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Short communication

Foliar moisture content variations in lodgepole pine over the diurnal cycle during the red stage of mountain pine beetle attack

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ABSTRACT

Widespread outbreaks of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in the lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests of North America have produced stands with significant levels of recent tree mortality. The needle foliage from recently attacked trees typically turns red within one to two years of attack indicating successful colonization by the beetle and tree death. Attempts to model crown fire potential in these stands have assumed that the moisture content of dead foliage responds similarly to changes in air temperature and relative humidity as other fine, dead surface fuels. However, this assumption has not been verified. In this exploratory study we sampled the moisture content of dead foliage on an hourly basis through two different diurnal cycles during the fire season and compared the results to measurements of 10-h fuel moisture indicator sticks and predictions made from models used to estimate dead fuel moisture in the USA, Canada, and Australia. The observed degree of variation in dead foliar moisture content was small (6.9–14.5%) with a mean value of ~10%. All existing models performed poorly, but measurements of 10-h fuel moisture and a modified version of an existing model where timelags were extended to ~20-h had the best fit to the data. The results from our study suggest that the dead foliage on attacked trees does not respond similarly to changing environmental conditions as other fine, dead surface fuels as has been assumed. This in turn has important implications for wildland fire suppression operations, including firefighter safety, and in modeling fire behavior, and solicits the need for further research.

1. Introduction

Recent and dramatic increases in the total area and severity of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) caused outbreaks in stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) have occurred throughout western North America (Bentz et al., 2010) sometimes producing a sea of "red and dead" trees. Once attacked, individual trees undergo substantial changes in foliar moisture content (FMC), chemistry, and resulting flammability as they progress from green-infested (attacked during the current summer), to yellow (attacked the previous summer), and to red (attacked two or more years previously) (Jolly et al., 2012; Page et al., 2012). During this dry down process, both Jolly et al. (2012), in north-central Colorado and western Montana, and Page et al. (2012), in far eastern Idaho, showed that successfully attacked trees experience a nearly 10-fold decrease in FMC. This process is similar to the decline in moisture content observed in logging slash following tree harvesting (Kiil, 1968) and to the seasonal changes that occur in grass fuels undergoing a transition from green to fully cured (Mutch, 1967). Once in the red stage, infested tree FMC was found to range from 6 to 32% with a mean of 12% by Jolly et al. (2012) and 9 to 41% with a mean of 13% by Page et al. (2012).

Concerns about increases in crown fire potential in recently attacked stands have been raised as a result of the observed increases in flammability caused by the reduction in FMC of infested tree foliage (Jenkins et al., 2012). Attempts to assess crown fire potential in MPB-affected lodgepole pine stands (Simard et al., 2011; Hoffman et al., 2012; Schoennagel et al., 2012) through the use of fire behavior modeling systems and simulators have assumed that the dead FMC of recently attacked trees respond similarly to changes in air temperature and relative humidity as other fine, dead surface fuels (Hartford and Rothermel, 1991). However, this assumption has yet to be verified.

The focus of this exploratory study was to examine the variations in dead FMC over the course of the diurnal cycle following the "bottoming out" of dead FMC during the red stage of MPB attack during rainless periods in the Intermountain Region of the western

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Table 1
Measures of long term dryness for the site for each of the sampling days. All values were calculated based on historical data from the Hewinta RAWS. Measures of dryness included the Energy Release Component (ERC) from the National Fire Danger Rating System, the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index System, and the Keetch–Byram Drought Index (KBDI). The means, standard errors, and 90th percentiles were based on the historical weather for that day from the period 1984 to 2012. Not all days had the same number of observations; May 29 (20 years of data), May 30 (19 years of data), August 3 and 4 (26 years of data).

Date (2012)	ERC			DMC			DC			KBDI		
	Obs	Mean ± S.E.	90th	Obs	Mean ± S.E.	90th	Obs	Mean ± S.E.	90th	Obs	Mean ± S.E.	90th
May 29	49	40 ± 2.4	54	55	30 ± 4	57	215	338 ± 38	573	87	14 ± 3	38
May 30	51	40 ± 2.6	55	58	29 ± 4	59	220	327 ± 39	579	88	14 ± 3	43
August 3	54	40 ± 2.8	60	44	41 ± 5	81	474	389 ± 45	734	87	62 ± 10	129
August 4	56	40 ± 2.7	56	48	38 ± 5	69	481	389 ± 45	736	90	59 ± 10	128

Note: Obs, observed value; S.E., standard error; 90th, 90th percentile.

United States. Sample data were collected during the course of two distinctly different diurnal cycles during the early (May) and later portions of the fire season (August) in order to first examine the variations in dead FMC and then use that data to compare to measurements of 10-h fuel moisture indicator sticks and to evaluate models of dead fuel moisture considered suitable for estimating dead FMC.

2. Material and methods

2.1. Study area

Sampling was conducted on the Evanston-Mountain View Ranger District of the Uinta-Wasatch-Cache National Forest in north-eastern Utah (40° 57′ 3.7″ N, 110° 29′ 6.4″ W), immediately adjacent to the Hewinta remote automated weather station (RAWS) (Weather Information Management System ID 420705) (Zachariassen et al., 2003). The site is flat (<5% slope) and at an elevation of 2800 m above mean sea level on the north slope of the Uinta Mountains. Vegetation is dominated by extensive stands of mature lodgepole pine which have experienced widespread MPB-caused mortality since the mid-2000s.

The Hewinta RAWS is maintained by the U.S. Forest Service and currently meets the criteria for designation as a year round data collection station with hourly transmissions of precipitation duration and amount, a 10-min average measurement of relative humidity, wind direction and speed (6.1-m height), a 60-min average of solar radiation, and an instantaneous air temperature (National Wildfire Coordinating Group, 2012). The instantaneous and 10-min average readings are taken within 5 and 15 min of the transmission time, respectively. The temperature and moisture of a ponderosa pine (*Pinus ponderosa* Laws.) dowel mounted to the station located approximately 25–30 cm above a representative surface fuelbed are also transmitted instantaneously (National Wildfire Coordinating Group, 2012).

2.2. Field procedures

Hourly collections of dead FMC from red needles of six MPB-attacked lodgepole pine trees were made in 2012 during a 28-h period from May 29 to 30 (period 1) and a 27-h period from August 3 to 4 (period 2). Previous seasonal sampling of dead FMC in red needles of lodgepole pine by Page et al. (2012) indicated relatively small variation in moisture content from tree to tree, thus three different trees each sampling period was deemed adequate for this study.

Weather data from the RAWS station for the years 1984–2012 were used to compare the current level of dryness with historic levels for each sampling period based on four fire danger indexes. These indexes included the Energy Release Component (ERC) from the U.S. National Fire Danger Rating System (NFDRS) (Deeming et al., 1977), the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index System (Van Wagner, 1987), and the Keetch–Byram Drought Index (KBDI) (Keetch and Byram, 1968).

During each sampling period, the three most suitable red trees were selected for sampling based upon (*i*) minimizing the distance from the RAWS Station, and (*ii*) similarity in terms of diameter at breast height (DBH), total tree height, crown base height, and estimated year of attack. All sample trees were located within 200 m of the RAWS and had DBHs of 24.4, 23.4, 41.9, 22.1, 18.5 and 22.4 cm and total tree heights of 15, 13, 15, 16, 12, and 13 m. All trees were judged to have been attacked in 2009 based on characteristics of MPB-attacked trees as described by Safranyik and Carroll (2006). The stand adjacent to the station where sampling took place was open with an estimated basal area of 18–23 m^{-2} ha^{-1} and 500–800 stems ha^{-1}.

The sampling procedure consisted of the removal of approximately 15–30 g of foliage from the lower third of the crown taken at 10 min past the hour on each tree, every hour, corresponding to the transmission time of the RAWS. It is recognized that the moisture content of the lower crown may not be representative of the entire tree, however, the lower crown FMC is the most important in terms of crown fire initiation and thus the focus of our sampling. Each sample was immediately weighed to the nearest 0.01 g in the field to obtain a fresh or wet weight and placed in a bag and labeled for transport back to the laboratory.

In total 84 samples were collected during sampling period 1 and 81 samples during period 2. Five samples were excluded due to illegible wet weight observations recorded in the field. In the laboratory, samples were placed in a forced air-drying oven for 24 h at a temperature of 105 °C (Matthews, 2010). The samples were then removed from the oven and reweighed to obtain the dry weight which was used to compute dead FMC as a percentage of the oven-dry weight.

2.3. Performance of dead fuel moisture models

The sampled dead FMCs were compared to predicted values of dead fuel moisture using the following mathematical models: (*i*) the 1-h and 10-h timelag[1] fuel moisture of the NFDRS (Deeming et al., 1977; Bradshaw et al., 1984); (*ii*) the NFDRS adapted Nelson (2000) model for 1-h and 10-h timelag fuel moisture; (*iii*) the hourly Fine Fuel Moisture Code (FFMC) model (Van Wagner, 1977a) of the Accessory Fuel Moisture System of the Canadian Forest Fire Danger Rating System (Stocks et al., 1989); (*iv*) the fine dead fuel moisture look-up table procedures presented by Rothermel (1983); (*v*) the AERIAL model of Pook (1993) for suspended dead needles of radiata pine (*Pinus radiata* D. Don) in Australia; and (*vi*) a simple index of fine fuel moisture content devised by Sharples et al. (2009) using a scaling factor of $\alpha = 0.5312$ taken from Sharples and McRae (2011).

A modified NFDRS model was also evaluated using the adsorption and desorption timelag values for recently cast lodgepole pine needles, 34.43 h and 20.75 h respectively, from Anderson (1985), which were used to modify the NFDRS fine fuel moisture content equations provided by Bradshaw et al. (1984). Additionally, the equilibrium moisture content (EMC) regression equations provided by Anderson (1990a) for recently cast ponderosa pine needles were substituted for the original EMC equations used by Bradshaw et al. (1984). Weather observations from the five days prior to each sampling period were used to initialize the modified model with a starting fuel moisture of 10%.

To evaluate model performance, four deviation statistics were calculated based on recommendations of Fox (1981) and Willmott (1982). These were the root mean square error (RMSE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias error (MBE). RMSE and MAE describe the average error and are often considered better measures of model performance because RMSE is in the same units as the original data and MAE is less sensitive to extreme values. MAPE calculates overall fit using the average of the sum of the absolute values expressed as a percentage while MBE is the average sum of the difference between the predicted and observed values which allows interpretation of the direction of average bias. The R software package was used for all statistical analysis (R Development Core Team, 2011).

3. Results

3.1. Observed dead foliar moisture contents

The weather conditions at the site during both sampling periods were fair and dry compared to historical averages (Table 1). Both sampling periods had been rain-free for two days prior to sampling with the last recorded 24-h rainfall of 0.5 mm and 2.0 mm for sampling period 1 and 2 respectively. Sampling periods 1 and 2 had ERCs and KBDIs that were above the historical average with the ERC

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[1] The concept of timelag is defined to be the amount of time required for a fuel particle to lose approximately two-thirds of its initial moisture content. Whereas the equilibrium moisture content (EMC) is the moisture content a dead fuel particle would obtain in constant environmental conditions when there is no longer a net moisture exchange (Bradshaw et al., 1984).

Table 2
Range in observational data obtained from the Hewinta RAWS over the course of two diurnal sampling periods during the 2012 fire season.

Measure	Units	May 29–30	August 3–4
Air temperature	°C	−1.7 to 15.6	1.1–23.3
Relative humidity	%	18–74	10–71
Solar radiation	W m^{-2}	0–1170	0–1194
10-h timelag fuel temperature	°C	−3.3 to 26.1	−1.1 to 34.4
Dew point temperature	°C	−9.6 to −1.5	−13.9 to 1.1

on August 4 at the 90th percentile for that date. The ranges in hourly weather observations were typical for the high elevation site during the early and middle portions of the fire season (Table 2). Sampling period 1 had lower air temperatures and higher relative humidities compared to period 2, while period 2 had the lowest observed relative humidity of 10% on August 3.

The hourly data for dead FMC of red needles and the corresponding observations of air temperature, relative humidity, and solar radiation for both sample periods are shown in Fig. 1. The dead FMC displayed little variability in response to changes in relative humidity with observed dead FMCs ranging from 6.9 to 14.5% with the majority of observations occurring near the mean dead FMC of 9.7% (standard error 0.08%).

3.2. Evaluation of dead fuel moisture models

All existing models generally did a poor job of predicting the dead FMC of red needles throughout the diurnal cycle for both sampling periods (Table 3). The dead fuel moisture models underpredicted dead FMC during the day and over-predicted at night (Fig. 2). The modified NFDRS model had the best fit of the data in terms of MAE and MAPE with an overall over-prediction bias while the measured 10-h timelag fuel moisture values were the best fit in terms of RMSE, also having a slight over-prediction bias (Table 3). The modified NFDRS model had an over-prediction bias during period 1 and under-prediction bias during period 2 (Fig. 2).

4. Discussion and conclusions

The small degree of variation observed in dead FMC over relatively wide ranges in air temperature and relative humidity was unexpected. Based on logical reasoning, previous attempts to model crown fire potential in recently attacked stands assumed that the FMC of red needles on attacked trees would be similar to the moisture content of other fine, dead surface fuels. However, it is now clear from the data reported here that this assumption is not valid. Due to the lack of variation observed, the dead fuel moisture models evaluated in this study did a poor job of predicting dead

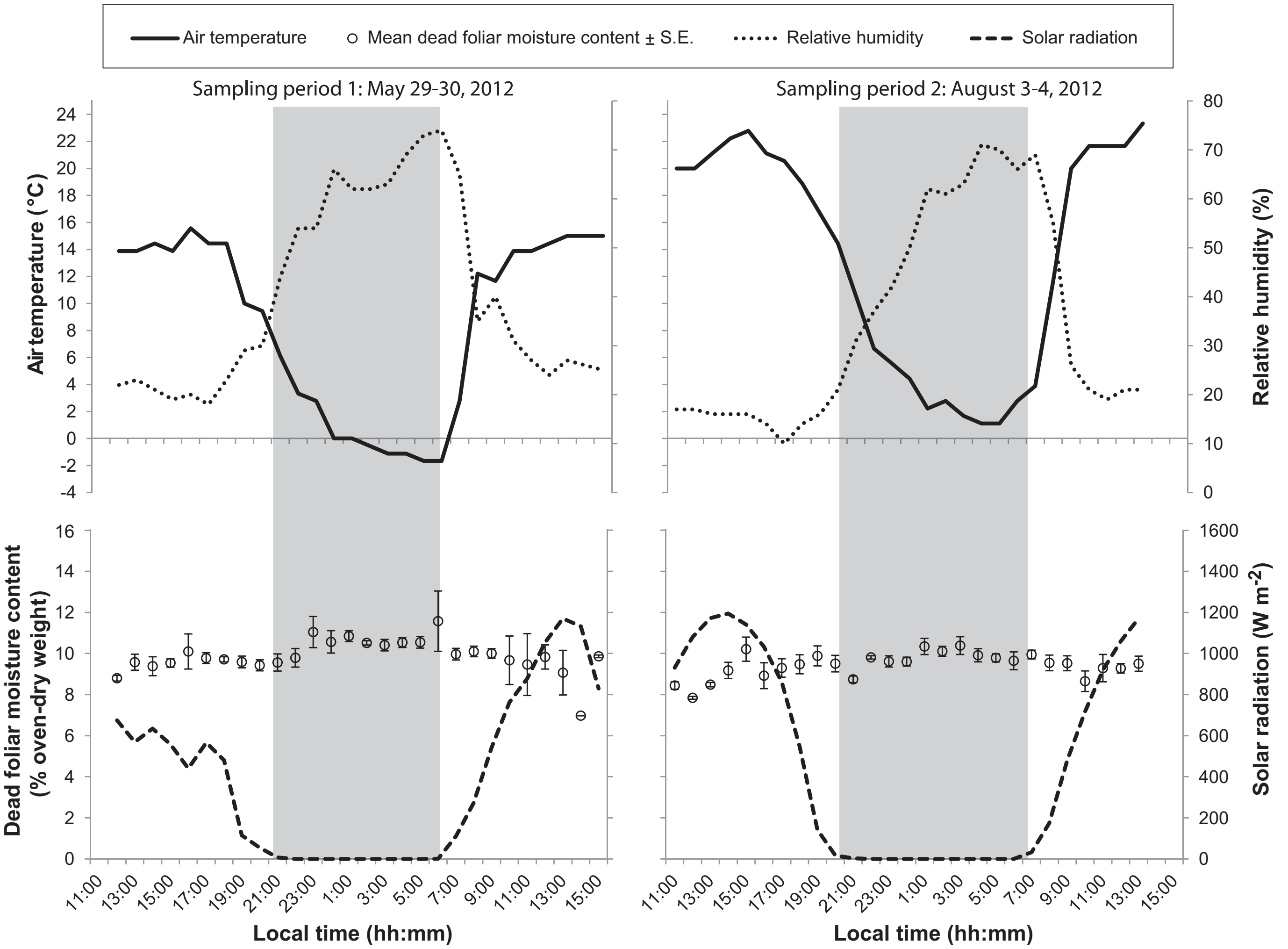

Fig. 1. Diurnal changes in weather conditions and in dead foliar moisture content of red needles on mountain pine beetle attacked lodgepole pine trees during both sampling periods in May and August, 2012. The shaded area signifies the night-time period.

Table 3
Summary of statistics associated with the comparison of predicted fine dead fuel moistures versus observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees. The deviation statistics are root mean square error (RMSE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias error (MBE).

Model	Mean	Range	RMSE	MAE	MAPE (%)	MBE
NFDRS, 1-h timelag	5.8	2.0–11.0	49.0	4.0	41.6	−3.88
Nelson (2000), 1-h timelag	10.2	3.9–17.7	5.8	3.6	37.1	0.46
Van Wagner (1977a)	11.2	4.7–19.8	19.4	3.7	37.7	1.53
Rothermel (1983)	8.5	3.0–15.0	15.8	3.0	31.1	−1.25
Pook (1993)	13.5	7.0–22.0	47.6	4.5	45.3	3.76
Sharples et al. (2009)	8.9	3.9–15.4	9.7	3.1	32.4	−0.77
NFDRS modified	10.0	7.8–11.7	4.0	1.8	11.4	0.31
RAWS, 10-h timelag fuel moisture indicator stick	10.0	7.0–13.0	0.2	5.5	28.4	0.02
NFDRS, 10-h timelag	6.2	2.0–10.0	67.4	37.5	76.5	−7.53
Nelson (2000), 10-h timelag	7.0	4.4–9.3	51.9	22.1	58.0	−5.80

Note: All units except MAPE are percent of oven-dry weight.

FMC because they were built on the assumption of timelags close to one hour. Inspection of the existing literature revealed that timelags of needles from many of the conifers found in the western United States can vary substantially from one hour and can be in excess of 20 h when recently cast (Anderson, 1985) due to their low moisture diffusivities (Anderson, 1990b).

The modification of an existing NFDRS fine fuel moisture model, as recommended by Anderson (1985), improved model accuracy, which suggests that the timelags associated with drying of red stage needles may be quite long, assuming that the needles follow an exponential drying function. Measurements of the 10-h timelag fuel moisture indicator stick also showed promise for being able to estimate dead FMC, but this requires measurements from a RAWS station or the placement of temporary fuel moisture indicator sticks in the field that then must be manually weighed, which may not always be possible.

An understanding of the daily, diurnal FMC pattern found in red needles of MPB-attacked trees is necessary to insure safe and effective fire suppression operations. Although existing models of crown fire initiation or rate of spread (e.g. Van Wagner, 1977b) may not be sensitive enough to distinguish significant changes in fire behavior in relation to the diurnal changes in dead FMC found in this study it is important that wildland firefighters and fire behavior modelers are aware of this lack of variation. Fire suppression operations personnel should not expect to see large increases in dead FMC during typical night-time recovery in relative humidity (Countryman, 1971). The low dead FMCs observed throughout the day and night and their influence on ignitability (Jolly et al., 2012; Page et al., 2012) would suggest that wider windows of potential torching and crowning activity are possible than would otherwise be expected.

Spotting potential into red tree crowns, which has been noted as a significant issue during fire suppression operations (Stiger and Infanger, 2011), is also affected by the lack of variability in dead FMC. To aid in estimating the potential of spotting into red tree crowns a probability of ignition (POI) table was released in late July 2012 (Hoyt and Jolly, 2012) for use with the National Wildfire Coordinating Group (2010) incident pocket response guide (IRPG). The POI table indicates that the FMC of green-attacked and red needle foliage can be estimated using the fine dead fuel moisture tables given in Rothermel (1983). The results of the present study suggest that the dead FMC of lodgepole pine in the red stage of MPB attack cannot be reliably estimated by this means, thus making the use of the POI table questionable.

Further field sampling of dead FMC over the course of other diurnal cycles is needed in order to further test the existing fuel moisture models for their applicability and with a view to

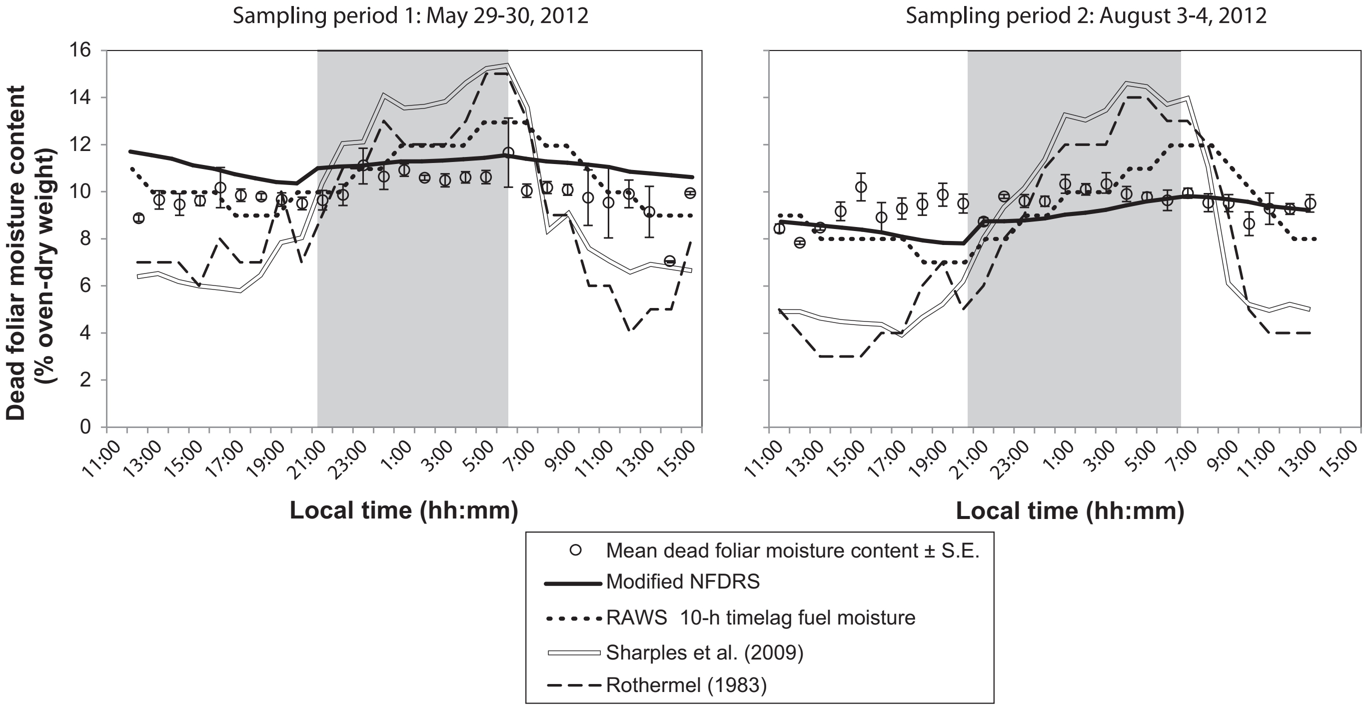

Fig. 2. Plots of the observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees during the red stage with the predicted values from the National Fire Danger Rating System (Bradshaw et al., 1984) modified model, the Rothermel (1983) lookup tables, the Sharples et al. (2009) model, and the 10-h timelag fuel moisture indicator stick for both sampling periods. The shaded area signifies the night-time period.

developing a more robust model. This would include under moister conditions (i.e. relative humidities closer to 100% for extended periods of time) and during warmer and drier atmospheric conditions than captured to date.

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