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Research Note

A comparison of two methods for estimating conifer live foliar moisture content

W. Matt Jolly[A,B] *and Ann M. Hadlow*[A]

[A]US Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 Highway 10 W, Missoula, MT 59808, USA.
[B]Corresponding author. Email: mjolly@fs.fed.us

Abstract. Foliar moisture content is an important factor regulating how wildland fires ignite in and spread through live fuels but moisture content determination methods are rarely standardised between studies. One such difference lies between the uses of rapid moisture analysers or drying ovens. Both of these methods are commonly used in live fuel research but they have never been systematically compared to ensure that they yield similar results. Here we compare the foliar moisture content of *Pinus contorta* (lodgepole pine) at multiple sites for an entire growing season determined using both oven-drying and rapid moisture analyser methods. We found that moisture contents derived from the rapid moisture analysers were nearly identical to oven-dried moisture contents ($R^2 = 0.99$, $n = 68$) even though the rapid moisture analysers dried samples at 145°C *v.* oven-drying at 95°C. Mean absolute error between oven-drying and the rapid moisture analysers was low at 2.6% and bias was 0.62%. Mean absolute error was less than the within-sample variation of an individual moisture determination method and error was consistent across the range of moisture contents measured. These results suggest that live fuel moisture values derived from either of these two methods are interchangeable and it also suggests that drying temperatures used in live fuel moisture content determination may be less important than reported by other studies.

Additional keywords: Computrac, fuel moisture, live fuels, oven-drying, rapid moisture analyser.

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Introduction

Wildland fires spreading through living plants are common throughout the world. Fire-adapted ecosystems such as the South African fynbos, the Mediterranean maquis, coastal south-western US chaparral and intermountain conifer forests of North America commonly support intense fires that are difficult to control but are ecologically important. Many factors regulate fire potential in these systems but live foliar moisture content (LFMC) is commonly used to determine the likelihood that fires will ignite and spread (Xanthopoulos and Wakimoto 1993; Dimitrakopoulos and Papaioannou 2001; Weise *et al.* 2005; Pellizzaro *et al.* 2007). LFMC is measured routinely throughout the world to evaluate seasonal plant flammability and these field measurements are used to assess potential fire behaviour during planned and unplanned wildland fire ignitions (Weise *et al.* 1998; Brenner 2002).

Live fuel moisture content is driven by both changes in the moisture status of the plant and seasonal changes in the dry weight of the foliage. Foliar water is generally lost through transpiration and small amounts of water are also evaporated through the cuticle (Kozlowski and Pallardy 1979). This water deficit is usually replenished by the uptake of water from the soil but in periods of drought stress, the foliage may not completely hydrate. A complete review of the water relations of forest fuels can be found in Nelson (2001). Because live fuel moisture is commonly expressed as a percentage of dry matter, seasonal changes in dry matter can also be important factors that determine the 'apparent' seasonal changes in conifer foliar moisture content (Little 1970).

Live foliar moisture content expresses the ratio of the weight of the water contained in a sample to the dry weight of the sample. Foliar samples are collected, weighed fresh, dried and reweighed. Their moisture content is expressed as a percentage of their dry weight as follows:

$$\text{Foliar moisture content (LFMC)} = ((\text{wet weight} - \text{dry weight})/\text{dry weight}) \times 100 \quad (1)$$

where wet weight is the fresh weight of the sample in grams and dry weight is the weight of the sample after it has been completely dried. Drying samples in an oven at a temperature between 60° and 105°C for 48 h is a widely accepted method (Countryman and Dean 1979; Norum and Miller 1984; Viegas *et al.* 1992; Samuelsson *et al.* 2006; Matthews 2010). Oven-drying can be inconvenient in some research and management applications because these measurements take 2 days to complete.

However, other tools exist to determine foliar moisture content more rapidly. One such apparatus is the rapid moisture

analyser. These analysers combine a radiant heater and precision balance and can estimate LFMCs in less than 15 min *v*. the 2 days required for conventional oven-drying. The rapid moisture analyser calculates fuel moisture content by heating a sample until the sample mass loss rate is below a user-specified value. The final moisture concentration is extrapolated from the curve by a microprocessor and results are available within a few minutes. These moisture analysers have been used in a variety of wildland fire-related research programs (Sun *et al.* 2006; Castillo *et al.* 2007; Manzello *et al.* 2008; Pickett *et al.* 2010).

Despite the prolific use of both of the methods in various research programs, no systematic comparison has been done to show that these two approaches are comparable. Here we present the results of a study aimed at assessing the seasonal relationship between oven-dried and rapid moisture analyser-determined fuel moistures for *Pinus contorta* (lodgepole pine), a common intermountain US conifer. Mean LFMCs were compared to determine if these two methods produce similar values for both a given point in time and throughout the season and thus could be used interchangeably in live fuel-related research and management programs.

Materials and methods

Sample sites

Foliar samples were collected from *Pinus contorta* trees at two proximal sites located on an exposed south or south-west aspect in western Montana, USA. The first site (Lubrecht) was at 1262-m (4141-ft) elevation and was located on the Lubrecht Experimental Forest (46°53′52.26″N, 113°26′22.2″W). The second site (Garnet) was at 1699-m (5575-ft) elevation and was located on the Garnet Range Road (46°51′6.59″N, 113°24′12.96″W). Additionally, *Pinus ponderosa* (ponderosa pine) samples were collected at the Missoula Fire Sciences Laboratory (46°55′35.44″N, 114°37′37.56″W, 978-m (3209-ft) elevation) and *Larix occidentalis* samples were collected from a site on a southerly aspect at 2031 m (6666 ft) on the Lolo National Forest (47°0′49.18″N, 114°0′51.48″W). *Abies lasiocarpa* (subalpine fir) samples were also collected from the Garnet site.

Collection methods

Samples were collected weekly from May through October 2010 and they were taken from branches at the lower third of trees growing in road cuts or at the edge of a meadow. Sampling only from exposed crowns helped to control for within-crown foliar moisture content differences that are observed due to shading (Pook and Gill 1993). Needles were cut from the branch with scissors to remove dead material contained in the fascicle but were otherwise left intact and placed in aluminium cans with lids. Current-year foliar growth was collected separately from previous growth because there are generally large differences between old and new foliar moisture content until the new foliage is fully matured (Chrosciewicz 1986). Old growth was sampled irrespective of age but was generally 1–5 years old. All samples were kept cool after collection and all laboratory measurements were made on the day of collection, usually within 2 hours. Three 2-g samples of needles from each needle age class (new or old), site and species were processed separately using both the oven-drying method and the rapid moisture analyser as detailed below. The three other species were sampled once in the spring and once in late summer to increase the range of species and fuel moistures included in the dataset.

Oven-drying method

Samples were weighed as soon as possible after collection to obtain their fresh (wet) weight using a scale accurate to the nearest 10 mg. Samples were weighed with lids on to prevent moisture loss and sample can weights were determined and recorded before sampling. Samples were dried with lids off in a 95°C forced-air convection oven for 48 h. Cans were reweighed after drying to determine dry weight. Can weights were subtracted from fresh and dry weights and fuel moisture was calculated using Eqn 1.

Rapid moisture analyser method

We chose the Computrac Max2000XL (Arizona Instruments, Chandler, AZ, USA) for the rapid moisture analyser in this study primarily because this instruments is used commonly in research studies and field applications throughout the world (Southwest Area 2004; Sun *et al.* 2006; Castillo *et al.* 2007; Manzello *et al.* 2008). However, many other similar instruments exist and similar work could be done to determine their efficacy in research and applied forestry applications. Computrac samples were kept in sealed cans and all tests were performed the same day the samples were collected. The internal scale was calibrated using factory guidelines before use (Arizona Instruments LLC 2002). The Computrac allows the user to store a custom set of test parameters that include: tare options, sample size, test temperatures, test ending criteria and display options. To begin sample testing, a clean pan placed on the scale was weighed to the nearest 0.1 mg to determine tare weight. A 2-g sample of cut conifer needles was loaded onto the pan and the test was started by heating the chamber to 145°C. As the sample heats up, the balance continually records the mass of the sample and transmits this information to a microprocessor. The analyser returns a final moisture content value when the mass loss of the sample drops below a user-specified value (0.08% per minute for our tests). This process usually takes less than 15 min.

There are three ways the Computrac can use to end a test. ‘End Test on Prediction’ (Prediction) terminates the test based on predictions from an exponential drying curve. ‘End Test on Rate’ (Rate) terminates the test when the mass loss rate falls below a user-defined mass loss rate. ‘End Test on Time’ (Time) terminates the test after a selected amount of time. This test appears to be the least efficient for forestry purposes because samples may be completely dried minutes before the test is forced to terminate or they may not be completely dry when the test terminates. Prediction and Rate modes produced the most accurate results compared with the oven-dried method although it is recommended that each of these ending criteria is tested before sampling to determine an acceptable accuracy or testing time. We chose the Rate mode as ending criteria for this study because it decreased the time of individual tests while maintaining repeatable results. Each test on conifer leaves lasted ~15 min, and the ‘dry weight’ setting, which displays the fuel moisture as a percentage of dry weight, was chosen for the result display option. Results were recorded manually and stored in the

Table 1. Computrac Max2000XL rapid moisture analyser parameters used for all tests in this study

Test parameter	Setting
Sample size	2 g
Test temperature	145°C
Test HiStart temperature	25°C
Idle temperature	25°C
Ending criterion	End test on rate
Ending rate	0.080% min^{-1}
Pan tare option	Standard
Sample tare option	Start when stable
Special tare option	Off
Lift compensation option	100%
Linked test options	Off
Ending criteria display	Dry weight

Computrac data memory, and the heating unit was allowed to return to an idle temperature between tests (Southwest Area 2004). The full set of parameters used for the Computrac Max2000XL is given in Table 1.

Data analysis

Mean LFMCs were calculated for each site, species, age class and sampling date for both the oven-dried and rapid moisture analyser methods. Standard deviations and ranges were calculated for both the oven-dried and rapid moisture analyser methods for each sampling date. Sampling-date standard deviations were used to calculate the maximum allowable error for 95% confidence using a standard sample size equation with sample size equal to three (Thompson 2002). This metric helps to define how closely we can measure LFMC given the variability of the estimate and a fairly small sample size for a particular method. This provided us with both a series of paired moisture content measurements and some simple metrics of within-mean variability that we were able to use for further analysis. Mean absolute error and bias were estimated from the paired samples to determine the average error between these two sets of measurements (Ruiz González *et al.* 2009). Data were analysed using the non-parametric Wilcoxon signed-ranked test, which is designed to test that the difference between a set of paired observations is zero (Sokal and Rohlf 1997). This test was used because the time series data were not normally distributed based on a Shapiro–Wilk normality test and because the time series data by nature were serially correlated. Data were also displayed and compared using a simple, no-intercept linear regression and their time series were also displayed and analysed using a Pearson's correlation. Finally, we used a simple diagnostic plot of the mean moisture contents *v.* their difference to determine if errors were consistent across the range of measured LFMCs (Altman and Bland 1983).

Results

We found that moisture contents derived from the rapid moisture analyser (RMA) were nearly identical to oven-dried moisture contents. The relationship between oven-dried- and RMA-determined LFMCs is shown in Fig. 1. The coefficient of determination (R^2) for the no-intercept regression line for *Pinus contorta* was 0.99 ($n = 68$) and the slope of the line fit was 0.99, suggesting that these two methods produce very similar measurements of LFMC across this large range of measured values. Samples from three other conifer species for two sampling dates are also shown in Fig. 1 and these additional samples also show very good agreement between the two methods. The Wilcoxon signed rank test ($V = 1539$, $P = 0.4159$) indicated that the difference between the two paired measurements was not significantly different from zero.

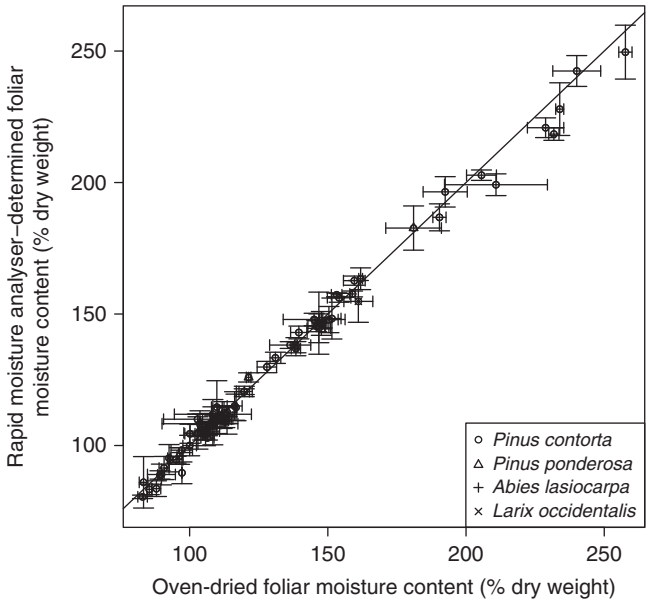

Fig. 1. Comparison of mean live foliar moisture content measurements for new and old *Pinus contorta* needles using two methods: oven-drying and a rapid moisture analyser. Error bars show the 95% confidence limits of the mean for each method. The coefficient of determination (R^2) is 0.99 and the slope of the no-intercept regression line is 0.99. Regression line shown is based only on *Pinus contorta* but three additional species (*Pinus ponderosa*, *Abies lasiocarpa* and *Larix occidentalis*) are also plotted. These two moisture content measurement methods produce very similar moisture content measurements across the full range of live foliar moisture contents reported in the literature.

The range of moisture contents measured in this study spans the full range of LFMCs generally observed in conifers throughout the growing season (Chrosciewicz 1986; Philpot and Mutch 1971). A time series for the new and old *Pinus contorta* samples from both sampling sites is shown in Fig. 2. Seasonal correlations between oven-dried- and RMA-determined LFMCs were also high. Fig. 2 shows that throughout the season, both methods describe the same seasonal variations. Seasonal Pearson's correlation coefficients for new needles at both sites were 0.99 and for old needles 0.96 and 0.97 for Garnet and Lubrecht respectively.

Fig. 3 shows the relationship between the differences in foliar moisture as measured by the two methods relative to their means. The difference was calculated as:

$$|\mathrm{LFMC}_{\mathrm{oven}} - \mathrm{LFMC}_{\mathrm{rma}}| \qquad (2)$$

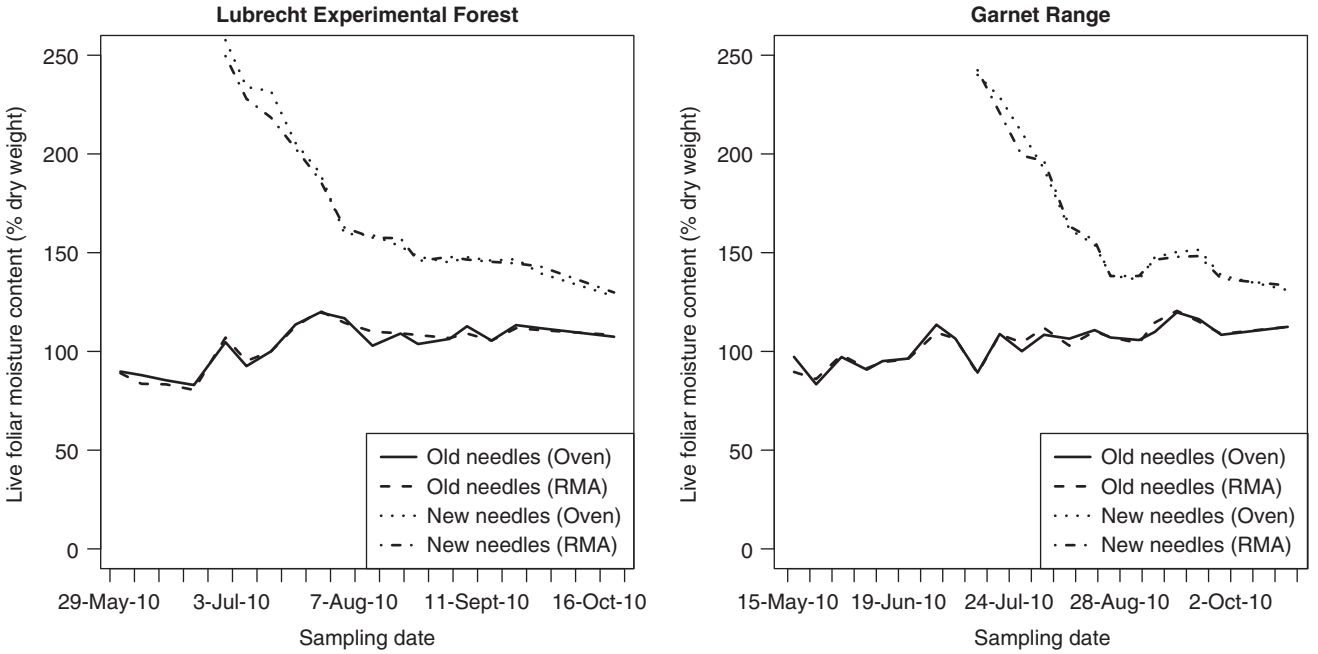

Fig. 2. Live foliar moisture content from two different sites of new and old *Pinus contorta* needles measured throughout the growing season using two methods: oven-drying and a rapid moisture analyser (RMA). Both methods capture the same seasonal variations in foliar moisture content and they also depict the differences between the new and old needle moistures and the differences between sites. Pearson's correlation coefficients between the mean moisture contents for the two methods for new needles at both sites were 0.99 and for old needles 0.96 and 0.97 for Garnet and Lubrecht respectively.

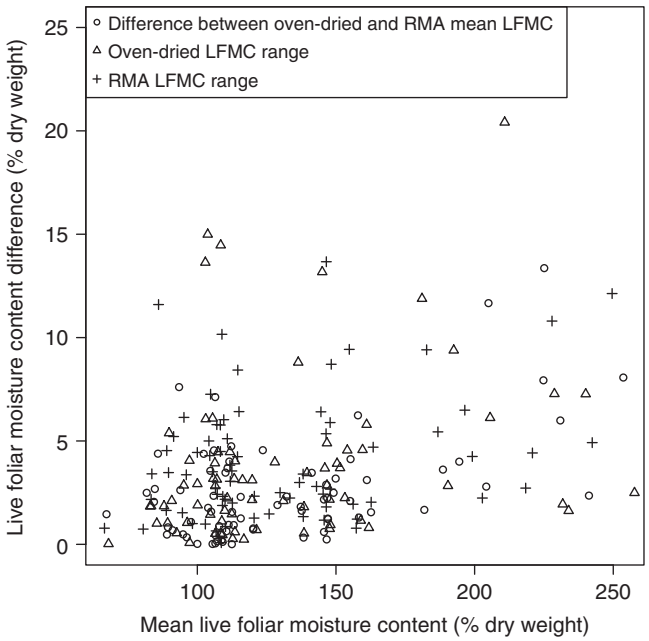

Fig. 3. Relationship between the mean live foliar moisture content (LFMC) of samples and their difference across the range of moisture contents sampled. The mean was calculated as $(LFMC_{oven} + LFMC_{rma})/2$ and the differences were calculated as $|LFMC_{oven} - LFMC_{rma}|$. Additionally, the within-sample ranges and their means are shown for both the oven-drying and rapid moisture analyser (RMA) methods to give an indication of the within-method variability. This graph shows a slight increase in the differences at higher moisture content ranges but these errors are consistent with the errors observed within a particular measurement method.

where $LFMC_{oven}$ is the sample period mean oven-dried LFMC and $LFMC_{rma}$ is the sample period mean RMA-derived LFMC. The mean was calculated as:

$$(LFMC_{oven} + LFMC_{rma})/2 \quad (3)$$

where the abbreviations are the same as those described for Eqn 2. For the individual moisture measurement methods, we plotted the range of values measured for a given species, age class, site and sampling date against their mean moisture. These types of diagnostic plots have been shown to be more informative than simple regressions and correlations when comparing measurement methods (Altman and Bland 1983). The plot shows that the error observed between oven-drying and the RMA measurements is similar to errors observed within a particular sampling method. In fact, we observed larger differences between samples in the oven-drying method than were observed between the two methods. The maximum difference between the two methods was 13.4%. The mean absolute error (MAE) was 2.6% and the bias was 0.62%. A positive bias suggests that on average, oven-dried moisture contents are slightly higher than those derived from the RMA but given that the value is close to zero, it suggests that the bias is minimal. Across the range of mean moisture contents, the differences between the two methods are generally consistent except in the highest ranges (>200% LFMC).

Table 2 shows the minimum and maximum of the within-sampling period ranges of moisture contents for each of the two measurement methods. The maximum difference between oven-dried samples from the same date, site and species was

Table 2. Minimum and maximum of within-sample period ranges and minimum and maximum of the maximum allowable error for 95% confidence for a sample size of three for both the oven-dried method and the rapid moisture analyser methods

Method	Minimum sample period range (% dry weight)	Maximum sample period range (% dry weight)	Seasonal minimum of maximum allowable error for 95% confidence (% dry weight)	Seasonal maximum of maximum allowable error for 95% confidence (% dry weight)
Oven-dried method	0.08	20.41	0.07	14.98
Rapid moisture analyser method	0.08	12.13	0.08	8.25

20.41%. Rapid moisture analyser methods showed a slightly lower seasonal maximum range at 12.13%. Maximum allowable error estimates based on an inversion of the standard sample size equation using our sample size of three showed that across the entire sampling period, we were able to measure moisture content to within ±14.98% or less for the oven-drying method and ±8.25% for the RMA method.

Discussion

Both oven-drying and the RMA have positive and negative traits that should help guide their application. Oven-drying is highly suited when many samples need to be processed for a given day because an individual oven can be filled with many samples, with minimal time required to obtain their fresh and dry weights. In contrast, the RMA excels when only a few samples need to be processed in a given day or those moisture content measurements are needed quickly. Fuel moistures are commonly needed to help guide fire management decisions about how to manage a particular fire that is ongoing or to determine whether or not a prescribed burn can proceed on a given day. These time-sensitive applications are a prime candidate for fuel moisture measurements from a RMA whereas projects that require many samples from many species may be better suited to the oven-drying method. Also, the RMAs are generally more expensive than the equipment required for the oven-drying method.

Recent research has suggested that oven temperatures are an important factor in determining fuel moisture content and that all samples should be dried at 105°C (Matthews 2010). However, our results indicate that there is no such temperature dependency when assessing LFMC when the natural sampling variability is considered. We dried our samples in a 95°C oven and used a 145°C heater temperature for the RMA and we found that moisture content measurements were nearly identical, regardless of the drying temperature used. The work presented by Matthews (2010) was done only in dead fuels whose moisture content is already very low (generally less than 30%) and the reported changes of up to 3.5% may be significant. However, we found that in live fuels, a 3.5% or greater difference is common within the same measurement method for samples taken from the same tree, site, age class and sampling date.

The results presented here are only for live conifer species that are common to intermountain North America. We did not test the efficacy of these methods for estimating LFMC of broadleaf trees, shrubs or grasses. Future work would be needed to ensure that the results we present here are applicable across the full range of plant functional types. However, other data not presented here have confirmed that these methods are similar for live broadleaf fuels and for dead conifer needles (W. M. Jolly and A. M. Hadlow, unpubl. data).

One significant difference between these two methods is the precision of the balances used in each application. The standard bench-scale balance that we used for the oven-dried moisture content determination was only accurate to the nearest 10 mg whereas the RMA was accurate to the nearest 0.1 mg. This discrepancy could explain some of the differences that we observed between the methods, especially in the higher moisture content ranges. A simple mathematical exercise using Eqn 1 and 2 g for our fresh weight shows that if we vary the dry weights from 1.001 to 1.009 g (beyond the precision of the balance), we find that our calculated moisture contents vary from 100 to 98.22%, a difference of 1.78%. If we vary the dry weights from 0.600 to 0.609 g, the calculated moisture contents vary from 233.33 to 228.41%, a difference of nearly 4.92%. Essentially, the higher the calculated moisture content, the higher the potential error when using a lower-precision balance. However, a balance with a precision of 1 mg or less would produce errors of less than 0.72% across the full range of potential LFMCs up to 300%. Additionally, this could help explain the higher maximum range of values observed in our oven-dried samples (Fig. 3).

In this paper, we have described a simple study aimed at comparing two methods that are commonly used throughout the literature to estimate LFMC: the oven-drying method and the RMA. It is the first study to characterise the relationship between these two foliar moisture content measurement methods over an entire growing season. We have shown that these two methods produce very similar estimates of conifer LFMC both at a point in time and throughout the growing season for new and old pine needles. We suggest that these methods can be used interchangeably to determine moisture content depending on the particular application. Both of these methods have strengths and weaknesses in both research and management applications and their application is primarily driven by the number of samples that need to be processed on a given day or the speed at which moisture content needs to be derived. Additionally, we found that even though our drying temperatures were significantly different between methods, their resulting estimated moisture contents were very similar, suggesting that oven temperature may not have a large influence on live foliar moisture estimates in these fuels.

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