ASSESSING LIVE FUEL MOISTURE FOR FIRE MANAGEMENT APPLICATIONS

David R. Weise
U.S. Department of Agriculture, Forest Service, Forest Fire Laboratory, Pacific Southwest Research Station, Riverside, CA 92507

Roberta A. Hartford
U.S. Department of Agriculture, Forest Service, Intermountain Fire Sciences Laboratory, Intermountain Research Station, Missoula, MT 59807

Larry Mahaffey
U.S. Department of the Interior, Bureau of Land Management, National Interagency Fire Center, Boise, ID 83705

ABSTRACT

The variation associated with sampling live fuel moisture was examined for several shrub and canopy fuels in southern California, Arizona, and Colorado. Ninety-five % confidence intervals ranged from ±5% to ±100%. Estimated sample sizes varied greatly. The value of knowing the live fuel moisture content in fire decision making is unknown. If the fuel moisture is highly variable, then it is possible for the confidence intervals to span one or more fire behavior or danger classes. Errors in live fuel moisture data may directly affect the costs in safety and resources associated with prescribed fire and wildfire suppression.

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INTRODUCTION

As a result of the firefighter fatalities that occurred on the South Canyon Fire near Glenwood Springs, Colorado in 1994, the importance of live fuel moisture is being examined once again. The moisture content of living fuels is believed to play a role in fire initiation and spread in these fuels; however, we presently can not model the process. We can, however, monitor live fuel moisture content, associate it with observed fire behavior and develop prescribed fire management guidelines. In order to devise an effective monitoring system, we must be able to describe the variability in live fuel moisture content. This paper describes the variability observed in live fuel moisture data collected at several locations in Colorado, Arizona, and California.

Recognition of the importance of the moisture content of living plants in various fire management decision processes is not a new topic. Research studies examining seasonal changes in moisture content of both shrub species and ponderosa pine (*Pinus ponderosa*) foliage were conducted by fire scientists as early as the 1930's (Connaughton and Maki 1935, Buck 1938, Richards 1940, Fons 1943, Dell and Philpot 1965). These early studies monitored fuel moisture in shrub species such as manzanita (*Arctostaphylos patula, A. glauca*), chamise (*Adenostoma fasciculatum*), ceanothus (*Ceanothus velutinus, C. oliganthus, C. crassifolius*), and scrub oak (*Quercus dumosa*). The purpose of much of this early research was to use live fuel moisture content to adjust the estimated moisture content of sticks used to calculate fire danger (Fons 1943). After additional research, networks to monitor live fuel moisture in selected vegetation types were established. To our knowledge, there are currently several operational networks in the United States collecting live fuel moisture content data for fire danger purposes (Cohen et al. 1995, Weise and Saveland 1996). The use of live fuel moisture data in fire danger prediction continues to be investigated. The roles of living fuels and live fuel moisture in fire behavior prediction are not as clearly defined. Although BEHAVE (Burgan and Rothermel 1984, Andrews 1986), the current operational implementation of the Rothermel fire spread model (Rothermel 1972), uses live fuel moisture content as an input, the state of the art of fire spread modeling in living fuels is in question (Cohen et al. 1995).

In recognition of the role that the moisture content of living plants plays in assessing fire danger, the Interagency Management Review Team for the South Canyon Fire charged a task force to develop a sampling and communication network to collect and disseminate live fuel moisture information (IMRT 1994, Recommendation A.8). The Interagency Live Fuel Moisture Task Force (hereafter Task Force) reviewed sampling protocols and networks (active and inactive), developed sampling and communication guidelines, and proposed a two-year implementation of the network. The pilot year implementation would be used to

Table 1. Range in sample size and frequency of sampling of live fuel moisture for several chaparral plant species at several locations in southern California during 1995.

Location	Species	Sampling frequency	Sample size range
Boquet Canyon	Black Sage	17	1
	Chamise	17	2
Chantry Fuel Break	Chamise	2	3
Clark Motorway	Chamise	17	2
El Cariso	Chamise	4	3
Fobes	Chamise	1	3
Grasshopper Canyon	Purple Sage	17	1
	Sagebrush	17	1
Lady Bug	Chamise	9	2–3
	Manzanita	9	1–2
Little Tujunga	Chamise	13	3
Nacimiento	Chamise	13	1
North Main	Chamise	3	3
Pico Canyon	Chamise	17	2
Piney Creek	Chamise	8	1
Placerita Canyon	Chamise	17	2
Red Box	Chamise	1	2
	Manzanita	1	1
San Marcos	Chamise	14	3
Sandlin Flat	Chamise	1	3
Silverado	Chamise	5	3
Strawberry	Chamise	11	4–6
Sycamore Canyon	Chamise	15	2
	Hoaryleaf Ceanothus	15	2
Tanbark	Chamise	21	2–3
Temescal	Chamise	9	3
Templin Highway	Chamise	17	2
Texas Canyon	Chamise	8	3
	Manzanita	8	1
Trippet Ranch	Black Sage	17	1
	Chamise	17	2
Upper Oso	Chamise	12	3
Warm Springs	Chamise	9	3
Woolsey Canyon	Chamise	17	2

Table 2. Range in sample size and frequency of sampling of live fuel moisture for shrub and conifer species at several locations in Arizona and Colorado during 1995.

Location	Species	Sampling frequency	Sample size range
Black Canyon	Gambel Oak	9	1–20
Cattle Creek	Sagebrush	7	5–20
	Gambel Oak	6	4–20
Chapin	Juniper	7	12–20
	Pinyon	7	20
	Sagebrush	3	20
Ernie Gulch	Juniper	1	2
	Pinyon	1	2
	Gambel Oak	1	10
Grass Mesa	Juniper	1	3
	Gambel Oak	4	1–21
Hualapai Mountain	Turbinella Oak	4	1–10
Iron Springs	Turbinella Oak	7	9–20
Iron Springs Bench	Sagebrush	25	24
Lightner Creek	Gambel Oak	8	1-20
Manhattan	Sagebrush	2	10
	Lodgepole Pine	2	10
	Ponderosa Pine	2	9–10
Morefield	Gambel Oak	6	10–30
Park Point	Gambel Oak	6	10–20
Payson Heliport	Turbinella Oak	9	3–12
Redfeather	Sagebrush	3	3–4
	Lodgepole Pine	3	2
	Ponderosa Pine	3	2
Russell Gulch	Scrub Oak	1	3
Sanborn	Ponderosa Pine	8	3–4
	Gambel Oak	7	3–4
Sage Hill	Pinyon	7	5–20
The Crown	Gambel Oak	2	2–5
Trappers Peak	Engelmann Spruce	7	9–20
Yankee Joe	Scrub Oak	4	3

identify where changes were needed in terms of sampling techniques as well as disseminating live fuel moisture information (Cohen et al. 1995, Weise and Saveland 1996). One key issue to be resolved during the pilot year was the size of sample that must be collected to insure accurate estimation of live fuel moisture. This paper analyzes the variability in live fuel moisture samples collected in Colorado, Arizona, and California during 1995. We also discuss implications of the variability of live fuel moisture on fire management decision processes.

METHODS

Live fuel moisture data were compiled from two networks established to monitor live fuel moisture. A network was established in the early 1980's for California chaparral (Countryman and Dean 1979). This network consisted of federal, state, and local partners in California. Components of the network continue to collect live fuel moisture data. Data gathered during 1995 were consolidated from the four national forests in southern California and the Los Angeles County Fire Department. The primary species monitored in this network is chamise. Sampling frequency varies radically (Table 1). Most, if not all, sites are sampled by gathering a composite sample from several shrubs. The second network of sample sites was established in 1995 in Arizona and Colorado by Roberta Hartford and Larry Mahaffey. The study was requested by Forest Service and Bureau of Land Management personnel following the South Canyon fire incident. A larger sampling intensity was used at several of these sites in accordance with the guidelines proposed in the Task Force report (Table 2) and each sample represents an individual plant. The principal shrub species sampled were Gambel oak (*Q. gambellii*), turbinella oak (*Q. turbinella*), and sagebrush (*Artemisia tridentata*). Sagebrush live fuel moisture data collected at Dinosaur National Monument by National Park Service personnel from 1988 to 1992 were also made available for analysis by Steve Petersburg. Data collected in 1990 were arbitrarily chosen from this data set.

Live fuel moisture content was estimated by weighing and drying the samples following standard methodology (Countryman and Dean 1979, Norum and Miller 1984). Fuel moisture samples were collected for new growth, old growth, and for mixed growth samples for several of the species monitored. Summary statistics (sample mean, sample variance, and coefficient of variation) were calculated by growth type, species, and collection time for each sample site. A sample size of 20 was recommended by the Task

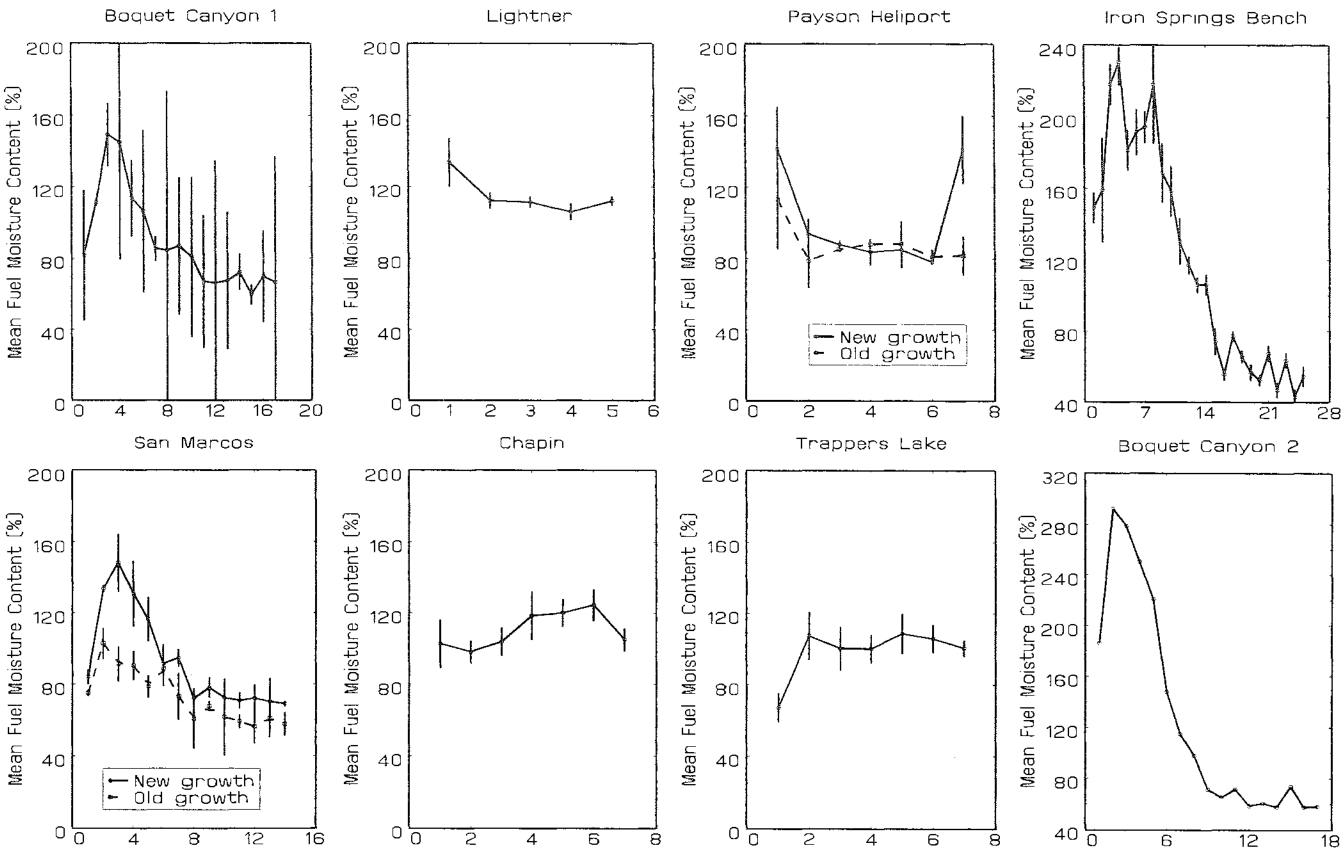

Figure 1. Mean live moisture content of shrub and canopy fuels sampled at locations in southern California, Arizona, and Colorado during one growing season. Vertical lines indicated 95% confidence intervals. The X-axis is sample time (1 denoting 1st sample collection, 2 denoting 2nd sample collection, etc.). Chamise was sampled at Boquet Canyon 1 and San Marcos, Gambel oak at Lightner, turbinella oak at Payson Heliport, sagebrush at Iron Springs Bench, piñon at Chapin, Engelmann spruce at Trappers Lake, and black sage at Boquet Canyon 2.

Force for use in the pilot year for each species of interest. The data presented in this study can be used to evaluate that recommendation. The coefficient of variation and sample size were used to estimate the sample sizes necessary to estimate mean live fuel moisture content at allowable error levels (*AE*) of 5, 10, and 25% of the mean using equation 1 (Husch et al. 1982). A 95% confidence level was selected to determine values of Student's *t*.

$$n = \frac{t^2(CV)^2}{(AE)^2} \qquad (1)$$

where

n = estimated sample size

t = Student's statistic for n degrees of freedom, 95% confidence level

CV = coefficient of variation (100*standard deviation/mean)

AE = allowable error.

Student's *t* values were also used to calculate 95% confidence intervals about each sample mean. Both the estimated sample size and confidence intervals demonstrate the effects of variation in live fuel moisture content. Sample means, confidence intervals, and the coefficient of variation were plotted over the sampling period to visually detect changes that occur seasonally. The width of the confidence levels and the constancy of the coefficient of variation provide a measure of the variation of the data.

Ninety-five % confidence intervals were calculated (equation 2) and plotted for each sample time for each species, where $t_{0.05,n-1}$ is a value of Student's statistic for n-1 degrees of freedom and α level of 0.05, $s_{\bar{x}}$ is the standard error of the mean, *LFM* is mean live fuel moisture, and *CI* is the 95% confidence interval. The width of the confidence interval is affected by the sample size (n), the desired level of precision (α), and the variation in the data ($s_{\bar{x}}$). Increasing sample size and decreasing level of precision decrease the size of the confidence interval for a given level of variation.

$$CI = LFM - t_{0.05,n-1} s_{\bar{x}} \qquad (2)$$

RESULTS

Live fuel moisture data from 27 locations in southern California and from 19 locations in Arizona and Colorado were available for analysis in 1995 (Tables

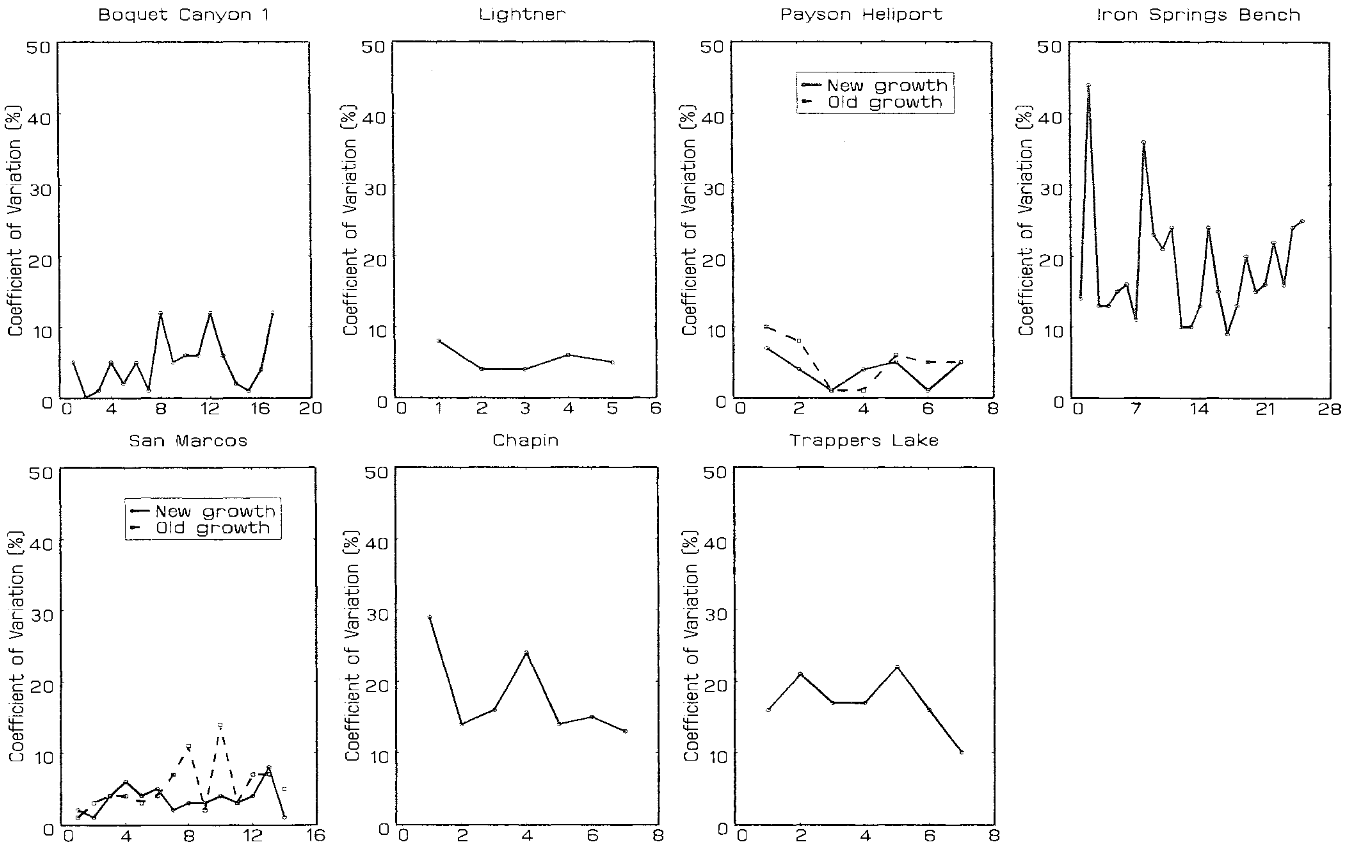

Figure 2. Coefficient of variation of live moisture content of shrub and canopy fuel samples collected at locations in southern California, Arizona, and Colorado during one growing season. The X-axis is sample time (1 denoting 1st sample collection, 2 denoting 2nd sample collection, etc.). Chamise was sampled at Boquet Canyon 1 and San Marcos, Gambel oak at Lightner, turbinella oak at Payson Heliport, sagebrush at Iron Springs Bench, piñon at Chapin, Engelmann spruce at Trappers Lake, and black sage at Boquet Canyon 2.

1, 2). Sampling frequency, which is defined as the number of times samples were collected in 1995 (1990 for Dinosaur National Monument), ranged from a low of 1 to a high of 21 in southern California and from a low of 1 to a high of 25 in the Arizona-Colorado data. Excluding the Dinosaur National Monument data, the highest sampling frequency was 9. Sample size (the number of individual live fuel moisture samples collected at one time) ranged from 1 to 6 in southern California and from 1–30 in Arizona-Colorado. Two live fuel moisture observations are required to compute variance; therefore, all sample sets with a sample size of one were excluded from any variance analysis. Locations with sampling frequencies of 6 or less were also dropped from further analysis because of the small number of sampling times.

For most shrub species, live fuel moisture followed a "typical" pattern. Fuel moisture increased rapidly due to the spring "greenup" and then gradually decreased over the growing season (Figure 1). Tree foliage live fuel moisture did not appear to exhibit the same seasonal trends that shrub fuels did. This could be due in part to different seasonal trends, the lower sampling frequency, or the timing of collection. Greenup most likely occurred before sampling began.

The confidence intervals varied considerably for the sample locations selected. For chamise at Boquet Canyon 1, confidence intervals ranged from approximately ±5% to ±100%. Many of the confidence intervals at this site were ±40% (Figure 1). No seasonal trend in the size of the confidence intervals was visually apparent; further statistical analysis is necessary to make this statement with certainty. Most other locations had confidence intervals of ±20% or less. At several locations (Lightner, Iron Springs Bench, San Marcos, Chapin, and Trappers Lake), the confidence intervals decreased in size as the season progressed. The seasonal trend in black sage (*Salvia mellifera*) at Boquet Canyon 2 is quite evident in Figure 1. However, because sample size was one for each sampling period, it was not possible to calculate a confidence interval because variance in the data can not be estimated.

The coefficient of variation ($100s/\bar{x}$) for several sites was less than 20% (Figure 2). Of the 8 sites in Figure 1, Iron Springs Bench exhibited the widest range in coefficient of variation. No statistical tests were performed to test for constant variance over time. Future analyses will address this issue.

Estimated sample sizes needed to estimate mean live fuel moisture within 5, 10, and 25% of the mean ranged from 1 to > 1000. Maximum mean estimated

Table 3. Mean estimated sample sizes needed to achieve desired allowable errors in estimation of mean live fuel moisture for several chaparral plant species at several locations in southern California during 1995.

Location	Species	Allowable error (5%)	Allowable error (10%)	Allowable error (25%)
Boquet Canyon	Chamise	259[1]	65	10
Clark Motorway	Chamise	221	55	9
Lady Bug	Chamise (N)	587	147	23
	(O)	630	157	25
	Manzanita (N)	597	149	24
	(O)	0	0	0
Little Tujunga	Chamise (N)	183	46	7
	(O)	57	14	2
Pico Canyon	Chamise	156	39	6
Placerita Canyon	Chamise	212	53	8
San Marcos	Chamise (N)	12	3	0
	(O)	30	8	1
Strawberry	Chamise	97	24	4
Sycamore Canyon	Chamise	170	43	7
	Hoaryleaf Ceanothus	156	39	6
Tanbark	Chamise	513	128	20
Temescal	Chamise (N)	81	20	3
	(O)	24	6	1
Templin Highway	Chamise	211	53	8
Texas Canyon	Chamise	131	33	5
	Manzanita	159	40	6
Trippet Ranch	Chamise	156	39	6
Upper Oso	Chamise (N)	34	9	1
	(O)	10	3	0
Warm Springs	Chamise (N)	47	12	2
	(O)	33	9	1
Woolsey Canyon	Chamise	89	22	3

[1] Mean estimated sample size necessary to achieve desired level of allowable error based on observed variation.

Table 4. Mean estimated sample sizes needed to achieve desired allowable errors in estimation of mean live fuel moisture for shrub and conifer species at several locations in Arizona and Colorado during one growing season.

Location	Species	Allowable error (5%)	Allowable error (10%)	Allowable error (25%)
Black Canyon	Gambel Oak	55[1]	14	2
Cattle Creek	Sagebrush	60	15	2
	Gambel Oak	41	10	2
Chapin	Juniper	71	18	3
	Pinyon	61	15	2
Iron Springs	Turbinella Oak	70	17	3
Iron Springs Bench	Sagebrush	38	9	1
Lightner Creek	Gambel Oak	8	2	0
Morefield	Gambel Oak	189	47	8
Park Point	Gambel Oak	164	41	7
Payson Heliport	Turbinella Oak (M)	3	1	0
	(N)	14	4	0
	(O)	25	6	1
Sanborn	Ponderosa Pine (N)	74	19	3
	(O)	135	34	6
	Gambel Oak (M)	230	58	9
	(N)	91	23	4
	(O)	3	1	0
Sage Hill	Pinyon	161	40	6
Trappers Peak	Engelmann Spruce	57	14	2

[1] Mean estimated sample size necessary to achieve desired level of allowable error based on observed variation.

sample size (mean of all estimated sample sizes for a specific species, location, and growth type) was 630 for the southern California data and 230 for the Arizona-Colorado data (Table 3, 4). Both of these maximums were estimated for 5% allowable error. As the allowable error increased to 25%, the mean sample sizes associated with the 2 maximum values were 25 and 9, respectively. In general, increasing the allowable error decreased the necessary sample size.

FIRE MANAGEMENT IMPLICATIONS

As pointed out in the Live Fuel Moisture Task Force Report (Cohen et al. 1995), live fuel moisture information is currently best used in strategic decisions instead of tactical decisions because of the current limitations in our understanding of live fuels and fire behavior. Since the 1940's, live fuel moisture information has been used in fire danger calculations, a strategic level use of the data. In the first version of the National Fire-Danger Rating System (NFDRS), live fuel moisture was sampled along transects at each fire danger station. This approach was replaced by live fuel moisture models for herbaceous and shrub fuels in the 1978 NFDRS (Bradshaw et al. 1983). The 1978 NFDRS live fuel moisture model transfers herbaceous fuels into the 1-hour timelag fuel class; however, live woody fuels are not transferred into the corresponding dead fuel classes. Live fuels can still contribute heat to the combustion process (Richards 1940, Bradshaw et al. 1983).

Some users of live fuel moisture information have used the data to develop general guidelines related to fire behavior and danger (Cohen et al. 1995). Monitoring live fuel moisture data over several years has enabled others to use the data to estimate what the current fire danger is relative to previous years' fire danger. By developing an "average" annual live fuel moisture profile, a fire management agency can make these fire danger assessments. Data collected in southern California have been used for just such a purpose. However, error associated with live fuel moisture samples should be considered when using live fuel moisture data in this fashion.

Consider the following example. The confidence intervals for chamise at Boquet Canyon 1 were roughly ±40% and at San Marcos were roughly ±10%. Assume guidelines such as: 1) live fuel moisture > 120%—low fire danger; 2) 80% ≤ live fuel moisture ≤ 120%—moderate fire danger; 3) 60% ≤ live fuel moisture ≤ 80%—high fire danger; and 4) live fuel moisture ≤ 60%—extreme fire danger; have been developed. If live fuel moisture is estimated to be 90%, fire danger would be rated anywhere from low to extreme at Boquet and moderate at San Marcos because of the width of the confidence intervals. This may have serious implications for fire management applications.

If only one sample of a particular species is collected, it is not possible to have a sense of the range of actual live fuel moisture. The decision to use a single sample may be based on one or more assumptions. These assumptions may include: live fuel moisture response to annual weather at this location is relatively constant and deterministic (not subject to error), the error or bias introduced by different people performing the sampling is constant or nonexistent, collecting additional samples is not cost-effective or the decisions made based on the data are only weakly influenced by the actual live fuel moisture value or the error in live fuel moisture. All of these assumptions are within the realm of possibility, but a user of the data must be aware of these assumptions.

Sampling error should also be considered if live fuel moisture is to be used in tactical decisions such as prescribed burning or wildfire suppression. The sensitivity of fire behavior to live fuel moisture is presently unknown; however, anecdotal observation suggests that fire spread in live fuels may be a go/no-go phenomenon under certain conditions. Thresholds that define different levels of fire behavior in live fuels are postulated. One such threshold is the point at which a fire will successfully spread; another threshold is the change from a surface fire to a crown fire. Observed fire behavior information is readily available when making many tactical decisions; potential fire behavior represented by live fuel moisture should also influence tactical decisions.

Large sampling error may become quite important when allocating and positioning fire suppression forces on an active fire. Assume that the guidelines above for fire danger have the following associated fire behavior: 1) low fire danger—discontinuous fire spread, 2) moderate fire danger—continuous fire spread with moderate flame lengths, 3) high fire danger—continuous fire spread with some spotting, and 4) extreme fire danger—spotting, crowning and other extreme fire behavior. If the error in live fuel moisture data spans a threshold of fire behavior which defines the type of tactical response, then confidence in the data is necessary. If actual live fuel moisture is well above a threshold (fire danger is lower than the data indicate), unnecessary costs may be incurred. Alternatively, firefighters could potentially be at risk if actual fuel moisture is well below a threshold (i.e., fire danger is higher than the data indicate).

SUMMARY

The variation associated with sampling live fuel moisture was examined for several shrub and canopy fuels in southern California, Arizona, and Colorado. Ninety-five % confidence intervals ranged from ±5% to ±100%. Estimated sample sizes also varied greatly. At allowable error of 5%, maximum mean estimated sample size was as high as 630. Increasing allowable error to 25% reduced estimated sample sizes to less than 30.

The value of live fuel moisture in fire decision making is unknown. If the fuel moisture is highly variable, then it is possible for the confidence intervals to span one or more fire behavior or dangers classes. Errors in live fuel moisture data may directly affect the costs in safety and resources associated with prescribed fire and wildfire suppression. If live fuel moisture content is to be sampled to provide information for fire management decisions, care should be taken to collect an adequate sample to insure that the precision of the estimate is within acceptable bounds.

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