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Effects of season on ignition of three species of live wildland fuels using the FIST apparatus

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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 three species: lodgepole pine (*Pinus contorta*), big sagebrush (*Artemisia tridentata*), and chamise (*Adenostoma fasciculatum*). The ignition delay and the mass loss rate at ignition were measured using the FIST 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. Contrary to dead fuel results, the ignition time of the lodgepole pine and chamise were not correlated at all to the moisture content. The mass loss rate at ignition was somewhat positively correlated to the moisture content for the chamise, not correlated at all for sagebrush, and somewhat negatively for the lodgepole pine. The mass loss rate at ignition was somewhat negatively correlated to the ignition time for lodgepole pine as well. Both sagebrush and chamise showed no correlation of mass loss with ignition time. Clearly, the trends in ignition are species dependent and may not follow the expected trends based on dead fuels.

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, 2, 3]). However, there is growing indication that this is a poor assumption (see for example [4]). Unfortunately, there have only been a few studies that examined live fuels [5, 6, 7, 8, 9]. Early work estimated heat content of several live fuels and found differences between live and dead forms of the same fuel type [10]. Several live fuels were found to have significant quantities of volatile compounds with higher energy content [11]. 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 [12]. White and Zipperer [13] summarized results and difficulties of examining combustion characteristics of live fuels using the cone calorimeter. Fletcher and coworkers ([8, 14, and 15) 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*. [6] and McAllister *et al*. [7] also noted a difference in the ignition behavior of live fuels than cannot be solely explained by moisture content. Jervis *et al*. [6] 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*. [7] 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 [7]. 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 [16]. 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], [17], and [18]). 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 [19, 20]. 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) and Brigham Young University (BYU) was undertaken to examine 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 first year of the radiation only tests are reported here, while a companion paper presents the first year results of the convection only and convection with radiation tests [21]. 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, and western Montana). Samples 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 [22, 23]), 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) [24-28], 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-$6 \cdot 10^4$, well under the transition to turbulent flow).

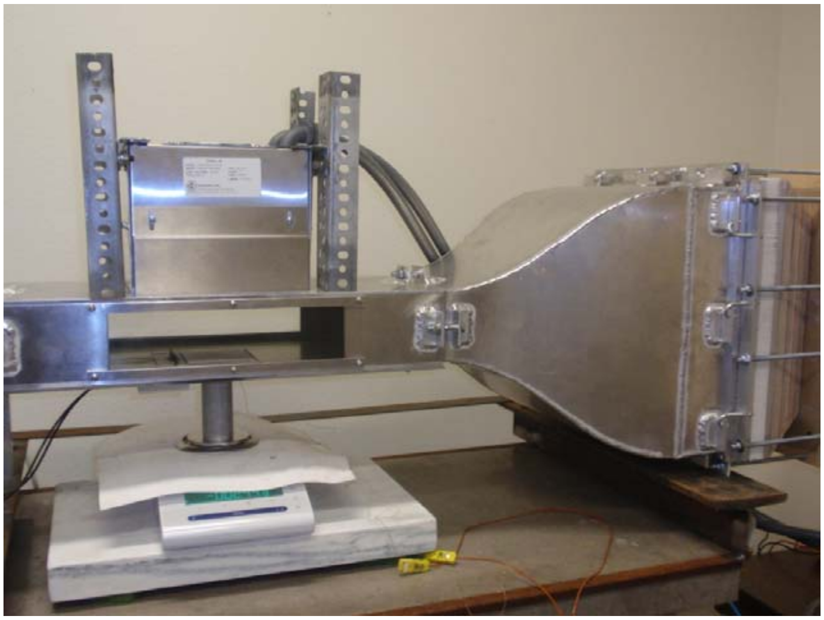

Figure 1 – FIST apparatus

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-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 is 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 is 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 is recorded visually as the time from the initiation of heating until a flame is 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 surface area to find the mass flux. All tests are 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/m^2. Though wildfires typically produce radiant heat fluxes in the range of 50 to 250 kW/m^2 [30 and 31], 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*) from western Montana, big sagebrush (*Artemisia tridentata*) from Utah, and chamise *(Adenostoma fasciculatum*) from southern California. 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 and southern California were shipped overnight to the testing facility. All samples were tested within two days of collection.

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[1] Business and trade names used for reference and do not constitute official endorsement.

As mentioned above, physiological processes throughout the year can alter both the moisture 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 (April 2012 – March 2013), monthly samples sagebrush and chamise 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. The sample site (location, aspect, etc.) was the same each month, but different trees and shrubs were sampled from month to month.

Lodgepole pine was tested using needles pulled from the branch, only taking healthy-looking needles. Because of the length of the needles, no cutting was necessary to fit them into the sample holder. After the new needles burst from the bud and began to separate (August 2012), old and new needles were tested separately until no difference between the two was seen either in ignition time or moisture content (October 2012). For both sagebrush and chamise, 4 cm-long branch tips were used. Sample size was 2g for all species tested and was weighed within 0.05 g. The sample size was chosen so that all species of fuel could lie in the sample holder as a single layer. 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 [32 and 33], 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.

Figure 2 – Lodgepole pine needles in sample holder

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 [29]).

3. Results and Discussion

A visible and audible difference between species was noticed when conducting the tests. The lodgepole pine needles in particular made loud popping and snapping noises while being heated. In fact, they would visibly jump around in the sample holder. The chamise branch tips did as well to some extent, though not nearly as much as the lodgepole needles. The sagebrush branch tips, on the other hand, gradually produced more and more white vapors during the heating process and silently ignited. As shown below in Figure 3, the lodgepole needles had the highest moisture content (103.7 – 163.0%), chamise the lowest (47.9 – 78.4%), with sagebrush in the middle (75.0 – 143.0%). This behavior is thus not strictly a result of moisture content, but is it suspected that it is a result of structural differences between species. Sagebrush leaves are very soft and pliable and do not have the hard, waxy coating that both chamise and lodgepole pine have. The waxy coating on both chamise and lodgepole 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 [14].

Figures 3, 4, and 5 show the trends in moisture content, ignition time, and mass loss rate at ignition, respectively, with the date the fuels were collected and tested. As one can see, there is quite a bit of variation in these trends. For example, the moisture content of the chamise is slightly higher in the spring and winter months which is typical of plants from Mediterranean environments such as California. The moisture content of the sagebrush follows the same trend but shows a much larger variation, ranging from 75% to 263%. On the other hand, the moisture content of the old lodgepole pine needles is nearly constant through the summer, fall, and winter, but shows the “spring dip” commonly seen in conifers. No clear trend in the ignition time with testing date is seen for the chamise, but the sagebrush appears to have a minimum during the summer months. 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 lodgepole pine appears to slowly increase during the testing period. The mass loss rate at ignition for chamise was almost constant through the summer, but increased during the winter and early spring. Note that the measured mass loss includes both the loss of moisture due to evaporation and pyrolysis of the solid fuel; we are currently unable to separate these two signals with the existing apparatus. The mass loss rate of the sagebrush shows a minimum in the fall, while the lodgepole gradually decreased through the testing period. Some of the differences during the sample period may be attributed to geographical location. For example, spring occurs much earlier in southern California than in western Montana. However, this would merely explain shifts in the trends with respect to testing date, but not all of the variation seen here. Clearly, the physiological response of vegetation varies strongly from species to species.

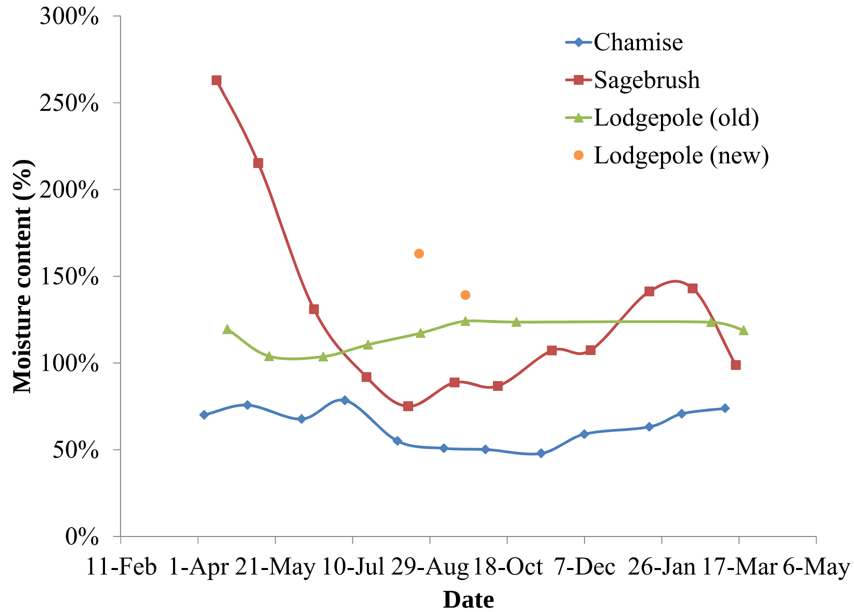

Figure 3 – Trend in moisture content with collection and testing date.

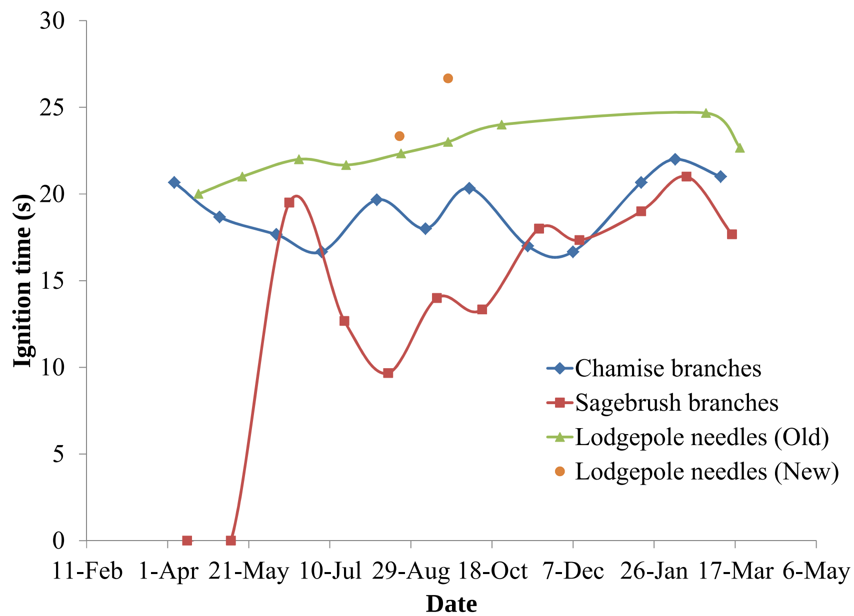

Figure 4 – Trend in ignition time with collection and testing date.

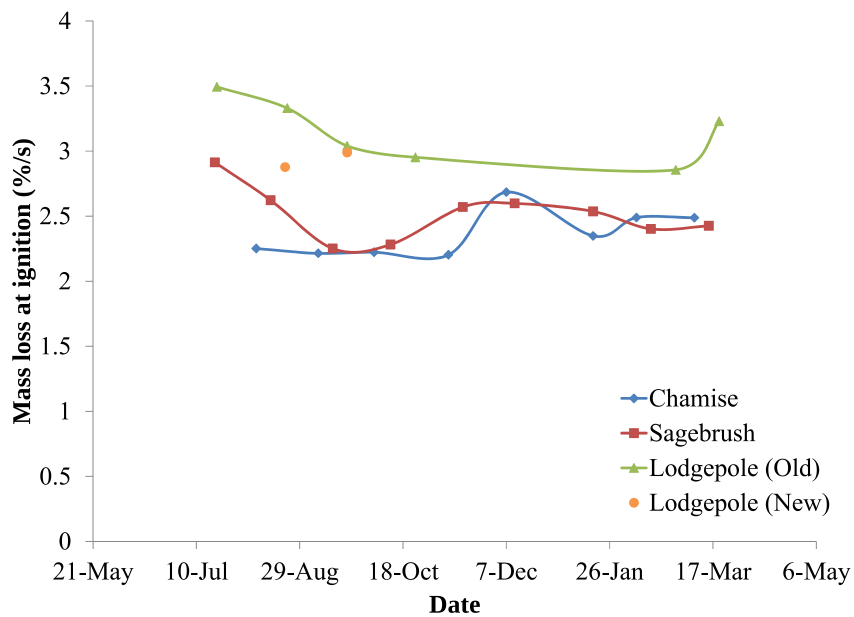

Figure 5 – Trend in mass lost at ignition with collection and testing date.

As shown in Figure 6, the only species that showed a correlation between the ignition time and the moisture content was sagebrush (r^2 = 0.82). Only a slight correlation was found for lodgepole pine (r^2 = 0.28) and virtually no correlation was found for chamise (r^2 = 0.03). This interesting and counter-intuitive result could be partially due to the different structure of sagebrush as discussed above. Again sagebrush leaves are soft, not hard and waxy like the lodgepole pine needles and chamise leaves thus making the evaporation more diffusive and like a dead fuel.

There are some interesting trends as well in the rate of mass loss of the fuels at the moment of ignition as a function of the moisture content as seen in Figure 7. The sagebrush shows no correlation at all (r^2 = 0.0044), while the chamise shows some *increase* with moisture content (r^2 = 0.44), and the lodgpole pine shows some *decrease* with moisture content (r^2 = 0.44). In dead wood, it's been shown in [34] that the mass loss rate at ignition increases with moisture content, just as in the chamise case. Oddly, the lodgepole pine needles show the opposite trend. Both the chamise and sagebrush were tested as branch tips so there was a component of wood along with the leaves. Chamise leaves, however, are very small so the woody component was probably larger than for the sagebrush. The lodgepole needles were tested off the branch, with no woody component. It is unknown, however, whether the mass loss at ignition of *live* wood would follow the same trends as *dead* wood. Also, if the woody component was dominating the behavior, a correlation of the ignition time with the moisture content would be expected. It is also worth noting here that for the lodgepole pine needles, the old and the new needles were tested separately, so the data points with moisture contents of about 160 and 140% are new needles with very different composition (amount of sugars and starches compared to cellulose and lignin) compared to the old needles [16].

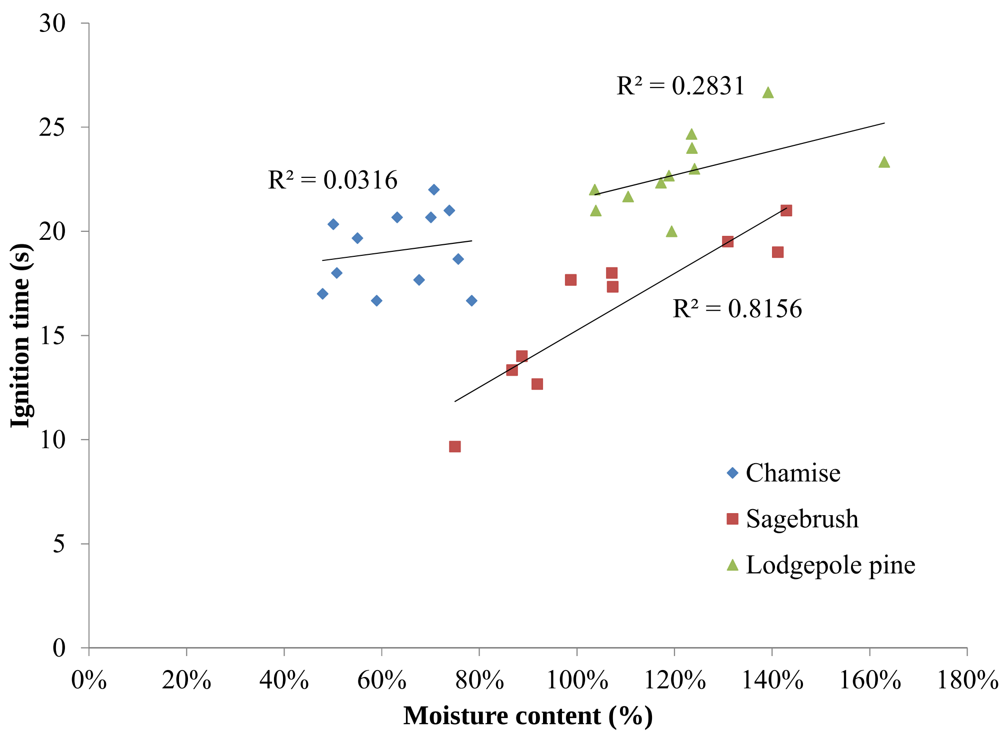

Figure 6 – Ignition time and moisture content

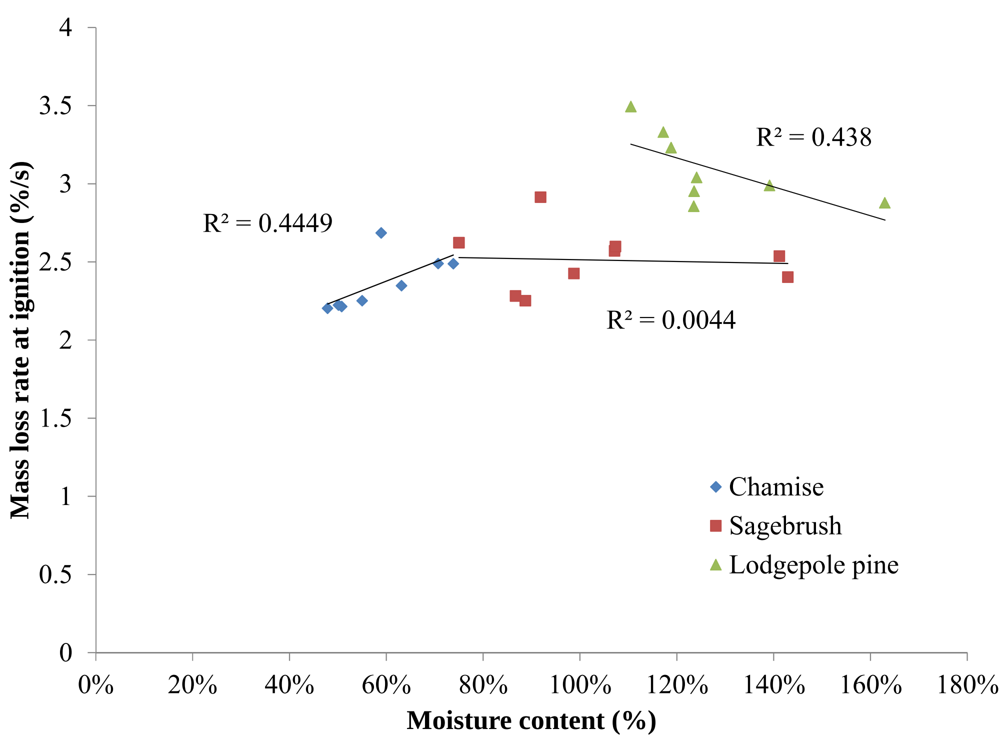

Figure 7 – Mass loss rate at ignition and moisture content

Figure 8 shows the mass loss rate at ignition as a function of ignition time. As shown, the mass loss rate at ignition is somewhat correlated to the ignition time for only the lodgepole pine needles (r^2 = 0.47). Interestingly, this is a *negative* correlation – the samples with the longer ignition time had the lowest rate of mass loss at ignition. Figure 9 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, 35, 36]) – the change in thermal properties slows the heating of the solid while the water vapor dilutes the pyrolyzates [37]. 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 ([7, 38]). 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) [39]. 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.

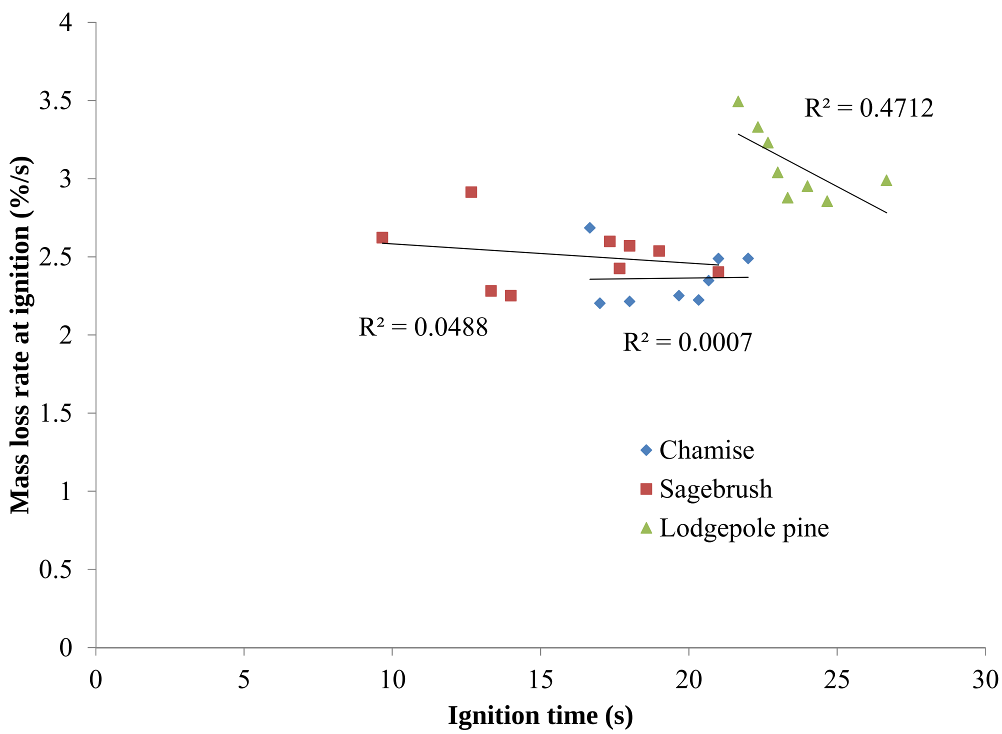

Figure 8 – Mass loss rate at ignition and ignition time

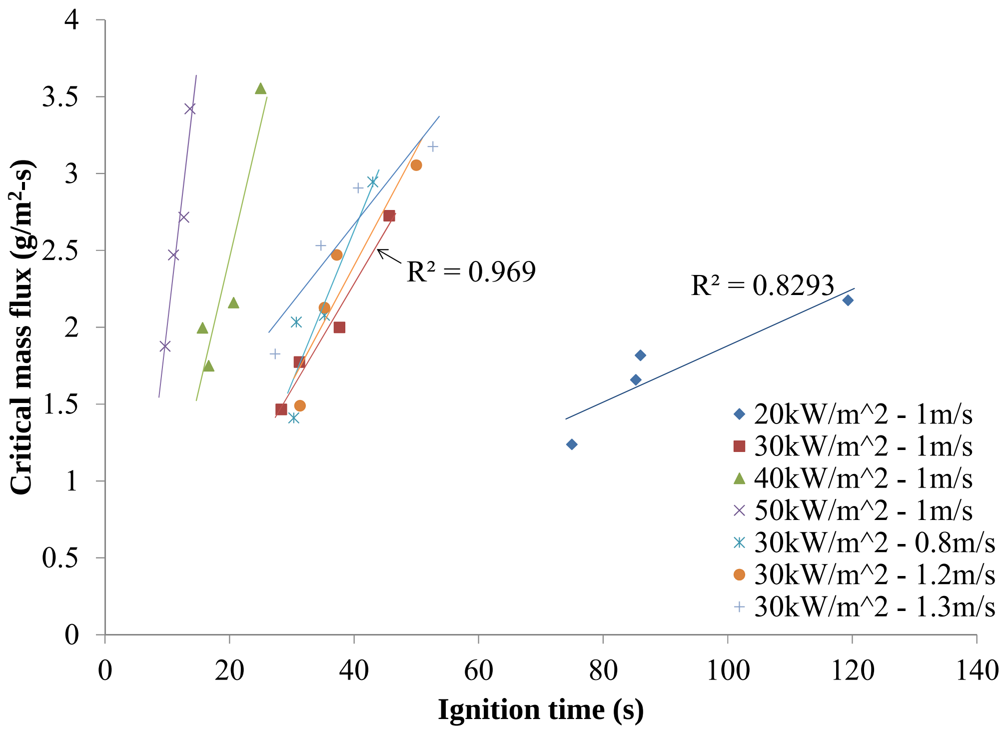

Figure 9 – Critical mass flux for ignition of wet wood and ignition time from [34]

5. 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 three common 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. Future work will focus on examining these trends in different species.

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