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## DIFFERENCES IN BURNING BEHAVIOR OF LIVE AND DEAD LEAVES, PART 1: MEASUREMENTS

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*Burning behaviors of individual live and dead leaves were measured in a well-instrumented, well-controlled flat-flame burner. Manzanita (*Arctostaphylos glandulosa*) branches were harvested from the Chaparral near Riverside, California. Leaves were conditioned to several moisture contents. Two “live” (i.e., not fully dried) groups remained above the fiber saturation point at 34% moisture content (MC; dry basis) and 63% MC. Two “dead” groups were dried to about 4% MC, and one was rehydrated back up to 26% MC. Distinct plateaus in surface temperatures at 175°C were observed while burning live leaves, but dead leaves showed weaker plateaus, if any. Evidence of high internal leaf pressures during burning of live leaves was seen in flame patterns. Moisture was retained in live and dead leaves with local surface temperatures in the 160°C to 220°C range. This article describes the measured results, while a second article describes mass release modeling for the same data set.*

**Keywords:** Leaf combustion; Manzanita; Moisture content; Pyrolysis; Wildfire

### INTRODUCTION

The burning behavior of live fuels is clearly different than that of dead fuels. Fire spread is sustainable at higher fuel moisture contents in live fuels than in dead fuels, but the fundamental reasons for this difference are not well understood (Finney et al., 2012). Studies have examined the ignition times, rates of fire spread, moistures of extinction, and the fuel temperature histories of both dead and live fuels in a variety of conditions (Catchpole et al., 1998; Dimitrakopoulos and Papaioannou, 2001; Dimitrakopoulos et al., 2010; Fletcher et al., 2007; Pickett, 2008; Pickett et al., 2010; Weise et al., 2005). However, a detailed study of the temperature distribution and mass history of single live and dead leaves of similar moisture contents in a wildfire condition has not previously been performed.

Finney et al. (2012) summarized several ways that fire spread in live vegetation is not explained by current modeling and theory, including: (a) the ability of live fuels to sustain fire spread at higher moisture contents than is possible in dead fuels, and (b) that upon preheating, water is released in live fuels due to structural failure rather than by diffusion as in dead fuels. Although the moisture of extinction (dry basis) is usually between 12% and 30% for dead fuels (Burgan and Rothermel, 1984), Dimitrakopoulos and Papaioannou

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(2001) have measured moistures of extinction as high as 140% moisture content in live foliage. Moisture content ( $MC$ ) is defined in terms of the sample mass ( $m_0$ ) and its oven-dry mass ( $m_{dry}$ ):

$$MC = \frac{m_0 - m_{dry}}{m_{dry}} \quad (1)$$

While burning live fuels, Pickett (2008) observed temperature plateaus indicative of evaporation at mean leaf temperatures of 140°C and 200°C and suggested that the elevated boiling point of water solutions was a possible explanation for the plateau at 140°C. This is supported by a measured elevated boiling point of 140°C for 95% concentrated sucrose-water solutions at 100 kPa (Ozdemir and Pehlivan, 2008). An alternate explanation for the temperature plateaus in live leaves observed by Pickett (2008) at 200°C may be related to elevated internal pressures. Carpita (1985) used a gas decompression technique to pressurize cells and then measured the fractions of intact cells at various pressures, observing that plant cells burst at elevated pressures. Under the high heat flux conditions of a fire, live leaves may close stoma, which inhibits mass transfer of moisture, and which may increase internal pressure and allow water to reach temperatures above its normal boiling point without evaporating.

Water in dead fuels is bound in cell walls to the hygroscopic constituents, cellulose, and hemicellulose. Moisture content in cured biomass responds quickly to relative humidity. At 100% relative humidity, biomass approaches its fiber saturation point, which is usually between 30% to 35% MC. Moisture contents higher than 35% occur in dead biomass only when liquid water on the leaf surface is absorbed into cell cavities (e.g., from rain or dew) (Catchpole et al., 2001; Viney, 1991). Lignocellulosic materials have been described as a composite, forming a transient microcapillary network in which water can occur as monolayer water (closely associated with OH groups) or polylayer water (more loosely associated) (Hill et al., 2009, 2010, 2012). Though moisture in dead fuels is not trapped in living cells during heating, elevated pressures may still develop as moisture diffuses through cell walls.

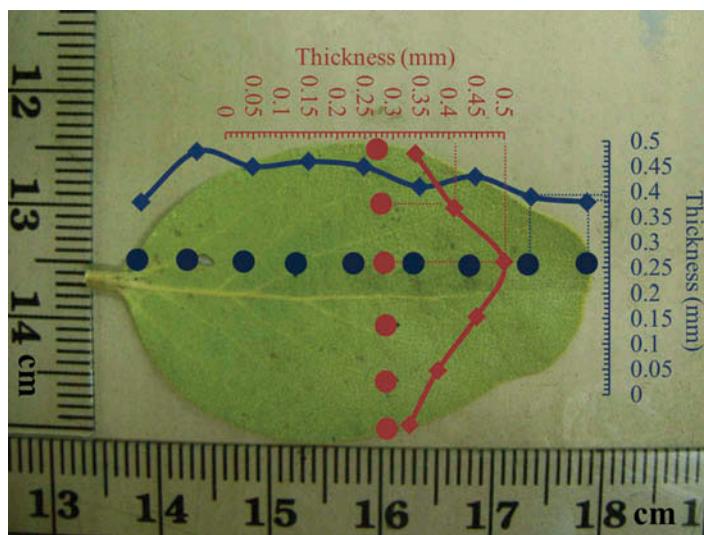
## OBJECTIVE

The objective of this work was to examine the differences in burning behavior of live and dead leaves, especially near the transition that occurs at the fiber saturation point (part 1, this article). Furthermore, fundamental models for the mass release of volatiles and water were applied to enable the prediction of mass release at broader conditions (part 2, in a following article).

## EXPERIMENTAL METHODS

### Fuel Description

Manzanita (*Arctostaphylos glandulosa*) shrubs are prevalent in California shrublands and their leaves were selected to investigate devolatilization and water release. Manzanita branches were collected in the mountains near Riverside, California, and shipped to Brigham Young University in Provo, Utah. Four leaf conditions were achieved: (i) fully cured; (ii) rehydrated from a cured state in a humidity chamber; (iii) dried to near the fiber



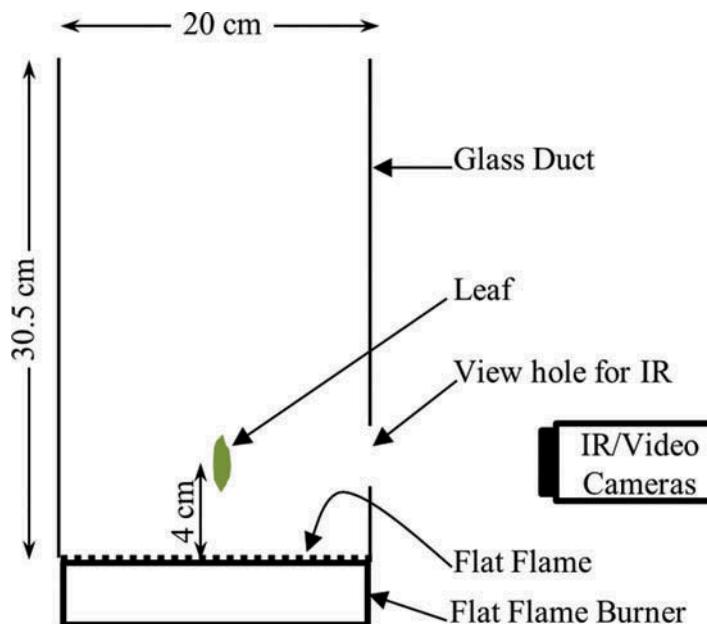
**Figure 1** Plotted thickness of a dry dead manzanita leaf superimposed on an image of the leaf. The measurement locations are marked and correspond to the plots.

saturation point; and (iv) slightly dried. Leaves given these treatments are hereafter referred to, respectively, as dry dead (4% moisture content, MC, dry basis), rehydrated dead (26% MC), dehydrated live (34% MC), or fresh live (63% MC). Dead and live labels correspond to whether or not the sample had been cured to well below the fiber saturation point (i.e., no water is left in cell lumens and cell walls have contracted). The thickness profile of a sample dry dead leaf is shown in Figure 1. The average and standard deviation of leaf thickness of leaves for each group were  $0.43 \pm 0.05$  mm (dry dead);  $0.51 \pm 0.04$  mm (rehydrated dead);  $0.52 \pm 0.04$  mm (dehydrated live); and  $0.57 \pm 0.05$  mm (fresh live).

Drying was performed at room temperature with leaves on their branches. Stems were cut at the base of the leaf prior to burning. Several leaves were selected from each group for a moisture content analysis using a Computrac Max 1000 (Arizona Instruments). The moisture content of live (fresh and dehydrated) and dry dead manzanita leaves was stable enough that a single moisture analysis performed during a half-hour sequence of burns was representative of the group. However, additional care was needed for rehydrated dead leaves, which respond quickly to the ambient humidity. Before rehydrating, leaves were individually weighed, and a representative moisture content was measured to determine their dry masses. Each rehydrated leaf was weighed immediately before burning to determine its moisture content. The physical properties of live and dry dead leaves (mass, length, width, and height) were also measured just prior to testing. The dimensions of rehydrated dead leaves were measured several hours before burning, and were then replaced in the chamber to maintain their moisture.

### Experimental Apparatus and Instrumentation

Each leaf was suspended in the center of a tempered glass duct by a cantilever mass balance, which was synchronized and time-stamped with video images. A porous  $7.5 \times 10$  in. flat-flame burner (FFB) was quickly rolled into position directly under the leaf and glass



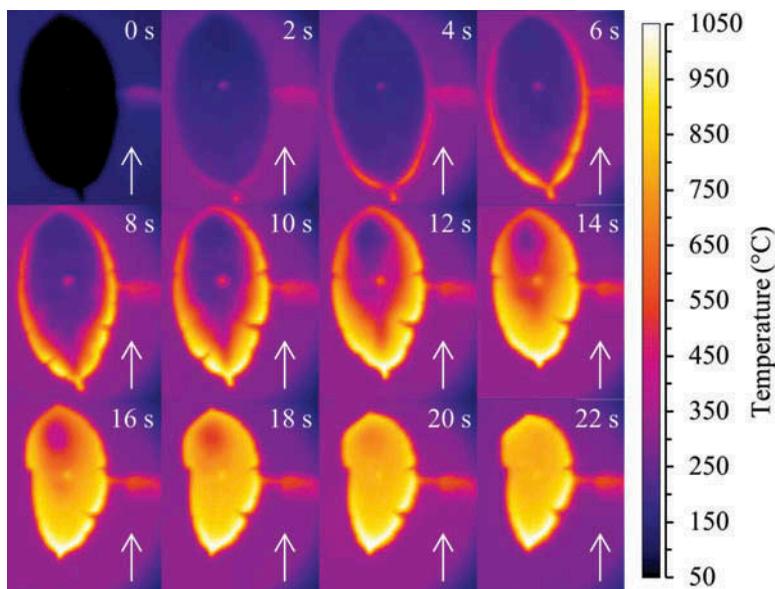
**Figure 2** Schematic of experimental setup. A leaf is held on the tip of a rod extending from a mass balance through a slot cut in the far glass panel. The FFB is pulled under the glass duct and leaf to begin heating. Temperature and flame behavior are recorded with IR and video cameras. The IR is shot through a 1-in. diameter hole in the glass.

cage. The FFB produced a thin hydrogen-methane-air flame ( $\sim 1$  mm thick) with 10 mol%  $O_2$  in the post-flame gas. A K-type thermocouple placed in the post-flame gas at 2 cm, 4 cm, and 6 cm above the burner surface measured  $997^\circ C$ ,  $985^\circ C$ , and  $962^\circ C$ , respectively. Correcting for radiation, the estimated gas temperatures at these heights were  $1036^\circ C$ ,  $1023^\circ C$ , and  $997^\circ C$ . Details of the radiation correction are described in Prince (2014). The long dimension of each leaf was oriented vertically with its center at approximately 4 cm. A schematic of the experimental setup is shown in Figure 2.

A detailed surface temperature of one side of the leaf was recorded with a FLIR Systems, Inc. camera (Thermovision A20, wavelength  $7.5\text{--}13\ \mu m$ ). Leaves were estimated to have an emissivity of 0.98 (Lopez et al., 2012). At these wavelengths, the IR camera sees the solid leaf surface but not the soot from the flame. A Matlab script was developed to automatically identify leaf boundaries from IR images, with optional user guidance. In the later portion of a run, leaf folding or twisting sometimes occurred with occasional misidentification of the leaf boundary. These events were monitored but were not observed to significantly impact measured temperature distributions.

## RESULTS

The dry dead and fresh live groups each consisted of 18 runs. The rehydrated dead and dehydrated live groups each consisted of 19 runs. The following results focus on the average measurements for each group, and when practical, 95% confidence intervals are included.



**Figure 3** IR thermal images of a fresh live manzanita leaf during heating at 2-s intervals. Temperature maps such as these were averaged with other runs to produce the histograms in Figures 5 and 9. The bright dot in the middle is a metal needle skewering the leaf. The arrows show direction of upward gas flow.

### Heating Pattern

Manzanita leaves did not heat isothermally under rapid convective heating conditions. Infrared images show a fresh live leaf heating from the edges in, led by heating at the bottom (Figure 3). Several factors may have contributed to this heating pattern, for example: (a) boundary layer development reduces convective heating along the gas flow path across the leaf, and (b) leaf properties at the edges, such as reduced thickness or moisture content, may accelerate edge heating relative to the rest of the leaf. Large temperature differences were observed between different points of the leaf at the same time. Averaging the runs of each group together, the largest difference between the 10% and 90% percentiles at any time was 225 K (dry), 332 K (rehydrated), 395 K (dehydrated), and 445 K (fresh). The interval increased with the starting moisture content of the group.

### Differences in Early Temperature Distribution

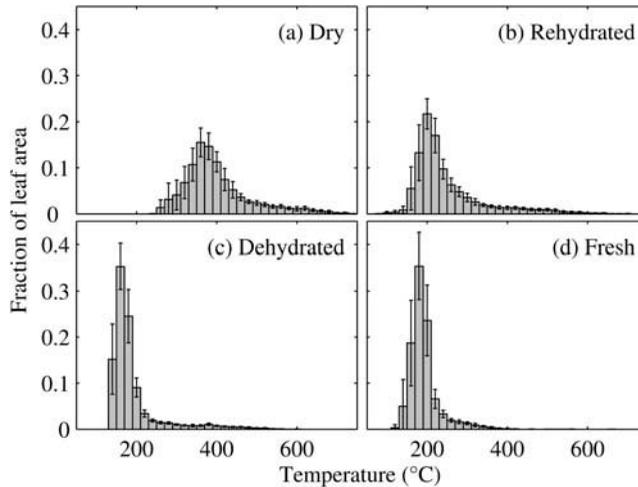
Differences were measured in the temperature distributions of live and dead leaves at a residence time of 3 s (see Table 1). While there were strong similarities between the live groups (i.e., dehydrated and fresh), the temperature distribution statistics at 3 s for the live groups differed from either of the dead groups (i.e., dry and rehydrated).

Histograms of surface temperature with 20 K bin-widths and a 95% confidence interval (CI) on each bin at a residence time of 3 s are shown in Figure 4. Fractions of leaf surface area in each bin were determined by pixel counting. The statistics listed in Table 1 are reflected in Figure 4. Particularly, the values of kurtosis (a measure of peakedness) quantify the relative height of the peaks and sharp shoulders observed for live leaves (Figures 4c and 4d). The kurtosis, coupled with the lower dispersion of live leaves, indicates a high

**Table 1** Statistics on average leaf temperature distributions after 3 s of heating

	“Dead” leaves		“Live” leaves	
	Dry	Rehydrated	Dehydrated	Fresh
Mean (°C)	400 ± 17	248 ± 14	190 ± 5	191 ± 8
Dispersion* (K)	80	68	30	23
Skewness	1.5 ± 0.1	2.0 ± 0.2	2.9 ± 0.1	2.6 ± 0.3
Kurtosis	4.7 ± 0.4	6.9 ± 1.3	11.7 ± 1.2	11.3 ± 2.2

\*Dispersion is represented by the interquartile range.

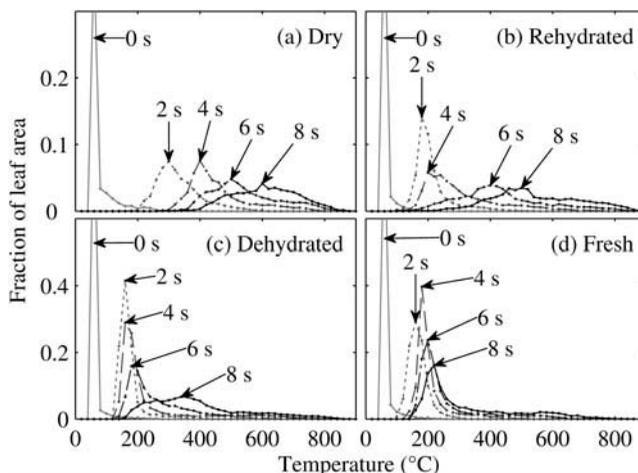


**Figure 4** Temperature histograms at 3 s of heating averaging all runs for (a) dry dead leaves, (b) rehydrated dead leaves, (c) dehydrated live leaves, and (d) fresh live leaves. Error bars represent 95% CIs on the fraction of leaf area. Fraction of leaf area is determined by pixel counting of the IR images.

level of temperature uniformity. In contrast, the kurtosis of dead leaves (Figures 4a and 4b) was closer to three, or that of a normal distribution, indicating a smoother transition from edge temperatures to middle temperatures. Furthermore, the temperatures of dead leaves were distributed over a wider range, as indicated by their high values of dispersion. The interquartile range was used as an appropriate measure of the dispersion for this log-normal distribution as suggested by Shoemaker (1999). Live leaves exhibited more temperature uniformity and lower temperatures than dead leaves (even the moist rehydrated leaves) during early residence times.

### Effects of Moisture Content and Moisture History

Average temperature histograms of each leaf group at 2-s intervals are presented in Figure 5. Over the 8-s period shown, the temperature rise stalled for all moist groups, but not for the dry group. This suggests that moisture is the cause of the observed temperature stall (e.g., by moisture evaporation or desorption). The temperature stall was least pronounced for the rehydrated dead group, even though its moisture content was similar to that of the dehydrated live group. This further suggests that moisture history (or state)



**Figure 5** Traces of temperature histograms at 2 s, 4 s, 6 s, and 8 s, averaging all runs for (a) dry dead leaves, (b) rehydrated dead leaves, (c) dehydrated live leaves, and (d) fresh live leaves. Each marker represents one histogram bin (see Figure 4).

also influences moisture's effect on heating. When previously dried leaves absorb humidity from the air, water binds to cellulose and hemicellulose. Leaves that have not been dried past the fiber saturation point retain some moisture as bulk (or liquid) water. The temperatures stalled above the normal boiling point of water: 170°C to 210°C (rehydrated dead), 150°C to 190°C (dehydrated live), and 150°C to 230°C (fresh live). The likelihood of water accounting for temperature stalls at elevated temperatures is discussed later.

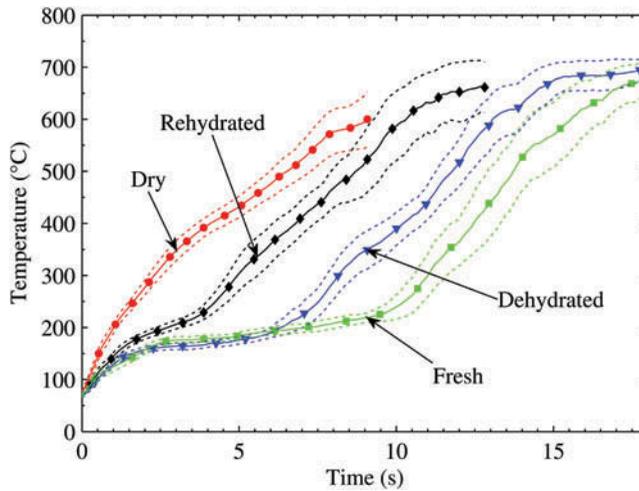
### Effects of Moisture Content on Temperature Plateaus

Moisture held in live leaves had a different effect on the leaf temperature of heating leaves than moisture held by dead leaves. Taking the mode from histograms (20 K bin widths) and plotting over time reveals a temperature plateau for all moist groups (Figure 6). The modes are bounded by 95% point-wise confidence bands. The temperature plateau of the rehydrated dead leaves was less flat and at a higher temperature (about 200°C) than that of the dehydrated or fresh live leaves (both at about 175°C). Dry dead leaves showed no temperature plateau.

The duration of the temperature plateaus were 2 s (rehydrated), 5 s (dehydrated), and 8 s (fresh). Though the amount of moisture affected the duration of the dehydrated and fresh leaf plateaus, their temperatures and slopes were similar. The temperatures, slopes, and durations of the rehydrated and dehydrated leaves differed, demonstrating that moisture held in live leaves had a stronger effect on leaf temperature than did moisture held in dead leaves. Again, this may reflect differences in the behaviors of bulk and adsorbed water.

### Use of Mode as a Moisture Marker

The mode temperature, taken from histograms (20 K bin widths), is well-suited to identifying regions where water is being released. The mode is the largest isothermal leaf



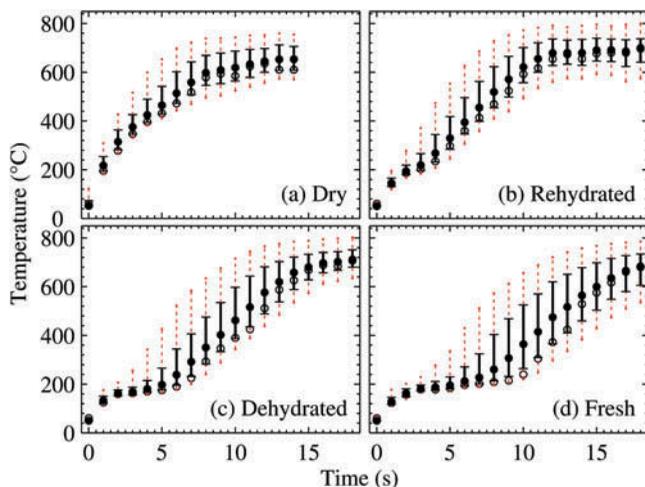
**Figure 6** Mode temperatures averaged for each leaf group. Average values (solid with markers) are bounded by 95% CIs (dotted).

area. Further, areas where water evaporates are roughly isothermal because water evaporation is highly endothermic and stabilizes temperature at the boiling point. The boiling temperature and diffusion rates of moisture from the leaf are both functions of internal leaf pressure. Pressure and boiling temperature are stabilized when steam diffusion rates equal evaporation rates, and the heat absorbed by evaporation balances heat transfer to the leaf region. A leaf region where water is being lost therefore becomes isothermal compared to the temperature distribution of the remaining leaf. Thus, the mode temperature was tracked in order to recognize areas of water release.

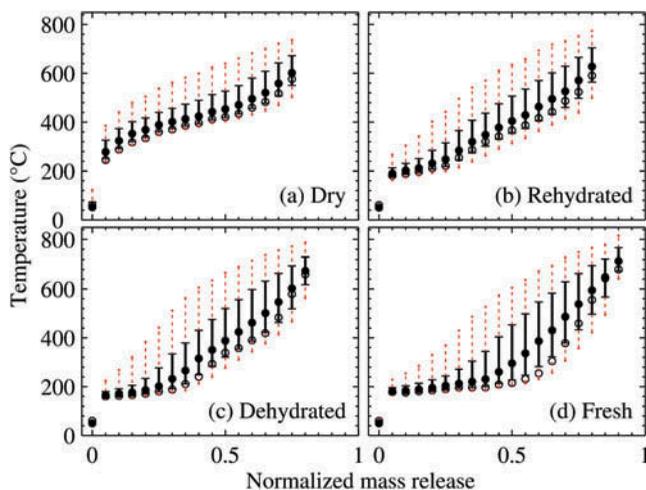
The mode temperature (plotted as open circles) is shown in context of the leaf temperature distribution in [Figure 7](#) at 1-s intervals. The range from the 25% to 75% percentiles is drawn with solid inner bars, the 10% to 90% range is drawn with dotted outer bars, and the median is plotted as filled circles. While not plotted, the mean temperature closely followed the median temperature. The mode stagnated between 165°C and 220°C for dehydrated and fresh leaves, while other parts of the leaves increased in temperature. Above these temperatures it is unlikely that pockets of moisture remained, so the mode was no longer regarded as a moisture marker.

### Additional Evidence of Moisture Release During the Temperature Plateau

Little moisture was released before the moist leaves reached temperature plateaus. [Figure 8](#) plots the leaf temperature distribution versus normalized mass release at 5% increments for each leaf group. The same markers were used as were described for [Figure 7](#). The temperatures plateaued by the time 5% of the mass was released. Depending on the group, at least 76% to 87% of the starting moisture was retained upon reaching the plateau temperature (based on a moisture mass balance and assuming that water accounts for all of the initial mass release). The remaining moisture was released afterwards, providing cooling to the leaves.

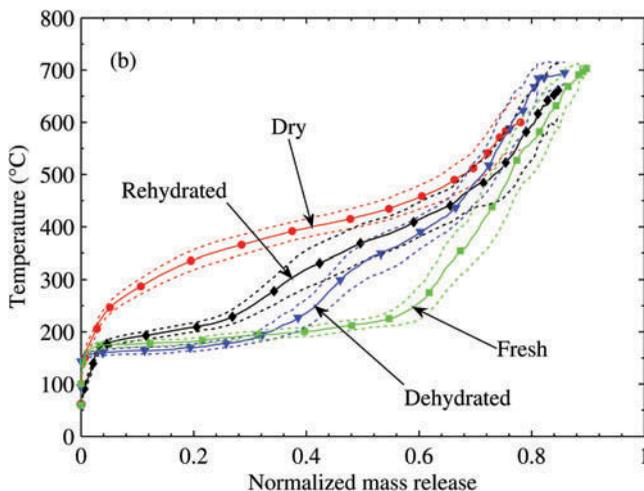


**Figure 7** The average distribution of leaf surface temperature is plotted vs. time for each leaf group. Temperature distributions are described by the median (circle), middle 50% (inner bar), middle 80% (outer dotted bar), and mode (diamond).



**Figure 8** The average distribution of leaf surface temperature is plotted at various stages of conversion for each leaf group. Temperature distributions are described by the median (circle), middle 50% (inner bar), middle 80% (outer dotted bar), and mode (diamond).

Moisture comprised 21% (rehydrated), 25% (dehydrated), and 39% (fresh) of the starting leaf mass for each moist leaf group. Plotting mode temperature (from histograms with 20-K wide bins) for each leaf group shows that the temperature plateaus did not end until the mass release was equal to or greater than the starting moisture mass (Figure 9). If the moisture was completely released before any portion of other leaf components, water would persist in the leaves until more than half way (by mass) through the temperature plateaus. However, because the hottest parts of the leaves were above 400°C by the end of the temperature plateaus (see Figure 8), it is more likely that some of the mass release was



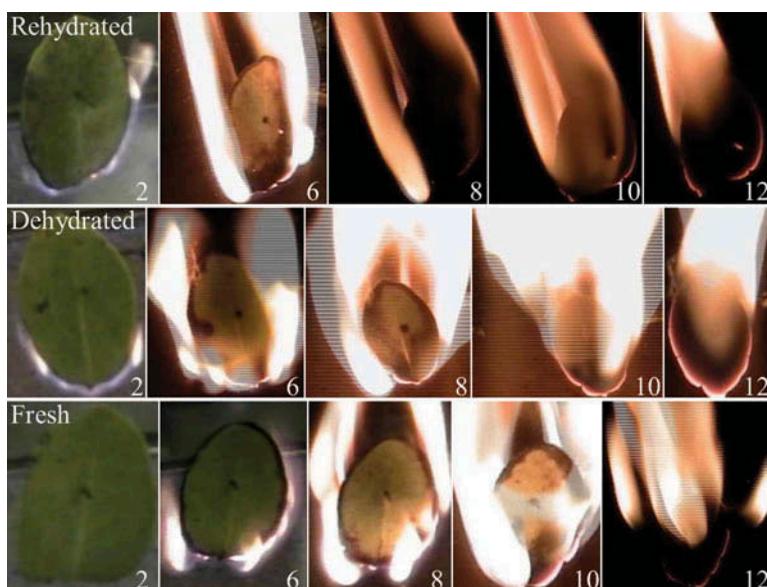
**Figure 9** Average mode temperature vs. normalized mass remaining for each leaf group. Average mass (solid with markers) is bounded by point-wise 95% CIs (dotted).

due to pyrolysis and that water provided cooling until the end of the temperature plateaus. This is not to suggest that lignocellulosic decomposition could account for the temperature plateaus, since the plateaus began at temperatures below the decomposition temperatures given by Di Blasi (2008) and Biagini and Tognotti (2014).

The shape and behavior of the flames of moist leaves were consistent with the scenario of moisture release during the temperature plateaus. Substantial pressure would be required to maintain liquid water at the leaf temperatures measured during the temperature plateaus. The flames of dehydrated and fresh live leaves were unsteady and distorted, consistent with the release of high-momentum jetting vapors (Figure 10). This momentum was observed disrupting and propelling the flame in downward or outward directions. However, the flames of rehydrated dead leaves were, on average, less erratic than those of live leaves. Images in Figure 10 show that the rehydrated leaves frequently had smoother and steadier flames than the live leaves. Since the moisture of rehydrated leaves is in an adsorbed rather than liquid state, it is not surprising that the flames of the rehydrated leaves showed less effect of high-momentum vapor release. Still, effects of high momentum mass release were seen in many rehydrated runs. The erratic jetting behavior of live leaves seems to be a key difference in flame behavior between live and dead fuels, and is ultimately evidence of pressurized moisture release.

For leaves to withstand the vapor pressure of water at approximately 200°C, they must tolerate internal pressures approaching 8 atm. This is equivalent to the vapor pressure of water at 170°C or of a solution with a 30°C boiling point elevation at 200°C. Plant cells have been observed to withstand pressures exceeding these levels (Carpita, 1985). Additionally, evidence of high internal pressure (i.e., bursting, bubbling, crackling, hissing, and jetting) has been observed for numerous species, including manzanita (Fletcher et al., 2007; Shen, 2013; Smith, 2005). The violent release of moisture (e.g., bursting) is associated with high initial moisture contents (Fletcher et al., 2007).

This study builds on previous work performed using methods described by Pickett (2008). Previously unreported experiments were performed to measure the amount of water



**Figure 10** Images of rehydrated dead, dehydrated live, and fresh live leaves during heating at 2 s, 6 s, 8 s, 10 s, and 12 s. Zooming is adjusted to include relevant flame behavior.

**Table 2** Summary of water content measurements for nitrogen-quenched manzanita leaves of various heating intervals

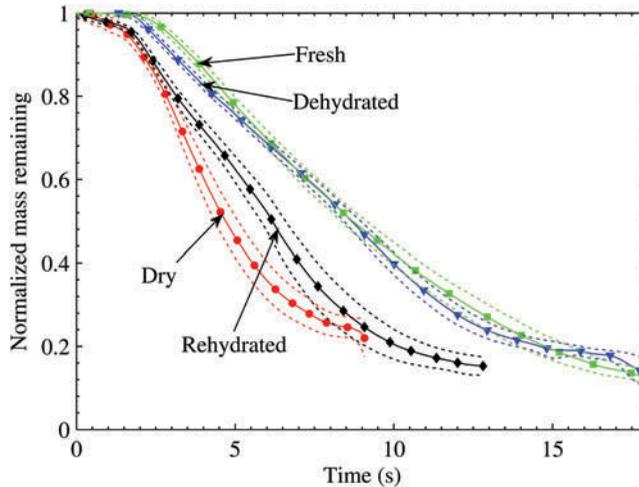
Quenching time (s)	<i>n</i>	$MC_{quench}$	Initial MC of leaves (%)
1	20	$48\% \pm 2.8\%$	79
2	20	$43\% \pm 3.7\%$	77
3	69	$35\% \pm 2.6\%$	107, 61, 47, 75
4	20	$29\% \pm 5.8\%$	77
5	20	$24\% \pm 5.4\%$	70
6	31	$17\% \pm 4.1\%$	80, 47, 74
7	20	$13\% \pm 6.7\%$	79

$MC_{quench}$  = mean mass of water at quenching as a fraction of the initial leaf mass  $\pm$  the 95% confidence interval, *n* = number of measurements.

remaining in manzanita leaves (47–107% MC) after precisely controlled heating exposures. The leaves, immediately quenched with nitrogen, were then weighed and their moisture contents evaluated to determine the amount of moisture retained. The exposure time was controlled by a timer and a solenoid valve. Table 2 shows the mean water mass at each quenching time as a fraction of the original leaf mass,  $MC_{quench}$ . At 7 s of exposure, moisture was still present. These data provide direct measurements of the longevity of moisture release at similar gas temperatures and O<sub>2</sub> concentrations as in the experiments described earlier in this article.

### Differences in Mass Release

Dead leaves released mass more quickly than did live leaves in these experiments (Figure 11). This difference is statistically significant based on the non-overlap of their



**Figure 11** Average normalized mass remaining for each leaf group vs. time. Average mass (solid with markers) is bounded by point-wise 95% CIs (dotted).

95% confidence bands. Moisture content delayed mass release in rehydrated dead leaves. The dehydrated and fresh live leaves had similar mass release profiles and their confidence bands partly overlapped.

## DISCUSSION

The measured burning behaviors of live and dead foliage have implications for wildfire models. Leaf edges reached ignition temperatures first, indicating that ignition and burning does not occur simultaneously across a manzanita leaf, but progresses from the edges towards the center. Moisture content and moisture state impact the duration and flatness of temperature plateaus. Go-no-go predictions for prescribed fires depend on correctly describing heat transfer from burning fuels in the flame zone to neighboring fuels. The temperature distribution, moisture release, and combustion behavior of live and dead leaves are important factors in modeling heating and heat release in a rigorous manner. Thermal modeling of leaves heated in wildfire conditions can better distinguish between the behavior of live and dead fuels using the results presented here.

## CONCLUSIONS

A flat-flame burner was brought under individual live and dead manzanita leaves in a well-controlled, well-instrumented apparatus. The burning behavior of each leaf was measured and analyzed. This is the first set of experiments to determine fundamental differences in the burning behavior of live and dead fuels near the fiber saturation point. First, the temperature plateaus of live leaves were cooler (occurring at approximately 175°C), flatter, and longer-lasting than the temperature plateau of rehydrated dead leaves (occurring at approximately 200°C), even though rehydrated leaves had a similar moisture content as dehydrated live leaves. Second, live leaves showed radial and non-uniform flame movement due to high-momentum jetting, indicating high internal leaf pressures. The flames of rehydrated

dead leaves were smoother and less erratic than those of live leaves, and high-momentum mass release effects were observed to a lesser extent. Third, moisture was retained for all moisture-laden leaves into the 160°C to 220°C range, which is above the normal boiling point (100°C) of water. This finding was supported by direct measurements of moisture content at precise residence times. Concurrent release of pyrolyzates and moisture was identified.

A single temperature does not adequately describe rapidly heated manzanita leaves. Kinetic modeling of leaves or other biomass of similar size should consider their wide temperature distribution during rapid heating, such as in wildfire conditions. Water release models for these conditions should not assume a classical water release model.

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