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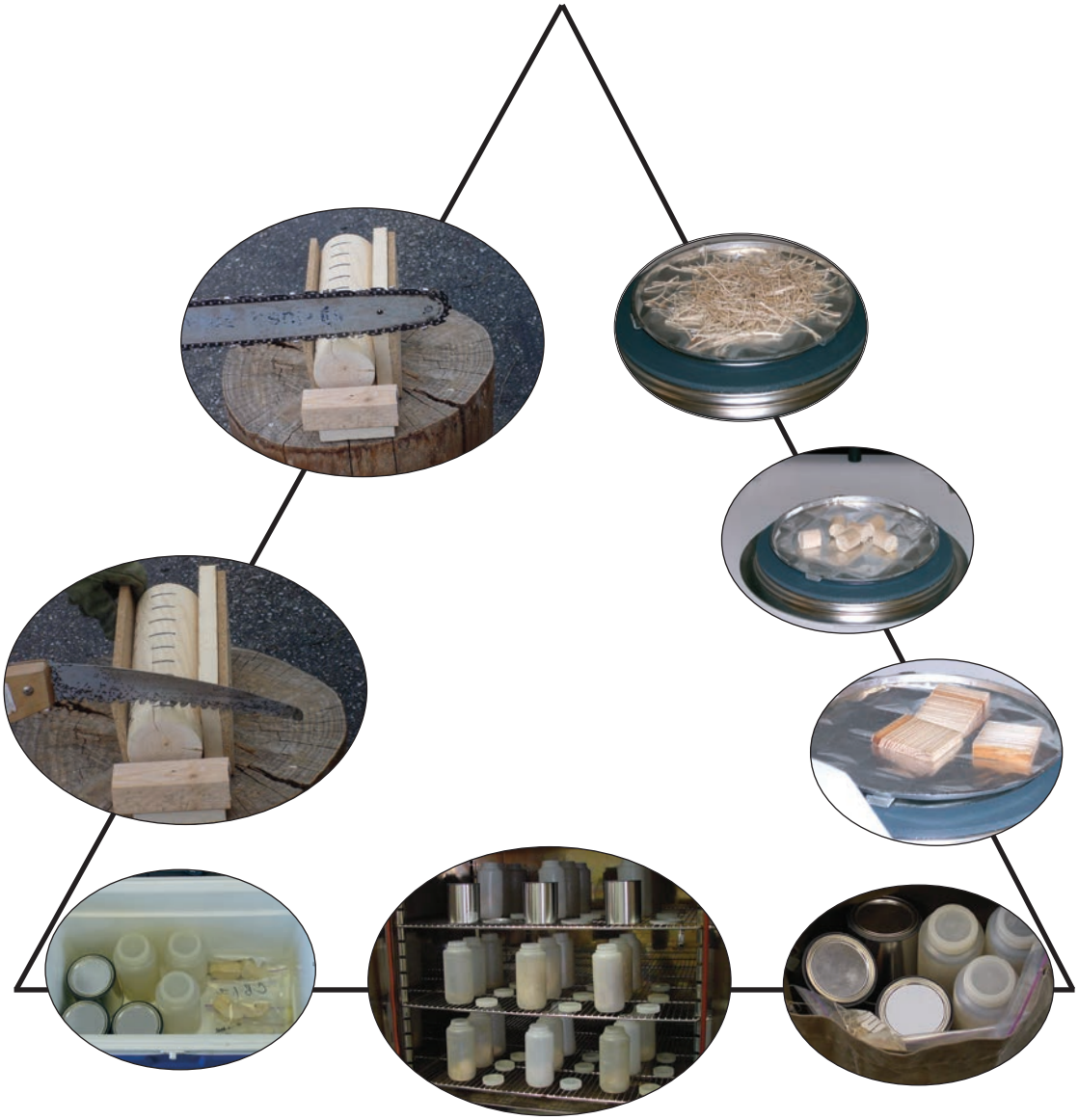
Evaluation of Standard Methods for Collecting and Processing Fuel Moisture Samples

Sally M. Haase, José J. Sánchez, and David R. Weise



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Abstract

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A variety of techniques for collecting and processing samples to determine moisture content of wildland fuels in support of fire management activities were evaluated. The effects of using a chainsaw or handsaw to collect samples of large-diameter wood, containers for storing and transporting collected samples, and quick-response ovens for estimating moisture content were evaluated against the ASTM standard method D4442 to determine the moisture content of wood. Saw type and most sample containers did not influence the moisture content; however, polyethylene bags lost moisture owing to poor seal or perforation, making them unsuitable for storing fuel for processing. Generally, most of the quick-response oven tests indicated that drying fuels at higher temperatures than the ASTM standard method provided comparable results.

Keywords: Oven-dry, rapid-response, coarse woody debris, 1-hr, 10-hr, 100-hr, 1000-hr.

Summary

Fuel moisture is key to the rate and completeness of fuel consumption by wildland fire and is therefore fundamental to the knowledge of fire behavior and effects. In 1979, the Pacific Southwest Research Station (PSW) published a fuel moisture collection guide, which came to be used in California and other parts of the United States where live fuels are an important fuel type. This publication served as the standard for sampling live fuel moisture for many years. Since then, additional guides based on the original methods have been developed but with various modifications to address additional fuel types. Many of these modifications have not been tested to determine how they might affect fuel moisture estimation. The Forest Service's San Dimas Technology and Development Center accepted a project to revise and standardize fuel moisture sampling procedures and produced two guides to assist fire and fuel managers. As part of the effort to revise and standardize methods to collect and process live and dead fuels to estimate fuel moisture content, we performed a series of experiments to evaluate several of the methods and equipment that have come into use since the original guide was produced.

A variety of techniques to collect and process samples to determine moisture content of wildland fuels in support of fire management activities were evaluated. The effects of using a chainsaw or handsaw to collect samples of large-diameter wood, containers to store and transport collected samples, and quick-response ovens to estimate moisture content were evaluated to determine moisture content of wood. Saw type and most sample containers did not influence the moisture content; however, polyethylene bags lost moisture owing to poor seal or perforation making them unsuitable for storing fuel for processing. Generally, most of the quick-response oven tests indicated that drying fuels at higher temperatures than the ASTM standard method provided comparable results.

Contents

Introduction

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When a manager is making decisions about a wildland fire or prescribed burn, one of the major goals is to accurately predict fire behavior under current conditions. Fuel moisture is one of the main variables that influence fire behavior. In addition to being an important calculation in fire danger rating, moisture content is one of the variables used to define acceptable conditions under which a prescribed burn or wildland fire can be used to accomplish resource management objectives. While methods to predict dead fuel moisture content have improved (Nelson 2000) and remote sensing is used to estimate live fuel moisture content (Weise and Wright 2014), these estimates may not represent actual conditions on the project site. This is because local weather patterns that determine fuel moisture are influenced by highly variable topography, and remotely sensed data do not always detect important fuels. The moisture content of litter can vary appreciably within a forest stand depending on the ability of solar radiation to penetrate the canopy (Countryman 1977). The most accurate way to determine fuel moisture content for a project is to measure or collect fuels on site and then process the collected data following

established procedures that assure quality control. As part of the handbook revision, we conducted three experiments:

1. Evaluate two methods of collecting 100-hour time lag fuels
2. Evaluate three containers used to store fuel moisture samples
3. Compare quick-response ovens (QROs) to a convection drying oven to determine moisture content

The detailed results of these experiments will be presented in this report.

Evaluate Two Methods of Collecting 100-Hr Time Lag Fuels: A Handsaw Versus a Chainsaw

Dead large woody fuels (100-hr and 1000-hr time lag; Fosberg 1970, Fosberg et al. 1981), also known as coarse woody debris, are an important component of ecosystems and can contribute significantly to fire behavior on a site (Albini and Reinhardt 1995). Because of the size of these fuels (100-hr and 1000-hr fuel sizes are 1 to 3 and 3 to 8 inches in diameter, respectively), a sample is usually collected using a saw. Field personnel have been instructed not to use a chainsaw when collecting large woody fuels for moisture content information; it was thought that chainsaw bar oil would affect the sample by adding additional weight to it. A traditional pruning handsaw has always been the recommended cutting tool. The objective of this study was to determine if the sawing method affected the estimated moisture content of 100-hr time lag woody fuel.

Study Design and Analysis

Two fuel moisture conditions (dry, wet) were examined in separate test phases. The dry phase tests occurred in three batches on November 19, 2004, November 22, 2004, and December 2, 2004. The wet phase tests occurred similarly on June 10, 2005, June 13, 2005, and June 17, 2005. Three-inch-diameter posts of 10-inch-long lodgepole pine (*Pinus contorta* Douglas ex Loudon) were marked to make 1-inch discs, allowing for individual saw kerf. The dry test used low moisture content material obtained by submerging ten 10-inch-long sample pieces of 3-inch-diameter kiln-dried lodgepole pine poles in tubs of water for 6 hours, producing moisture contents that ranged from 14 to 18 percent. After the soaking period, the pieces were shaken to remove surface water and then placed in an environmental chamber for 24 hours, humidity set at 90 percent. The cutting treatment, chainsaw or handsaw, was randomly assigned to a piece as it was removed from the chamber.

The sample piece was placed on a "jig" to safely hold the piece while "discs" were cut with either a handsaw (a collapsible pruning saw) or a chainsaw (model 520SP Jonsered with a 16-inch bar[1]). Six discs or cookies were quickly cut from each piece using the same tool, a wood chisel and hammer, and all pieces from that cookie were sealed in an autoclavable polypropylene bottle (fig. 1). All 10 pieces were treated this way (n = 60). Each bottle was weighed then uncapped and placed in a drying oven previously set at 95 ºC (203 °F) and dried until there was no weight loss from drying (ASTM International 2007). The ASTM standard specifies an oven temperature of 103 ± 2 ºC (215.6 + 35.6 °F) unless the material contains volatile products. If the material does contain volatile products, a distillation method to determine moisture content is recommended. After 24 hours of drying, test bottles (3 and 4) were randomly selected and capped, cooled, and weighed at 6- and 12-hour intervals. All sample bottles were capped, cooled to room temperature, and weighed after the test bottles showed no further weight loss.

In the wet phase, immersion of the sample pieces for 6 days achieved higher fuel moisture than the dry phase. The resulting moisture content of the sample pieces ranged from 16 to 51 percent, with the interior discs exhibiting lower moisture content. The only difference in procedure for the wet phase occurred when we used a different chainsaw (model 141 Husqvarna with a 16-inch bar). Analysis of the wet and dry phases occurred separately using paired t-tests to detect differences between the two cutting methods.

Results and Discussion

A total of 90 fuel moisture samples was collected for each cutting method/moisture content combination. One observation was omitted from the analysis owing to a recording error. The complete data set is available in the Forest Service Research Data Archive (Haase et al. 2014). Mean moisture content of the dry test phase was 15 percent, and moisture content of the wet test phase was 39 percent (table 1). The fiber saturation point of dead wood is nominally 30 percent, and the moisture content of green lodgepole pine heartwood has been reported to be 41 percent (Glass and Zelinka 2010). The standard errors were less than 1 percent of the mean values,

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

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Figure 1—Three types of containers used in fuel storage container study. The containers are (from left to right) 1-quart steel paint can, 32-ounce autoclavable polypropylene bottle, and 1-quart self-sealing freezer-grade polyethylene plastic bag.

Table 1—Moisture content (percentage) of wet and dry samples of lodgepole pine slices extracted with a chainsaw or a handsaw

	Chainsaw		Handsaw	
Experiment	Mean (std. error)	Number	Mean (std. error)	Number
Dry test	15.41 (0.11)	90	15.41 (0.12)	89
Wet test	39.28 (0.42)	90	39.24 (0.42)	90

indicating very good experimental control. There was no significant difference between the two cutting methods at either level of moisture content:

The results of these tests demonstrate it is appropriate to use a well-operating chainsaw to collect 100-hr time lag or larger woody fuels for moisture content provided that there is not excessive bar oil use.

Evaluate Three Containers for Fuel Moisture Sampling

The primary objective of this study was to determine which of three commonly used fuel sampling containers maintained the most accurate moisture content of three representative fuel-size-class materials over time under two ambient conditions. Containers currently used by field personnel include (fig. 1):

- One-quart steel paint cans (Countryman and Dean 1979)
- Thirty-two ounce polypropylene plastic bottles
- One-quart (7- by 8-inch, 2.7 mil thickness) self-sealing polyethylene plastic bags

ASTM Standard D4442 dictates that an airtight container be used for fuel moisture samples. The variety of airtight containers has increased over time from the originally recommended paint cans and soil cans as plastics have become more readily available. Fuel sampling recommendations include storing collected fuels in a cool location prior to initial weighing. Personal-use ice chests and firehose packs store samples during transport from the field to the office for further processing, which typically occurs within a day of collection. Fuel sampling occurs from spring through fall (and sometimes in winter in areas where live fuels grow year round) and ambient conditions may affect storage effectiveness. The second objective of the study was to determine if sample processing time in the lab affected moisture content.

Design

The study used three fuel sizes (aspen [*Populus tremuloides* Michx.] excelsior, ¼-inch pine dowels, 3-inch lodgepole discs), three container types (described above), two storage containers (ice chest with no ice, firehose pack), and two ambient conditions (cool, hot). Two locations, a greenhouse with temperatures 100 to 131 °F and a laboratory with temperatures 62 to 75 °F, provided a range of temperature extremes. The fuels nominally represented 1-, 10-, and 100-hr time lag fuels (fig. 2) based on particle diameter, although 3 inches is the breakpoint between the 100- and 1000-hr fuel classes. The diameter classes associated with 1-, 10-, 100-, and 1000-hr time lag classes are 0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches, and 3 to 8 inches, respectively (Deeming et al. 1974, Lancaster 1970). Note that Anderson (1990) reported that many response times for fine fuels classified as 1-hr fuels were in fact longer than anticipated. The range of response time represented by the timelag classes are 0 to 2, 2 to 20, 20 to 200, and 200 to 2000 hr, which correspondingly cover a broad range of fuel particle diameters. For instance, Carlson et al. (2007) conducted a long-term moisture study in Oklahoma using wooden cylinders with ⅛-, ½-, 1½-, and 5-inch diameters to represent 1-, 10-, 100-,

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Figure 2—Fuel types used in container evaluation study. The fuels are (clockwise from right) aspen excelsior, ¼-inch diameter pine dowel, 3-inch diameter lodgepole pine post.

and 1000-hr fuels. While the fuel diameters in our study were different, the objectives of the study were not affected.

Within each size class, we cut fuels into similar-length pieces prior to soaking. Excelsior samples were standardized into hand-size clumps. Dowels were cut to 3-inch lengths, and 10 pieces made an individual sample. Each 3-inch-diameter cookie was 1-inch thick and split into quarter sections when placed in a container. All fuel samples were initially oven-dry and then submerged fully in water for 67 hours. After soaking, samples were placed in an environmental chamber for 24 hours to stabilize the surface moisture. Each fuel type was placed in a container and then placed in a storage container. The study design contained three replications of the 18 treatments within the two locations. Two control samples of each fuel processed as above in a convection oven estimated the moisture content at the start of the test. Sample mass was weighed using a calibrated electronic balance to the nearest 0.01 gram (0.0004 ounces) in 30-minute increments for the first 6 hours followed by a break of 14 hours. The next measurements were taken every 30 minutes for the next 4 hours, and the last six measurements were taken every hour for a total of 27 measurements. The test terminated when the sample was placed in a convection oven to determine final moisture content. The plastic bags we used melted at

the drying temperature in the oven so we placed these samples in bottles prior to drying. The standard basis for determining moisture content in the wood industry (and fire management) is oven-dry weight.

Two analyses were performed to accomplish the two objectives. An assessment of the change over time as determined by the slopes of the relatively smooth moisture content history (drying curve) accomplished the primary objective. An assessment of deviation from the initial moisture content from the control samples examined if processing time affected moisture content (secondary objective). Both analyses used an analysis of variance process that accounted for correlations induced by the experimental design using PROC MIXED in SAS. Type III sums of squares were used to test the significance of the fixed effects on the initial moisture content. Because of the relatively smooth linear transition of moisture content over time for all samples and combinations of conditions, linear fits to the data were constructed and the estimated slopes were used as the response variable in an analysis of variance.

Results and Conclusions

Plots of the moisture content over time for each sample showed a relatively smooth linear trend throughout the 29-hr experimental time period for all fuel class sizes, ambient temperatures, transport methods, and container types. The smooth linear trend enabled the identification of the few data entry errors and removal of extreme data points that had no obvious explanation from the data set. A more detailed look at the changes in moisture content over time can be seen in figure 3. The initial moisture content of a sample was subtracted from all subsequent values so figure 3 displays the change in moisture content. Examination of these plots immediately shows polyethylene bags consistently lost more moisture than the other two container types.

The initial moisture content for the various combinations of fuel size class, ambient temperature, transport method, and container type compared to control samples showed few differences (table 2). The analysis of variance of the initial moisture content found significant differences between the fuel size classes. The significant interaction among combinations of fuel size classes and ambient temperature was most likely due to the Excelsior/High Ambient Temp/Bag/Can combination having a lower mean moisture content (104.5 percent) than any other excelsior fuel combination. The only way to explain this is that it was just the luck of the draw when the sample containers were filled with material. Within the other two fuel size classes, all other combinations of the remaining factors showed homogeneity with respect to initial moisture content. The fuel size classes differed by the initial moisture content in a predictable way: the larger the fuel size class, the lower

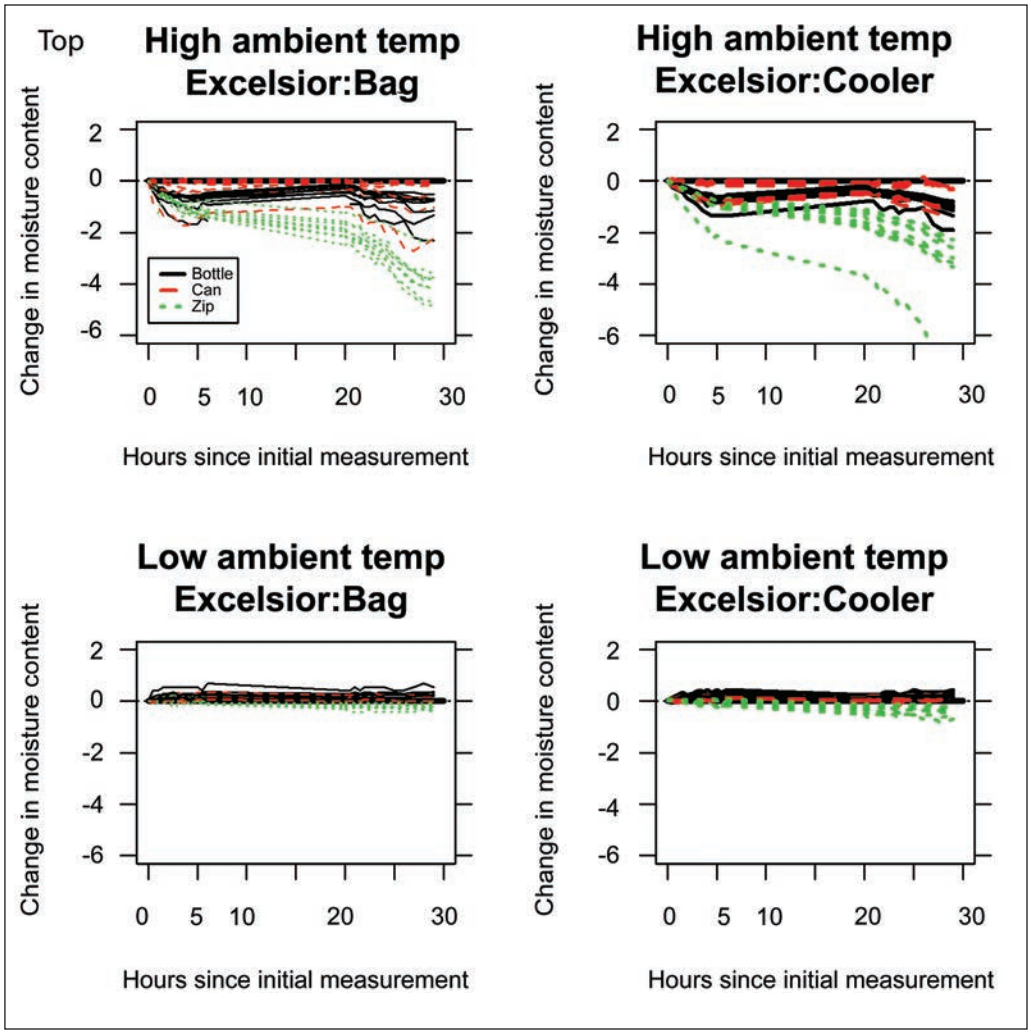

Figure 3—Change in moisture content (percentage) over time from initial moisture content value.

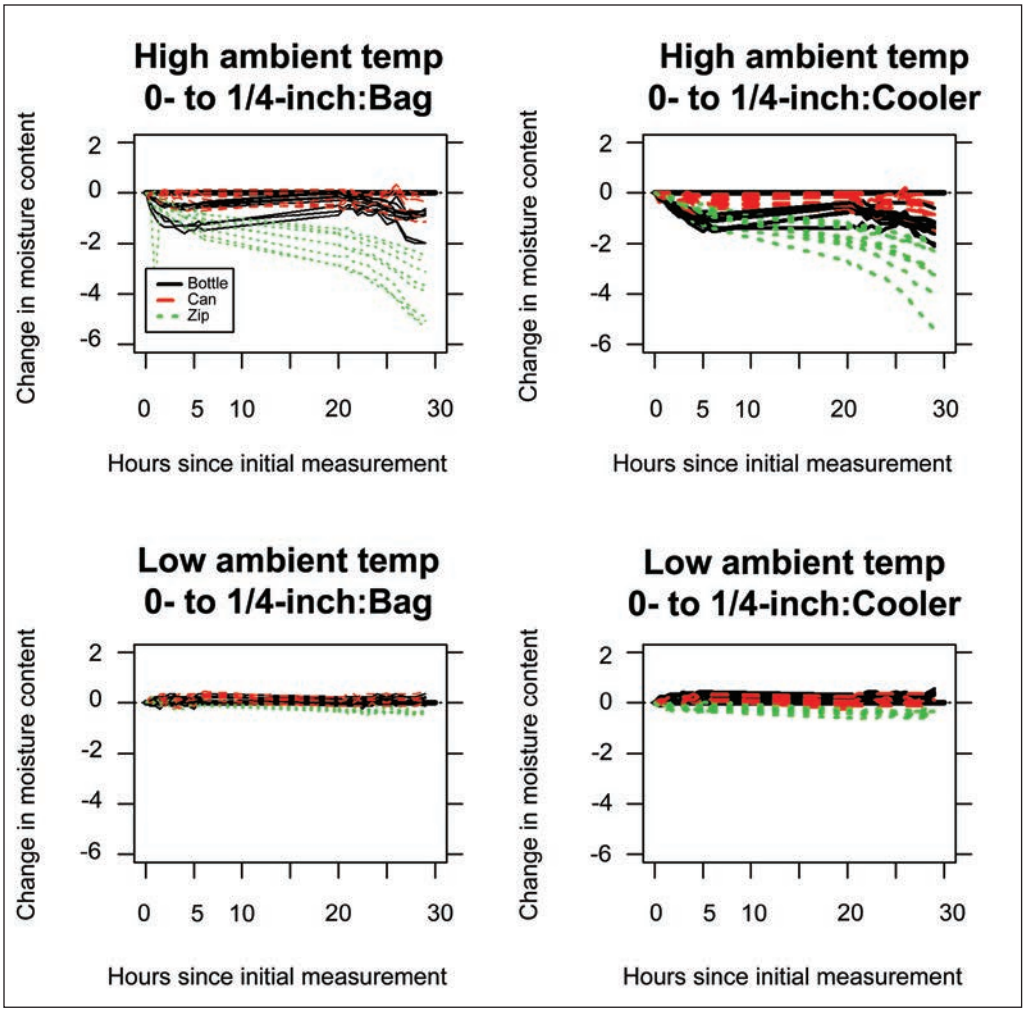

Figure 3—continued

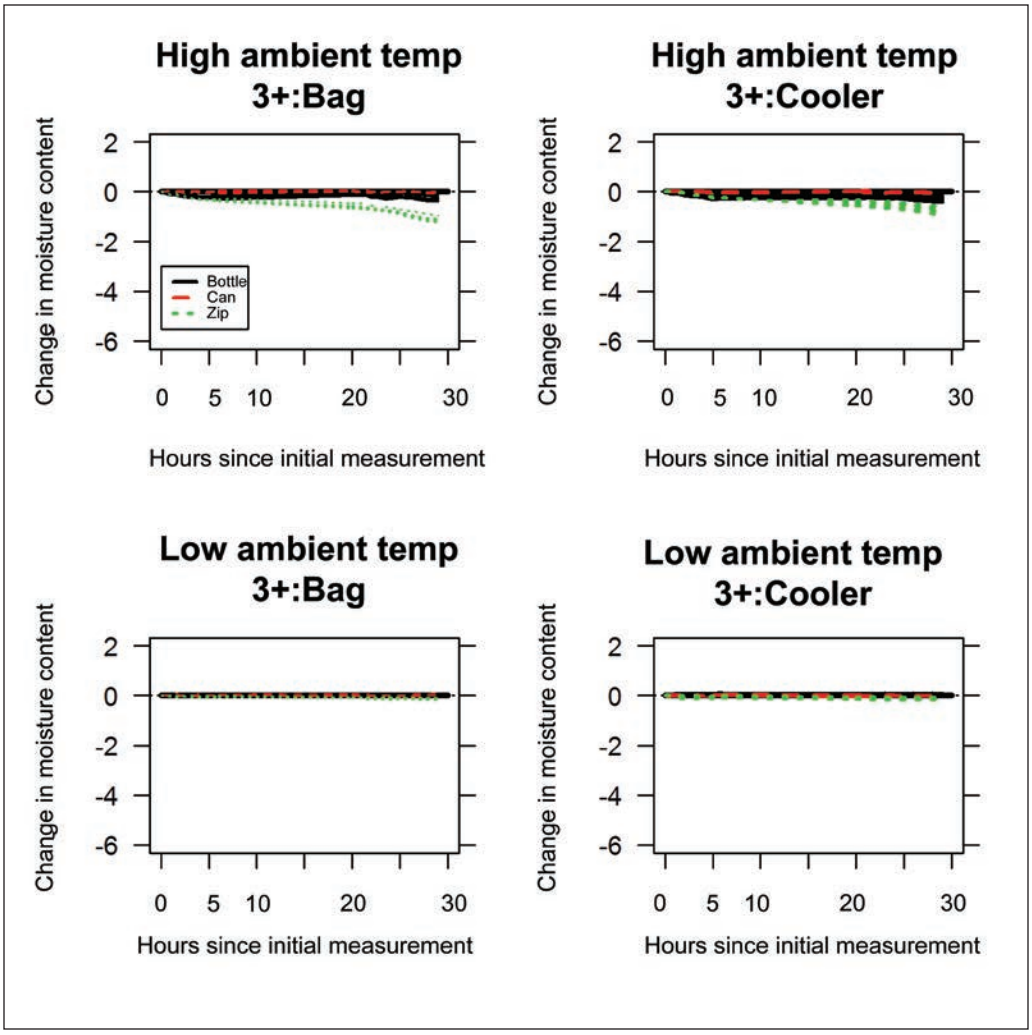

Figure 3—continued

Table 2—Mean initial moisture content for various combinations of fuel size classes, ambient temperature, transport method, and container types[a]

Fuel size class	Transport method	Container type	Ambient temperature	
			High	Low
			Percent	
Excelsior	Bag	Bottle	154.1	155.3
		Can	104.5	154.9
		Zip	140.5	164.4
	Cooler	Bottle	151.3	157.6
		Can	130.7	160.5
		Zip	153.1	170.3
	Control	Control	162.0	162.7
¼-inch dowel	Bag	Bottle	98.9	94.2
		Can	92.5	89.0
		Zip	94.1	100.0
	Cooler	Bottle	93.2	95.8
		Can	96.9	81.4
		Zip	96.2	98.0
	Control	Control	92.5	98.7
3-inch disc	Bag	Bottle	80.5	76.5
		Can	83.7	77.2
		Zip	77.6	73.5
	Cooler	Bottle	83.1	77.2
		Can	79.3	77.5
		Zip	73.8	71.6
	Control	Control	79.5	76.6

[a] The control moisture content was determined using an oven bottle and immediate drying following collection of the sample. Estimated standard error for the control = 6.9 and for the treated samples = 9.6.

the mean initial moisture content. In other words, the larger the fuel size, the longer it would take to soak up the same amount of water as a much finer fuel size class. Given that all sample material was soaked in water for the same amount of time, the finer fuel size classes soaked up more water. The mean initial water content for the excelsior, ¼-inch dowels, and 3-inch discs was 151.6, 94.4, and 77.7 percent, respectively. We accounted for the blocking of sets of replicates in the experimental design and found homogeneity: the blocking by replicates showed no additional variation over and above the residual variability. Tables 3, 4, and 5 present the mean slope (and the associated standard error) for various combinations of fuel size

Table 3—Fitted hourly rate of change (slope), standard errors, and P-values for moisture content over a 30-hr time period of aspen excelsior for various combinations of ambient temperature, transport method, and container type

Ambient temperature	Transport method	Container type	Slope	Std. error	P-value
High	Bag		-0.0392	0.0037	0.0000
	Cooler		-0.0354	0.0037	0.0000
Low	Bag		-0.0027	0.0011	0.0160
	Cooler		-0.0025	0.0011	0.0255
High		Bottle	-0.0082	0.0019	0.0000
		Can	-0.0109	0.0015	0.0000
		Zip	-0.0929	0.0074	0.0000
Low		Bottle	0.0008	0.0003	0.0211
		Can	0.0019	0.0004	0.0000
		Zip	-0.0104	0.0022	0.0000
	Bag	Bottle	-0.0041	0.0013	0.0027
		Can	-0.0037	0.0011	0.0012
		Zip	-0.0550	0.0055	0.0000
	Cooler	Bottle	-0.0032	0.0013	0.0174
		Can	-0.0052	0.0011	0.0000
		Zip	-0.0483	0.0055	0.0000
High	Bag	Bottle	-0.0088	0.0026	0.0012
		Can	-0.0088	0.0022	0.0001
		Zip	-0.1001	0.0105	0.0000
	Cooler	Bottle	-0.0075	0.0026	0.0051
		Can	-0.0130	0.0022	0.0000
		Zip	-0.0858	0.0105	0.0000
Low	Bag	Bottle	0.0005	0.0005	0.2285
		Can	0.0013	0.0005	0.0177
		Zip	-0.0099	0.0031	0.0023
	Cooler	Bottle	0.0011	0.0005	0.0226
		Can	0.0025	0.0005	0.0000
		Zip	-0.0109	0.0031	0.0008

Table 4—Fitted hourly rate of change (slope), standard errors, and P-values for moisture content over a 30-hr time period of ¼-inch pine dowels for various combinations of ambient temperature, transport method, and container type

Ambient temperature	Transport method	Container type	Slope	Std. error	P-value
High	Bag		-0.0379	0.0034	0.0000
	Cooler		-0.0379	0.0034	0.0000
Low	Bag		-0.0045	0.0004	0.0000
	Cooler		-0.0032	0.0004	0.0000
High		Bottle	-0.0108	0.0021	0.0000
		Can	-0.0097	0.0020	0.0000
		Zip	-0.0932	0.0066	0.0000
Low		Bottle	0.0005	0.0007	0.4602
		Can	0.0010	0.0003	0.0023
		Zip	-0.0131	0.0005	0.0000
	Bag	Bottle	-0.0048	0.0016	0.0028
		Can	-0.0016	0.0014	0.2685
		Zip	-0.0573	0.0047	0.0000
	Cooler	Bottle	-0.0055	0.0016	0.0006
		Can	-0.0071	0.0014	0.0000
		Zip	-0.0490	0.0047	0.0000
High	Bag	Bottle	-0.0099	0.0030	0.0011
		Can	-0.0032	0.0028	0.2592
		Zip	-0.1005	0.0094	0.0000
	Cooler	Bottle	-0.0117	0.0030	0.0002
		Can	-0.0162	0.0028	0.0000
		Zip	-0.0858	0.0094	0.0000
Low	Bag	Bottle	0.0004	0.0009	0.6595
		Can	0.0000	0.0005	0.9709
		Zip	-0.0140	0.0007	0.0000
	Cooler	Bottle	0.0006	0.0009	0.5455
		Can	0.0021	0.0005	0.0000
		Zip	-0.0122	0.0007	0.0000

Table 5—Fitted hourly rate of change (slope), standard errors, and P-values for moisture content over a 30-hr time period of 3-inch lodgepole pine discs for various combinations of ambient temperature, transport method, and container type

Ambient temperature	Transport method	Container type	Slope	Std. error	P-value
High	Bag		-0.0112	0.0004	0.0000
	Cooler		-0.0096	0.0004	0.0000
Low	Bag		-0.0010	0.0001	0.0000
	Cooler		-0.0008	0.0001	0.0000
High		Bottle	-0.0012	0.0002	0.0000
		Can	-0.0030	0.0005	0.0000
		Zip	-0.0271	0.0007	0.0000
Low		Bottle	0.0000	0.0002	0.8915
		Can	0.0005	0.0001	0.0014
		Zip	-0.0031	0.0002	0.0000
	Bag	Bottle	-0.0005	0.0002	0.0031
		Can	-0.0009	0.0004	0.0243
		Zip	-0.0169	0.0005	0.0000
	Cooler	Bottle	-0.0007	0.0002	0.0000
		Can	-0.0016	0.0004	0.0002
		Zip	-0.0133	0.0005	0.0000
High	Bag	Bottle	-0.0010	0.0002	0.0000
		Can	-0.0020	0.0008	0.0112
		Zip	-0.0308	0.0010	0.0000
	Cooler	Bottle	-0.0013	0.0002	0.0000
		Can	-0.0040	0.0008	0.0000
		Zip	-0.0234	0.0010	0.0000
Low	Bag	Bottle	0.0000	0.0002	0.8521
		Can	0.0001	0.0002	0.3904
		Zip	-0.0031	0.0002	0.0000
	Cooler	Bottle	0.0000	0.0002	0.9622
		Can	0.0008	0.0002	0.0000
		Zip	-0.0031	0.0002	0.0000

class, ambient temperature, transportation method, and container type. Most of the estimated slopes were significantly different from zero.

Obtaining a variety of moisture contents for each fuel size class was desirable, but the larger fuel size classes ended up with significantly smaller mean initial moisture contents. Reasonable variation in moisture content did exist for like combinations of fuel size class, ambient temperature, transport method, and container type, so that inferences to the variety of moisture content found in the field are appropriate. There was very little difference in transportation methods (coolers and fire packs). Not surprisingly, higher ambient temperatures were associated with larger losses of moisture content. Only the use of polypropylene bags showed a relatively large loss of moisture content after 30 hr from initial collection in the field. For high ambient temperatures and fuel size class 0 to ¼ inch (excelsior) there was an average change in moisture content of -0.0392 per hour, which is about 9 to 10 times higher than that of cans and bottles (table 6). This corresponds to a 2.2 percent decrease in moisture content in 24 hours. We estimated a measurement error owing to the scale and other factors of about 1 percent.

A contributing factor that led to this result was the necessity of transferring sample material to a container that could withstand drying temperatures. Two issues contributed to the errors: the loss of sample material and the unaccounted for weight of condensation on the bag wall. If material remained in the sample bag after

Table 6—Rate of change in moisture content (percentage per hour) of three woody fuels transported in two container types in two ambient environments

Fuel type	Ambient temperature	Transport method	Moisture content	P-value
Excelsior	High	Bag	-0.0392	0.0000
		Cooler	-0.0354	0.0000
	Low	Bag	-0.0027	0.0160
		Cooler	-0.0025	0.0255
¼-inch dowel	High	Bag	-0.0379	0.0000
		Cooler	-0.0379	0.0000
	Low	Bag	-0.0045	0.0000
		Cooler	-0.0032	0.0000
3-inch disc	High	Bag	-0.0112	0.0000
		Cooler	-0.0096	0.0000
	Low	Bag	-0.0010	0.0000
		Cooler	-0.0008	0.0000

weighing and transferring, the weight of that material was erroneously included as moisture loss. This would produce higher moisture content than the actual value for that sample. We made a concerted effort to avoid this material loss. The loss of sample material could be expected more with the smaller size class material that had some small or loose pieces, but this relationship was still seen with the larger fuel size class (dowels or post) material where sample material remained in solid intact pieces. Condensation was not an issue using the other two ovenproof containers because it was included in the sample wet weight.

When using natural fuels, the problem of moisture condensation and loss of sample could be a factor for all size class material since natural, dead fuels are usually in various stages of decomposition. When ambient conditions were extremely warm, the plastic bags expanded and seals were easily broken when pressure was applied to the sides of the bag. They had to be checked regularly when being handled for proper seals and punctures.

Polypropylene bottles maintained fuel moisture content of the sample best for the duration of the 29 hours measured. They consistently had small weight loss under both ambient temperatures (high and low) and were easiest to use in terms of weighing, uncapping, and putting directly into the drying oven. Paint cans also did well in maintaining sample moisture, as they are able to go directly into the drying oven without transferring the sample. Negative aspects of using paint cans include the requirement of using a special paint can opener or key to reduce damage to the lip of the lid, and the needed care of not collapsing the can when using a hammer to seal the can. The seal also seems to deteriorate with repetitive opening and sealing, which reduces the container's longevity. Cans also require regular inspection for rust and need frequent updating of tare weights.

Comparison of Quick-Response Ovens With Convection Drying Ovens to Determine Fuel Moisture Content

Forest Service Research worked with the Motorola Company to define appropriate parameters of the initial drying system to determine the moisture content of fine dead fuels (Sackett 1980). At that time, the system used the 95 °C (203 °F) temperature for drying, and moisture content was determined based on rate of weight loss. The current device (Computrac®) is now capable of drying with a large range of temperatures (25 to 225 °C [77 to 437 °F]) and multiple sample sizes. With so many additional options and combinations of settings, concerns about drying at higher temperatures and the small sample size have arisen. The impact of these higher drying temperatures on volatilization of more than just water on moisture content

is unknown. Other companies have developed similar systems. Many agencies are acquiring "quick-response" systems (i.e., Computrac and Neosystem®) for use in their local areas to estimate fuel moisture content in live and dead fuels. The main objective in using these devices is to reduce the time involved in determining the moisture content of fuels, which takes a minimum of 24 hours if a conventional forced-air convection oven is used following ASTM standard D4442 (ASTM International 2007). The distillation method described in D4442 also takes an appreciable amount of time to determine moisture content. Methods to provide a quick estimate of fuel moisture content of forest fuels and woody biomass have been examined (e.g., Harris 1982, Hartmann and Böhm 2001, Norum and Fischer 1980, Nyström and Dahlquist 2004, Palmer and Pace 1974). Some of the indirect methods were designed to estimate the moisture content of a moving feedstock of wood chips. A desirable characteristic for use with forest fuels is that the devices be self-contained and portable, removing the need to have a balance and convection drying oven to obtain moisture content of organic material or soils. Stirring of the drying sample to ensure uniform drying, as is recommended with microwave methods, is an undesirable characteristic. There has been much debate on the appropriate use of the self-contained fast-response systems within the research/forest community as a result of the limited size of sample (less than 60 grams [2.12 ounces]) and higher than recommended drying temperatures; the ASTM standard is 103 °C (214.4 °F), and the approach recommended by Countryman and Dean (1979) is 103 to 105 °C [214.4 to 221.1 °F].

A recent study used foliage from lodgepole pine, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), western larch (*Larix occidentalis* Nutt.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) to compare a Computrac system (145 °C [293 °F]) with a convection oven (95 °C [203 °F]) and found that the estimated moisture contents were very similar (Jolly and Hadlow 2012). The objective of the present study was to compare fuel moisture estimates from these QROs using higher drying temperatures and shorter drying times with estimates from a convection oven with longer drying time and lower drying temperature.

Methods

We chose the NeoSystem Moisture Meter Model FMM-1 manufactured by Sigma Technologies (Australia) and the Computrac MAX 2000XL system as the two rapid-response systems to compare with a convection oven/manual weighing approach (fig. 4). We used three dead fuel sizes (fig. 5) and two live fuel types: aspen excelsior, ¾-inch aspen dowels, 3-inch lodgepole pine discs, mountain laurel (*Kalmia latifolia* L.) leaves, and scrub oak (*Quercus berberidifolia* Liebm.)

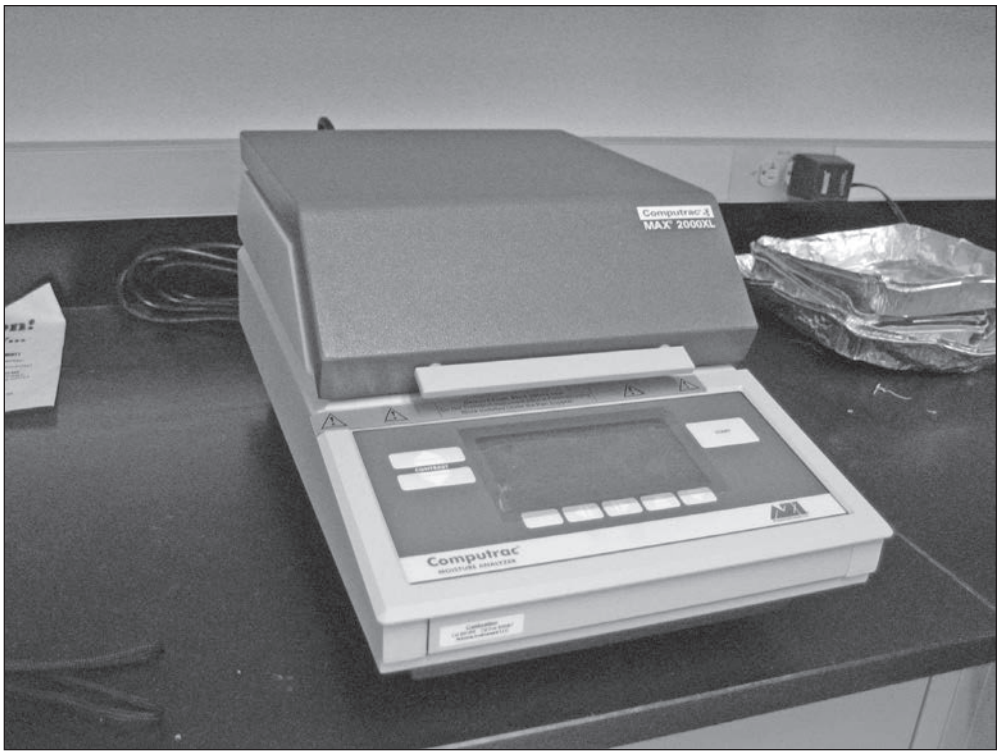

Figure 4—Quick-response ovens compared with conventional forced convection oven to determine effects of departures from standard drying method on moisture content determination.

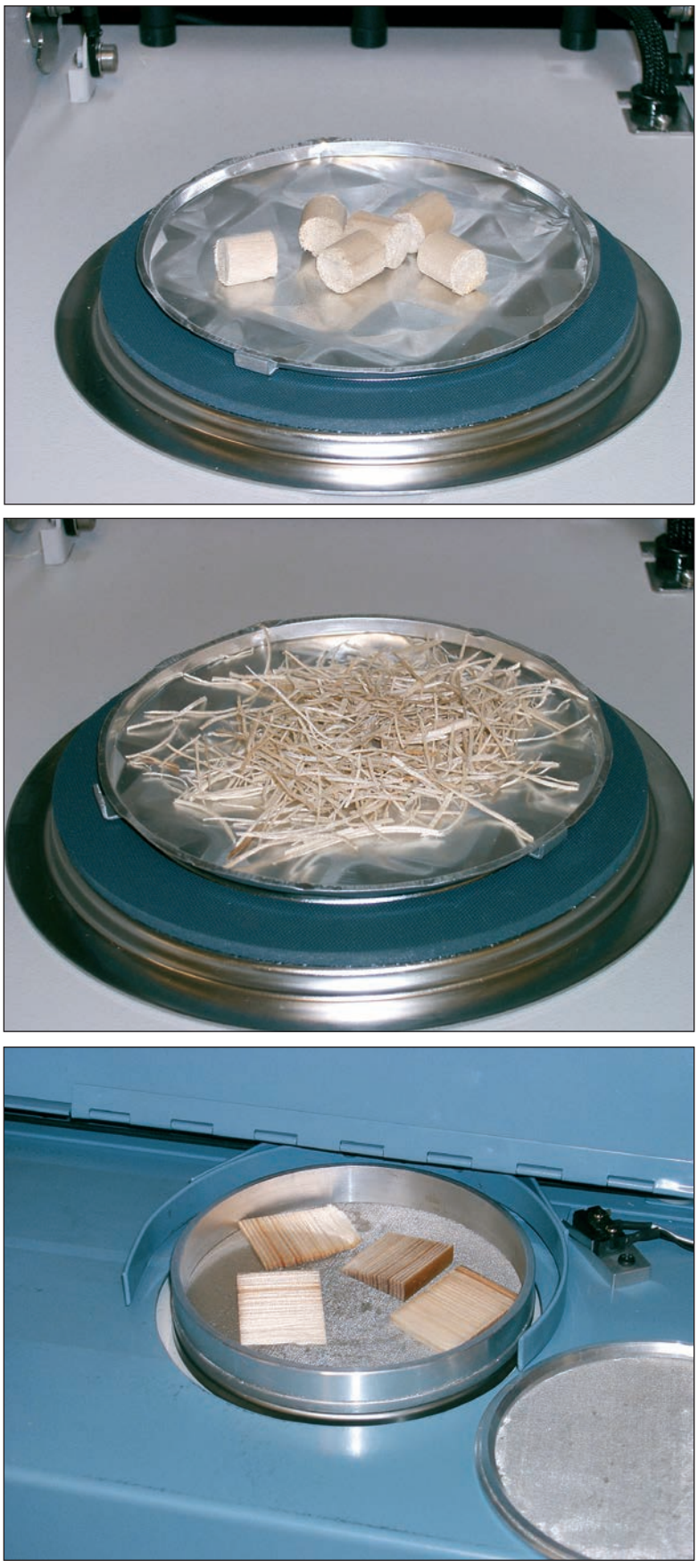

Figure 5—Dead fuels (excelsior, ¾-inch dowel, 3-inch slice) used in the evaluation of quick-response ovens in test 1 and test 2. (Photo courtesy of USDA Forest Service)

leaves. Dead sample material was cut into similar size pieces for each size class. Hand-size clumps (about 40-grams [1.4 oz] dry weight) of excelsior were bound with rubber bands prior to soaking. The ¾-inch dowels were cut into 1-inch lengths and the 3-inch pine posts were cut into 1-inch discs. The dry, dead fuels were fully submerged in water for 12, 48, or 72 hours for the excelsior, dowels, and discs, respectively, to ensure measurable moisture content changes. After soaking, the dowels and discs were air dried on a table for 12-hours to remove surface moisture, and excelsior samples were spun in a salad spinner to remove surface water.

Several different drying test configurations were performed (table 7). In the first test (test 1), excelsior and the dowels were dried in the Computrac at 170 ºC (338 °F) and the discs were dried at 180 ºC (356 °F). The "prediction ending criterion" was used to conclude each run. With this criteria, the instrument predicted the final moisture content as a function of the moisture loss rate and concluded the test when the prediction stabilized (Arizona Instrument LLC 2002). All fuel sizes were dried in the NeoSystem at 140 ºC (284 °F). Two sets of dead fuels were dried in the convection oven at 95 ºC (203 °F). One set (denoted "soil can") used a sample mass equal to that used in the QROs, and one set used a much larger sample mass (denoted "bottle"). A second test (test 2) was performed with the Computrac using the "rate ending criterion." This criterion ended the test when the rate of weight loss dropped below a preset rate. The third set of tests (test 3 and test 4) dried 4- and 8-gram (0.14 to 0.28 oz) samples of the live fuels at 140 ºC (284 °F) in the Computrac and NeoSystem and at 95 ºC (203 °F) in the convection oven.

A paper cutter cut the bound excelsior into ≤ ½-inch pieces. Two randomly selected discs were each broken into at least 16 smaller pieces. No additional handling of the dowels was necessary. All material was sealed immediately in moisture proof, autoclavable polypropylene bottles until dried in their assigned ovens. Each 8-gram (0.28-ounces) sample was placed in each QRO, the "soil can" and "bottle" samples were sealed for bulk sample drying in the convection ovens. Ten samples of each fuel type were dried in each of the ovens and the entire set of runs was replicated three times over the course of the experiment (table 8). The wet mass of the bottle samples ranged 47 to 76 (1.66 to 2.68), 40 to 49 (1.41 to 1.73), and 122 to 144 grams (4.30 to 5.08 ounces) for the excelsior, ¾-inch dowel, and 3-inch discs, respectively.

Live fuel tests used both 4- and 8-gram (0.28-oz) samples separately. Ten polypropylene bottles of mountain laurel foliage harvested from a single site in the Pisgah National Forest in North Carolina and shipped overnight to Riverside, California, provided the first evaluation using live fuels. The harvested material was cut into ½-inch pieces in the field before shipping. Samples were processed the

Table 7—Configuration of fuel type, drying temperature, and algorithm criteria for experiments used to test effect of oven type on fuel moisture

	Test			
Variable	**1**	**2**	**3**	**4**
Fuel type	Excelsior ¾-inch dowel 3-inch disc	Excelsior ¾-inch dowel 3-inch disc	Mountain laurel leaves	Scrub oak leaves
Computrac QRO	Excelsior–170 °C Dowel–170 °C Disc–180 °C	95 °C 95 °C 95 °C	140 °C	140 °C
NeoSystem QRO	140 °C	140 °C	140 °C	140 °C
Convection oven	95 °C	95 °C	95 °C	95 °C
Total number of samples	360	360	210	210

Note: Different criteria were used to end each run in the Computrac quick-response ovens (QROs) between the different tests. See the text for a detailed explanation. 170 °C = 338 °F, 180 °C = 356 °F, 140 °C = 284 °F, 95 °C = 208 °F.

Table 8—Structure of analysis of variance tables used to test effects of drying oven type on fuel moisture estimates for live and dead fuels

Fuel type	**Source**	**Degrees of freedom**	**Effect type**
Excelsior	Replication	2	Random
¾-inch dowel	Oven type	3	Fixed
3-inch disc	Samples/oven type	9	
(test 1, 2)	Error	105	
	Total	119	
Mountain laurel	Replication	2	Random
Scrub oak	Oven type	3	Fixed
(test 3, 4)	Sample mass	1	Fixed
	Samples/oven type	9	
	Error	194	
	Total	209	

next day or stored in a cool location until the next workday. A full set of samples consisted of 70 runs (10 samples by 2 fixed masses by 3 ovens + 10 bottles). Sample material collected on 3 separate days comprised three replications. A bottle was randomly selected and shaken before a sample was extracted with forceps and placed in the QRO or in the soil can. Soil cans and bottles were bulk dried in the convection ovens. Soil cans and bottles were weighed using an electronic balance. Scrub oak leaves harvested near Riverside, California, using the same procedures produced the second live fuel evaluation. The QRO systems came to room temperature between runs. The final moisture and time involved in each run were recorded. Wet mass of the bottle samples ranged from 25 to 70 (0.88 to 2.47) and 36 to 122 grams (1.27 to 4.30 ounces) for the scrub oak and mountain laurel, respectively.

Statistical Analysis

Four specific hypotheses correspond to the four tests performed. In test 1, we tested to see if there was any difference between moisture content estimated from a convection oven method and from the QROs at the various drying temperatures. Each dead fuel type was analyzed separately. Test 2 repeated test 1 with the exception that the temperature used by the Computrac QRO matched the convection oven temperature. Tests 3 and 4 matched the two QRO drying temperatures and examined differences caused by the oven type and fuel sample mass for the two live fuel types.

A mixed-effects linear model (Pinheiro and Bates 2000) described the experimental design for all four tests (table 8). For tests 1 and 2, the random effect was the experimental run, and oven type was the fixed effect. The variance-covariance structure was based on the random effect (sample id) and on the replication of oven type (bottle, can, Computrac 2000 MAX 2000XL, and NeoSystem). The sample id and replication of oven type and material type were selected as the random-effect variables owing to the sampling design; the same sample material was placed randomly into the different oven types and was different for each replication. For the live fuel tests (tests 3 and 4) oven type and size of sample were fixed effects. The variance-covariance structure was based on the random effect (sample id) and on the replication of oven type and size of sample. Evaluation of the residuals determined if there was a trend in the ranking of each of the treatments when analyzed within each of the samples. Each test was analyzed independently. Equality of treatment means was tested using Tukey's test (Mason 1989), a conservative multiple comparison test, with a significance level of 5 percent.

Results and Discussion

Test 1 was designed to determine if the ovens operated under the manufacturer's recommended settings would produce equal moisture content estimates. Mean moisture content was about 167, 75, and 58 percent for the excelsior, dowel, and disc fuel types, respectively. Mean moisture content of the ¾-inch dowels and 3-inch discs did not differ between the QRO and convection oven (table 9). For excelsior, the Computrac mean was significantly higher than the NeoSystem, and the soil cans dried in the convection oven. Drying the fuels in cans or bottles in the convection oven did not significantly affect moisture content. The second test (test 2) compared the effect of using a 95 ºC (203 °F) drying temperature in the Computrac to determine moisture content of dead fuels as was done originally (Sackett 1980). At this drying temperature, the mean moisture content of the Computrac treatment was significantly lower for all fuel size classes by 16 to 30 percent. There was no significant difference between the other ovens.

Test 3 and 4 evaluated the effects of the different ovens and sample mass on moisture content of mountain laurel and scrub oak leaves, respectively. The Computrac QRO ran at the same temperature as the NeoSystem QRO, which was lower than the manufacturer's recommendation. For both live fuels, the means for the fuel containers used in the convection oven did not differ significantly (table 10) and the values were within 1 to 2 percent. For scrub oak (test 4), the NeoSystem did not differ from the convection oven nor did the Computrac with a small sample

Table 9—Summary of multiple comparison tests of fuel moisture means for three dead fuel types using two quick-response ovens and a convection oven[a]

		Fuel type		
Test	**Oven type**	**Excelsior**	**¾-inch dowel**	**3-inch disc**
				disc
Test 1	Computrac	172.03a	76.95a	57.71a
	NeoSystem	165.06b	74.95a	57.08a
	Convection–can	165.22b	75.41a	57.95a
	Convection–bottle	170.28ab	74.78a	58.49a
Test 2	Computrac	127.92a	58.27a	49.19a
	NeoSystem	155.06b	79.81b	65.76b
	Convection–can	155.58b	79.87b	65.50b
	Convection–bottle	160.98b	79.67b	65.71b

[a] Test description contained in table 7. Comparison of means performed using Tukey test. Moisture content means (percentage) followed by same letter did not differ at 0.05 level.

Table 10—Summary of multiple comparison tests of fuel moisture means for two live fuel types using two quick-response ovens and a convection oven[a]

		Fuel type	
Oven type	**Sample mass**	**Scrub oak**	**Mountain laurel**
Convection–bottle	(variable)	64.14 a	146.89a
Convection–can	4	61.45 ab	147.42a
Convection–can	8	62.50 a	145.75a
Computrac	4	60.28 ab	139.7 b
Computrac	8	57.30 b	132.14c
NeoSystem	4	60.01 ab	138.93b
NeoSystem	8	60.78 ab	141.68b

[a] Test description contained in table 7. Comparison of means performed using Tukey test. Moisture content means (percent) followed by same letter did not differ at 0.05 level. Sample mass in grams; variable ranged from 25 to 122 g.

mass. The Computrac with the large sample mass was significantly lower than the convection oven; however, the difference ranged from 4 to 7 percent. For mountain laurel (test 3), which had a mean moisture content of 147 percent, estimates from both QROs were lower than the convection oven, and the Computrac QRO with the large sample mass was l5 percent lower than the convection oven.

When discussing the results of all of these tests, the treatment means are ultimately, compared to the bottle results, considered most accurate. Using the manufacturer's recommended drying temperatures of 170 or 180 ºC (338 or 356 °F), the Computrac performed well when compared to the bottle for the 1-hr dead fuel-size class (higher but not significantly higher) and consistently well when compared with the other treatments for large fuel size material. It was unclear whether the difference in treatment mean moisture contents was due to the size of material or the level of moisture in the sample material. Additional testing of the three fuel-size classes with more similar moisture content levels would easily determine the relationship between these two issues. Because the test design incorporated the original drying temperature, we expected the results of the Computrac to be similar to the bottle results, especially for the 1-hr fuel-size class. Currently, we recommend that field personnel use the quick-response systems for general information about project work and not for drying trend information. They appear to be accurate when run at higher drying temperatures recommended by the manufacturer. The Computrac was not accurate when set at the lower temperature of 95 ºC (203 °F). The present

study supports the conclusion reached by Jolly and Hadlow (2012) that drying live fuels in a Computrac with temperature set at 145 °C (298 °F) will provide results comparable to a convection oven in a shorter period of time.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches	2.54	Centimeters
Feet	.305	Meters
Mils	2540	Centimeters
Pounds	454	Grams
Ounces (fluid)	0.0296	Liters
Quarts	0.947	Liters

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