

Effects of Season on Ignition of Live Wildland Fuels Using the Forced Ignition and Flame Spread Test Apparatus

S. McAllister^a and D. R. Weise ^b

^aUSDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Lab, Missoula, Montana, USA;

^bUSDA Forest Service, Pacific Southwest Research Station, Fire and Fuels Program, Riverside, California, USA

ABSTRACT

An understanding of what variables affect the ignition of live wildland fuels is crucial to predicting crown fire spread, the most poorly understood type of wildland fire. Ignition tests were performed over the course of an entire year for ten species (three species in year one, seven in year two) to evaluate seasonal changes in flammability. Ignition delay and mass loss rate at ignition were measured for a radiant heat flux of 50 kW/m² and flow velocity of 1 m/s. Large species-to-species variation occurred in two-variable linear correlations between moisture content, ignition time, and mass loss rate at ignition. Only a few species showed the same behavior as wet wood. Due to potential physical and chemical changes that live fuels undergo during the growing season, moisture content is not a particularly useful descriptor of ignition behavior for live fuels.

ARTICLE HISTORY

Received 1 February 2016

Revised 16 May 2016

Accepted 22 June 2016



KEYWORDS

Ignition; Live fuels; Wildland fires

Introduction

The most dangerous and unpredictable wildland fires are fires in which the live, green foliage in the crowns of shrubs and trees ignites and propagates the fire. Live, green foliage may also burn during prescribed fires. Thus, an understanding of what variables affect the ignition of these live fuels is crucial to predicting fire spread in living forest and shrub fuels. Even though there is a well-established literature on water relations in plants (Nelson, 2001), live forest fuels have often been treated as wet, dead fuels in wildfire spread models (Linn, 1997; Mell et al., 2007; Rothermel, 1972). This includes using the thermal properties of wood, as measured values for actual foliage are quite rare in the literature (Byram et al., 1952a, 1952b; Hays, 1975). In some cases, however, a higher heat content is used for selected fuel types (Hough and Albin, 1978; Rothermel and Philpot, 1973). Limited modeling work to address the unique nature of live chaparral fuels occurred (Mardini et al., 1989) but did not advance to the point of model validation. There is growing indication that the assumption of wet, dead fuels was a poor assumption for live fuels (Alexander and Cruz, 2013; Finney et al., 2013).

Unfortunately, there have only been a few studies that examined ignition of live fuels (Dimitrakopoulos and Papaioannou, 2001; Engstrom et al., 2004; Fletcher et al., 2007; Jarvis and Rein, 2016; McAllister et al., 2012; Smith, 2005; Weise et al., 2005a;

CONTACT S. McAllister  smcallister@fs.fed.us  USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Lab, 5775 W US Highway 10, Missoula, MT 59808, USA.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gcst.

This article is not subject to U.S. copyright laws.

Xanthopoulos and Wakimoto, 1993). Early work estimated heat content of several live fuels and found differences between live and dead forms of the same fuel type (Hough, 1969). Several live fuels were found to have significant quantities of volatile compounds with higher energy content (Philpot, 1969; Susott, 1982). Differences in peak heat release rate and time to ignition in a cone calorimeter were observed in intact green and oven-dry samples of foliage and branches and the difference was attributed to moisture content (Weise et al., 2005a). Similarly, Sun et al. (2006) found differences in mass loss rate and flame height in live and dead chaparral fuels burned in circular “pool fire” configurations that were attributed, in part, to fuel moisture content. However, White and Zipperer (2010) pointed out the difficulties of examining combustion characteristics of live fuels and not all studies have had success when correlating flammability measures with moisture content. For example, Fletcher and coworkers (Engstrom et al., 2004; Fletcher et al., 2007; Smith, 2005) attempted to correlate the ignition time with leaf thickness and moisture content, however, almost no correlation with moisture content and only a slight correlation with leaf thickness were found. Both Jervis and Rein (2016) and McAllister et al. (2012) also noted a difference in the ignition behavior of live fuels that cannot be solely explained by moisture content. Jervis and Rein (2016) suggested that volatiles were lost in drying the fuels, which contributed to the very different ignition behavior seen between live and dried. McAllister et al. (2012) looked to the variation in the chemical composition of the live fuel to help explain the discrepancies.

Dead forest fuels are primarily composed of cellulose, lignin, and hemicellulose, and their dry mass remains constant. Live fuels, however, can be up to half nonstructural carbohydrates like sugars and starches (McAllister et al., 2012). Because these nonstructural carbohydrates are vital for the biological processes of the plant, the amount stored can vary during the growing season and thus the dry mass of the fuel can vary (Little, 1970). Thus, it is very possible that the apparent moisture content of the fuel can change solely due to changes in the dry mass while the relative amount of water stays constant (see, e.g., Finney et al., 2013; Jolly et al., 2012, 2014; Kozłowski and Clausen, 1965). A still unexplained empirical observation is the “moisture of extinction” (Cohen and Bradshaw, 1986; Rothermel, 1972; Weise et al., 2005b). Wildland fires in dead fuels will not spread above some threshold of fuel moisture content, typically assumed to be between 10% and 40% (Rothermel, 1972). However, in crown fires, live fuels with moisture contents 70% to 135% are what carry the fire (van Wagner, 1977; Zhou et al., 2007). Clearly there is a complicated and unknown relation between the chemical composition and moisture content that has a significant effect on the ignition of live fuels.

Another common assumption in wildland fire models (e.g., Linn, 1997; Mell et al., 2007) is that wildland fuels are thermally thin. However, Picket et al. (2010) showed significant moisture (30–60%) remained in live leaf samples at the time of ignition for a variety of western and southern species. This observation has recently been reproduced by Yashwanth et al. (2016) using 3D modeling of the pyrolysis of a leaf. McAllister et al. (2012) also showed that significant water was still being released from live lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*) needles at the moment of ignition. Furthermore, the ignition times were equally well correlated by the thermally thick and thin assumption, indicating thermally intermediate behavior for live wildland fuels.

A 2-year joint project between the Forest Service (Pacific Southwest and Rocky Mountain Research Stations), Brigham Young University (BYU), and the University of

Alabama in Huntsville was undertaken to examine and model live fuel ignition. Of particular interest is whether there are predictable seasonal trends in the ignition behavior of live fuels. Similar experiments have been performed at BYU to determine whether these ignition time trends are apparatus and heating mode dependent. As both apparatus have their strengths, weakness, and outputs, the results are reported separately. The results of the radiation only tests are reported here, along with unique critical mass loss at ignition data. The results the convection only and convection with radiation tests are reported by Gallacher (2015, 2016), along with unique ignition temperature and flame height data. As discussed in more detail later, these tests involved sampling representative fuels that typically burn as a crown fire (i.e., fire spreading through elevated living vegetation not in contact with the ground) from a variety of locations (southern California, Utah, western Montana, and Florida). Samples of each species were taken for an entire year to take advantage of the natural changes in moisture content and chemical composition. Trends in the ignition time, moisture content, and mass loss rate at ignition are noted and discussed. As previous work examined only a limited number of plant species (e.g., McAllister et al., 2012; Pickett et al., 2010), this work provides a much more broad sampling of live fuels of interest to land managers.

Experiment design

Because wildland fires can produce a wide range of heat fluxes and are very often associated with wind, due to both weather and in-drafts to the fire (Countryman, 1972; Nelson et al., 2012), an apparatus was built to measure the ignition time and critical mass flux for sustained flaming ignition of cellulosic materials under these varying environmental conditions. This apparatus, based on the forced ignition and flame spread test (see, e.g., Fereres et al., 2011), consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance (see Figure 1). The tunnel is 9 cm tall, 25 cm wide, and 60 cm long. A fan at the entrance produces a laminar forced airflow through the tunnel with a velocity ranging from 0.8 to 1.6 m/s (corresponding to Reynolds numbers of $3\text{--}6 \cdot 10^4$, well under the transition to turbulent flow).

The sample holder, measuring 9 cm by 9 cm with a depth of 2.5 cm, is a thin, lightweight aluminum box lined with Cotronics-brand ceramic paper and a 1.27-cm-thick Cotronics-brand ceramic board on the bottom. The sample holder sits on top of

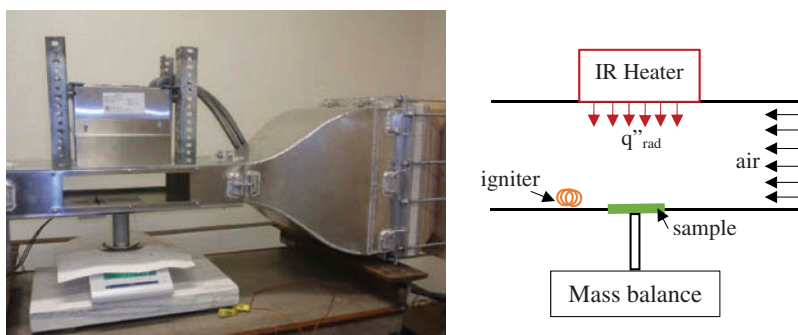


Figure 1. FIST apparatus.

the mass balance with the upper surface of the sample flush with the bottom of the tunnel. The sample was heated from above using an infrared heater capable of producing a uniform heat flux of 0–50 kW/m² over the sample surface. Ignition was by means of a coiled Kanthal wire kept above 1000°C. The igniter was located a fixed distance downstream and in the fuel-rich portion of the boundary layer that removed the igniter location as a potential variable in the experiments. Though the ignition time could have been recorded from the mass loss data, the time to ignition was recorded here visually as the time from the initiation of heating until a flame was sustained over the surface of the sample. The mass of the sample was recorded at 5 Hz. The balance used has a capacity of 320 g and a precision of 0.1 mg. To minimize errors in the balance readings due to vibrations, the entire apparatus is mounted on a granite weighing table with the balance on an isolated marble block. A temporary wind screen is also placed around the balance to reduce the effect of any ambient air currents (not shown in the picture). Care is also taken to maintain a constant balance temperature to prevent drifts in the readings from elevated temperature. To obtain the mass loss rate at ignition, a locally weighted scatterplot smoothing regression was performed. The slope of the regression at the moment of ignition was taken as the mass loss rate at ignition. No attempt was made to calculate the exposed surface area to find the mass flux unlike Weise et al. (2005a). All tests were repeated three times to provide an estimate of the experimental variability.

To mimic the wind and high heat fluxes associated with a wildfire, all tests were performed with a fixed airflow velocity of 1 m/s and an irradiance of 50 kW/m². Though wildfires typically produce radiant heat fluxes in the range of 50 kW/m² to 250 kW/m² (Butler et al., 2004; Silvani et al., 2009), an irradiance of 50 kW/m² was chosen for these tests because it is the maximum attainable with this apparatus.

For the first year of the project, tests were performed with three species: lodgepole pine (*Pinus contorta* Douglas ex Loudon; USDA, 2016), big sagebrush (*Artemisia tridentata* Nutt.), and chamise (*Adenostoma fasciculatum* Hook. & Arn.). For the second year of the project, tests were performed with seven species: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.), hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.), Gambel oak (*Quercus gambelii* Nutt.), fetterbush (*Lyonia lucida* (Lam.) K. Koch), gallberry (*Ilex glabra* (L.) A. Gray), and sand pine (*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg). In all cases, to provide samples as close as possible to the living plants, small branches were cut from the trees and shrubs. The branches were then placed in airtight bags to minimize moisture loss. Samples from Utah (sagebrush and Gambel oak), southern California (chamise, manzanita, and ceanothus), and Florida (fetterbush, gallberry, and sand pine) were shipped overnight to the testing facility in Montana. To ensure that all samples could be tested in a timely manner, each region was assigned a “testing week.” For example, samples from Montana were collected the first Tuesday of the month, Utah the second, and so on. This allowed for all samples to be tested within 2 days of collection. While we followed procedures recommended to minimize moisture loss in the live samples—air tight sample containers stored in a cool location (Countryman and Dean, 1979; Zahn and Henson, 2011), we acknowledge that there was invariably moisture loss from the time of harvest to the time of testing. The methodology we have used for at least 15 years has retained the moisture content at the high levels that are typical of live fuels (Fletcher et al., 2007; Pickett et al., 2010; Weise et al., 2005a, 2005b). We have measured the moisture loss to be in the range of 5–10% over

a 2–3-day period, but the data have never been published. A recent study examined several factors affecting fuel moisture content estimation and found that moisture content of dead, moist fine fuels stored in plastic, zipseal bags lost about 2.2% of moisture per 24-h period (Haase et al., 2016), while samples stored in polypropylene bottles and steel cans lost about 0.2% per 24 h. We used the zipseal type of bag; our unpublished results are consistent with this study using wet, dead fuels.

As mentioned above, physiological processes throughout the year can alter both the water content of leaves and the types of chemical compounds found in them. Advantage was taken of this natural variation in moisture content and chemical composition. For an entire year (1st year species: April 2012–March 2013; 2nd year species: May 2013–April 2014), monthly samples of each species were tested. The lodgepole pine site was inaccessible during the months of December 2012–February 2013, so only 9 months of sampling were performed for the lodgepole pine. Gambel oak is deciduous and only has leaves from about May to October, so only 6 months of samples were taken. As the sampling site condition will affect the samples and results (e.g., Zahn and Henson, 2011), an effort was made to control for this as much as possible. Each month's samples were collected from various individuals in the same site and mixed together. The same tree or shrub was not sampled in great quantity for fear of stressing it. Variables, such as slope and aspect, were kept constant and an attempt was made to sample individuals over a relatively small area. Additionally, only mature trees and shrubs were sampled.

Lodgepole pine, Douglas-fir, and sand pine were tested using needles pulled from the branch, only taking healthy-looking needles. For sagebrush and chamise, 4-cm-long branch tips were used. Gambel oak, manzanita, ceanothus, fetterbush, and gallberry were tested using only healthy-looking leaves pulled from the branch. Because of the length of the needles and leaves, no cutting was necessary to fit them into the sample holder. For lodgepole pine, Douglas-fir, and manzanita, the new growth was easily identifiable so the old and new growth for these species was tested separately until no difference was seen either in the ignition time or moisture content. Sample size was 2 g for most species tested and was weighed within 0.05 g. Due to the size of the leaves, the sample sizes of the Gambel oak, fetterbush, and gallberry leaves differed and were 0.5 g, 0.8 g, and 1 g, respectively. Unpublished scoping experiments indicated that the ignition time was a function of sample mass when samples were large enough to consist of multiple layers. To avoid sample mass as an additional variable, the sample size was chosen so that all species of fuel could lie in the sample holder as a single layer thus eliminating the potential problem of shading of portions of the sample from the heat flux (Weise et al., 2005a). All samples were coated in a thin layer of graphite powder to increase the sample absorptivity. It has been shown that vegetation shows spectral absorptivity, particularly for wavelengths below 2.8 μm (Boulet et al., 2011; Monod et al., 2009), and the wavelength of the radiant energy from the quartz lamps is 0.955 μm at 50 kW/m^2 . In previous work, by comparing the ignition time of coated and uncoated needles, the absorptivity of lodgepole pine and Douglas-fir needles was shown to be 0.576 and 0.699, respectively (McAllister et al., 2012). Because the absorptivity seems to vary even between similar needles, the coating was necessary to provide a consistent and known heat flux in all tests. When placed into the sample holder, sheets of ceramic paper (also darkened) were used to support the fuels such that they were flush with the surface of the holder; all samples were arranged to cover as much surface area as possible (see Figure 2). Previous work also



Figure 2. Lodgepole pine needles (left) and fetterbush leaves (right) in sample holder.

indicated that the ignition time was mildly sensitive to the color of the supportive ceramic paper when the fuels were left uncoated (McAllister et al., 2012). For this reason both fuel and background were darkened.

To obtain the moisture content, two 1.5–2 g samples of each fuel were generated using the same procedure as above for testing (without the graphite coating). These samples were weighed to the nearest 0.1 mg, dried in an oven at 80°C for at least 48 h, and then reweighed. This temperature was chosen because it was high enough to drive off the water, yet low enough to hopefully avoid driving off much of the low-temperature volatiles (Susott, 1980). Only two samples per fuel were tested as the measured moisture content values were typically within 2–3% of each other.

Results and discussion

A visible and audible difference between species was noticed when conducting the tests. The lodgepole pine needles, Douglas-fir needles, sand pine needles, fetterbush leaves, and gallberry leaves, in particular, made loud popping and snapping noises while being heated. In fact, they would all visibly jump around in the sample holder. The chamise branch tips, manzanita leaves, and ceanothus leaves did as well to some extent, though not nearly as much as these other species. The sagebrush branch tips and Gambel oak leaves, on the other hand, gradually produced more and more white vapors during the heating process and silently ignited. Interestingly, this display of different behaviors seems to be regionally grouped—those that pop vigorously are from Montana and Florida, those that mildly pop are from southern California, and those that do not are from Utah. As shown in Figure 3, the species from southern California (chamise, manzanita, and ceanothus) generally had the lowest moisture contents (average values of 63.5%, 86.7%, and 91.1%, respectively). All other species had average moisture contents above 100% (lodgepole pine: 122.5%; Douglas-fir: 131.9%; sand pine: 154.2%; gallberry: 130.2%; fetterbush: 104.5%; sagebrush: 129.1%; and Gambel oak: 102.5%). This behavior is thus not strictly a result of moisture content, but it is suspected that it is a result of structural differences between species. The climate in

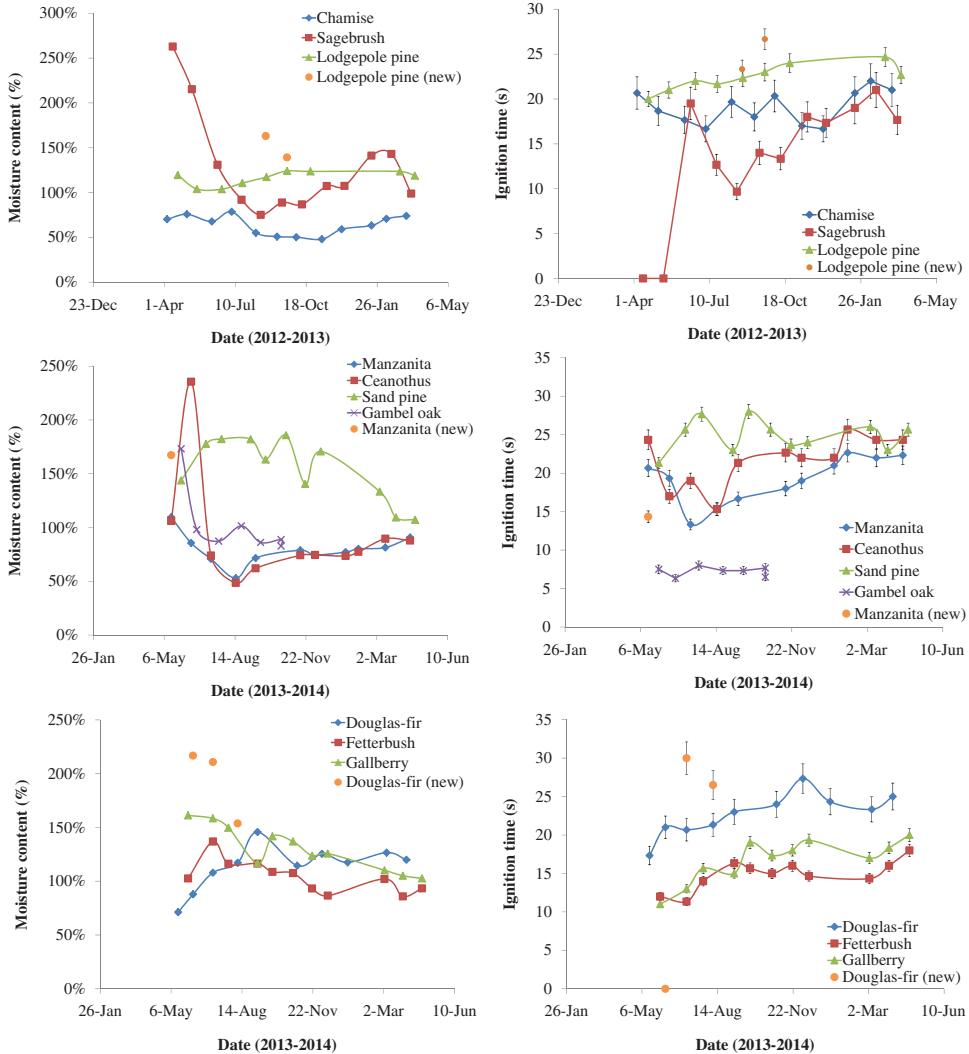


Figure 3. Left column: moisture content vs. sample date. Right column: ignition time vs. sample date. Note that new growth is reported separately when possible. No ignition is shown as zero. Error bars represent one standard deviation and are smaller than the symbol for MC.

each region may require different water management strategies for survival, generating these regional patterns. Sagebrush leaves in particular were very soft and pliable and did not have the hard, waxy coating that the species from Montana, southern California, and Florida have. This thick, impermeable leaf cuticle and cuticular waxes are adaptations by plants designed to reduce water loss (Spurr and Barnes, 1980); an effect of this coating makes the process more of an explosive (and noisy) one than a diffusive one. Engstrom et al. (2004) reported the formation of liquid bubbles on leaf surfaces prior to ignition, which they hypothesized were either water or the cuticular waxes, and the explosive behavior was observed in manzanita leaves prior to ignition (Fletcher et al., 2007).

Figure 3 shows the trends in moisture content and ignition time with the date the fuels were collected and tested. As one can see, there is quite a bit of variation in these trends. The species from southern California (chamise, manzanita, and ceanothus) show a clear pattern of higher moisture contents in the spring months and lower moisture contents in the summer. The trend is typically more pronounced in these species than shown here (Countryman and Dean, 1979); these samples were collected during a 4-year drought in California when the winter precipitation was significantly reduced. The pattern is typical of previous years' foliage in chaparral. Sagebrush, a non-deciduous shrub in Utah, shows the same winter-summer trend. Gambel oak, however, is deciduous so the leaves are dropped in the fall. Thus, moisture content of this species starts high when the leaves first emerge in the spring, then decreases as the leaves dry out during the summer before they ultimately fall off. As mentioned above, the new growth on the two species from Montana (lodgepole pine and Douglas-fir) was clearly distinguishable from the previous year's growth and was tested separately. The moisture content of the previous year's growth for lodgepole pine was nearly constant throughout the summer, fall, and winter, but shows the "spring dip" commonly seen in several northern conifers (Chrosciewicz, 1986; Springer and Van Wagner, 1984; Van Wagner, 1967). For Douglas-fir this "spring dip" appears to be more pronounced. For both species, the moisture content of the new growth starts out quite high (above 200%) and gradually decreases until it matches the previous year's growth. The one month with new manzanita leaves also had a much higher moisture content. It is very likely that the ceanothus leaves tested in June were new leaves, but it was difficult to distinguish them from the old (possibly due to the ongoing drought). The species from Florida (sand pine, gallberry, and fetterbush) had moisture contents that are relatively high during the summer that gradually decrease through the winter.

Some of these differences may be attributed to geographical location and typical weather patterns. The four locations have three distinct Köppen-Geiger climates (Montana and Utah similar; Kottek et al., 2006); however, the western locations are characterized by wet winters and hot, dry summers (see Table 1). The dry season in Florida tends to be the winter. Additionally, spring occurs much earlier in southern California than in Utah and especially earlier than in western Montana. This may explain shifts in the trends with respect to testing date—the fuels are dry during the dry season. However, the moisture content of the lodgepole pine and Douglas-fir was the lowest in the wet spring while the new needles are actively growing. Clearly, the physiological response of vegetation varies strongly from species to species.

The right column of Figure 3 shows the trend in ignition time with sample date. The average standard deviation of the ignition time for all species is 5.9% of the mean value, and ranged from 0% to 21.2%. No clear trend in the ignition time with testing date is seen for the chamise, Gambel oak, and sand pine. Sagebrush, manzanita, and ceanothus appear to have a minimum ignition time in the summer. Note that no ignition of the sagebrush was achieved in April or May, when the moisture content was over 200%. The ignition time of the previous year's lodgepole pine and Douglas-fir needles, along with the fetterbush and gallberry leaves appears to have a minimum in May and June.

Dead fuels typically have increased ignition time as the moisture content increases (Babrauskas, 2003; McAllister, 2013; Simms and Law, 1967). As shown in Figure 4, only two species showed the expected positive linear relationship between the ignition time and the moisture content: sagebrush ($r^2 = 0.82$) and Douglas-fir ($r^2 = 0.72$). The simple linear

Table 1. Monthly rainfall (cm) in each location during the sample period (National Climatic Data Center, n.d.; Desert Research Institute, n.d.).

	4/12	5/12	6/12	7/12	8/12	9/12	10/13	11/12	12/12	1/13	2/13	3/13
Missoula, MT	3.07	4.34	7.09	2.64	0.43	0.00	4.57	3.56	4.22	2.90	0.76	1.45
Provo, UT	1.96	1.19	0.00	2.51	0.38	2.26	1.78	4.62	6.32	2.67	1.37	0.51
Riverside, CA	3.63	0.25	0.00	0.36	4.57	1.65	0.69	3.53	4.32	4.24	1.07	0.94
Missoula, MT	5/13	6/13	7/13	8/13	9/13	10/13	11/13	12/13	1/14	2/14	3/14	4/14
Provo, UT	3.58	4.83	0.41	1.32	3.78	0.18	1.40	2.82	2.13	6.17	4.52	2.01
Riverside, CA	2.34	0.00	2.44	1.78	6.10	3.78	2.01	5.82	3.00	4.78	2.57	0.00
Crestview, FL	2.57	0.00	0.10	0.00	0.38	0.00	1.83	0.23	1.63	2.01	0.36	1.45
	2.77	15.98	48.49	14.22	16.81	3.71	8.66	13.13	5.59	0.00	15.06	37.52

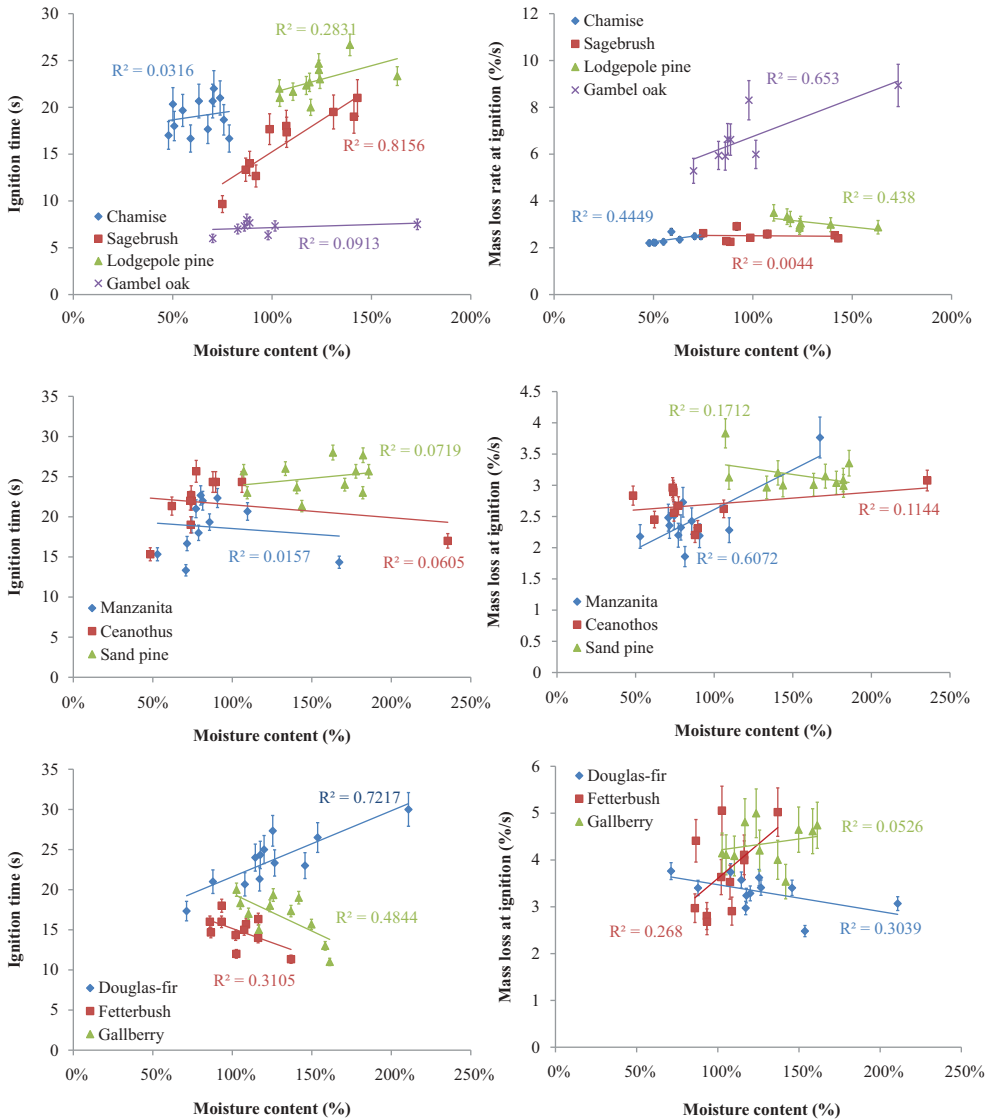


Figure 4. Left: Variation of ignition time with MC. Right: Variation in mass loss rate at ignition with MC. Error bars represent one standard deviation and are smaller than the symbol for MC.

regression equation generally accounted for little to none of the variation in ignition time: $r^2 = 0.28, 0.03, 0.09, 0.02, 0.06,$ and 0.07 for lodgepole pine, chamise, Gambel oak, manzanita, ceanothus, and sand pine, respectively. When the new leaves of manzanita and ceanothus were removed, the regression accounted for more of the variation ($r^2 = 0.37, 0.60,$ respectively). Oddly, fetterbush and gallberry actually showed a statistically significant (Table 2) negative linear trend between ignition time and moisture content ($r^2 = 0.31, 0.48,$ respectively) so that the ignition time decreased when the moisture content increased.

The average standard deviation in the mass loss rate at ignition for all species is 7.7% of the mean value and ranged from 0.5–27.2%. The right column of Figure 4 shows mass loss

Table 2. Linear regression statistics.

	Chamise	Sagebrush	Lodgepole pine	Douglas-fir	Manzanita	Ceanothus	Gambel oak	Fetterbush	Gallberry	Sand pine
MC	3.0963	13.6596	14.0335	8.2308	-1.4056	-1.6104	0.2957	-7.0875	-9.3177	1.9052
vs	5.4198	2.2963	4.0554	1.6163	3.5146	2.1149	0.8425	3.5207	3.2045	2.2818
t _{ig}	0.5713	5.9485	3.4604	5.0925	-0.3999	-0.7614	0.3510	-2.0131	-2.9077	0.8349
	0.5804	0.0003	0.0086	0.0005	0.6976	0.4659	0.7399	0.0750	0.0174	0.4254
MC	1.2033	-0.0566	-4.6681	-0.5718	1.2751	0.1906	3.0841	2.9393	0.4802	-0.3573
vs	0.5487	0.3217	7.0418	0.2737	0.3243	0.1768	1.1344	1.6194	0.6795	0.2621
m _{loss}	2.1930	-0.1760	-0.6629	-2.0894	3.9317	1.0781	2.7187	1.8151	0.7067	-1.3634
	0.0708	0.8653	0.5367	0.0632	0.0028	0.3091	0.0418	0.1029	0.4976	0.2059
t _{ig}	0.0023	-0.0123	-4.6681	-0.0510	-0.0654	-0.0519	-0.1310	-0.3860	-0.0906	0.0039
vs	0.0364	0.0205	7.0418	0.0298	0.0413	0.0229	0.9346	0.0747	0.0425	0.0405
m _{loss}	0.0632	-0.5990	-0.6629	-1.7122	-1.5829	-2.2631	-0.1402	-5.1654	-2.1323	0.0970
	0.9517	0.5681	0.5367	0.1176	0.1445	0.0499	0.8940	0.0006	0.0618	0.9248

Note: P-value \leq 0.1 (highlighted) is considered significant.

rate of the fuels at the moment of ignition as a function of the moisture content. There are some interesting trends here as well. Several species show the expected trend of increasing mass loss rate at ignition with moisture content (McAllister, 2013). The fitted linear regression accounted for more than 30% of the observed variation for chamise, Gambel oak, manzanita, lodgepole pine, and Douglas-fir ($r^2 = 0.44, 0.65, 0.61, 0.44, \text{ and } 0.30$, respectively). However, the regressions accounted for less variation in fetterbush, old manzanita leaves, sagebrush, ceanothus, sand pine, and gallberry ($r^2 = 0.27, 0.00, 0.00, 0.11, \text{ and } 0.05$, respectively). Interestingly, Douglas-fir shows a statistically significant negative correlation between the mass loss at ignition and the moisture content ($r^2 = 0.30$; see also Table 2). Unlike the manzanita leaves, when the data points from the new needles were excluded from the correlation, the trends did not change. It is worth remembering that old and new needles can have very different composition (amount of sugars and starches compared to cellulose and lignin; Little, 1970).

Figure 5 shows the mass loss rate at ignition as a function of ignition time. As shown, linear regressions using ignition time accounted for very little of the variation in mass loss for chamise, sagebrush, Gambel oak, sand pine, and old manzanita leaves ($r^2 = 0.00, 0.05, 0.00, 0.00, \text{ and } 0.02$, respectively). The regression accounted for more of the variation for all other species (for example, for all manzanita leaves and fetterbush, $r^2 = 0.20 \text{ and } 0.75$, respectively). *t*-Tests of the significance of the slope term (Table 2) indicated that this is a *negative* correlation—the samples with the longer ignition time had the lowest rate of mass loss at ignition. Figure 6 shows the data from McAllister (2013) for wet wood plotted in

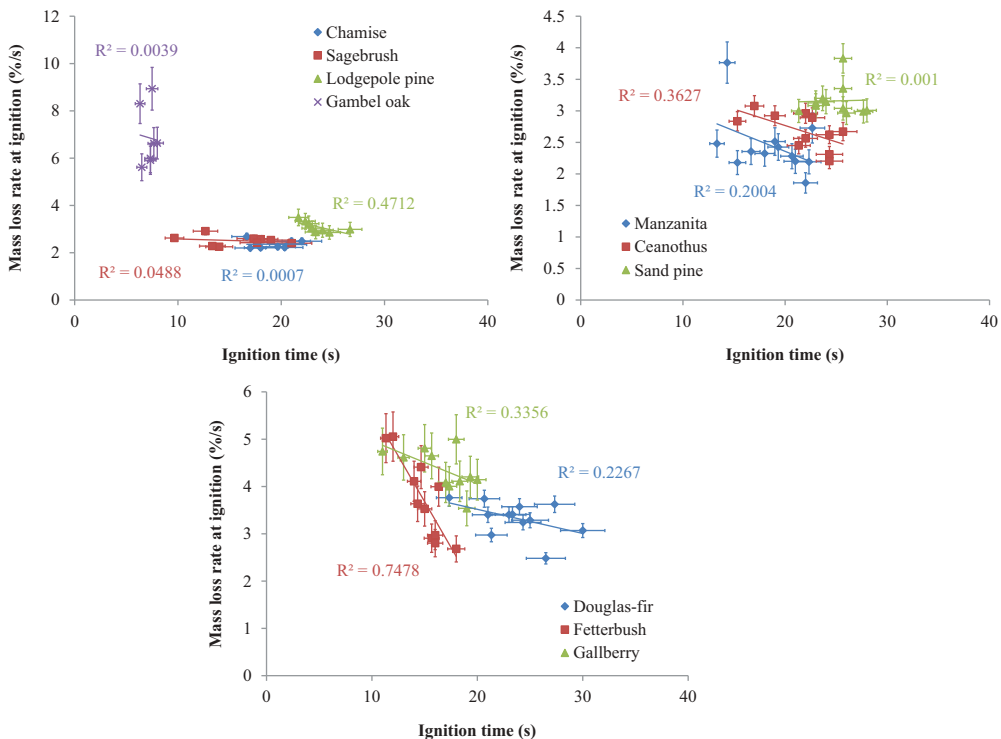


Figure 5. Mass loss rate at ignition and ignition time. Error bars represent one standard deviation.

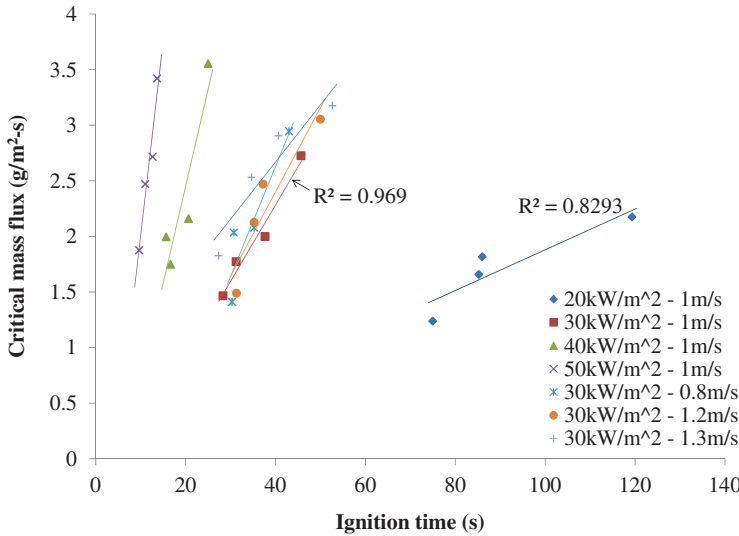


Figure 6. Critical mass flux for ignition of wet wood and ignition time (data from McAllister, 2013).

this form. As shown, the critical mass flux for ignition of thermally-thick wet wood is *positively* correlated to the ignition time ($r^2 = 0.83\text{--}0.97$). In fact, for the conditions tested here (50 kW/m^2 and 1 m/s), the critical mass flux at ignition dramatically increases with ignition time. This is attributed to both the solid and gas-phase effects of the moisture content (Babrauskas, 2003; McAllister, 2013; Simms and Law, 1967)—the change in thermal properties slows the heating of the solid while the water vapor dilutes the pyrolyzates, which can affect the flame temperature (e.g., Ferguson et al., 2013). Though the fuel species tested here seem physically thin, it has been demonstrated that, due to such high moisture contents, live wildland fuels behave more as a thermally-intermediate solid, if not a thermally-thick solid (Benkousas et al., 2007; McAllister et al., 2012; Yashwanth et al., 2016). This would imply that the live fuels should follow the same trends as the thermally-thick wet wood. However, there are a couple of differences between live and dead fuels that could be playing a role here. Dead fuels can only store water as “free” water, whereas live fuels can store much of their water as “interstitial” water (inside cells; Nelson, 2001). This could dramatically change the way the water is released from the fuel and possibly even how the moisture changes the thermal properties. Also, the chemical composition of wood is fixed, whereas the chemical composition of live fuel changes due to plant metabolic processes. This change in composition can influence the pyrolysis products, possibly making them more or less flammable.

Summary

The most dangerous and unpredictable wildland fires are crown fires in which the live, green foliage ignites and carries the fire. Prescribed fires are also conducted in fuel beds containing live, green foliage. Thus, an understanding of what variables affect the ignition of these live fuels is crucial to predicting fire spread in living forest and shrub fuels. The moisture content, ignition time, and mass loss rate at ignition were measured monthly for

Table 3. Summary of trends.

Species	MC vs tig	MC vs mloss	tig vs mloss
Wet wood	↗	↗	↗
Chamise	NT	↗	NT
Sagebrush	↗	NT	NT
Lodgepole pine	↗	NT	↘
Douglas-fir	↗	↘	↘
Manzanita	NT (↗ if only old leaves)	↗ (NT if only old leaves)	↘ (NT if only old leaves)
Ceanothus	NT (↗ if only old leaves)	NT	↘
Gambel oak	NT	↗	NT
Fetterbush	↘	↗	↘
Gallberry	↘	NT	↘
Sand pine	NT	NT	NT

Note. NT = no trend ($r^2 < 0.2$ and $p > 0.1$).

ten common North American fuels for an entire year. It was clearly demonstrated that live fuels do not obey the same trends and rules as dead fuels. Species-to-species variation was also shown to be a major issue. A summary of all trends is provided in Table 3. Due to the potential physical and chemical changes that live fuels undergo, moisture content is not a particularly useful descriptor of live fuels when discussing ignition behavior. Future work will focus on examining other physical and chemical properties of live fuels that may be more productive predictors of ignition behavior. A first step may be measuring the thermal properties of these live fuels and how they vary during the growing season. This may allow for deeper understanding of these trends by non-dimensional analysis and allow for comparisons between species.

Disclaimer

The use of trade names is provided for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Acknowledgments

The authors would like to thank Scott Pokswinski for the samples from Florida, and Joey Chong for the samples from southern California. The authors would also like to thank the folks at BYU (Tom Fletcher, Jonathan Gallacher, Dallan Prince, Victoria Lansigner, and others) for the samples from Utah, and for the discussions of the results from their apparatus.

Funding

The authors acknowledge the funding provided by JFSP Grant 11-1-4-14. S. McAllister was also funded by the National Fire Decision Support Center.

ORCID

D. R. Weise  <http://orcid.org/0000-0002-9671-7203>

References

- Alexander, M.E., and Cruz, M.G. 2013. Assessing the effect of foliar moisture content on the spread rate of crown fires. *Int. Wildland Fire*, **22**, 415–427.
- Babrauskas, V. 2003. *Ignition Handbook*, Fire Science Publishers, Issaquah, WA, p. 1116.
- Benkoussas, B., Consalvi, J.L., Porterie, B., Sardoy, N., and Loraud, J.C. 2007. Modelling thermal degradation of woody fuel particles. *Int. J. Therm. Sci.*, **46**, 319–327.
- Boulet, P., Parent, G., Acem, Z., Collin, A., and Séro-Guillaume, O. 2011. On the emission of radiation by flames and corresponding absorption by vegetation in forest fuels. *Fire Saf. J.*, **46**, 21–26.
- Butler, B.W., Cohen, J., Latham, D.J., Schuette, R.D., Sopko, P., Shannon, K.S., Jimenez, D., and Bradshaw, L.S. 2004. Measurements of radiant emissive power and temperatures in crown fires. *Can. J. Forest Res.*, **34**, 1577–1587.
- Byram, G.M., Sauer, F.M., Fons, W.L., and Arnold, R.K. 1952a. Thermal conductivity of some common forest fuels. Interim Technical Report AFSWP-405. USDA Forest Service, Division of Fire Research, Washington, DC. Available at: <http://www.treearch.fs.fed.us/pubs/42677>.
- Byram, G.M., Sauer, F.M., Fons, W.L., and Arnold, R.K. 1952b. Thermal properties of forest fuels. Interim Technical Report AFSWP-404. USDA Forest Service, Division of Fire Research, Washington, DC. Available at: http://www.fs.fed.us/psw/publications/documents/cfres_series/cfres_itr_afswp404.pdf.
- Chrosiewicz, Z. 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. *Can. J. For. Res.*, **16**(1), 157–162.
- Cohen, J., and Bradshaw, B. 1986. Fire behavior modeling—A decision tool. In A. L. Koonce (Ed.), *Proceedings Prescribed Burning in the Midwest: State of the Art*, University of Wisconsin at Stevens Point, Stevens Point, WI, pp. 1–5. <http://www.treearch.fs.fed.us/pubs/47678>.
- Countryman, C.M. 1972. The fire environment concept. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.
- Countryman, C.M., and Dean, W.A. 1979. Measuring moisture content in living chaparral: A field user's manual. General Technical Report PSW-36. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Berkeley, CA. Available at: <http://www.treearch.fs.fed.us/pubs/24092>.
- Desert Research Institute. Western Regional Climate Center. Vista Grande California. Available at: <http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?caCVIS>.
- Dimitrakopoulos, A.P., and Papaioannou, K.K. 2001. Flammability assessment of Mediterranean forest fuels. *Fire Technol.*, **37**, 143–152.
- Engstrom, J.D., Butler, J.K., Smith, S.G., Baxter, L.L., Fletcher, T.H., and Weise, D.R. 2004. Ignition behavior of live California chaparral leaves. *Combust. Sci. Technol.*, **176**(9), 1577–1591.
- Fereres, S., Lautenberger, C., Fernandez-Pello, C., Urban, D., and Ruff, G. 2011. Mass loss rate at ignition in reduced pressure environments. *Combust. Flame*, **158**, 1301–1306.
- Ferguson, S.C., Dahale, A., Shotorban, B., Mahalingam, S., and Weise, D.R. 2013. The role of moisture on combustion of pyrolysis gases in wildland fires. *Combust. Sci. Technol.*, **185**, 435–453.
- Finney, M.A., Cohen, J.D., McAllister, S.S., and Jolly, W.M. 2013. On the need for a theory of wildland fire spread. *Int. J. Wildland Fire*, **22**(1), 25–36.
- Fletcher, T.H., Pickett, B.M., Smith, S.G., Spittle, G.S., Woodhouse, M.M., Haake, E., and Weise, D. R. 2007. Effects of moisture on ignition behavior of moist California chaparral and Utah leaves. *Combust. Sci. Technol.*, **179**(6), 1183–1203.
- Gallacher, J.R. 2016. The influence of season, heating mode and slope angle on wildland fire behavior. PhD. Brigham Young University, Provo, UT.
- Gallacher, J.R., Lansinger, V., Hansen, S., Weise, D.R., and Fletcher, T.H. 2015. Effects of season and heating model on ignition and burning behavior of ten species of live fuel measured in a flat-flame burner system. Presented at the 9th US National Meeting, Cincinnati, OH, May 17–20.
- Haase, S.M., Sánchez, J.J., and Weise, D.R. 2016. Evaluation of standard methods for collecting and processing fuel moisture samples. USDA Forest Service, Pacific Southwest Research Station, Albany, CA.

- Hays, R.L. 1975. The thermal conductivity of leaves. *Planta*, **125**(3), 281–287.
- Hough, W.A. 1969. Caloric value of some forest fuels of the southern United States. Res. Note SE-120. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
- Hough, W.A., and Albini, F.A. 1978. Predicting fire behavior in palmetto-gallberry fuel complexes. Res. Paper SE-174. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
- Jervis, F.X., and Rein, G. 2016. Experimental study on the burning behavior of *Pinus halepensis* needles using small-scale fire calorimetry of live, aged and dead samples. *Fire Mater.*, **40**(3), 385–395.
- Jolly, W.M., Hadlow, A.M., and Huguet, K. 2014. De-coupling seasonal changes in water content and dry matter to predict live conifer foliar moisture content. *Int. J. Wildland Fire*, **23**(4), 480–489.
- Jolly, W.M., Parsons, R.A., Hadlow, A.M., Cohn, G.M., McAllister, S.S., Popp, J.B., Hubbard, R.M., and Negron, J.F. 2012. Relationships between moisture, chemistry, and ignition of *Pinus contorta* needles during the early stages of mountain pine beetle attack. *For. Ecol. Manage.*, **269**, 52–59.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. 2006. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, **15**(3), 259–263.
- Kozłowski, T.T., and Clausen, J.J. 1965. Changes in moisture contents and dry weight of buds and leaves of forest trees. *Bot. Gaz.*, **126**(1), 20–26.
- Linn, R.R. 1997. A transport model for prediction of wildfire behavior. Technical Report LA-13334-T. Los Alamos National Laboratory, Los Alamos, NM.
- Little, C.H.A. 1970. Seasonal changes in carbohydrate and moisture content in needles of balsam fir (*Abies balsamea*). *Can. J. Bot.*, **48**, 2021–2028.
- Mardini, J., Lavine, A.S., Dhir, V.K., and Anderson, E.B. 1989. Heat and mass transfer in live fuel during the process of drying, pyrolysis, and ignition. In *Heat Transfer Division* (Publication HTD), Vol. 106, pp. 367–373, American Society of Mechanical Engineers (ASME), Philadelphia, PA.
- McAllister, S. 2013. Critical mass flux for flaming ignition of wet wood. *Fire Saf. J.*, **61**, 200–206.
- McAllister, S., Grenfell, I., Hadlow, A., Jolly, W.M., Finney, M., and Cohen, J. 2012. Piloted ignition of live forest fuels. *Fire Saf. J.*, **51**, 133–142.
- Mell, W., Jenkins, M.A., Gould, J., and Cheney, P. 2007. A physics based approach to modeling grassland fires. *Int. J. Wildland Fire*, **16**, 1–22.
- Monod, B., Collin, A., Parent, G., and Boulet, P. 2009. Infrared radiative properties of vegetation involved in forest fires. *Fire Saf. J.*, **22**, 88–95.
- National Climatic Data Center. Annual Climatological Summary. Available at: www.ncdc.noaa.gov.
- Nelson, Jr., R.M. 2001. Water relations of forest fuels. In E.A. Johnson and K. Miyanishi (Eds.), *Forest Fires: Behavior and Ecological Effects*, Academic Press, San Diego, CA, pp. 79–149.
- Nelson, Jr., R.M., Butler, B.W., and Weise, D.R. 2012. Entrainment regimes and flame characteristics of wildland fires. *Int. J. Wildland Fire*, **21**, 127–140.
- Philpot, C.W. 1969. Seasonal changes in heat content and ether extractive content of chamise. USDA Forest Research Paper INT-61. Forest Service, Ogden, UT.
- Pickett, B.M., Isackson, C., Wunder, R., Fletcher, T.H., Butler, B.W., and Weise, D.R. 2010. Experimental measurements during combustion of moist individual foliage samples. *Int. J. Wildland Fire*, **19**(2), 153–162.
- Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Research Paper INT-115. Forest Service, Ogden, UT.
- Rothermel, R.C., and Philpot, C.W. 1973. Predicting changes in chaparral flammability. *J. For.*, **71**(10), 640–643.
- Silvani, X., Morandini, F., and Muzy, J.F. 2009. Wildfire spread experiments: Fluctuations in thermal measurements. *Int. Commun. Heat Mass*, **36**, 887–892.
- Simms, D.L., and Law, M. 1967. The ignition of wet and dry wood by radiation. *Combust. Flame*, **11**(5), 377–388.
- Smith, S.G. 2005. Effects of moisture on combustion characteristics of live California chaparral and Utah foliage. MS Thesis. Brigham Young University, Provo, UT.

- Springer, E.A., and Van Wagner, C.E. 1984. The seasonal foliar moisture trend of black spruce at Kapuskasing, Ontario. Canadian Forestry Service, Petawawa National Forestry Institute, Chalk River, Ontario. Available at: <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/23532.pdf>.
- Spurr, S.H., and Barnes, B.V. 1980. *Forest Ecology*, 3rd ed., Wiley, New York.
- Sun, L., Zhou, X., Mahalingam, S., and Weise, D.R. 2006. Comparison of burning characteristics of live and dead chaparral fuels. *Combust. Flame*, **144**(1–2), 349–359.
- Susott, R.A. 1980. Thermal behavior of conifer needle extractives. *For. Sci.*, **26**(3), 347–360.
- Susott, R.A. 1982. Characterization of the thermal properties of forest fuels by combustible gas analysis. *For. Sci.*, **28**(2), 404–420.
- USDA NRCS. 2016. The PLANTS Database. National Plant Data Team, Greensboro, NC. Available at: <http://plants.usda.gov>.
- Van Wagner, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Government of Canada, Department of Forestry and Rural Development, Petawawa Forest Experiment Station, Chalk River, Ontario. Available at: <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/24741.pdf>.
- Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. *Can. J. For. Res.*, **7**(1), 23–34.
- Weise, D.R., White, R.H., Beall, F.C., and Etlinger, M. 2005a. Use of the cone calorimeter to detect seasonal differences in selected combustion characteristics of ornamental vegetation. *Int. J. Wildland Fire*, **14**, 321–338.
- Weise, D.R., Zhou, X., Sun, L., and Mahalingam, S. 2005b. Fire spread in chaparral—“Go or no-go?” *Int. J. Wildland Fire*, **14**, 99–106.
- White, R.H., and Zipperer, W.C. 2010. Testing and classification of individual plants for fire behavior: Plant selection for the wildland–urban interface. *Int. J. Wildland Fire*, **19**, 213–227.
- Xanthopoulos, G., and Wakimoto, R.H. 1993. A time to ignition–temperature–moisture relationship for branches of three western conifers. *Can. J. For. Res.*, **23**, 253–258.
- Yashwanth, B.L., Shotorban, B., Mahalingam, S., Lautenberger, C.W., and Weise, D.R. 2016. A numerical investigation of the influence of radiation and moisture content on pyrolysis and ignition of a leaf-like fuel element. *Combust. Flame*, **163**, 301–316.
- Zahn, S., and Henson, C. 2011. *A Synthesis of Fuel Moisture Collection Methods and Equipment—A Desk Guide*, USDA Forest Service, San Dimas Technology and Development Center, San Dimas, CA. Available at: http://www.fs.fed.us/t-d/php/library_card.php?p_num=1151%201806P.
- Zhou, X., Mahalingam, S., and Weise, D. 2007. Experimental study and large eddy simulation of effect of terrain slope on marginal burning in shrub fuel beds. *Proc. Combust. Inst.*, **31**, 2547–2555.