Sub Topic: Fire

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

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Abstract: 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 understand the effects of heating mode on ignition and burning. Experiments were performed for ten species over a two-year period, with 25 runs completed each month for each species. A flat flame burner (1000°C, 10 mol% O_2) and radiant panel (50 kW/m^2) provided the convection and radiation sources, respectively. Time-dependent mass, surface temperature and flame characteristics were measured. Moisture content (dry basis) varied with season and location, with the lowest measured moisture content corresponding to the local fire season. The effect of moisture content on ignition time varied with species. Ignition time showed a strong dependence on heating mode, with broadleaf species showing a much stronger response to added radiation than non-broadleaf species. No samples exposed to the radiant panel alone ignited. Heating mode and moisture content affected flame characteristics and the relationship depended upon season and species. Some species showed a significant relationship between fractional mass loss rates and ignition times. The observed relationship did not agree with the relationship observed in wet wood. Moisture content alone did not adequately describe seasonal changes in ignition and burning.
Keywords: live fuel, ignition, wildland fire

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 some of the results from 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.

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 gas phase flammable mixture exists. Researchers often measure ignition temperature and time. These values are then used as empirical estimates of the surface temperature at which pyrolysis rates can support a continuous flame and the time required to reach that temperature, respectively. The bulk of the work has focused on ignition temperature. Experimental conclusions to date are mixed. Babrauskas [1, 2] compiled the results of ignition temperature experiments on wood fuels and foliage, respectively. After eliminating the experiments in which the fuel sample was pressed against a hot surface, the reported ignition temperatures ranged from 200-530°C for wood and 201-450°C for foliage. Babrauskas noted the large amount of scatter in the data and suggested that, in addition to variations in experimental setup and measurement techniques, sample condition (e.g. moisture content and size) and species could affect ignition temperature.

Wildland fire observations that species burn differently support Babrauskas's postulate that plant species could be one source of variation in measured ignition temperatures [3]. However, results by Susott [4] showed that material ground from various plant species has the same heat of combustion and similar TGA (thermogravimetric analysis) pyrolysis mass release curves, and should therefore burn similarly. Thus, one possible explanation for the observed differences in ignition properties is the shape and structure of the plant and the effect shape has on heat and mass transfer. However, this explanation has not been tested experimentally. Most empirical correlations used to predict ignition behavior, particularly for live fuels, are species specific [5-8]. Work must be done to understand the differences in ignition behavior between various species.

Investigation of the effect of moisture content on ignition has been studied extensively and supports Babrauskas's postulate that sample condition affects ignition. Most of the work has focused on dead or woody fuels, with the result that moisture increases both ignition time and temperature [5, 6, 9-11]. The results for live fuels are fewer and less consistent [3, 12-15]. Many fire spread models use moisture content as a predictor for ignition. These models have varied success with dead fuels but little success with live fuels [13]. One possible reason for the difference in ignition between live and dead fuels and the performance of fire spread models in predicting fire behavior in live fuels is the difference in water storage between live and dead plants and the resulting treatment of water storage in fire spread models. Water evaporation in dead fuels has been assumed complete in fine fuels once the sample temperature passes 100°C [16, 17], but Fletcher et al. [3] showed there is still a significant amount of moisture in live fuels when ignition occurs. Pickett [18] showed water release still occurring at surface temperatures in excess of 200°C and Prince [14] showed significant differences in the temperature profiles of live and dead foliage during ignition and burning even with the same moisture content. Work by McAllister et al. [13] showed significant differences in the ignition behavior between live and dead pine needles. These differences have led researchers to postulate that there is significant interaction between the free water and the cells in live plants that does not occur in dead plants [13, 19]. Finney et al. [20] postulated that water release in live fuels is not complete until breakdown of the cellular structure occurs. Still other work has been done indicating root structure [21], plant dry mass [22], and chemical composition [13, 23] could have a larger effect on ignition of live fuels than moisture content, though results are mixed in work to quantify the effect of chemical composition (e.g. [15]). 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.

Another of Babrauskas's postulates was that differences in ignition temperature arise due to differences in experimental setup. This is particularly true when looking at the different heat transfer mechanisms. Much of the work looking at heat transfer mode has focused on dead and woody fuels [10, 17, 24-31]. Experiments performed by Rothermel [17] showed fuel pre-heating in no-wind and backing-fire situations, leading to the conclusion that radiation drives fire spread. This conclusion and his resulting fire spread model established a precedent that radiation is the dominant form of heat transfer in wildland fires. However, other experiments have shown that significant amounts of pyrolyzates are not formed at the fuel temperatures associated with radiant pre-heating [32]. Anderson [33] concluded that radiant heat flux can provide no more than 40% of the energy required for sustained fire spread. Still other work has shown flame propagation to depend strongly on direct flame contact with un-burned fuel [34, 35]. Many researchers have concluded that radiation heat transfer dominates in large fires [24, 31, 36, 37] and fires with little to no wind in homogeneous fuel beds [28, 38-40], but the relative effect of radiation and convection for fires outside these conditions is still unknown [28, 40]. Only a limited amount of work has been performed for live fuels and foliage [13, 41]. 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 to better understand what physical processes drive fire spread in live shrubs.

2. Experimental Setup

Each month, combustion experiments (25 replicates for each species) were performed in the flat flame burner (FFB) apparatus at Brigham Young University (BYU) (see Figure 1). In total, ten species were tested over a two year period. Table 1 shows the species, timing, sampling location and fuel element description for each species. Non-local species were sealed in plastic bags to minimize moisture loss and shipped overnight to BYU. Experiments were usually conducted within 48 hours of collection. Care was taken to keep the bags sealed and to minimize exposure to light until it was time to complete the experiments.

Table 1. Species tested, timing, sampling location and fuel element description

Species[1]	**Timing**	**Location**	**Fuel Element Description**
Chamise (*Adenostoma fasciculatum*)	Year 1	Riverside, CA	4 cm branch tip with needles attached (diameter < 2mm)
Big sagebrush (*Artemisia tridentata*)	Year 1	Provo, UT	4 cm branch tip with leaves attached
Lodgepole pine (*Pinus contorta*)	Year 1	Missoula, MT	2 cm branch tip with needles attached (diameter < 5mm)
Manzanita (*Arctostaphylos glandulosa*)	Year 2	Riverside, CA	Single leaf
Ceanothus (*Ceanothus crassifolius*)	Year 2	Riverside, CA	Single leaf
Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)	Year 2	Missoula, MT	2 cm branch tip with needles attached (diameter < 3mm)
Gambel oak (*Quercus gambelii*)	Year 2	Provo, UT	Single leaf
Gallberry (*Ilex glabra*)	Year 2	Crestview, FL	Single leaf
Fetterbush (*Lyonia lucida*)	Year 2	Crestview, FL	Single leaf
Sand pine (*Pinus clausa*)	Year 2	Crestview, FL	2 cm branch tip with needles attached (diameter < 3mm)

[1.] USDA, NRCS. 2014. The PLANTS Database (http://plants.usda.gov, 21 October 2014). National Plant Data Team, Greensboro, NC 27401-4901 USA

Average moisture content for each species was measured by drying several fuel element in a MAX1000 Computrac Moisture Analyzer† at 95°C. Moisture content (MC) was reported on a dry mass basis [42]. Relative moisture content (RMC) was measured by comparing the water weight in a fresh sample to the water weight in the turgid sample [22]. Video images, mass and temperature data were collected using the apparatus shown in Figure 1. Samples were individually weighed and placed within the apparatus. The water-cooled FFB produced exhaust gases at 1000°C and 10 mol% oxygen that flowed 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 [7] corrected these temperature measurements for thermocouple radiation losses and found the losses to be small at these temperatures. An Omega QH-101060 radiant panel was used to provide a 50 kW/m^2 flux at the sample location. Heat flux was measured using a Medtherm 64-series heat flux sensor. Video data were captured using a Panasonic SDR S50 Camcorder and were post-processed to extract the flame characteristics listed Table 2.

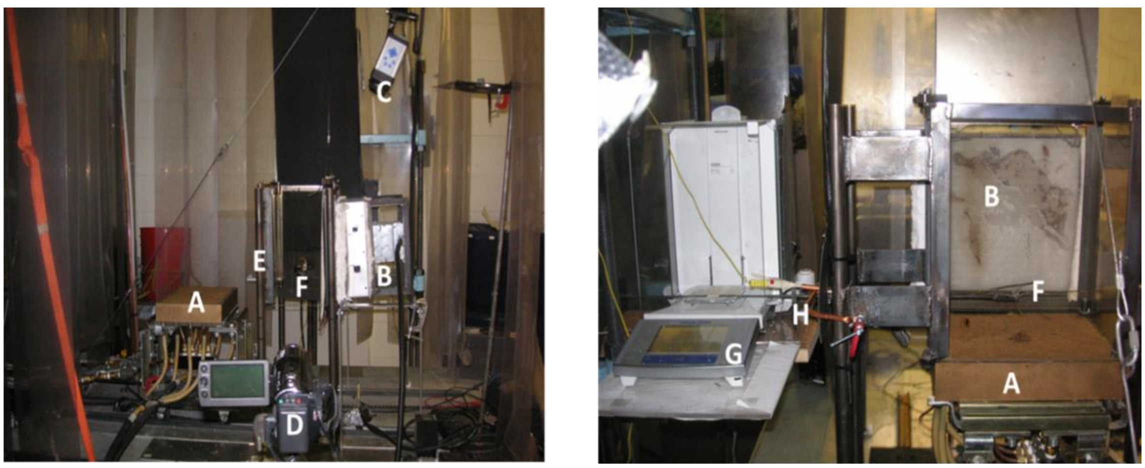

Figure 1. Experimental apparatus: flat flame burner (A), radiant panel (B), IR camera (C), video camera (D), glass cage to prevent ambient air entrainment (E), sample location (F), mass balance (G) and sample holding rod (H).

Table 2. Flame characteristics derived from video data

Variable	**Description**
Ignition Time (s)	Time when a visible, sustained flame appears
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

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

3. Results and Discussion

Moisture content varied throughout the year (see Figure 2). Each species has a unique moisture content curve. Samples from the same area of the country exhibit similar but not identical patterns. California species had the lowest moisture content on average. Conifer species (lodgepole pine, Douglas-fir, and sand pine) had consistently higher MC than other species from the same area. California and Rocky Mountain species had the lowest moisture content during the summer and fall months while Florida species experienced a high in MC during late summer. As the lone deciduous species, gambel oak showed a strong relationship between moisture content and the growing season.

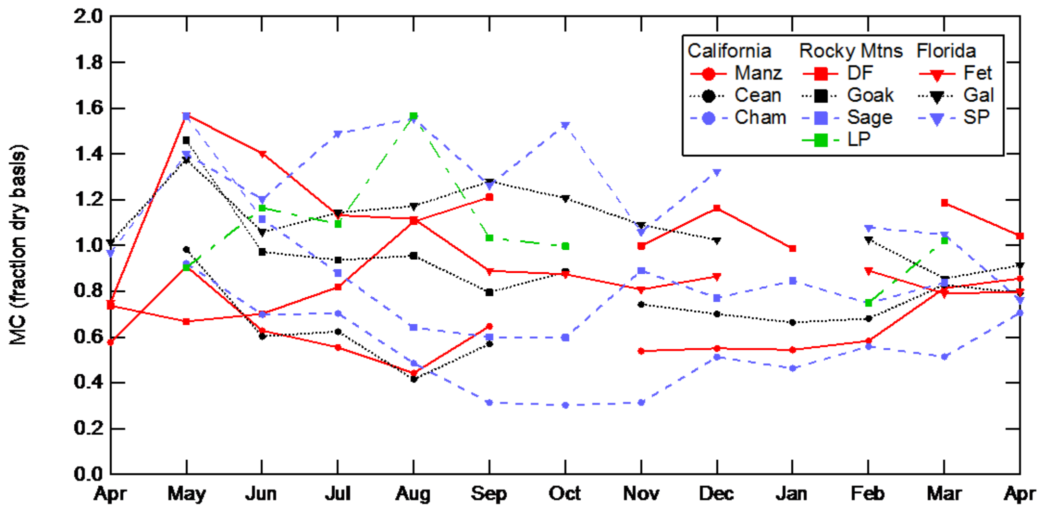

Figure 2. Moisture content (fractional dry basis) by month for the ten species studied

Table 3. Significance of yearly trends by species

	Ignition Time (s) vs MC		**MFH (cm) vs MC**		**Ignition Devol (%/s) vs MC**		**Ignition Devol (%/s) vs Ignition Time (s)**	
Species	Conv*	Comb**	Conv	Comb	Conv	Comb	Conv	Comb
Manzanita	0	0	0	0	0	0	N	0
Ceanothus	P	P	0	0	0	0	0	0
Douglas-fir	P	0	N	0	0	0	0	0
Gambel Oak	P	P	N	N	0	0	0	0
Fetterbush	0	0	0	0	0	0	N	0
Gallberry	0	0	0	0	0	0	N	0
Sand Pine	0	P	0	0	0	0	0	0
Chamise	P	P	0	0	0	0	0	0
Sagebrush	0	0	0	0	0	0	0	0
Lodgepole Pine	0	0	0	0	0	0	0	0
Wet Wood (expected)	P	P	N	N	P	P	P	P

*Conv means convection-only experiments; **Comb means combined convection and radiation

Table 3 contains a summary of some selected results for ignition and burning behavior. Simple linear regression was performed for each species for the variable combinations shown in the top row of Table 3. These models were compared to a constant model to see if the trend was significant at a 95% confidence level. Zeros in the table indicate relationships with no statistical significance. Non-zero entries indicate the sign of the slope for the associated model—P for a statistically significant slope > 0 and N for slope < 0. This behavior is very different than the expected behavior if live fuels behaved the same as wet, dead fuels [13].

Figures 3-5 show specific results for ignition time versus moisture content, maximum flame height versus moisture content, and ignition mass loss rate versus ignition time, respectively. Ceanothus, Douglas-fir, gambel oak and fetterbush were chosen to illustrate the results in a clear manner. The behavior of the different species varies widely.

As seen in Figure 3, ceanothus exhibited a much stronger relationship between moisture content and ignition time than the other species shown. This was true for all three California species tested. Figure 4 shows the range of flame heights observed in our apparatus. Interestingly, Douglas-fir, gambel oak and fetterbush all had similar flame heights, even though the fuel particles were different in size and shape. Figure 5 presents an interesting observation. It appears from the figure that longer ignition times were associated with a smaller fractional mass loss rate at ignition. Only three species (manzanita, fetterbush and gallberry) had a statistically significant relationship between fractional devolatilization rate at ignition and ignition time, yet the bulk trend seemed to indicate that ignition devolatilization rate correlates with ignition time rather than with things that influence heat and mass transfer like size and shape. As was noted, most species showed no relationship between ignition devolatilization and ignition time. Further analysis is needed to understand if this apparent trend is significant.

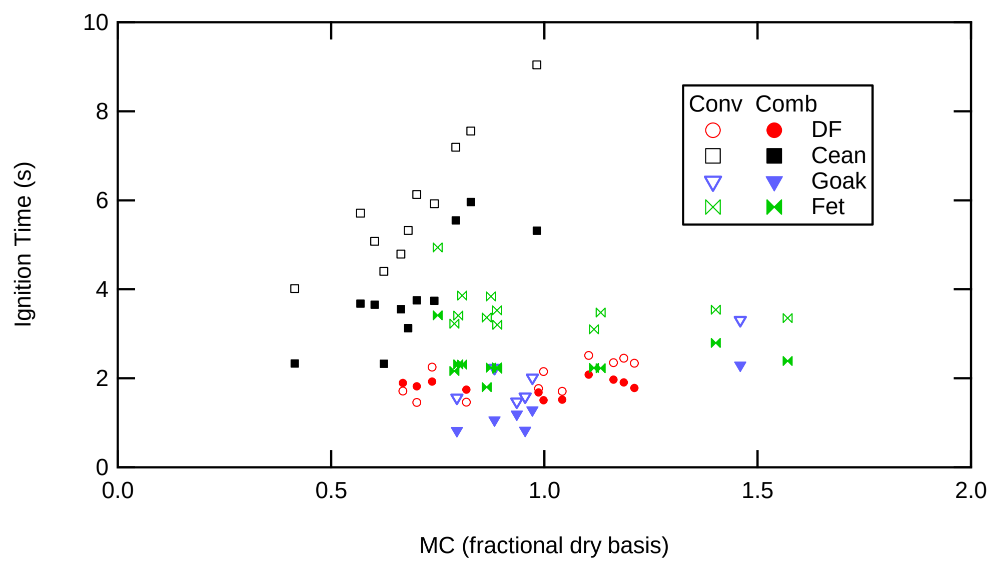

Figure 3. Ignition time versus moisture content for ceanothus, Douglas-fir, gambel oak and fetterbush. Closed symbols indicate radiation and convection ignition while open symbols indicate convection-only ignition.

For manzanita and Douglas-fir, no significant relationship between ignition time and moisture over the course of the year (see Figure 6) was observed. The manzanita moisture content was approximately the same in July and November, yet the ignition times in July were half as long as the ignition times in November. Douglas-fir moisture content doubled from May to September but there was no significant change in ignition time. While this doesn't explain why there are few significant trends, it does yield two important results: (1) seasonal changes had a large effect on burning behavior and (2) the seasonal changes that effect burning were not captured by measuring moisture content alone.

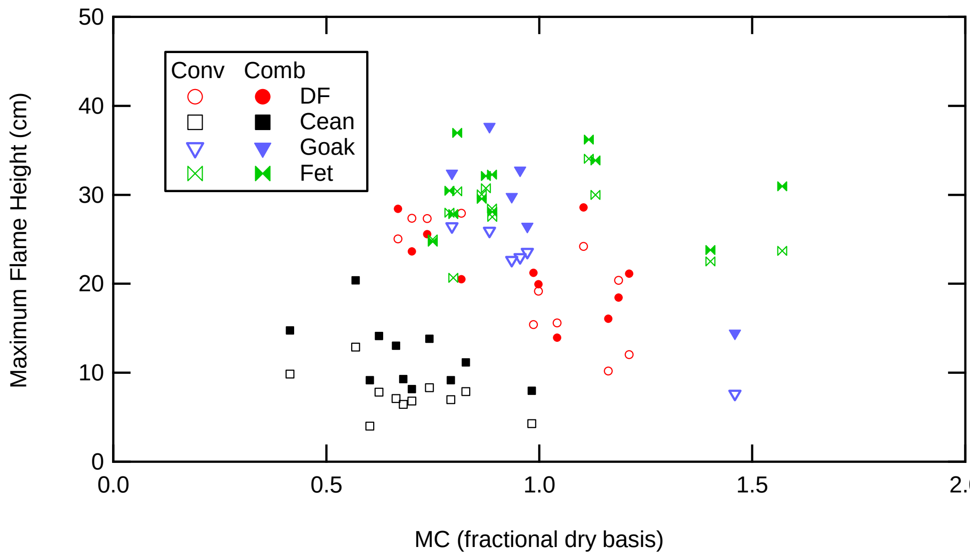

Figure 4. Maximum flame height (MFH) versus moisture content for ceanothus, Douglas-fir, gambel oak and fetterbush. Closed symbols indicate radiation and convection ignition while open symbols indicate convection-only ignition.

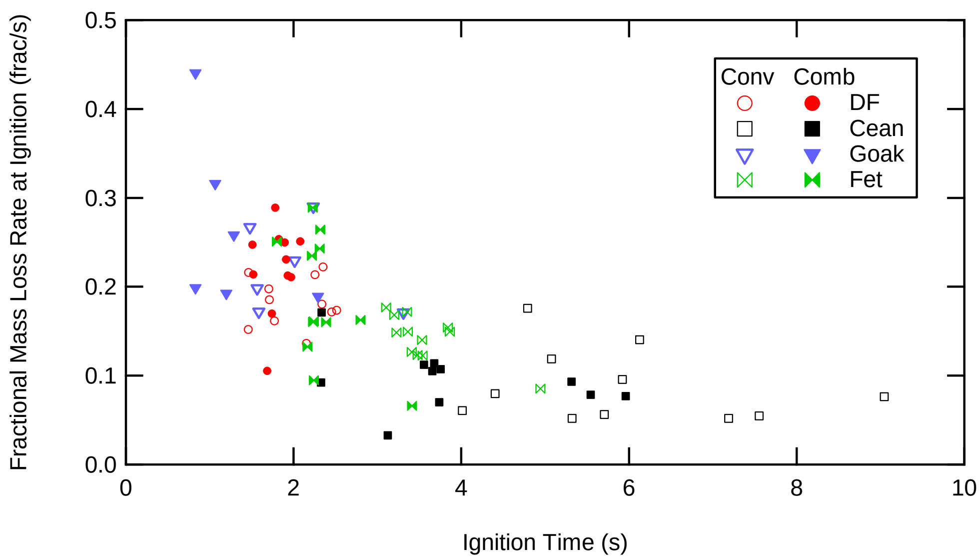

Figure 5. Fractional devolatilization at ignition versus ignition time for ceanothus, Douglas-fir, gambel oak and fetterbush. Closed symbols indicate radiation and convection ignition while open symbols indicate convection-only ignition.

Results from heating mode experiments were much clearer. Radiation alone was never sufficient to ignite the fuel samples without a pilot ignition source. This result suggests that models must include other modes of heat transfer as in [43, 44]. Table 4 shows the difference between convection-only ignition and combined convection and radiation ignition. We observed a stark contrast between the broadleaf species and the non-broadleaf species for ignition time and time to maximum flame height. The difference between convection-only and combined burns for the three other reported variables was less obvious, but the overall result was that the added radiation had a much larger effect on broadleaf species than on non-broadleaf species (Figure 6). The effect of ignition source on ignition time was large and consistent for manzanita—addition of radiation resulted in smaller ignition time. This was not true for Douglas-fir. Not only was the effect of ignition type not large enough to be significant, it was also not consistent.

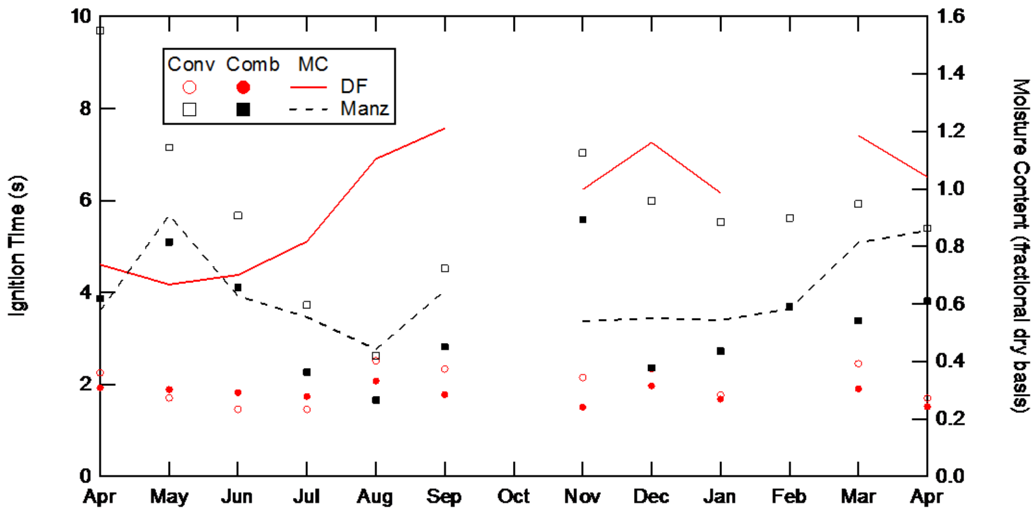

Figure 6. Ignition time and moisture content versus month for manzanita and Douglas-fir. Closed symbols indicate radiation and convection ignition while open symbols indicate convection-only ignition.

Table 4. Effect of heating mode on ignition variables. Table entries indicate the percentage of months that radiation and convection ignition differed significantly convection-only ignition at a 95% confidence level

Species*	Ignition Time	Time to Max Flame Height	Maximum Flame Height	Fraction Left at Ignition	Fraction Loss at Ignition
Manzanita	92	83	83	25	42
Ceanothus	100	91	100	45	18
Gambel oak	83	100	83	50	17
Fetterbush	100	100	8	17	25
Gallberry	92	100	0	17	58
Dougals-fir	9	27	27	0	9
Sand pine	25	25	8	0	17
Chamise	33	25	17	17	0
Sagebrush	22	22	22	11	11
Lodgepole pine	50	25	13	38	13

*The first five species listed are broadleaf species, the other five are non-broadleaf.

4. Summary and Conclusions

Ignition and burning behavior for ten live fuels were studied in a flat-flame burner apparatus. Experiments were performed over a two-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.

Results comparing ignition and burning characteristics with moisture content were mixed. Ceanothus, gambel oak, Douglas-fir and chamise all exhibited a positive correlation between ignition time and moisture content while the other six species show no correlation at a 95% significance level. Douglas-fir and gambel oak showed a negative relationship between maximum flame height and moisture content while the other eight species showed no relationship. No species exhibited a significant relationship between percentage mass loss rate at ignition and moisture content. Manzanita, fetterbush and gallberry showed a negative relationship between percentage mass loss rate at ignition and ignition time. Additionally, ignition behavior of live fuels in different seasons but at the same moisture content was different. These results suggest a significant difference between live fuels and dead fuels that isn’t explained by moisture content.

Heating mode results were clearer. Ignition occurred in none of the unpiloted radiation-only experiments. These results do not indicate radiation was unimportant, but rather that additional modes of heat transfer were needed. Inclusion of a radiant flux in the convective environment of a flat-flame burner significantly decreased observed ignition times for broadleaf species but not for non-broadleaf species. Maximum flame height time showed the same dependence as ignition time for all species while maximum flame height showed the opposite dependence, except for fetterbush and gallberry which showed almost no difference between convection-only and radiation with convection experimental runs. Mass loss rate and fraction remaining at ignition were affected much less by the differences in heating than other ignition characteristics.

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