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Effects of Season and Heating Mode on Ignition and Burning Behavior of Three Species of Live Fuel Measured in a Flat-flame Burner System*

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The effect of season and heating mode on ignition and burning behavior of living vegetation were studied in a flat-flame burner system with a radiant panel. The goal is to identify what plant characteristics have the greatest influence on burning behavior and to summarize the effects of heating mode on ignition and burning. Experiments were performed over a one-year period, with 25 runs completed for lodgepole pine, big sagebrush, and chamise each month. A flat flame burner (1000 °C, 10 mol% O_2) and radiant panel (39-50 kW/m^2) provide the convection and radiation sources, respectively. Time-dependent mass, surface temperature and flame characteristics were measured. Moisture content (dry basis) was found to vary with season and location, with the lowest measured moisture content corresponding to the local fire season. The effect of moisture content on ignition time and temperature varied with species. Ignition time and temperature showed a strong dependence on heating mode. Flame characteristics were affected by heating mode and moisture content, and the dependence varied by season and species.

1. Introduction

Ignition of wood and other cellulosic fuels has been studied for over 100 years. Research has largely focused on requirements for ignition, conditions during burning, and predictive modeling techniques (including rate of spread calculations). The ultimate goal in wildland fire research is two-fold: (1) to understand the physical phenomena that occur within wildland fires, and (2) to develop models that can predict wildland fire behavior. This study presents the first-year results of a two-year project to study ignition and burning phenomena relative to seasonal changes in plant growth and the mode of heat transfer used for fuel heating. Second-year data are still being collected. The application of these results to fire modeling will be presented at a later date.

1.2 Seasonal and Moisture Effects

Ignition can occur when a fuel sample is heated to the point where pyrolysis rates are high enough to support a gaseous flame *and* a flammable mixture exists in the gas phase. Researchers often simplify this problem by measuring an ignition time and temperature. These values are then used as empirical estimates of the time it takes to heat the sample and the surface temperature when pyrolysis rates can support a continuous flame, respectively. The bulk of the research in this area has focused on ignition temperature. Experimental conclusions to date are mixed. Babrauskas (2001, 2003) summarized the results of ignition temperature experiments on wood fuels and foliage, respectively, and noted the large amount of data scatter (see also Smith, 2005). Babrauskas also reported that ignition temperature ranged from 200-530 °C for wood and 210-450 °C for foliage. Along with variations in experimental setup and measurement techniques, Babrauskas suggested the condition of the sample (moisture content and size) and the species studied can affect the reported ignition temperature. Wildland fire observations support Babrauskas' postulation that species burn differently (Fletcher et al., 2007). However, results by Susott (1982) showed that various plant species have the same heat of combustion and similar TGA (thermogravimetric analysis) pyrolysis mass release curves, and should therefore burn similarly. Susott ground his samples to pass through a 20-mesh screen (<1 mm particles) before performing the analysis. This indicates that observed differences in burning behavior between species are not due to fundamental chemistry alone, but rather could be due to a combination of chemistry, bulk fuel characteristics and the individual cellular structure of various species. The discrepancy illustrates the need for a more thorough understanding of ignition behavior.

These discrepancies are magnified when working with live fuels. Moisture in dead fuels has been shown to increase both ignition time and temperature (e.g. Xanthopoulos and Wakimoto, 1993; Gill and Moore 1996; Moghtaderi et al., 1997; Dimitrakopoulos and Papaioannou, 2001; Catchpole et al., 2002). Water evaporation in dead fuels has been assumed complete in fine fuels once the sample temperature passes 100 °C (e.g. Albini 1967, Rothermel 1972), but Fletcher et al. (2007) showed there is still a significant amount of moisture in live fuels when ignition occurs. Later experiments at BYU (Pickett, 2008) showed water release still occurred at surface temperatures in excess of 200 °C, leading to the conclusion that there is significant interaction between the free water and the cells in live plants that does not occur in dead plants (McAllister, 2012; Prince and Fletcher, 2013). Finney et al. (2013) postulated that water release in live fuels is not complete until breakdown of the cellular structure occurs. Thus, a fundamental understanding of the physical processes that drive live fuel combustion is both absent and necessary if predictive models are to be developed.

1.1 Heating Mode Effects

The relative importance of the different heat transfer mechanisms in live-shrub fires is also not well understood. Much of the work looking at heat transfer mode has focused on dead and woody fuels (Simms, 1960; Simms 1963; McCarter and Broido, 1965; Simms and Law, 1967; Pagni, 1975; Moghtaderi et al., 1997; Morandini et al., 2001; Dupuy et al., 2003; Gratkowski et al., 2006; Pitts, 2007; Reska and Torero, 2008; Silvani and Morandini, 2009). Only a limited amount of work has been performed for live fuels and foliage (Stocks et al., 2004; McAllister et al., 2012). Experiments performed by Rothermel (1972) showed fuel pre-heating in no-wind and backing-fire situations, leading to the conclusion that radiation drives fire spread. However, other experiments have shown that the bulk of the temperature rise occurs within a few centimeters of the flame front in no-wind situations (Fang and Steward, 1969; Baines, 1990) and that significant amounts of pyrolyzates are not formed at the fuel temperatures associated with radiant pre-heating (Cohen and Finney, 2010). Anderson (1969) concluded that radiant heat flux can provide no more than 40% of the energy required for sustained fire spread. This leads to the conclusion that radiation alone is not sufficient to ignite fuel, and that convection is the dominant heat transfer mechanism. Still other work has shown flame propagation to depend strongly on direct flame contact with un-burned fuel (Vogel and Williams, 1970; Carrier et al., 1991). Many experimentalists and modelers have concluded that radiation heat transfer dominates in large fires (Simms, 1960; Balbi et al., 2007; Silvani and Morandini, 2009; Paudel, 2013) and fires with little to no wind in homogeneous fuel beds (Morandini et al., 2001; Morvan and Dupuy, 2001; Sullivan et al., 2003; Morvan and Dupuy, 2004), but the relative effect of radiation and convection for fires outside these conditions is still unknown (Morandini et al., 2001; Sullivan et al., 2003). Work to quantify the contributions of radiation and convection in live-shrub combustion is necessary to understand the basic theory of fire spread and to develop a model that accounts for both mechanisms of heat transfer.

The aim of this project is to explore the effect of season and heating mode on ignition and burning behavior with the hope of learning what physical processes drive fire spread in live shrubs.

2. Experimental Setup

Each month, chamise (Adenostoma fasciculatum), big sagebrush (Artemisia tridentata) and lodgepole pine (Pinus contorta) were burned in the flat flame burner (FFB) apparatus at Brigham Young University (BYU) (see Figure 1). Chamise was collected in Riverside, CA, lodgepole pine was collected in Missoula, MT, and big sagebrush was collected in Provo, UT. Non-local species were sealed in plastic bags to minimize moisture loss and shipped overnight to BYU. Combustion experiments (25 replicates for each species) were usually conducted within 48 hours of collection. Chamise samples consisted of 4 cm sections of branch (diameter < 2 mm) with the needles attached. Lodgepole samples consisted of 2 cm sections of branch (diameter < 5 mm) with the needles attached. Sagebrush samples consisted of groups of leaves connected to a main stem (length 4 cm).

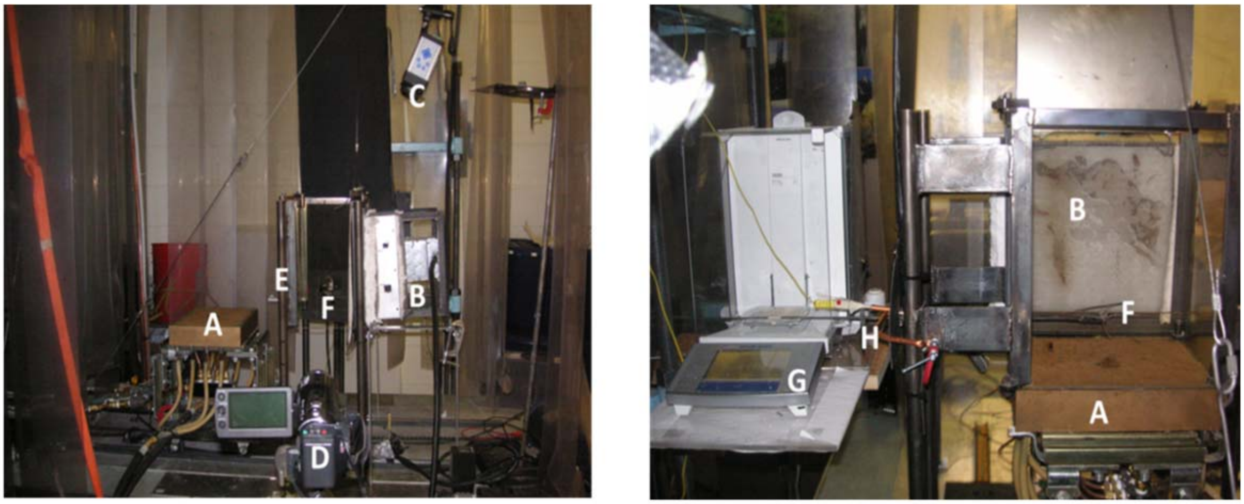

Figure 1: Experimental apparatus showing the flat-flame burner (A), radiant panel (B), FLIR ThermaCAM (C), Panasonic Camcorder (D), glass cage (E), sample location (F), mass balance (G), and holding rod (H).

Average moisture content for each species was measured by drying several samples in a MAX1000 Computrac Moisture Analyzer†. The samples were heated at 95 °C until the mass stopped changing; the moisture content was reported on a dry mass basis (ASTM Standard D4442-07, 2007). Video, mass and temperature data were collected using the apparatus shown in Figure 1. Samples were individually weighed and placed within the apparatus. A water-cooled flat-flame burner (FFB) produced exhaust gases at 1000 °C and 10 mol% oxygen that flow past the sample suspended on a holding rod using an alligator clip. The holding rod was connected to a Mettler Toledo XS204 Cantilever mass balance. Mass data were continuously measured using National Instruments Labview 8.6 Software. A glass cage surrounding the sample prevented ambient air from being entrained in the FFB exhaust gases. An Omega K-type thermocouple (0.013 mm diameter, 0.05 s response time) was used to measure the gas temperature. Smith (2005) corrected these temperature measurements for thermocouple radiation losses and found the losses to be small at these temperatures. A 60 W/in^2 Omega QH-101060 radiant panel was used in radiation experiments. Measured heat flux at the sample holding location was approximately 25-32 W/in^2 (39 – 50 kW/m^2). Video data were captured using a Panasonic SDR S50 Camcorder and were post-processed to extract the flame characteristics listed Table 1. Infrared images were captured using a FLIR ThermaCAM SC500 IR camera and were post-processed using ThermaCAM Researcher Pro 2.8 software with a sample emissivity set to 0.8 (Smith, 2005; Pickett, 2008) to extract surface temperature data.

† The use of trade names is provided for informational purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

Table 1: Flame characteristics derived from video data

Variable	Description
Ignition Time (s)	Time when a visible, sustained flame appears
Ignition Temperature (°C)	Surface temperature at onset of visible, sustained flame*
Burnout Time (s)	Time when the flame disappears
Maximum Flame Height (cm)	Height of tallest flame during a run
Time to Max Flame Height (s)	Time when tallest flame occurs
Maximum Flame Width (cm)	Width of widest flame during a run
Time to Max Flame Width (s)	Time was widest flame occurs

*Temperature averaged over entire surface at ignition time

3. Results

3.1 Seasonal Effects

Moisture content varied significantly throughout the year (see Figure 2). Lodgepole consistently had the highest moisture content, followed by sagebrush and chamise. Lodgepole data were not collected for part of the winter because heavy snow at the sample site made it impractical to collect samples.

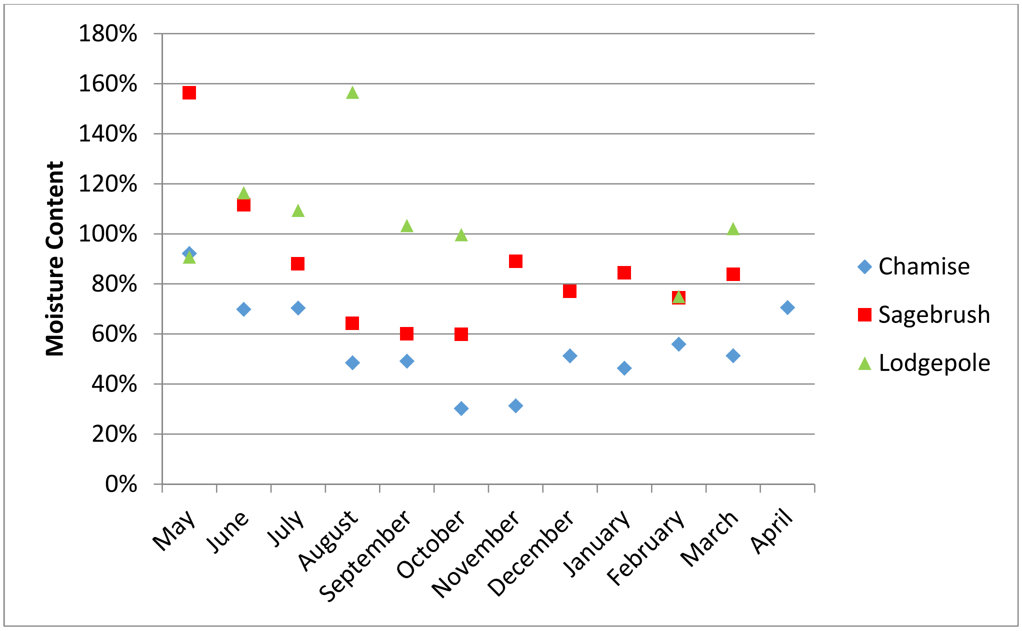

Figure 2: Moisture content versus month for chamise, sagebrush and lodgepole pine

Figure 3 shows the relationship between ignition time and moisture content. As seen in the figure, ignition times for chamise and sagebrush changed by as much as 300% as moisture content varied between high and low values while lodgepole ignition times show almost no dependence on moisture content. Average surface temperature at ignition data show similar trends to ignition time except lodgepole now exhibits a slightly negative relationship (see Figure 4). These observations can be partially explained using a surface area to volume ratio argument. A sample containing relatively large amounts of water would take longer to ignite and the surface temperature would remain low during water evaporation if the hypothesis of Albini and Rothermel is true. However, the observed trend in literature data suggests increased moisture causes longer ignition times and *higher* ignition temperatures. Our results are a combination of these two possible outcomes. Lodgepole pine suggests reduced ignition temperatures at higher moisture content but no dependence of ignition time on moisture. This could be because the high surface area to volume ratio of the lodgepole samples exposes most of the mass to high temperatures at the same time, causing high evaporation rates that keep the surface temperature low. Chamise and sagebrush do not have surface area to volume ratios nearly as high as lodgepole and as a result, we postulate they experience a more gradual water loss. This water loss dilutes pyrolysis gases and causes longer ignition times (e.g. Ferguson et al 2013). Since these samples are exposed to elevated temperatures for a longer time before ignition, this also results in higher surface temperatures at ignition.

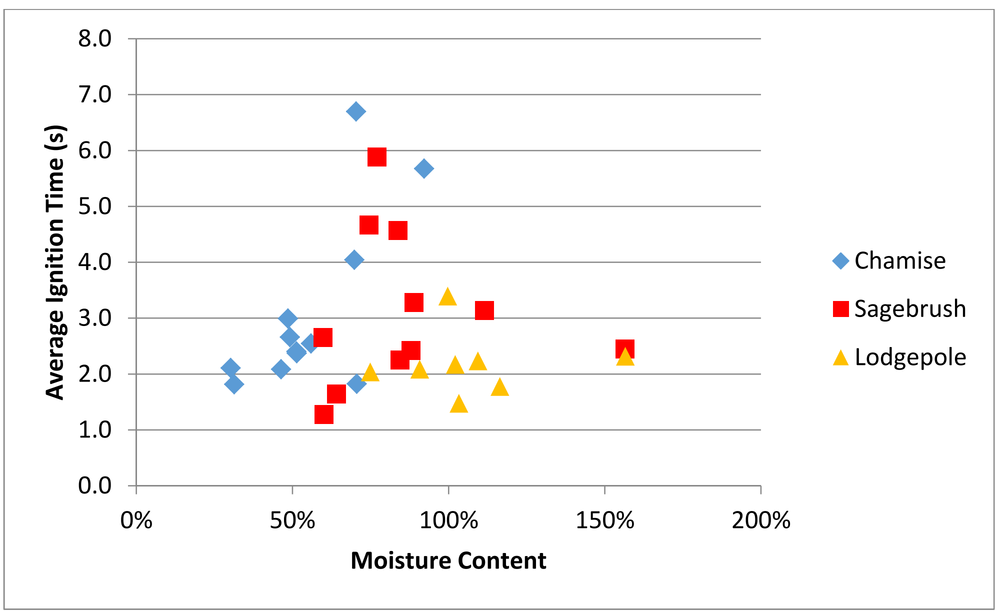

Figure 3: Average ignition time as a function of moisture content.

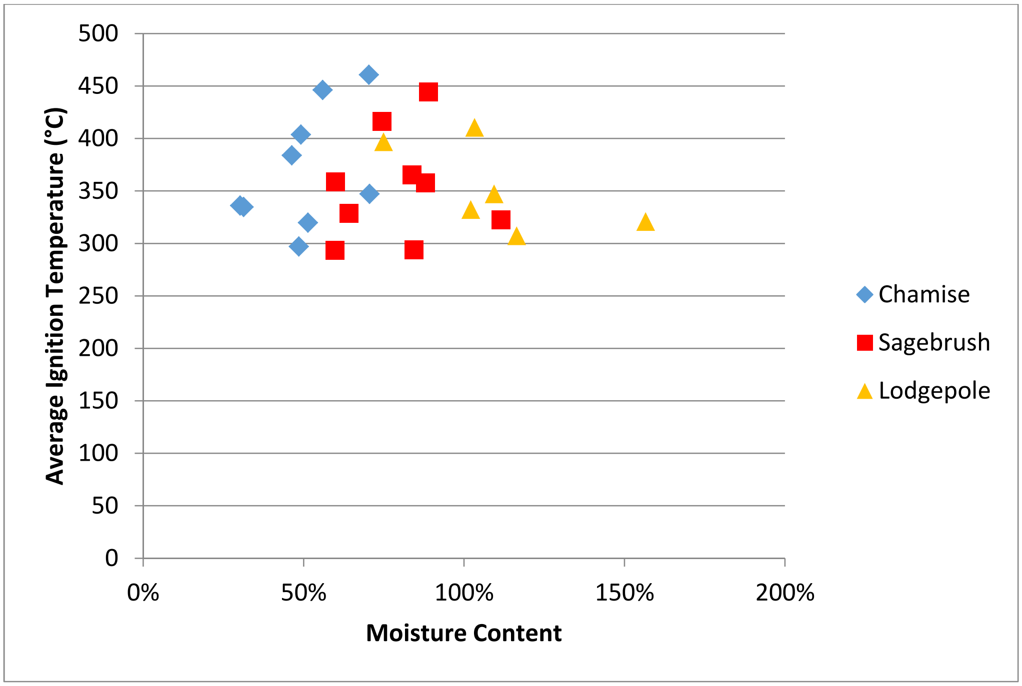

Figure 4: Average ignition temperature as a function of moisture content

Mass loss versus time curves for data from March, 2013 illustrate the differences in combustion behavior between species (see Figure 5). Moisture contents were 51% for chamise, 84% for sagebrush, and 102% for lodgepole. As seen in the figure, the initial mass loss rate was highest for lodgepole pine but tapered off rapidly after a few seconds. Approximately 20% of the initial mass was left at the end of the run. This remaining mass was the woody material in the stem of the lodgepole sample. Chamise initially lost mass at a rate similar to lodgepole but the chamise mass loss rate remained high for several seconds longer than the lodgepole mass loss rate. The result was a final mass of less than 10% of the initial mass. Sagebrush lost mass much slower than either chamise or lodgepole but ended with the same fraction of mass remaining as chamise. The anatomy of the samples may explain the differences. The high surface area to volume ratio resulting from long needles caused lodgepole to lose mass much more quickly at the beginning of the run than either chamise or sagebrush. Once the needles are consumed, the mass loss rate for lodgepole quickly reduces to near zero and is governed by surface oxidation. This oxidation is slowed by the difficulty that oxygen has in diffusing to the interior of the stem to oxidize the unreacted carbon. Chamise and sagebrush do not have thick stems and are not subject to mass transfer limitations. Therefore, almost all of the organic mass is consumed during flaming combustion, leaving mostly ash behind.

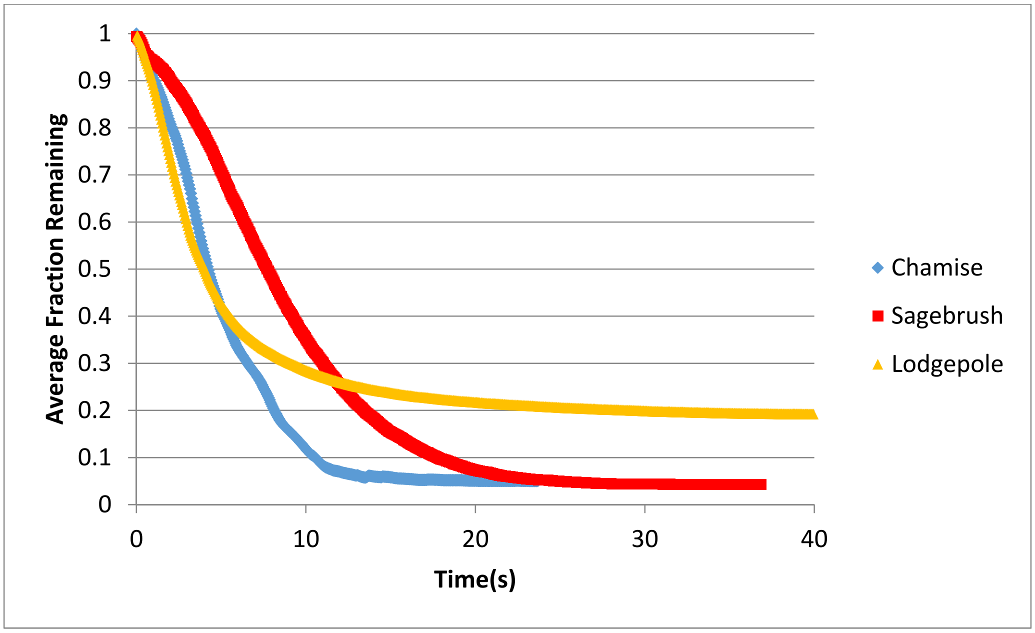

Figure 5: Time dependent mass curves for chamise, sagebrush and lodgepole in March, 2013.

Figure 6 shows mass loss curves for sagebrush from December, 2012 and March, 2013. This figure illustrates the fact that burning behavior for the same species can change during the year. Moisture contents for the samples were 77% and 84%, respectively. The higher moisture sample burned more rapidly, indicating moisture isn't the only variable that affects burning behavior.

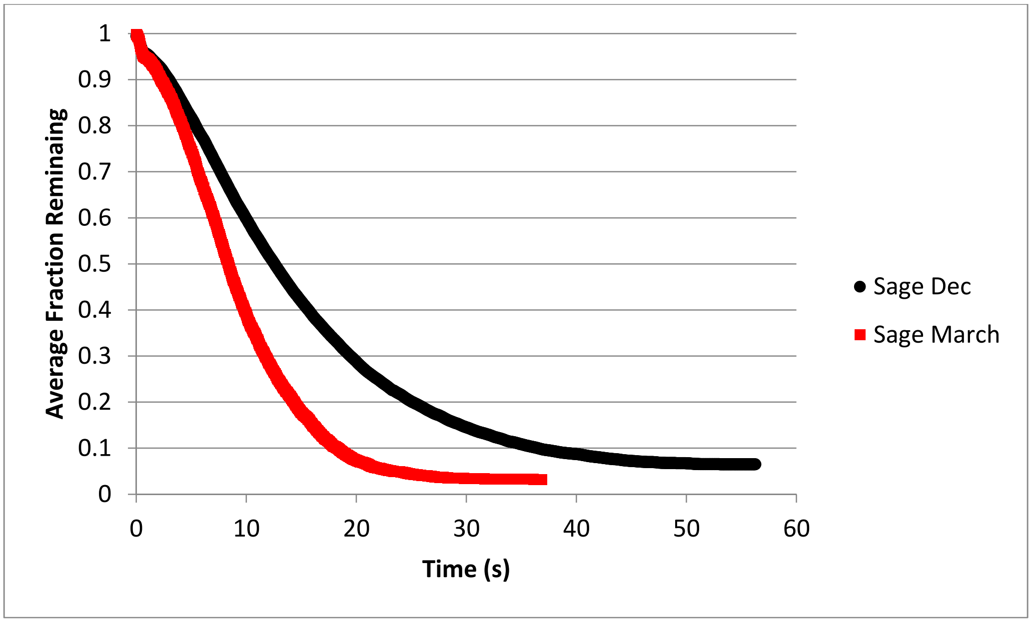

Figure 6: Time dependent mass curves for sagebrush in December, 2012 and March, 2013.

3.2 Heating Mode Effects

Figures 7 and 8 show ignition time and temperature data averaged across the entire year and illustrate the effect of heating mode on burning behavior. Ignition time decreased and ignition temperature increased when radiation was added to convective heating, both expected results.

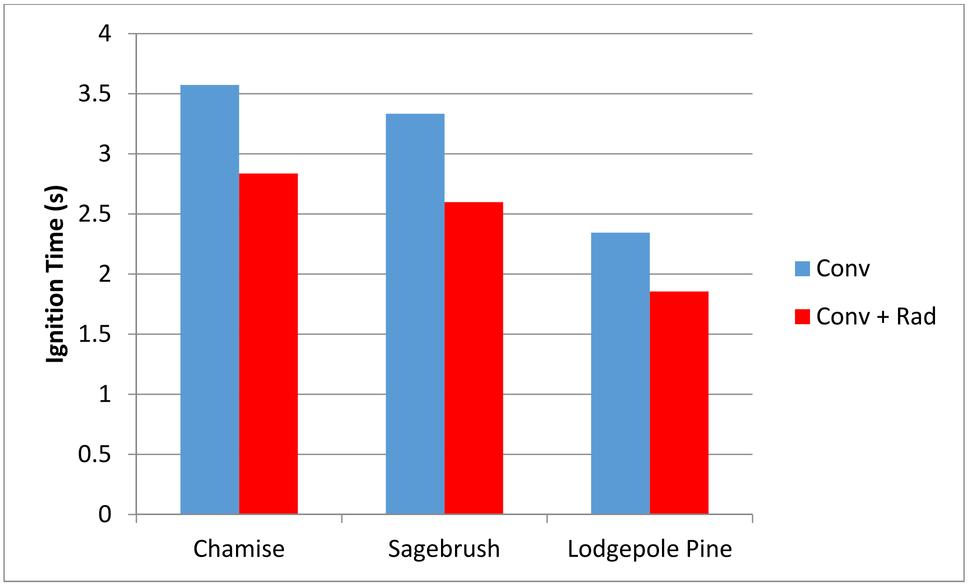

Figure 7: Ignition time for convection-only versus convection and radiation burns averaged over the whole year.

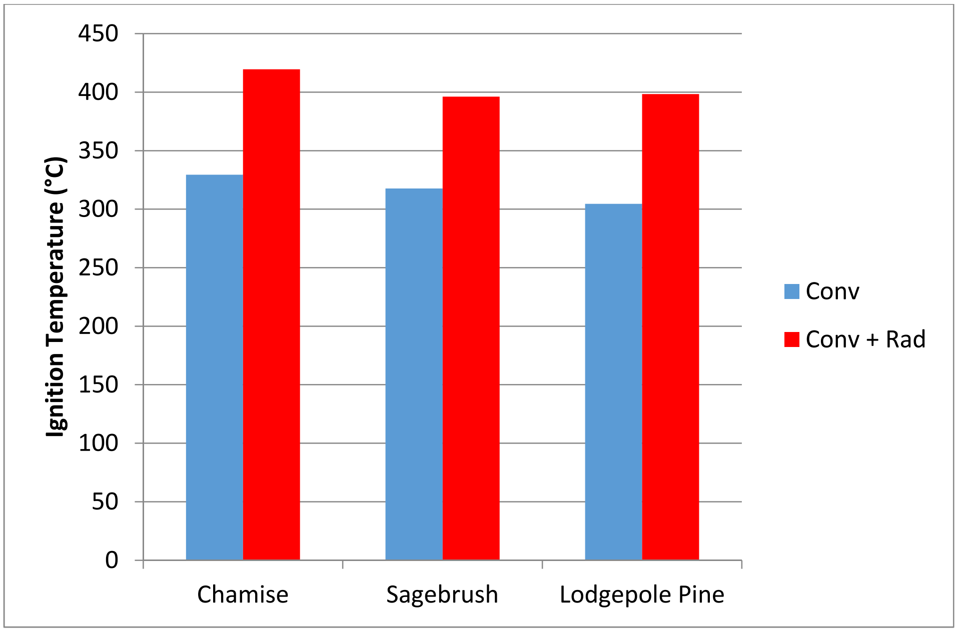

Figure 8: Ignition temperature for convection-only versus convection and radiation burns averaged over the whole year.

Figure 9 shows how the average maximum flame height changes during the year. As seen in the figure, lodgepole pine consistently produced that largest flame while sagebrush and chamise produce flames with similar heights. It is interesting to note the difference between convection-only burns and convection with radiation burns. During winter and early spring, experiments with both convection and radiation produce larger flames than convection-only experiments. These results are flipped during the summer, and convection-only burns resulted in similar or higher flame heights than convection and radiation burns. The exact reason for this result is unknown, but it may indicate that the plant physiological changes affect not only the composition of the fuel but also the fuel behavior when heated.

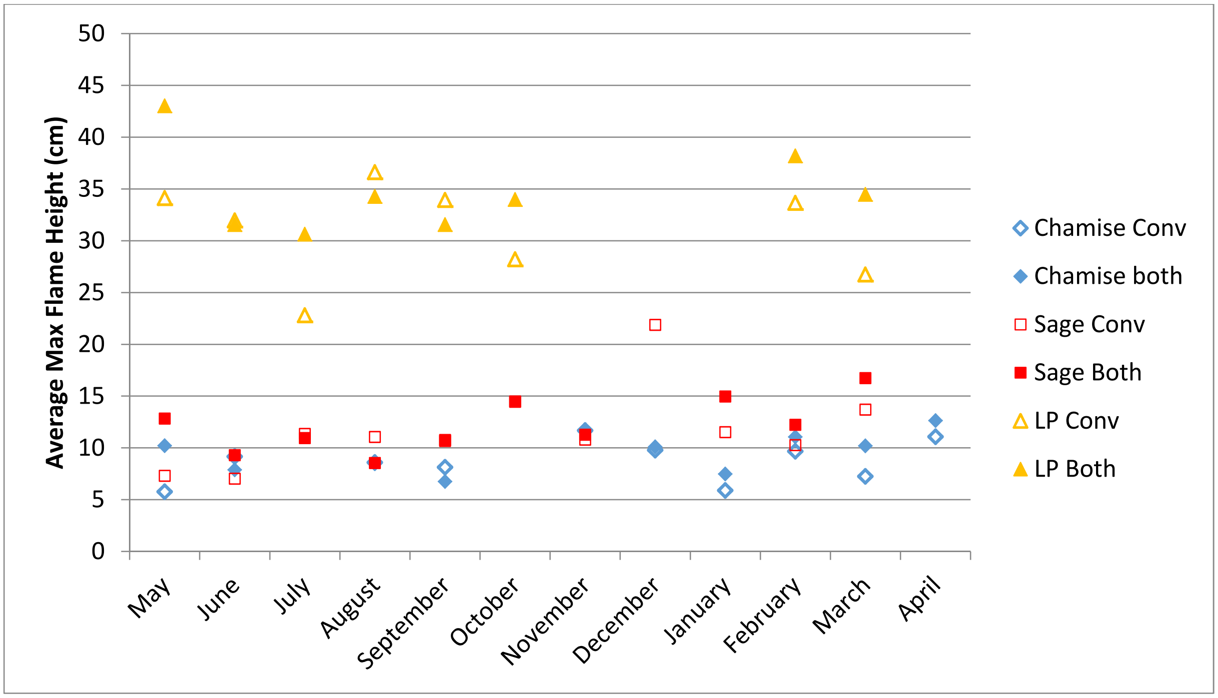

Figure 9: Average maximum flame height shown by species and heating mode throughout the year.

4. Summary and Conclusions

Ignition and burning behavior for three live fuels were studied in a flat-flame burner apparatus (see Figure 1). Experiments were performed over a one-year period to test the effect of season (specifically moisture content) on ignition and burning behavior. The effect of heat transfer mode was also tested by performing some of the seasonal experiments with a convection-only heat source, some with a radiation-only heat source, and some with both heat sources.

The results presented here indicate that there is a complex relationship betweenignition behavior and fuel properties such as surface chemistry, cellular structure, and bulk fuel geometry. All three species exhibited distinct ignition characteristics and mass loss profiles were largely affected by their bulk properties. However, similar moisture contents yielded very different behavior when measured at different times during the year, indicating surface chemistry and cellular structure may also influence burning behavior.

Heating mode data indicated that higher heat flux caused accelerated burning, but the differences in flame characteristics throughout the year suggest that it is not heat flux alone but rather a combination of heat flux and the phenomenological process by which that heating occurs that drives fire behavior. These results will help to increase the understanding of the physical processes that drive fire spread in live shrubs and provide a framework for modeling of live fuel combustion.

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