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Effects of Season on Ignition of Live Wildland Fuels Using the FIST Apparatus

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Abstract: The most dangerous and unpredictable wildland fires are crown fires in which the live, green foliage ignites and carries the fire. Live, green foliage also burns during prescribed fires in shrublands. 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. Of particular interest is how the flammability of these fuels changes with season. This paper presents the results of ignition tests performed over the course of an entire year for ten species: lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), big sagebrush (*Artemisia tridentata*), gambel oak (*Quercus gambelii*), chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos glandulosa*), ceanothus (*Ceanothus crassifolius*), fetterbush (*Lyonia lucida*), gallberry (*Ilex glabra*), and sand pine (*Pinus clausa*). The ignition delay and the mass loss rate at ignition were measured using the FIST (Forced Ignition and Spread Tests) apparatus with a radiant heat flux of 50 kW/m^2 and flow velocity of 1 m/s. The fuel moisture content was also measured. Large species-to-species variation was seen in the correlations between moisture content and ignition time, moisture content and mass loss rate at ignition, and between ignition time and mass loss rate at ignition. Only a few species showed the same behavior as wet wood. Due to the potential physical and chemical changes that live fuels undergo during the growing season, moisture content is not a particularly useful descriptor of live fuels when discussing ignition behavior.
Keywords: Wildland fire, live fuel, ignition

1. Introduction

The most dangerous and unpredictable wildland fires are crown fires in which the live, green foliage ignites and carries 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. Live forest fuels have often been treated as wet, dead fuels in wildfire spread models ([1-3]). However, there is growing indication that this is a poor assumption (see for example [4, 5]). Unfortunately, there have only been a few studies that examined live fuels [6-10]. Early work estimated heat content of several live fuels and found differences between live and dead forms of the same fuel type [11]. Several live fuels were found to have significant quantities of volatile compounds with higher energy content [12]. Differences in peak heat release rate and time to ignition in a cone calorimeter were observed in intact green and ovendry samples of foliage and branches and the difference was attributed to moisture content [13]. White and Zipperer [14] summarized results and difficulties of examining combustion characteristics of live fuels using the cone calorimeter. Fletcher and coworkers ([9, 15, 16]) 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 et al. [7] and McAllister et al. [8] also noted a difference in the ignition behavior of live fuels than cannot be solely explained by moisture content. Jervis et al. [7] 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. [8] 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 weight remains constant. Live fuels, however, can be up to half non-structural carbohydrates like sugars and starches [8]. Because these non-structural carbohydrates are vital for the biological processes of the plant, the amount stored can vary during the growing season and thus the dry weight of the fuel can vary [17]. It is thus very possible that the apparent moisture content of the fuel can change solely due to changes in the dry weight while the relative amount of water stays constant (see for example [4, 18, 19, 20]). A still unexplained empirical observation is the "moisture of extinction" [1]. Wildland fires in dead fuels will not spread above some threshold of fuel moisture content, typically assumed to be between 10 and 40% [1]. However, in crown fires, live fuels with moisture contents well above 70% are what carry the extremely vigorous fire [21]. 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.

A two-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 the trends in the ignition behavior of live fuels hold across experimental apparatuses, especially for different heating methods, viz. radiation only, convection only, and convection with radiation. The results of the radiation only tests are reported here. The results of the first year of the convection only and convection with radiation tests are reported in [22]. 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 variation in moisture content and chemical composition. Trends in the ignition time, moisture content, and mass loss rate at ignition are noted and discussed.

2. 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 [23, 24]), an apparatus was built to measure the ignition time and critical mass flux (CMF) for sustained flaming ignition of woody materials under these varying environmental conditions. This apparatus, based on the Forced Ignition and flame Spread Test (FIST) (see for example [25]), consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance (see Fig. 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[1]-brand ceramic paper and a 1.27 cm thick Cotronics[1]-brand ceramic board on the bottom. The sample holder sits on top of 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 to 50 kW/m^2 over the sample surface. Ignition was by means of a coiled Kanthal[1] wire kept above 1000°C, located a fixed distance downstream that was chosen to remove the igniter location as a potential variable in the experiments. The time to ignition was recorded 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. To obtain the mass loss rate at ignition, a locally weighted scatterplot smoothing (LOESS) 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. All tests were repeated three times to provide an estimate of the experimental variability.

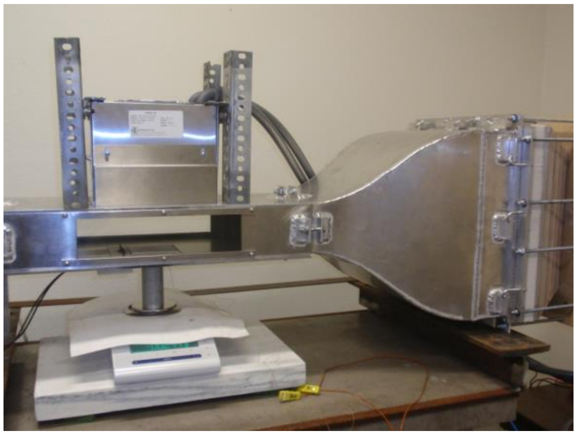

Figure 1: FIST apparatus.

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/m^2. Though wildfires typically produce radiant heat fluxes in the range of 50 to 250 kW/m^2 [27, 28], an irradiance of 50 kW/m^2 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*), big sagebrush (*Artemisia tridentata*), and chamise (*Adenostoma fasciculatum*). For the second year of the project, tests were performed with seven species: Douglas-fir (*Pseudotsuga menziesii*), manzanita (*Arctostaphylos glandulosa*), ceanothus (*Ceanothus crassifolius*), gambel oak (*Quercus gambelii*), fetterbush (*Lyonia lucida*), gallberry (*Ilex glabra*), and sand pine (*Pinus clausa*). In all cases, 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. All samples were tested within two days of collection.

[1] 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.

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 nine months of sampling were performed for the lodgepole pine. Gambel oak is deciduous and only has leaves from about May to October so only six months of samples were taken. The sample site (location, aspect, etc.) was the same each month, but different trees and shrubs were sampled from month to month.

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. 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 [13]. 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 2.8μm [29, 30], and the wavelength of the radiant energy from the quartz lamps is 0.955 μm at 50 kW/m^2. 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 and all samples were arranged to cover as much surface area as possible (see Fig. 2).

To obtain the moisture content, the fuels were weighed then dried in an oven at 80°C for at least 48 hours. 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 (see for example [26]).

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

3. 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 don't are from Utah. As shown in Figure 3 below, 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 each region may require different water management strategies for survival, generating these regional patterns. Sagebrush leaves in particular are very soft and pliable and do not have the hard, waxy coating that the species from Montana, southern California, and Florida have. This waxy coating may make it harder for water to leave the leaves or needles as it evaporates, making the process more of an explosive (and noisy) one than a diffusive one. This was also noted in manzanita leaves in work done by Fletcher and coworkers [15].

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 winter months and lower moisture contents in the summer. Sagebrush, a non-deciduous shrub in Utah, shows the same trend. Gambel oak, however, is deciduous so the leaves are dropped in the fall. The moisture content of this species thus 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 conifers. 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.

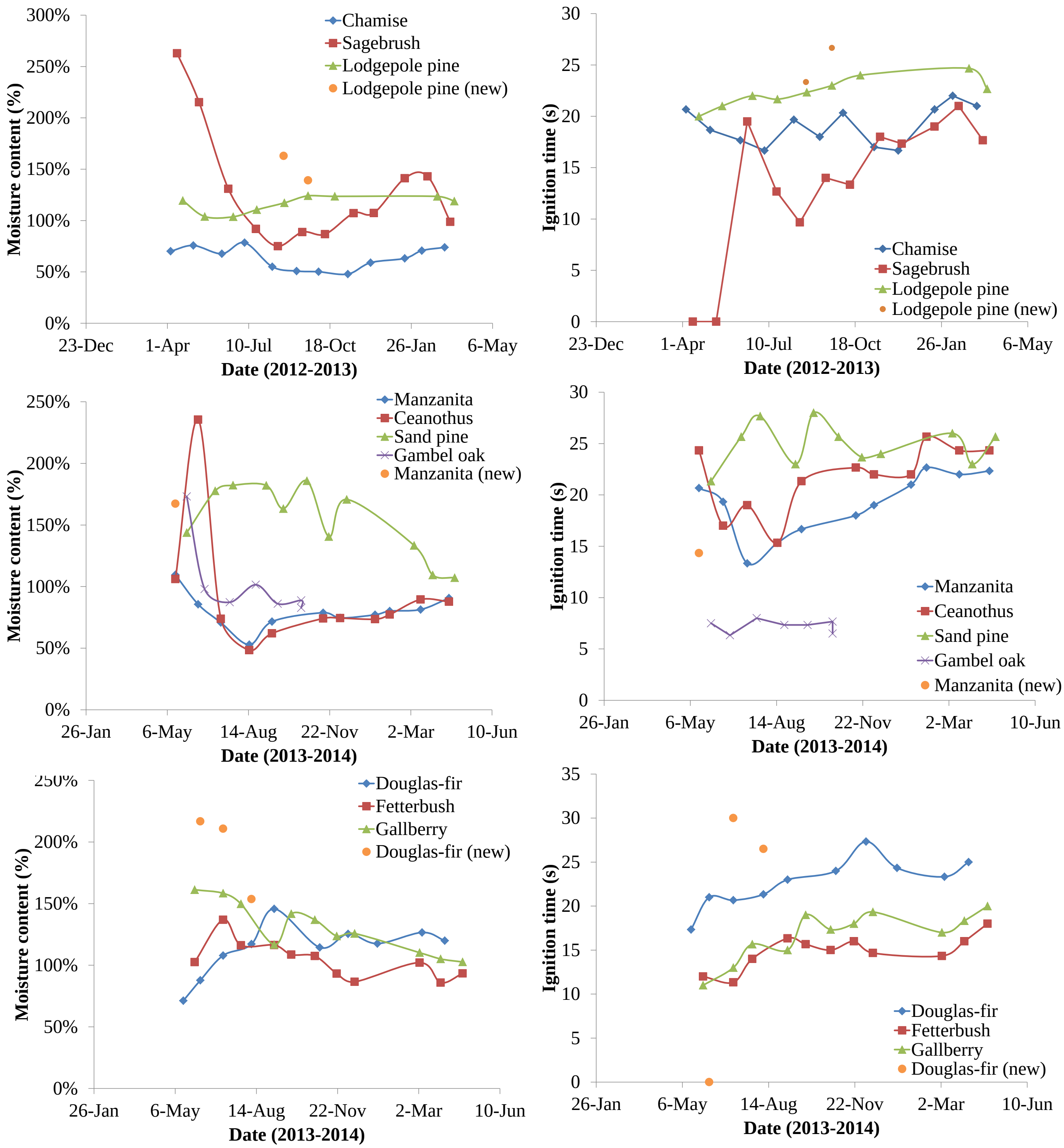

Figure 3. Left column – moisture content versus sample date. Right column – Ignition time versus sample date. Note that new growth is reported separately here when possible. No ignition is shown as zero.

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) [31]; 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 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 Fig. 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.

Table 1. Monthly rainfall (cm) in each location during the sample period [32, 33].

	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
	5/13	6/13	7/13	8/13	9/13	10/13	11/13	12/13	1/14	2/14	3/14	4/14
Missoula, MT	3.58	4.83	0.41	1.32	3.78	0.18	1.40	2.82	2.13	6.17	4.52	2.01
Provo, UT	2.34	0.00	2.44	1.78	6.10	3.78	2.01	5.82	3.00	4.78	2.57	0.00
Riverside, CA	2.57	0.00	0.10	0.00	0.38	0.00	1.83	0.23	1.63	2.01	0.36	1.45
Crestview, FL	2.77	15.98	48.49	14.22	16.81	3.71	8.66	13.13	5.59	0.00	15.06	37.52

Dead fuels typically have increased ignition time as the moisture content increases [34-36]. 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 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, chamise, gambel oak, manzanita, ceanothus, and sand pine, respectively. When the new leaves of manzantia 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 and the moisture content increased.

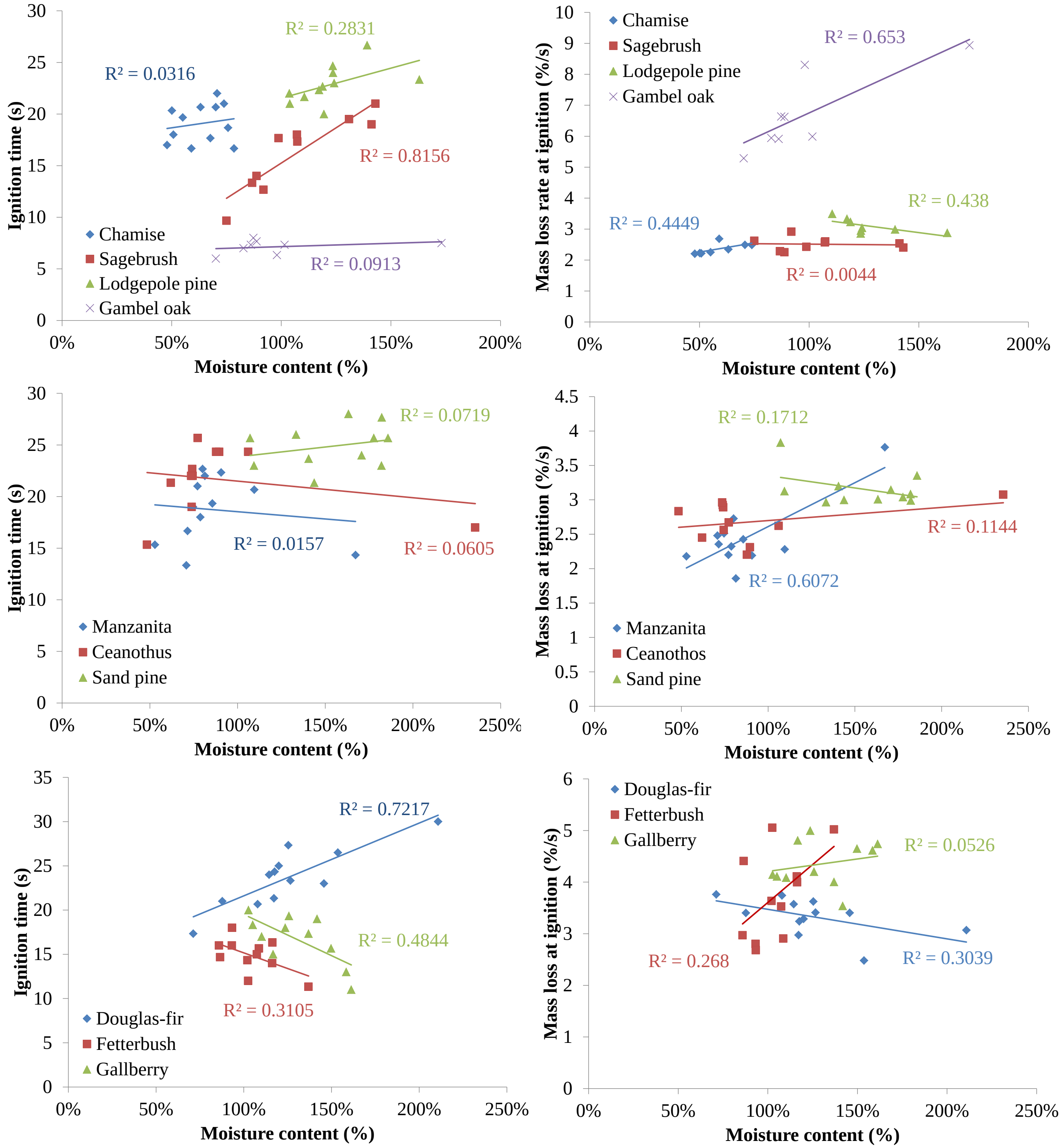

Figure 4. Left column – Variation of ignition time with moisture content. Right column – Variation in mass loss rate at ignition with moisture content.

Table 2. Linear regression statistics. P-value ≤ 0.1 (highlighted) is considered significant.

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

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% to 27.2%. The right column of Figure 4 shows mass loss 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 [34]. 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, and 0.30, respectively). However, the regressions accounted for less variation for fetterbush, old manzanita leaves, sagebrush, ceanothus, sand pine, and gallberry (r^2 = 0.27, 0.00, 0.00, 0.11 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 are excluded from the correlation, the trends do 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) compared to the old needles and leaves [17].

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, 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 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 [34] for wet wood plotted in this form. As shown, the critical mass flux for ignition of thermally-thick wet wood is *positively* correlated to the ignition time (r^2 = 0.83-0.97). 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 ([34-36]) – the change in thermal properties slows the heating of the solid while the water vapor dilutes the pyrolyzates. 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 ([8, 37]). 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) [38]. 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 the live fuel changes. This change in composition can influence the pyrolysis products, possibly making them more or less flammable.

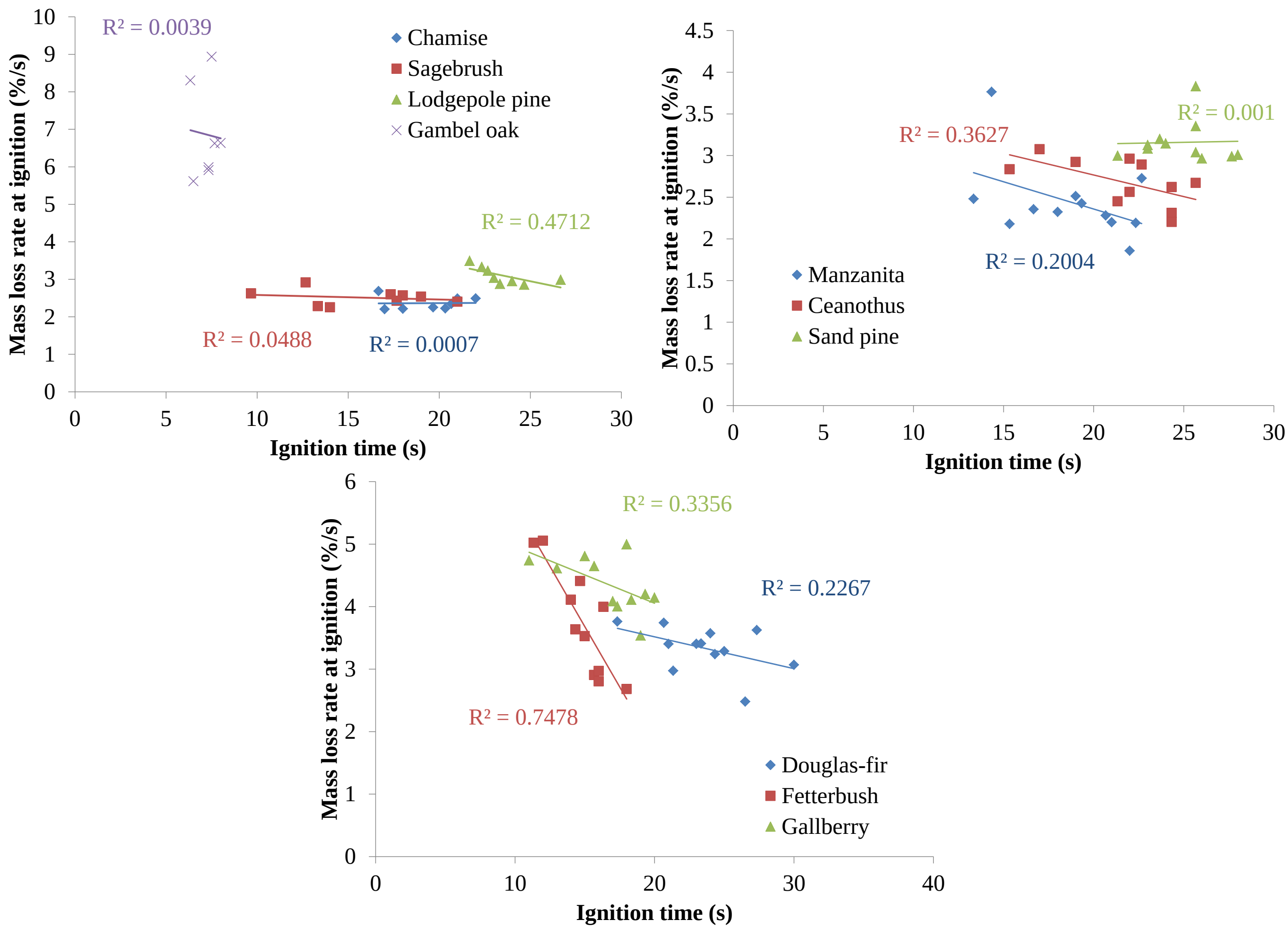

Figure 5. Mass loss rate at ignition and ignition time.

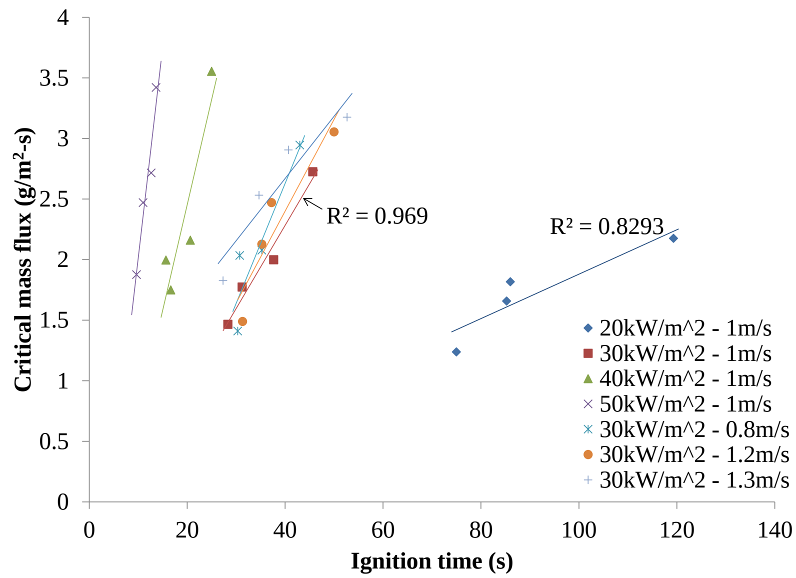

Figure 6. Critical mass flux for ignition of wet wood and ignition time from [34].

Table 3. Summary of trends. NT = no trend ($r^2 < 0.2$ and $p > 0.1$)

Species	MC vs t_{ig}	MC vs m_{loss}	t_{ig} vs m_{loss}
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

4. Conclusions

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 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.

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