7.1 BURNING CHARACTERISTICS OF LIVE CALIFORNIA CHAPARRAL AND UTAH LEAF SAMPLES

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1. INTRODUCTION

Current fire-spread models are based largely on empirical correlations based on fires burning through dead vegetation, such as pine needle beds (Rothermel, 1972; Albini, 1976; Susott, 1980). There is a need to increase the accuracy of modeling wildfires in live vegetation. This project investigates the quantitative and qualitative ignition characteristics of eight live fuels, four from southern California (manzanita (Arctostaphlos parryana), scrub oak (Quercus berberidifolia), ceanothus (Ceanothus crassifolius), and chamise (Adenostoma fasciculatum)) and four from Utah (gambel oak (Quercus gamelii), canyon maple (Acer grandidentatum), big sagebrush (Artemisia tridentate), and Utah juniper (Juniperus osteosperma)). Individual leaves were observed as they were exposed to hot gases from a flat flame burner (FFB). The California chaparral plants grow in a dry climate and contain many xerophytic adaptations such as waxy cuticles, thick leaves, and fewer stomata on the upper leaf surface. Sagebrush and Utah juniper also have xerophytic characteristics, while canyon maple and gambel oak are more mesophytic and have fewer adaptations to conserve water.

This paper presents recent findings regarding effects of species and moisture content on combustion behavior of individual leaves.

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2. EXPERIMENTAL METHODS

California shrub samples were collected from the North Mountain Experimental Area near Riverside, CA, shipped overnight to Provo, UT, and examined shortly thereafter. Utah samples were harvested locally. Individual leaf samples were suspended on a horizontal metal rod that was placed on a mass balance. A moveable flat flame burner (FFB) was brought under the leaf to simulate a flame front in a fire. Hydrogen and methane were introduced into the FFB along with air and nitrogen. Based on the flow rate of each type of gas, the flame temperature of the FFB could be altered from 815ºC to 1100ºC, along with the post-flame concentration of O_2. Most species were run at a FFB flame temperature of 1025ºC. For most experimental runs, a 127 μm diameter thermocouple (Type K) was placed at the tip of the leaf where ignition usually took place. Temperatures of the leaf surface measured by a FLIR (Model A20M – sensitive between 7.5 – 13 μm)[1] infrared camera matched thermocouple measurements to within approximately 5°C. Leaf heating rates of ~100 K/s were obtained, with convective heat fluxes of ~100 kW/m^2 at the leaf surface. Video images, thermocouple data, and mass data were all routed through a LabView program to place a common time stamp on all data. Video images were viewed frame by frame to determine the time that ignition was first observed, the duration of the flame, and the maximum flame height. Additional experimental details are available (Engstrom et al., 2004; Smith, 2005).

3. RESULTS AND DISCUSSION

Over 1100 experiments on individual leaf samples have been performed over a three year

[1] Tradenames are provided for informational purposes only and do not constitute endorsement by the U.S. Department of Agriculture.

period. Images were recorded as well as temperature and mass profiles. Both qualitative and quantitative results are discussed here. More detail can be found in Smith (2005).

3.1 Qualitative Results

Qualitative results were observed in various forms: bubble formation, bubble bursting, brand formation, and surface bending. Bubble formation is characterized by small amounts of liquid accumulating on the leaf surface or gas pockets forming under the leaf surface. Bubbling can be accompanied with mild crackling sounds. Bubble bursting is a small explosion within the leaf surface accompanied by violent crackling sounds. Bursting forms pockmarks on the surface of the leaf, and possibly causes leaf material to become detached and ejected from the main leaf body. Brand formation occurs when pieces of flaming material are thrown from the leaf or stem, causing it to be lofted to another area that may start new fires. Bursting could be considered one type of brand formation, but on a small scale. Surface bending is simply the movement of the leaf when exposed to a high convective heat flux.

These phenomena occurred in some of the species, but not in all. Bubbling was observed in all broadleaf species except sagebrush. Bursting was observed in all of the California chaparral broadleaf species. Brand formation was observed in all the chaparral species as well as in juniper and sagebrush. Bending was observed in all species.

3.1.1 Bubbling

Bubbling was observed in all the broadleaf species studied except sagebrush and occurred in two forms: (i) liquid droplets forming on the outer surface of the leaf, and (ii) miniature gas pockets within the surface of the leaf. Manzanita with moderate moisture content was the only species observed to have the liquid on the outer surface of the leaf. All broadleaf species (with moderate moisture content) except sagebrush experienced the miniature gas pockets within the surface.

Liquid bubbling was observed before ignition when liquid was seen collecting around the perimeter of the leaf. The liquid accumulation propagated towards the center of the leaf where the liquid began to dance like water on a hot skillet (Figure 1). A method to determine the liquid composition has not yet been determined; it is likely water or melted cuticular wax.

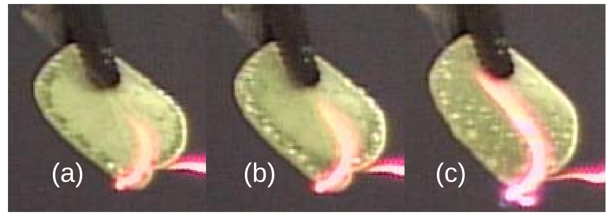

Figure 1. Liquid bubbling on a manzanita leaf's surface. (a) Bubbles starting to form. (b) Propagation towards the center. (c) Liquid covers the surface.

Interior gaseous bubbling was observed as visible spots or bubbles that appeared to originate in the intercellular space of the leaf (Figure 2) and did not move around as with exterior liquid bubbling. Mild crackling was observed with this type of bubbling in contrast to the violent crackling observed during bursting. Interior bubbling is probably caused as small gas pockets of water vapor escape the surface of the leaf. Pressure builds inside the leaf where the hot gases cannot escape and the surface expands, leaving bubbles or spots on the surface.

Gambel oak and canyon maple both experienced interior bubbling, but did not experience bursting. This may have been due to their thickness, which is about 0.15 mm thinner on average than the broadleaf California chaparral species, or due to the structural differences and compositions between different species of leaves. The thinner leaf may not have mass transfer resistance inside the leaf to create the pressure necessary for full-scale bursting. This interior bubbling may be bursting (see bursting section below) on a smaller scale; hence, only mild crackling is observed.

Figure 2. Interior bubbling of a gambel oak leaf sample with the tiny spots on the leaf surface.

3.1.2 Bursting

Bursting was first observed on the upper surface of manzanita with a moisture content of approximately 100% (dry mass basis), as shown in Figure 3. Due to this high moisture content, it is believed that the bursting is caused by an evaporation of the water on the inside of the leaf, similar to interior bubbling. The pressure increases inside the leaf and the surface explodes with violent crackling sounds, leaving pockmarks on the surface. Bursting is more prone to occur at a higher heat flux, allowing less time for the hot gases to escape the surface of the leaf.

However, bursting does not occur in every sample with high moisture content. Some experiments with high moisture content simply burned without bursting. It is believed that certain types of manzanita have a greater propensity to burst than others It is possible that this difference in behavior relates to new growth versus older leaves; this needs to be examined further. For example, the stems in Figure 4b seem more established than in Figure 4a, indicating older leaves.

In one recent shipment of chaparral samples, the manzanita leaves could be separated into two different types: a rounder, paler, smoother-to-the-touch manzanita leaf, and a straighter, slightly greener, and rougher-to-the-touch manzanita leaf (Figure 4). Upon burning the two types of manzanita leaf with the FFB, the rounder leaves with a moisture content of 78% did not burst; the straighter leaves with a moisture content of 68% nearly always exhibited bursting behavior.

Figure 3. Bursting manzanita leaf with moisture content of 97% on a dry basis.

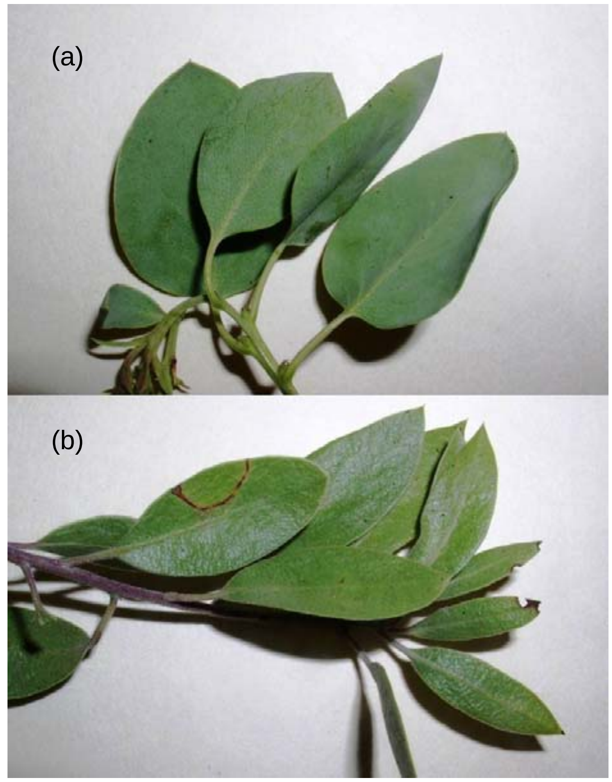

Figure 4. Two types of manzanita leaves: (a) round, pale, smooth leaf, (b) straight, green, rough leaf.

To better analyze the bursting characteristics of the straighter manzanita leaves, individual leaf samples were subjected to the convective gases of the FFB until bursting was observed, then they were quickly removed from the convective gases. As shown in Figure 5, the upper layer of a manzanita leaf appears to have detached from the main body of the leaf.

Figure 5. Burst upper surface of a straight manzanita leaf.

As seen from a diagram of the internal cell structure in Figure 6, the small coating of wax, called the cuticle, is visible. In addition, some plants may produce other waxes that help protect the leaf (Stern 2000). The cuticle and these other waxes may clog the stoma which causes internal leaf pressure and subsequent bubbling and bursting. The straighter, greener type of manzanita leaves may have an abundance of cutin and other waxes that cause a greater possibility for bursting. It is hypothesized that the amount of wax and subsequent bursting may also be due to the time of year; this will be an area of focus in future experiments.

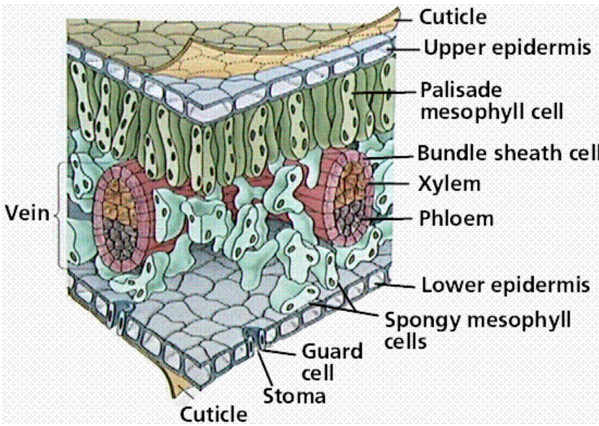

Figure 6. Diagram of internal leaf structure on a cellular level. (Purves et al. 1995)

One bursting manzanita leaf was recorded with the IR camera from which a temperature array can be acquired for the entire leaf surface. When the bursting manzanita was analyzed, a temperature drop of about 40ºC was observed at the location of the burst over a period of 0.10 seconds (Figure 7). It is believed that this is due to evaporated water escaping from the hot pocket inside the leaf surface following the burst.

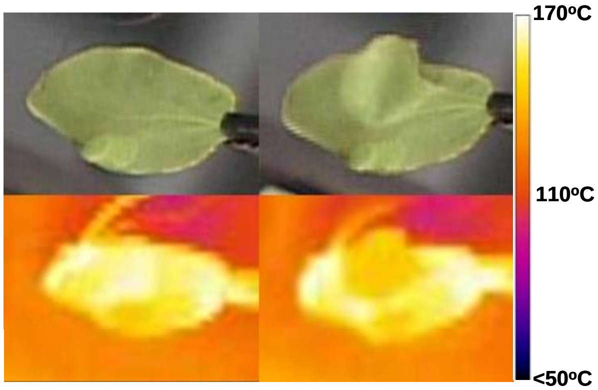

Figure 7. Video camera images and corresponding IR camera images of a bursting manzanita leaf. The duller yellow spots correspond to the lower temperature of the bursting region.

Ceanothus and scrub oak leaves were also observed to burst, but in a manner dissimilar to that of manzanita. The ceanothus and scrub oak leaves burst from the under side, causing the lower epidermis to be blown away from the bottom of the leaf. The upper side of these leaves did not burst, but evidence of the burst is noticeable by discoloration on the upper surface of the leaf, as shown in Figures 8 and 9.

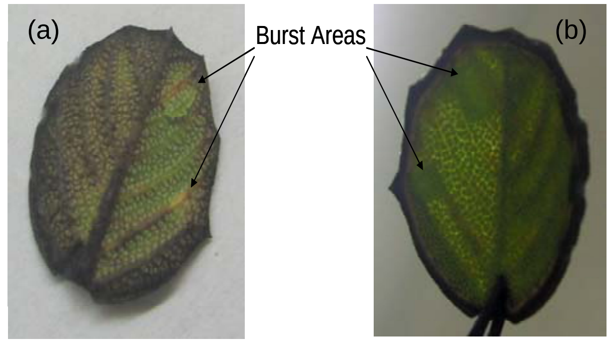

Figure 8. (a) Lower and (b) upper surface of burst ceanothus leaf. There is visible evidence of under side bursting from upper side.

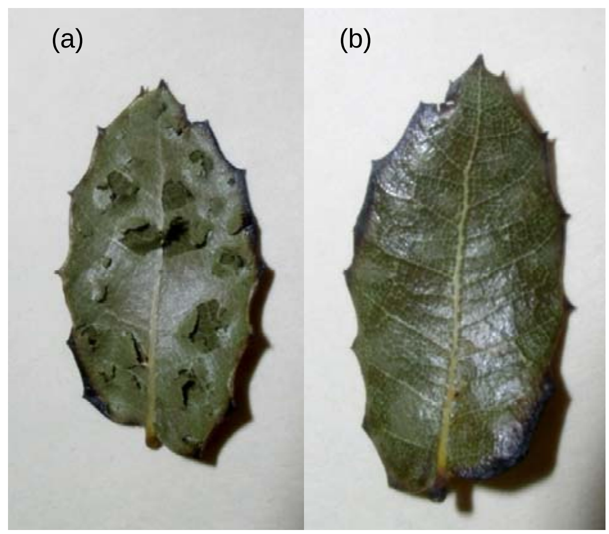

Figure 9. Upper and lower surface of burst scrub oak leaf. Visible evidence of (a) under side bursting from (b) upper side by the whitish spots on the upper side.

Bursting on the upper side of the manzanita leaves resulted in the separation of the epidermis from the palisade mesophyll cells (as seen in Figures 5 and 6). This could be due to a weak connection of the palisade mesophyll to the epidermis which is unique among the bursting species of this study.

It is believed that the columns of highly structured palisade mesophyll cells protect the upper surface of the ceanothus and scrub oak leaves; hence under side bursting occurs where there is less of a protective layer in the scattered spongy mesophyll cells. Bursting in the ceanothus was also observed to occur mainly between the veins of the leaf. The veins may provide structural integrity which prevents the overall structure of the leaf from bursting.

3.1.3 Brand Formation

The formation of small brands was observed in many of the species studied, but in a variety of ways. The most common type of brand formation was the ejected leaf material after a leaf has burst. As discussed above, at higher moisture content and with a high heat flux, the California broadleaf species burst and ejected small amounts of epidermis from the main body of the leaf. These pieces of epidermis were not observed to be ignited when ejected. However, in the hot environment of a wildland fire, this ejected material could possibly ignite and burn while entrained in the air.

Scrub oak also was observed to shed material in a different manner than associated with the bursting of the epidermis of the leaf. Scrub oak typically ignited along the perimeter of the leaf, where there are 8 to 25 spines or points. The leaf ignited at these points, and often caused these points to be ejected, causing small brands (see Figure 10).

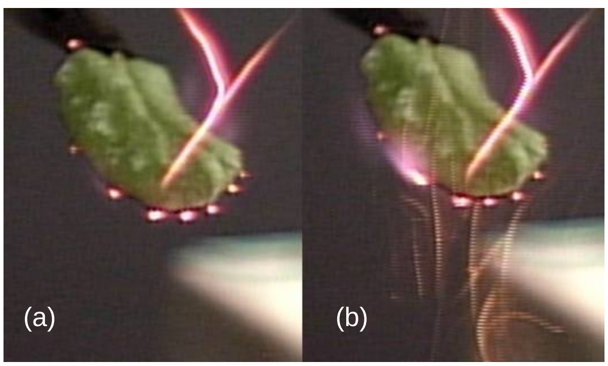

Figure 10. (a) Ignition points of scrub oak followed by (b) explosive branding of the points over a period of 0.25 seconds.

The non-broadleaf species (juniper and chamise) were observed to form significant amounts and sizes of brands after ignition. Most brands were whole sections of sample where the stem had burned enough to the point that it could not hold the weight of the upper section of the sample (Figure 11).

Sagebrush also experienced brand formation, but in a unique manner. Ignition for sagebrush would usually occur first on one or more of the lobes on the tip of the leaf. Not long after the tip ignition, the stem of the leaf would ignite (Figure 12). If this stem ignition occurred early in the experiment, the stem would burn well before the rest of the leaf, causing the whole leaf to be considered a brand.

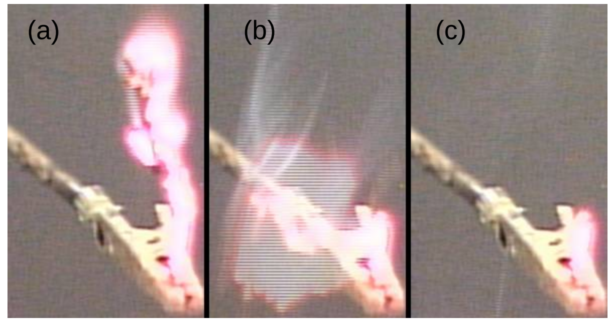

Figure 11. Branding of chamise sample where (a) the flaming stem begins to (b) fall and is left with (c) the smaller portion still attached to the alligator clip.

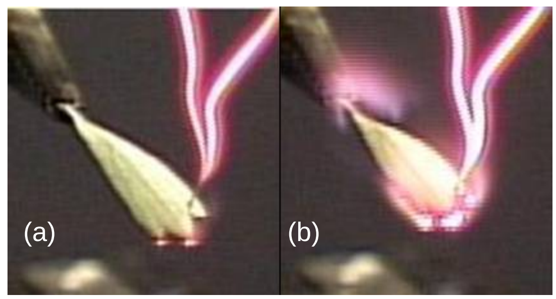

Figure 12. Ignition of sagebrush. (a) Primary ignition along the lobes on the tip of the leaf. (b) Ignition at the stem of the sagebrush following tip ignition.

When obtaining the sagebrush leaf samples, it was observed that the sagebrush leaves tended to fall off the branch very easily. The stems are prone to ignition and are not strong. This allows the leaf to ignite and then form brands shortly thereafter. Sagebrush leaves are also light in mass compared to the other samples under study. This would allow the leaves to remain aloft, possibly causing spotting in wildland fires.

3.1.4 Bending

When the leaf is exposed to the hot, convective gases of the FFB flowing upward, the leaf experiences bending, which opposes the direction of the convective gases (Figure 13). Bending can occur before and after ignition. All species experienced this phenomenon to a small degree. The amount of bending appears to correlate with the thickness of the leaf, i.e., thinner leaves allow for more bending.

It is believed that bending was caused by the pyrolysis of the leaf material or moisture evaporation on the bottom surface. The lower epidermis and spongy mesophyll cells are being destroyed while the leaf droops and bends. As more of the leaf's mass is released through pyrolysis, the influence of the momentum of the convective gases begins to take effect, causing the leaf to bend upward.

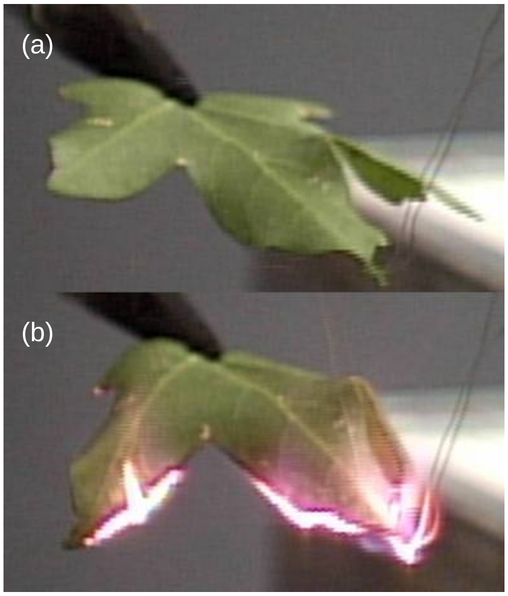

Figure 13. Bending of a maple leaf sample. (a) Maple leaf not subject to convective gases. (b) Bending maple leaf after introduction of convective gases.

3.2 Quantitative Results

3.2.1 Ignition Correlations

Quantitative experiments were performed on the eight different species. From the recorded video images from each run, the ignition and extinction times could be determined. With these times and the recorded temperature profile, ignition temperature (T_{ig}), time to ignition (t_{ig}), and flame duration (t_{flame}) could be determined. Average values and 95% confidence intervals of T_{ig} and t_{ig} for each species are shown in Table 1. The confidence intervals indicate that the T_{ig} is different for individual species. The average ignition temperatures ranged from 227ºC for gambel oak to 441ºC for ceanothus. The moisture contents and sizes of leaves for this data set varied greatly, and hence efforts were made to understand the variation in T_{ig} and t_{ig} due to these types of variables.

Physical characteristics for each sample were recorded prior to ignition, including thickness, mass, and approximate length and width. The effect of leaf thickness on ignition temperature was explored for both chaparral and Utah species as shown in Figure 14. The general trend shows that T_{ig} increases with increasing leaf thickness. However, the scatter in the data makes it difficult to determine the trend.

Table 1. Average values for T_{ig} and t_{ig} for each species.

Species	# of Runs	T_{ig} (ºC)	±	t_{ig} (sec)	±
Manzanita	267	405	16	3.00	0.32
Scrub Oak	215	299	24	1.24	0.22
Ceanothus	179	441	21	4.92	0.33
Chamise	43	248	18	1.80	0.31
Gambel Oak	129	227	20	0.70	0.08
Canyon Maple	115	238	22	0.64	0.11
Sagebrush	115	358	29	1.74	0.16
Juniper	67	247	45	1.48	0.34
All Species	1130	334	10	2.18	0.14

* The ± represents the 95% confidence interval

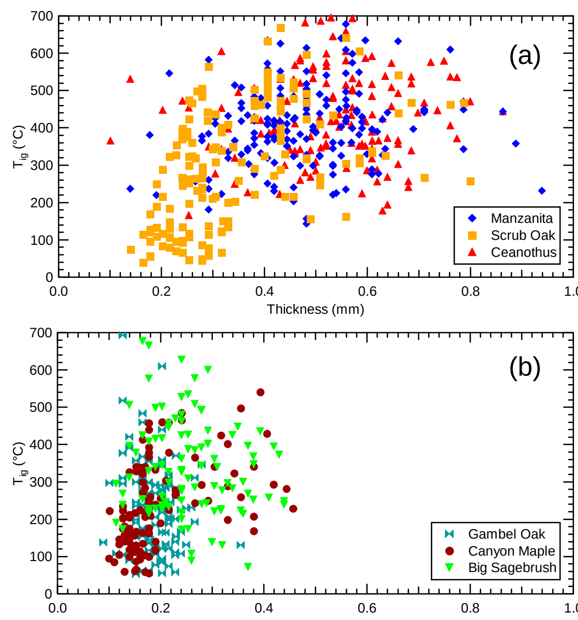

Figure 14. Ignition temperatures (T_{ig}) for (a) California chaparral and (b) Utah species versus leaf thickness.

The effect of thickness on t_{ig} was also explored. Figure 15 shows the effects of thickness on t_{ig} for the California and Utah species. Again, the data scatter makes it difficult to identify trends. There are several variables that may contribute to the scatter: moisture content, size and orientation of the leaf, mass, distance between the FFB and the sample, and seasonal effects. Most of the data on ignition temperature and time to ignition seem to correlate best with thickness, which is the same as the ratio of volume to surface area.

It is difficult to independently determine the effect of thickness on ignition characteristics because it is difficult, if not impossible, to isolate thickness from other variables such as moisture content. Ignition temperature and time to ignition are believed to be functions of both thickness and moisture content. It is believed that the scatter could be reduced if the effects of moisture content were included with thickness in this analysis.

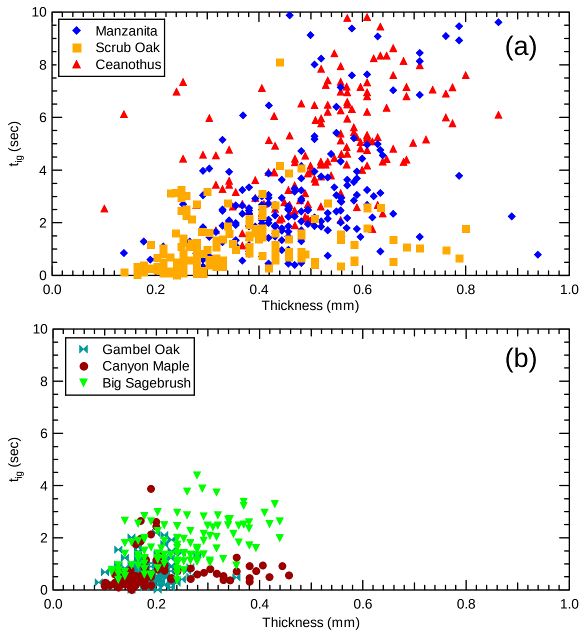

Figure 15. Time to ignition (t_{ig}) for (a) California chaparral and (b) Utah species versus leaf thickness.

The average values of T_{ig} and t_{ig} were misleading when analyzed as a function of moisture content only, since both thickness and mass were varying within a constant moisture content region. To account for the difference in mass and thickness, the amount of moisture in the leaf (m_{H2O}) was calculated and plotted versus the thickness, as shown in Figure 16. The manzanita and ceanothus species seem to correlate linearly with leaf thickness, while the scrub oak data seem to lie along two different lines. In all cases, there seems to be a definite correlation between the amount of moisture in a leaf and the thickness of the leaf.

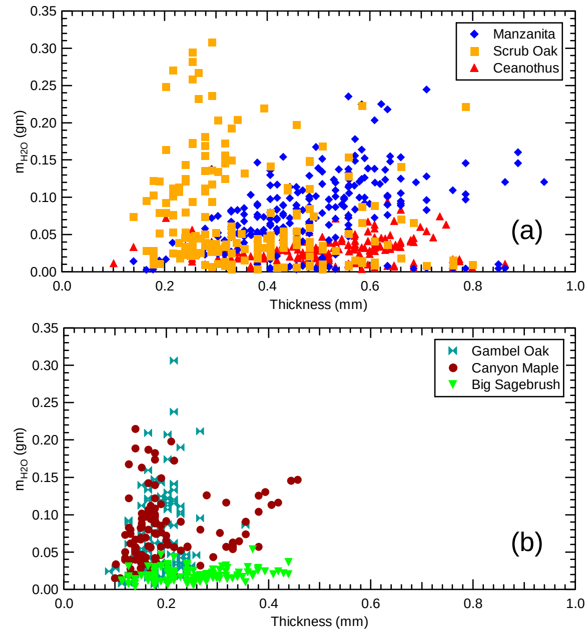

Figure 16. Initial mass of water (m_{H2O}) in the sample vs. leaf thickness for (a) California chaparral and (b) Utah species.

Table 2. Coefficients used in predicting (a) T_{ig} and (b) t_{ig} from Equations 1 and 2 for the individual species.

(a)	**T_{ig} (ºC)**		
Species	**a**	**b**	**c**
Manzanita	387 ± 223	-27 ± 496	221 ± 85
Scrub Oak	526 ± 174	-219 ± 346	144 ± 73
Ceanothus	157 ± 180	-296 ± 1340	401 ± 98
Gambel Oak	-858 ± 685	353 ± 446	359 ± 120
Canyon Maple	424 ± 269	-940 ± 554	270 ± 82
Sagebrush	83 ± 562	-2715 ± 4250	414 ± 142
All Species	452 ± 65	-541 ± 189	229 ± 28

(b)	**t_{ig} (sec)**	
Species	**a**	**b**
Manzanita	5.20 ± 1.35	1.55 ± 2.90
Scrub Oak	3.01 ± 0.46	-0.64 ± 0.72
Ceanothus	6.10 ± 0.95	29.9 ± 6.43
Gambel Oak	1.97 ± 0.81	1.68 ± 0.68
Canyon Maple	1.91 ± 0.44	0.33 ± 0.46
Sagebrush	3.61 ± 1.49	15.9 ± 8.10
All Species	7.10 ± 0.43	2.63 ± 0.84

* The ± represents 95% confidence interval

A simple combined correlation was made to predict T_{ig} and t_{ig} for the different species, as a function of moisture content (really m_{H2O} per leaf) and thickness. The T_{ig} and t_{ig} data were curve-fit using the following linear equations:

$$T_{ig} = a \cdot \Delta x + b \cdot m_{H2O} + c \qquad (1)$$

$$t_{ig} = a \cdot \Delta x + b \cdot \Delta H_{vap} \cdot m_{H2O} \qquad (2)$$

where a, b, and c are species-specific constants, Δx is the leaf thickness (mm), ΔH_{vap} is the heat of vaporization of water (2256.9 kJ/kg), and m_{H2O} (gm) is the mass of moisture in the sample. Table 2 contains constants a, b, and c for the broadleaf species correlations.

3.2.2 Burnout

The burnout time (t_{flame}) was defined as the amount of time that the flame was visible from the video images. Burnout time was expected to correlate with the amount of fuel available. Figure 17 shows the burnout time observed for the chaparral species versus the initial mass of the sample (m_{in}). The amount of fuel (m_{in}) correlates well with the burnout time, although the correlation differs from species to species. Burnout time data for the chaparral species showed more scatter, but also exhibited trends unique to each species. Utah samples fit even better than the California samples, which may be due to the wider variation of moisture content in California samples.

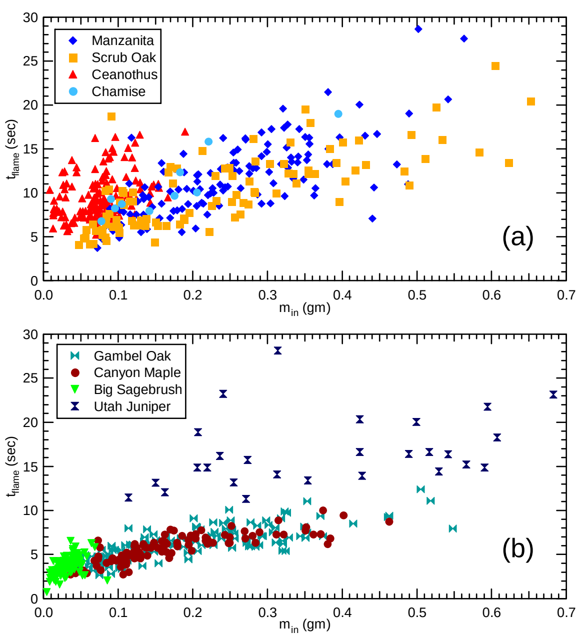

Figure 17. Burnout time (t_{flame}) vs. initial sample mass (m_{in}) for (a) California chaparral and (b) Utah species.

3.2.3 Flame Height

Along with the amount of time the sample burned, it was also expected that the flame height of the sample would correlate with the amount of fuel available. Others have correlated flame height with a mass reacted. The flame height of the sample reaches a maximum between ignition and burnout, usually around 2/3 of the time through the flaming period. For each individual run, all the video frames were analyzed, and an estimated maximum flame height and time were recorded. This flame height was estimated (±0.5 cm accuracy) from a known length in the image; the alligator clip.

The recorded flame height is compared with the amount of fuel available (m_{in}) in Figure 18a for the chaparral species. Similar to the burnout time, the amount of fuel seems to correlate with the flame height for each species. Utah samples followed similar trends (Figure 18b).

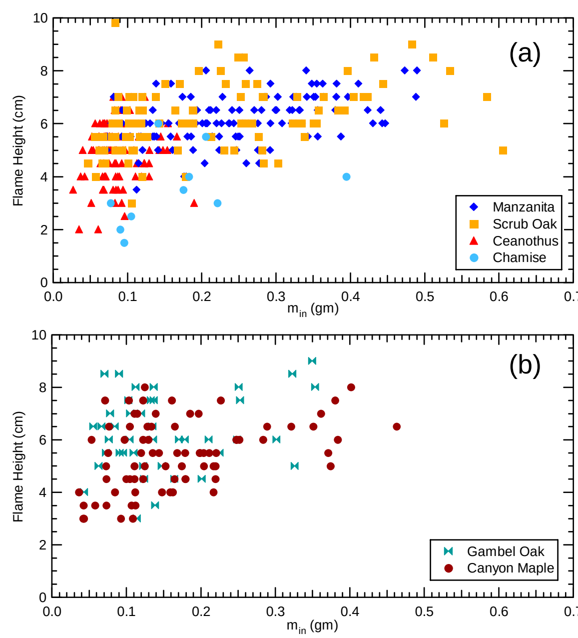

Figure 18. Estimated maximum flame height vs. initial sample mass for (a) California chaparral and (b) Utah species.

4. CONCLUSION

Quantitative and qualitative results were obtained from flat flame burner (FFB) experiments using California chaparral (manzanita, scrub oak, ceanothus, and chamise) and Utah (gambel oak, canyon maple, big sagebrush, and Utah juniper) leaf samples.

Qualitative observations were made of leaf bubbling, bursting, brand formation, and bending.

Bubbling occurred on all broadleaf species except sagebrush, and was observed as liquid bubbles on the outer surface of the leaf or pockets of gas forming underneath the leaf surface. Mild crackling was observed during interior bubbling, and was associated with small amounts of air escaping the leaf surface. Bursting was observed in all the chaparral broadleaf species and was observed as miniature explosions on the leaf. Violent crackling was observed during bursting. It is believed that these explosions cause the epidermis of the leaf to become separated from the rest of the leaf material. Scrub oak and ceanothus exhibited bursting on the underside of the leaf. Brand formation occurred in all California samples as well as in Utah sagebrush and juniper. Several types of brand formation were observed, including pieces ejected during bursting, ejection of spines or points at the leaf edge (scrub oak), or burning of the stem to release the leaf (chamise, juniper, and sagebrush). Bending was observed as the sample bent downward into the upward convective gases. It is believed that the under side (spongy mesophyll cells and epidermis) material is breaking down and droops into the hot gases.

Quantitative results show the effects of thickness and moisture content on the ignition temperature (T_{ig}) and the time to ignition (t_{ig}). Correlations to predict T_{ig} and t_{ig} were made for individual species, with thickness being the most significant variable (not moisture content). The burnout time (t_{flame}) correlates by species with the amount of fuel available (i.e., mass of the sample). The maximum flame height was also estimated from video images and again correlated by species with the amount of fuel available.

5. ACKNOWLEDGMENTS

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