture content between day and night than actually measured in the field for the first period, May 29–30 (Figure 3A), and the second period, August 3–4 (Figure 3B) reported by Page et al. (2013). The poorest fits were obtained from the corrected Rothermel (1983) and modified Catchpole et al. (2001) models.

Evaluation of the models with the data collected by Armitage (2004) indicated that most of the models produced a moderate to poor fit (Table 4). All models overpredicted dead foliar moisture content with the best fits obtained from the Van Wagner (1977) hourly FFMC and Rothermel (1983) fine dead fuel moisture corrected models.

Discussion and Conclusions

Based on the evaluation of the models described in this study, it appears that they are all capable of predicting the moisture content of dead lodgepole pine foliage during the red stage of MPB attack with reasonable accuracy. Comparisons of the predictions with the data collected by Armitage (2004) suggest that the models may not be applicable to lodgepole pine forests at higher latitudes, except for perhaps the FFMC-corrected model. However, the dataset provided

Table 2. Deviation statistics from the comparison of the observed dead foliar moisture contents with the predicted values from the five proposed models with their mean (± standard error [SE]) and range of observed values across all four sample periods at the study site in southeastern Wyoming.

Model	Mean (±SE)	Range	RMSE	MAE	PMAE (%)	MBE
Anderson (1985)	14.7 (±0.20)	8.9–20.2	4.35	3.18	26.0	1.77
Anderson (1985) lab time lag	15.8 (±0.35)	6.6–28.1	5.61	4.20	32.0	2.83
Rothermel (1983)-corrected	13.0 (±0.11)	10.1–16.1	2.61	1.90	14.0	0.00001
Van Wagner (1977) hourly FFMC-corrected	13.1 (±0.14)	10.3–17.8	2.23	1.48	10.6	0.0002
Catchpole et al. (2001)	12.9 (±0.10)	9.7–16.5	2.63	1.78	13.0	−0.06

Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percentage mean absolute error (PMAE), and mean bias error (MBE). All units are percentage oven-dry weight except for PMAE.

Table 3. Deviation statistics from the comparison of the observed dead foliar moisture contents from Page et al. (2013) at a site in northeastern Utah, with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values for both sample periods.

Model	Mean (±SE)	Range	RMSE	MAE	PMAE (%)	MBE
Anderson (1985)	10.0 (±0.09)	7.8–11.7	1.34	1.80	11.4	0.31
Anderson (1985) lab time lag	9.5 (±0.18)	5.7–13.5	2.14	1.82	18.9	−0.17
Rothermel (1983)-corrected	11.6 (±0.08)	10.1–13.4	2.10	1.90	20.2	1.85
Van Wagner (1977) hourly, FFMC-corrected	10.6 (±0.03)	10.1–11.2	1.26	1.05	11.5	0.90
Catchpole et al. (2001)	11.5 (±0.06)	10.4–12.8	2.02	1.84	19.7	1.79

Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percentage mean absolute error (PMAE), and mean bias error (MBE). All units are percentage oven-dry weight except for PMAE.

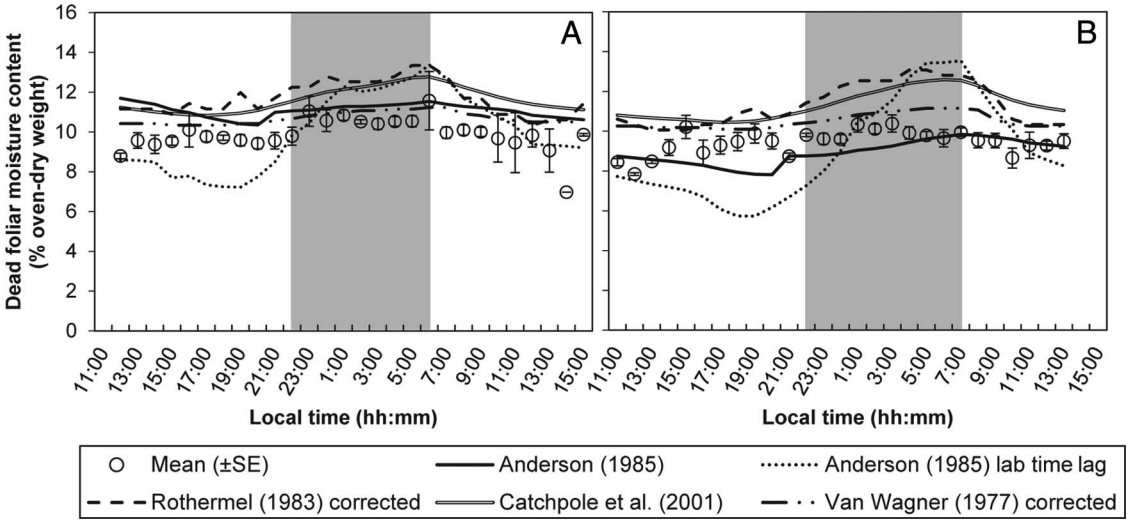

Figure 3. Time series of the observed mean dead foliar moisture contents (±SE) from Page et al. (2013) at a site in northeastern Utah, with the predictions made from the five proposed models for Period 1, May 29–30 (A) and Period 2, August 3–4 (B). The models were derived from the modification of the NFDRS fine fuel moisture equations suggested by Anderson (1985) using both the time lags reported for recently cast lodgepole pine foliage and the mean time lag from the laboratory analysis reported in this study. The corrected models from Rothermel (1983) (Equation 10) and the hourly FFMC (Van Wagner 1977) (Equation 11) were also used along with the fit obtained from the methods described by Catchpole et al. (2001). The shaded area represents the night-time period.

Table 4. Deviation statistics from the comparison of the observed dead foliar moisture contents from Armitage (2004) at a site in central British Columbia, Canada, with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values.

Model	Mean (±SE)	Range	RMSE	MAE	PMAE (%)	MBE
Anderson (1985)	15.6 (±0.32)	14.1–17.9	8.22	7.90	110.9	7.90
Anderson (1985) lab time lag	12.1 (±0.62)	9.7–18.3	5.24	4.85	65.3	4.39
Rothermel (1983)-corrected	11.7 (±0.13)	10.6–12.5	4.37	4.22	59.7	4.00
Van Wagner (1977) hourly, FFMC-corrected	10.7 (±0.04)	10.6–11.1	3.54	3.38	47.8	3.02
Catchpole et al. (2001)	12.2 (±0.17)	11.6–13.9	4.83	4.69	65.9	4.46

Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percentage mean absolute error (PMAE), and mean bias error (MBE). All units are percentage oven-dry weight except for PMAE.

by Armitage (2004) is limited ($n = 17$) and does not provide a measure of variability at each sample time, thus it is difficult to make a definite conclusion about geographic applicability beyond the Intermountain Region of the western United States. Additionally, the results indicate that there appears to be little benefit gained by using the more complicated bookkeeping-system type models based on diffusion theory. The corrected Rothermel (1983) and Van Wagner (1977) hourly FFMC models were reasonably accurate and therefore should be adequate for most applications, particularly for fire managers who already frequently use these models for other purposes.

The relatively short time lags observed in the laboratory study were initially unexpected given the previous work of Anderson (1985). Comparison of the laboratory testing methodology with Anderson (1985) indicated that there may be several reasons for the discrepancy, including, the testing of samples under a narrower range of temperature and relative humidity, the use of a higher equilibrium moisture content, the effects of increasing moisture diffusivity at higher moisture contents (e.g., Simpson and Liu 1991), and the influence of fuel load (Nelson and Hiers 2008). Despite these differences in methodology, we have confirmed that the moisture loss of dead lodgepole pine foliage on MPB-attacked trees does follow the typical exponential decay seen in other fine dead fuels and that models based on diffusion theory are capable of making accurate predictions.

Given the similar results between the bookkeeping-system type models with long and short time lags it is difficult to recommend

one over the other. Visual inspection of the time series of observed and predicted moisture contents (Figure 3) suggest that the observed data do not follow the highs and lows from the night and day time periods associated with the short time lags as well as for the long time lags offered by Anderson (1985). Thus, if a bookkeeping-system type model is desired, until further research can be done to better evaluate red needle time lag it is recommended that the long time lags reported by Anderson (1985) be used.

Using the corrected models based on Rothermel's (1983) fine dead fuel moisture tables and Van Wagner's (1977) hourly FFMC appears to be the simplest way for fire managers and fire behavior specialists to quickly and accurately predict the moisture content of dead lodgepole pine foliage associated with the red stage of MPB attack. These models will be useful to those interested in making assessments of crown fire potential in lodgepole pine forests recently attacked by the MPB. A more detailed time lag analysis of dead foliage on lodgepole pine recently attacked by the MPB is needed to better understand geographic variability and the difference between drying rates controlled by individual particle properties versus fuelbed properties.

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