Utility of an instantaneous moisture meter for duff moisture prediction in long-unburned longleaf pine forests

Eamon A. Engber[1*], J. Morgan Varner[1], Christopher Dugaw[2], Lenya Quinn-Davidson[1], and J. Kevin Hiers[3]

[1]Wildland Fire Laboratory, Department of Forestry & Wildland Resources, Humboldt State University, Arcata, CA 95521

[2]Department of Mathematics, Humboldt State University, Arcata, CA 95521

[3] Natural Resources Branch, Jackson Guard, Eglin Air Force Base, FL32578

* Corresponding author and contact information: Wildland Fire Laboratory, Department of Forestry &Wildland Resources, Humboldt State University, Arcata, CA 9552; Tel. 707-826-5622; Fax 707-826-5634. Email: eamon.engber@gmail.com.

Abstract

Duff fires have been implicated in overstory mortality and soil heating in long-unburned pine forests. In the South's punctuated climate, duff moisture can change rapidly, falling below moisture thresholds that protect trees or increasing following brief downpours. To date, managers lack an instantaneous measure of duff moisture, a hurdle to the implementation of prescribed burns. Here we evaluate a low-cost tool, the Campbell Scientific Duff Moisture Meter (DMM) 600, to estimate duff moisture content in the field. Comparisons of the DMM 600 outputs with paired oven-dried duff fuel samples revealed statistically significant differences, with DMM 600 moisture output explaining 54 percent of the variation in oven-dried moisture content. Comparisons with previously published data demonstrate that large variations in duff moisture calculations may predict a broad range of observed duff consumption and overstory tree mortality levels, limiting its applicability for some management objectives. DMM 600 outputs were only weakly correlated with Keetch-Byram Drought Index (R^2 = 0.30). In addition, we

encountered some operational difficulties in prolonged field use. In spite of a few shortcomings, the DMM 600 provides a low-cost tool to assist in prescribed fires where deep forest floor fuels exist.

Keywords: forest floor, fuel moisture, *Pinus palustris*, prescribed burning, smoldering fire

Introduction

Substantial evidence identifies forest floor accumulation as a driver of overstory pine stress and mortality following fires (Kush et al. 2004, Varner et al. 2005, 2007, O'Brien et al. 2010) and reduced understory plant diversity (Hiers et al. 2007). Accumulated forest floor fuels ignite during prescribed fires and wildfires then smolder, causing long-duration heating of surficial roots and basal cambium. Lower forest floor (i.e., humus or lower duff) moisture content has been implicated as a primary driver of forest floor smoldering and tree mortality in long-unburned longleaf pine stands (Varner et al. 2007, O'Brien et al. 2010) and in many other forest types where forest floor fuels have accumulated in the absence of frequent fire (see review in Hood 2010). In spite of the clear links between duff moisture, fuel consumption, and tree mortality, land managers lack a quick decision support tool to capitalize on duff moisture thresholds for ignition (Frandsen 1997).

The difficulty in obtaining rapid estimates of forest floor moisture in long-unburned longleaf pine forests poses a challenge for managers who require moisture estimates for the planning of burns. Ferguson et al. (2002) used time domain reflectivity (TDR) probes in combination with field collections to characterize forest floor moisture and combustion limits in longleaf pine forests in the Florida Panhandle. This approach required calibration of individual TDR probes with volumetric moisture content (VMC) at each probe location, and resulted in weak to moderate correlations between sample-based duff VMC and probe output (R^2 ranging from 0.12 to 0.51). Field collection and drying in a convection oven yields accurate moisture estimates, but multiple days of drying are required to ensure all moisture is removed before re-weighing. A few managers with experience restoring fire to long-unburned stands have developed experiential methods for estimating duff moisture (days since soaking rain, feel; e.g., Wade and Lunsford 1989), but those are often difficult to translate to the majority of managers who struggle with this increasingly common problem (Varner et al. 2005).

The objective of this study was to evaluate a simple, rapid method of duff moisture estimation for longleaf pine duff in northern Florida that may have applicability in other longleaf stands and perhaps in other long-unburned southern pine forests. We tested the Campbell Scientific (Logan, UT, USA) DMM 600 Duff Moisture Meter (Robichaud et al. 2004) against field fuel collections and the Keetch-Byram Drought Index (KBDI), an oft-cited tool for gauging the moisture of long timelag fuels. Additionally, we evaluated the DMM 600 for its operational utility in the field. We anticipate that these findings will be of use to managers facing similar issues in the large area of fire-excluded longleaf pine forest in the southeastern US (Outcalt 2000), and they might inform restoration burning in other pine stands targeted for future prescribed fire.

Methods

Study Site

Sampling took place at the Ordway-Swisher Biological Station near Melrose (Putnam County), Florida (N 29º 40’, W 81º 74’) and was supplemented, to a lesser extent, at Eglin Air Force Base in the Florida Panhandle (30º 38’N, 86º 24’W). The Brantley Lake stand at Ordway had not been burned in ca. 45 years; it was dominated by an overstory of longleaf pine, with a dense midstory of oaks (primarily *Quercuslaevis* Walt, *Q. geminata* Small, and *Q. hemisphaerica*Bartr.), and a thick organic forest floor (depths to 15 cm) typical of long-unburned xeric “sandhill” southeastern pine ecosystems (Varner et al. 2005). Soils of the site are deep, excessively well-drained hyperthermic, uncoated Lamellic Quartzipsamments in the Candler series (Readle 1990). The topography is gentle, with southwest-facing slopes <5 percent and elevations averaging 36 m above msl. The climate is humid, warm temperate with long, warm, and humid summers and short, mild winters, and annual temperatures and precipitation averaging 20ºC and 1432 mm, respectively (Readle 1990). Similarly, the Eglin site was a long-unburned longleaf pine stand with a sparse longleaf pine overstory and a hardwood-dominated midstory typical of fire-excluded sandhills. Annual temperatures at the Eglin site average 19.7º C, and mean annual precipitation is 1580 mm (Overing et al. 1995).

Fuel Moisture Sampling – Oven-dry Method

Fuel moisture sampling occurred on 14 separate days, totaling 58 moisture samples during a five week period beginning on 9 February 2011 and ending 16 March 2011. All moisture sampling was carried out at the Ordway site except for one sample day that occurred at Eglin Air Force Base. Lower duff (i.e., humus) moisture was sampled during experimental burns that were part of an ongoing project focused on combustion limits in long-unburned forests. On each of the 14 sampling days, humus moisture was sampled at two longleaf pines adjacent to experimental burn plots. At each tree, a ca. 15 × 15 cm^2 humus sample was collected from the basal duff mound (“tree base”) and at a distance of 2 m from the bole (“open”), for a total of four moisture samples per day (duff depth varied from ca. 5 to 15 cm). One sample day was an exception; an additional plot was burned, resulting in two additional open samples on that day. Fuel samples were sealed in plastic bags and stored in a cooler until transported to a weighing station at the field site on the afternoon of each burn day. Samples were then dried in a convection oven at 80ºC until no further moisture loss occurred, generally for 72 hours. Gravimetric moisture content (GMC; %) was calculated with the following equation:

$$GMC = 100 \times \frac{(wet\ weight\ -\ dry\ weight\ )}{dry\ weight}$$

Duff Moisture Meter 600

Duff VMC and GMC were also measured with a DMM 600 (Campbell Scientific, Inc., Logan, UT) duff moisture meter (Robichaud et al. 2004) in the field using a portion (ca. 120 cm^3) of duff from each oven-dry method duff sample. A detailed description of the DMM 600 and its development can be found in Robichaud et al. (2004). In short, the DMM 600 employs a sensor circuit where the output frequency is sensitive to the dielectric permittivity of a duff sample, which is influenced by moisture content. The output frequency of the sensor circuit is calibrated with VMC; user-defined calibration coefficients can be loaded onto the device using supplied software (PC DMM; Campbell Scientific, Inc.) to output GMC in addition to VMC. Duff samples are passed through a #4 mesh (5.16 mm) sieve into a sample chamber, and a compression knob is then turned to move a piston within the sample chamber and compress the duff sample against the sensor circuit. When sufficient compression (66 N) is achieved, an audible beep is emitted and the sample moisture content is displayed.

We used the standard calibration equation supplied with the DMM 600, which converts sensor circuit output frequency to VMC, where:

$$VMC = 5.288 + 5.905 \times freq - 0.142 \times freq^2$$

Though the standard calibration equation for VMC was based on duff samples from four forest types (Douglas-fir, western larch, lodgepole pine, and spruce/alpine fir), Robichaud et al. (2004) suggest that it has broad applicability; we were interested in how it performed for longleaf pine duff. We also wanted to document how well DMM GMC output compared with the standard oven-dry method, therefore the factory protocol for calibrating the standard VMC equation to GMC was followed. To obtain GMC, each coefficient in the standard VMC calibration equation was divided by the compressed humus bulk density and the resulting coefficients were uploaded to the DMM using the software supplied by Campbell Scientific. A humus bulk density of 0.113 g/cm^3 was estimated from 42 samples at the study site, and we used the DMM 600 to calculate a compressed bulk density of 0.2138 (SD = 0.0101) g/cm^3 from 15 of these samples. This compressed value was used to calibrate the VMC equation to GMC, where:

$$GMC = 24.733 + 27.619 \times freq - 0.664 \times freq^2$$

Data Analysis

Values for oven-dry method GMC were compared with the DMM GMC output, and a paired t-test was conducted to evaluate differences between the two. Simple linear regressions were carried out to determine the strength of the relationship between DMM 600 output and oven-dry GMC. Linear equations to convert DMM GMC or VMC to oven-dry method GMC are reported. Scatter plots include confidence intervals for predicted mean GMC and prediction intervals for predicted individual values of GMC based on regression results.

To assess the relationship between KBDI and duff moisture, KBDI data for sample days were compared to daily mean values for duff moisture. The single sample day from Eglin was removed from this analysis due to a KBDI value for that day that was more than six standard deviations from the mean KBDI for Ordway during the study period. KBDI data are available at the county level from the Florida Division of Forestry website (http://flame.fl-dof.com/fire_weather/KBDI/index.html). Simple linear regression was used to assess the relationship between KBDI (predictor) and mean daily values for tree-base, open, and all locations data, for each moisture calculation method (oven-dry method GMC, DMM GMC, and DMM VMC). Coefficients of determination (R^2) and P-values from simple linear regressions are reported. For all analyses, residual plots were assessed for compliance with the assumptions of statistical tests. Statistical significance was assessed at $\alpha \leq 0.05$ and the statistical software NCSS (Hintze 2007) was used for all analyses.

Lastly, regression equations relating DMM GMC output to oven-dry method duff moisture were used to predict DMM GMC values for duff consumption and overstory longleaf pine mortality data reported in a previous study (Varner et al. 2007). The relationship between duff moisture, duff consumption, and tree mortality provides a management-relevant example of DMM 600 values that could be expected for various levels of duff consumption and overstory mortality in long-unburned, xeric longleaf pine forests.

Results and Management Implications

DMM 600 versus Oven-dry Method

Oven-dry method humus GMC ranged from 48.0 to 144.1 percent and averaged 73.2 (SD = 18.7) percent over the study period (Figure 1). The mean difference between oven-dry method

GMC and DMM GMC was slight, at +4.45 percent (SD = 13.15), but statistically significant (P = 0.01; paired two-tailed t-test). A possible explanation for this difference could be the sieving of DMM 600 duff samples; fine roots would be removed from DMM 600 samples but not from oven-dry method samples, potentially changing the moisture content of DMM 600 samples. Mean values for DMM VMC and GMC were 14.2 (SD = 3.7) and 68.7 (SD = 17.2) percent, respectively, over the five week period. DMM GMC ranged from 38.5 to 131.7 percent, while DMM VMC ranged from 8 to 28 percent.

The relationship between oven-dry method GMC and DMM GMC was approximated by a linear equation, where: $Oven\ dry\ method\ GMC = 18.5574 + 0.7948 \times DMM\ GMC$, with the predictor DMM GMC explaining 54 percent of the variation in oven-dry method GMC (Figure 2). Oven-dry method GMC was similarly linearly related to DMM VMC, where: $Oven\ dry\ method\ GMC = 20.8535 + 3.6981 \times DMM\ VMC$ (Figure 3). The variability displayed in figures 2 and 3 could have resulted from multiple sources, including variable amounts of fine roots in oven-dry method samples; errors in dielectric permittivity sensing by the device itself; errors in the calibration of GMC resulting from spatial variability in duff bulk density or other duff properties differing from those species used in development of the DMM 600; and/or spatial variability in moisture content within the 15 × 15 cm^2 duff moisture samples. Given the fairly large prediction interval for oven-dry GMC (ca. 50 percent GMC), usefulness of the DMM 600 will depend on the management application.

Research burns correlating duff consumption with fuel moisture may require standard oven drying duff moisture sampling procedures to ensure sufficient precision in moisture estimation, yet the DMM 600 may suffice to obtain coarse moisture values for operational prescribed burns. Local spatial variation in duff moisture can also be substantial (Ferguson et al.

2002) and is an additional source of variability in duff moisture estimation. Analysis of daily oven-dry GMC data from this study (4 samples per day) showed a mean coefficient of variation of 17.7 percent and a range from 7.13 to 37.7 percent, suggesting multiple moisture samples throughout a stand may be required for precise estimates of duff moisture. In addition, spatial variation in humus bulk density is a potential source of error when predicting GMC using the DMM 600 calibration equation, and users must ensure that the compressed bulk density (calculated with the DMM 600), rather than field-based bulk density, is used in the GMC calibration equation.

Previously published data on duff moisture and consumption and subsequent pine mortality in longleaf stands at Ordway (Varner et al. 2007) provide a unique opportunity to link DMM 600 moisture predictions to observed fire effects. Of note is the wide range of consumption and mortality scenarios implicated by variable duff GMC predictions. For example, at 75 percent DMM GMC (dotted vertical line in Figure 4), the large prediction interval for GMC spans duff consumption levels from ca. zero to 50 percent and pine mortality from ca. zero to 40 percent. Individual managers must decide if this is an acceptable level of variation for their application before employing the DMM 600. Variation aside, duff consumption levels from ca. 45 to 65 percent occur below 60 percent DMM GMC (or 12 percent DMM VMC), and overstory longleaf pine mortality levels from 20 to 40 percent could be expected when DMM GMC falls below 50 percent (or DMM VMC below 11 percent) (Figure 4).

KBDI versus DMM 600

The KBDI was negatively, but weakly, correlated with duff moisture calculations (including standard oven-drying methods and the DMM 600) (Table 1), suggesting limited application for duff moisture prediction, at least at the stand level. Linear regression results reveal relatively stronger correlations between tree-base humus moisture and KBDI compared to open or all locations, though the only regression with a slope significantly different from zero was tree-base DMM GMC and KBDI ($R^2 = 0.30$, $P = 0.05$; Table 1). Relatively low R^2 values suggest a limited applicability of KBDI in duff moisture prediction at the stand level, a finding corroborated by other works (Sparks et al. 2002, Hood 2010); results from this study suggest the DMM 600 may be the better tool for duff moisture prediction.

Operational Issues

Over the course of the five week study period and ca. 60 measurements with the DMM 600, we encountered two operational problems. The first was related to the compression knob cap assembly (see Robichaud et al. 2004 for DMM 600 diagram). The compression knob screws into the sample chamber cap, lowering a compression plate that compacts the duff sample. With repeated use, the threads seated in the chamber cap became dislodged and migrated onto the compression knob, causing a failure of the cap assembly, which then had to be replaced. The second cap assembly began having the same issue until users became sensitive to binding and were able to avoid it. The second issue involved the sensor circuit plate housed at the base of the sample chamber. The sensor circuit plate sits on springs that are compressed when the sample is compressed. We found that duff particles became lodged between the sensor circuit plate and the sample chamber housing, causing the sensor circuit plate to bind under compression. This resulted in an immediate duff reading when the DMM 600 was turned on, before the sample was actually compressed. Frequent cleaning of the sample chamber reduces the likelihood of this issue.

Conclusion

In spite of the limitations addressed above, the DMM 600 remains a potentially valuable tool for natural resource managers needing rapid estimates of duff moisture. The time required for oven-drying or TDR installations, and the lack of a strong correlation between the KBDI and duff moisture, makes the DMM 600 the only tool available for instantaneous duff moisture estimation. Users are cautioned to consider appropriate error levels in moisture prediction for various applications, and to understand the limitations of the device. Relatively large variation in moisture prediction may preclude its utility for scientific investigations of moisture thresholds in duff combustion, yet the instrument may still prove practical for operational burns. As reintroduction fires are increasingly prescribed in long-unburned pine stands in the South, tools that support management decisions should be prioritized and refined.

Acknowledgements

This project was supported by funds provided by the Joint Fire Science Program. We appreciate the coordination and support of S. Coates and the Ordway-Swisher Biological Station and B. Williams at Jackson Guard, Eglin Air Force Base. Helpful comments and discussion were provided by P. Robichaud and L. Ashmun.

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Figure 1. Oven-dry method gravimetric duff moisture content (%), DMM 600 gravimetric duff moisture (DMM GMC, %), and DMM 600 volumetric duff moisture (DMM VMC, %) in long-unburned longleaf pine stands in northern Florida over a five-week study period. Bars represent the standard errors.

Figure 2. Oven-dry method gravimetric duff moisture content (GMC; %) compared to DMM 600 gravimetric duff moisture content (GMC; %). $R^2 = 0.54$; $P<0.001$. Oven-dry GMC = 18.557 + 0.795 ×DMM GMC. Inner lines represent the 95 % confidence interval while outer lines represent 95 % prediction interval.

Figure 3. Oven-dry method gravimetric duff moisture content (GMC; %) on DMM 600 volumetric duff moisture content (VMC; %). $R^2 = 0.54$; $P<0.001$. Oven-dry DMC = 20.853 + 3.698×DMM VMC. Inner lines represent the 95 % confidence interval while outer lines represent 95 % prediction interval.

Figure 4. Scatter plots depict duff consumption and pine mortality data taken from Varner et al. (2007), with Varner et al.'s GMC converted to DMM 600 GMC based on regression equations established in the present study. Horizontal error bars represent the prediction interval for GMC (spanning 50% GMC). As an example, at 75% DMM GMC (dotted vertical line), the large prediction interval for GMC spans duff consumption levels from ca. 0 to 50% and pine mortality from ca. 0 to 40%.

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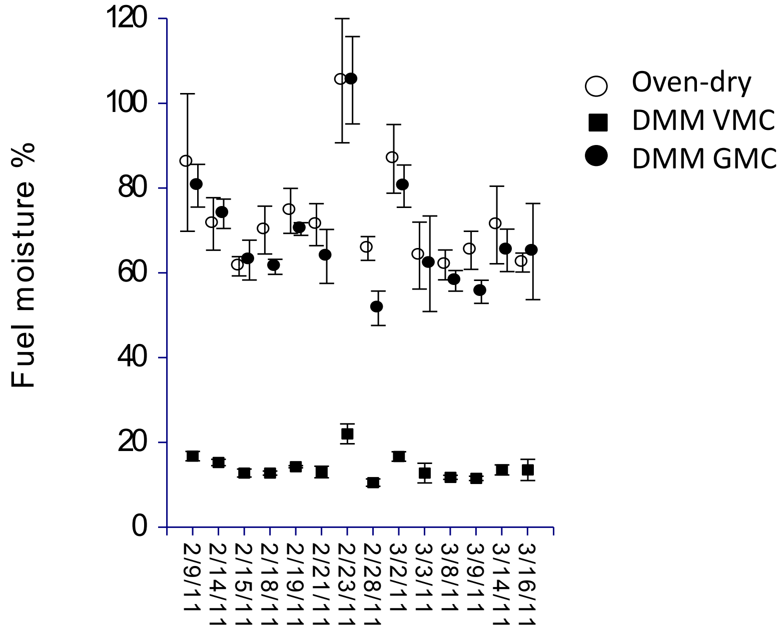

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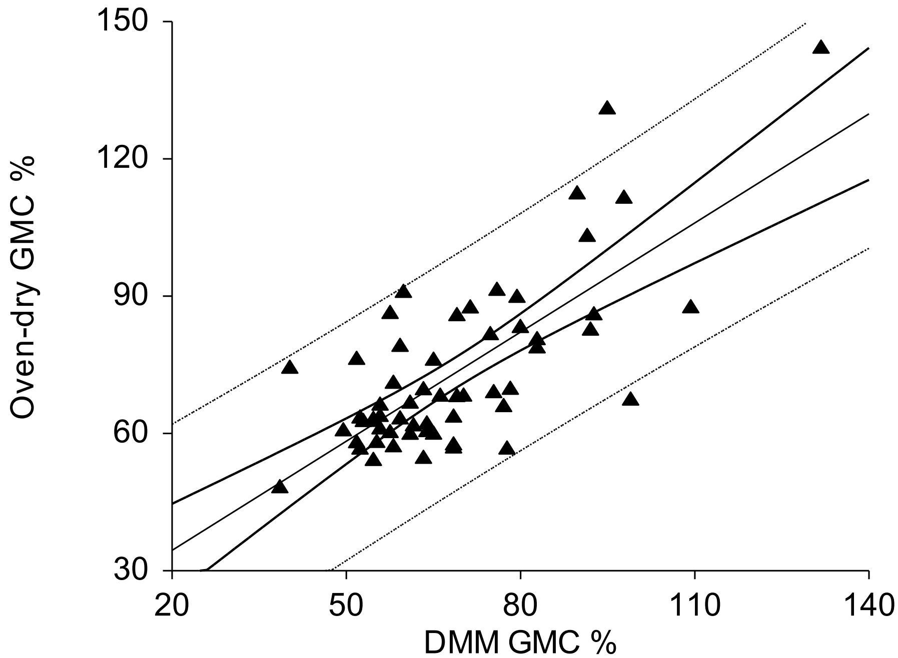

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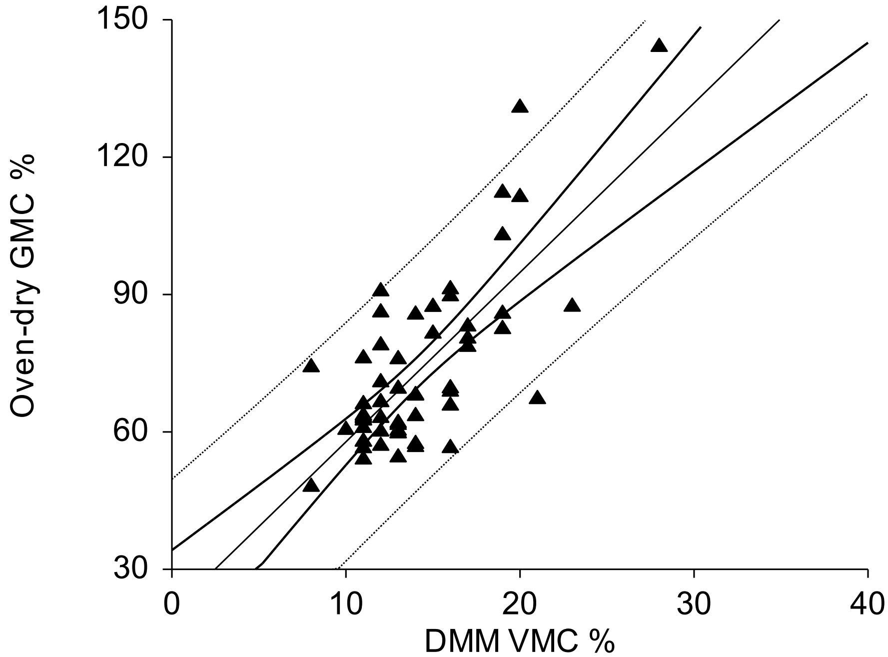

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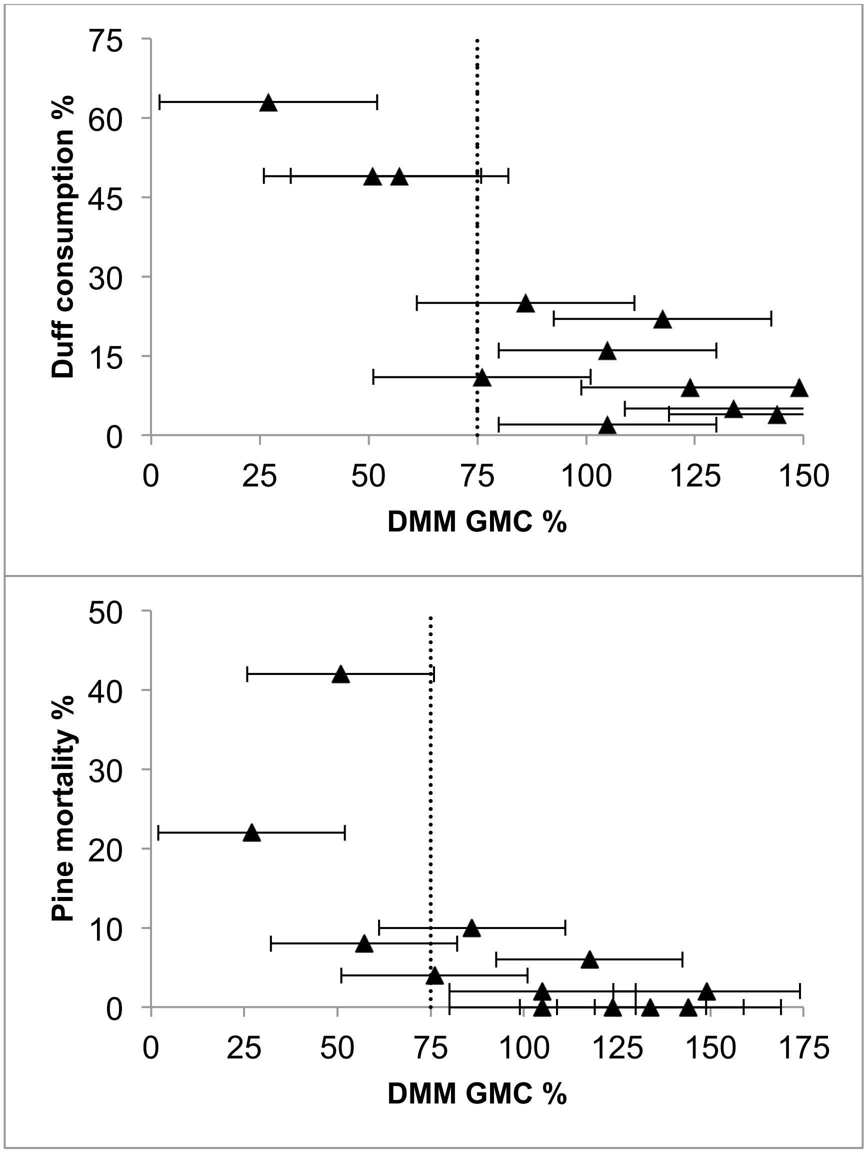

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Response	**Sample location**	**Predictor**	**R^2**	**P-value**
Oven-dry GMC	All	KBDI	0.09	0.32
Oven-dry GMC	Tree base	KBDI	0.21	0.12
Oven-dry GMC	Open	KBDI	0.04	0.52
DMM GMC	All	KBDI	0.24	0.09
DMM GMC	Tree base	KBDI	0.30	**0.05***
DMM GMC	Open	KBDI	0.06	0.43
DMM VMC	All	KBDI	0.23	0.10
DMM VMC	Tree base	KBDI	0.26	0.07
DMM VMC	Open	KBDI	0.06	0.41