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Experimental measurements during combustion of moist individual foliage samples[A]

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Abstract. Individual samples of high moisture fuels from the western and southern United States and humidified aspen excelsior were burned over a flat-flame burner at 987° ± 12°C and 10 ± 0.5 mol% O_2. Time-dependent mass and temperature profiles of these samples were obtained and analysed. It was observed that significant amounts of moisture remained in the individual samples after ignition occurred. Temperature histories showed a plateau at 200°–300°C at the leaf perimeter rather than at 100°C, with a plateau of 140°C for the leaf interior. Implications are that classical combustion models should be altered to reflect the behaviour of moisture in high moisture (live) samples. Mass release rates were determined at ignition and maximum flame height; these appeared to vary due to surface area and perimeter, but no significant correlation was found for all species.

Introduction

Wildland fires burn through large areas of live vegetation in shrubs and coniferous forests throughout the United States, particularly in the western and southern regions and cause significant economic and ecological impacts in these areas. Throughout the world, operational wildland fire spread models (models used by fire managers in the field) are based primarily on empirical correlations developed from 'dead' fuels (Byram 1959; McArthur 1966, 1967; Fosberg and Deeming 1971; Rothermel 1972; Van Wagner 1973; Albini 1976; Forestry Canada Fire Danger Group 1992) such as excelsior or cast pine needles. However, wildland fires do not exclusively spread through dead fuels, but rather through a combination of dead and 'live' (high moisture) fuels. Operational field models (Deeming *et al*. 1972; Andrews 1986; Forestry Canada Fire Danger Group 1992; Coleman and Sullivan 1996; Finney 1998) based on these dead fuel correlations can help fire managers better determine how fast a fire will move through a known area of fuel type, slope and wind speed (spread rate). These operational models can predict fire spread rate well for the conditions for which the model is correlated (e.g. dead fuels), but they are less accurate for live fuels.

Limited research has been performed on the burning characteristics of non-shredded live fuels. Dimitrakopoulos and Papaioannou (2001) performed flammability analyses of live, individual samples of 24 Mediterranean forest fuel species. Weise *et al.* (2005*a*) used a cone calorimeter to determine combustion characteristics of ornamental vegetation on foliage samples. They also provided a review of much of the flammability research for live fuels that has occurred over the past 30 years. Smith (2005) and Fletcher *et al.* (2007) investigated the effects of moisture on temperature and time to ignition but did not include mass results. Other studies on live fuels have been performed in fuel beds or in fuel baskets (Weise *et al*. 2005*b*; Zhou *et al*. 2005; Sun *et al*. 2006) but not on an individual sample basis. This paper will investigate the effects of moisture during combustion on individual forest fuel samples, particularly during the evaporation and ignition phases.

Materials and methods

Plant species were selected from three regions of the United States (south-west Mediterranean, dry interior west and humid southern) for testing. Four common species found in California chaparral were harvested at North Mountain Experimental Area adjacent to the San Bernardino National Forest: hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.)[B], chamise (*Adenostoma fasciculatum* Hook. & Am.), Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.) and scrub oak (*Quercus berberidifolia* Liebm.). Four common southern species were harvested on Eglin Air Force Base, 16 km (10 miles) south of Crestview, Florida: fetterbush lyonia (*Lyonia lucida* (Lam.) K. Koch), gallberry (*Ilex glabra* (L.) Gray), saw palmetto

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[B]The source for the botanical names is the USDA PLANTS database (http://plants.usda.gov, accessed 3 December 2009).

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(*Serenoa repens* (Bartr.) Small) and wax myrtle (*Morella cerifera* (L.) Small). Six interior west species were harvested in the forests surrounding Brigham Young University (BYU) in Provo, UT: canyon maple (*Acer grandidentatum* Nutt.), gambel oak (*Quercus gambelii* Nutt.), Utah juniper (*Juniperus osteosperma* (Torr.) Little), big sagebrush (*Artemisia tridentata* Nutt.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.). Species were harvested by cutting branches 0.15 to 0.45 m (0.5–1.5 ft) from the terminal ends of the bush or tree. Samples were sealed in a plastic bag and kept cool to minimise water loss. California and Florida samples were mailed overnight to BYU for testing. Excelsior made from the dead wood of *Populus tremuloides* Michx. was included for comparison.

Experimental apparatus

The experimental apparatus is designed to simulate a wildland fire approaching an individual fuel sample as described by Engstrom *et al*. (2004) and Fletcher *et al*. (2007). Specific detail about the instrumentation and data acquisition of the equipment is discussed in Pickett (2008). Individual samples (single-leaf for broadleaf species or terminal stems and needles for non-broadleaf species that fit within the domain of the heating source) were randomly selected from the harvested branches. The experiment mimics temperatures and heating rates in wildland fires, which are thought to be ~1200 K (Butler *et al*. 2004*b*) and 100 K s^{-1} (Butler *et al*. 2004*a*) respectively.

To simulate these wildland fire conditions, the fuel sample was attached by an alligator clip to a stationary horizontal rod positioned on a Mettler Toledo (Columbus, OH, USA)[C] cantilever mass balance with an accuracy of 0.1 mg. A counter weight stabilised the rod and fuel sample. A flat-flame burner (FFB) with dimensions 3 × 7.5 cm was placed on a moveable platform which provided a convective heat source to the fuel sample. The burner flame was 1–3 mm high, with post-flame conditions at 5 cm above the FFB of 987° ± 12°C (mean ± s.e.) and 10 mol% O_2 (Pickett 2008). Heat fluxes at the leaf location in this experiment were reported to be 80–140 kW m^{-2} for the species studied by Fletcher *et al*. (2007). The experiment was performed with samples in the horizontal position for both broadleaf and non-broadleaf species, giving a consistent heat source (temperature) to the entire samples.

Moisture content (MC) was determined on the day of experiments by a CompuTrac moisture analyser (MAX1000 v4.26B, Chandler, AZ, USA), which heated ~2 g of foliage to 98°C and maintained that temperature until mass ceased to change. This equilibrium criteria for the moisture analyser required that mass release be lower than 0.01% min^{-1} to finish the analysis. Each MC analysis took ~10–20 min depending on species and MC. Two to four replicates of MC were taken and averaged for that particular experimental period (burning 10–15 individual samples took about an hour). The mean MC was assigned to those samples burned during that experimental period. Freshly cut samples were burned within 2 days of arrival (bags remained sealed until experiment) since MC decreased as the sample sat in the laboratory (10–20% relative humidity). Individual excelsior samples were placed in a humid environment (~100% RH) for 2–3 h to increase their MC from ~4 to ~30% on a dry weight basis.

Individual samples (10–25) of the same species were burned in succession during the experimental period (1–1.5 h). Each species was burned in a random order and was not specific to the time of day (e.g. both morning and afternoon). Experimental samples were chosen at random but some samples had to be trimmed to fit within the boundaries of the FFB (e.g. saw palmetto was trimmed to a maximum length of 7.5 cm rather than burning the entire sample which measures 30–50 cm in length). Environmental conditions remained relatively constant through the experimental period (25°C room temperature, quiescent air, 10–20% RH).

Leaf temperature was obtained using a type-K (chromel-alumel) thermocouple (bead diameter of 127 μm) embedded in a pinhole near the perimeter of the broadleaf samples. Thermocouple readings were not obtained in non-broadleaf samples due to substantial movement of these samples during the experiment. Surface temperatures of samples were also measured at 30 Hz by a FLIR thermal infrared (IR) camera (model A20M, Boston, MA, USA) assuming an emittance of 0.75 (Fletcher *et al*. 2007).

Video images were recorded using an analog camcorder (Sony Handicam, CCD-TRV138 Video Hi8, San Diego, CA, USA). The mass data, thermocouple temperature data and video images were acquired at 18–19 Hz and synchronised and time-stamped using a National Instruments LabView 7.1 program (Austin, TX, USA). Visual inspection of the video images resulted in determination of time to ignition, maximum flame height and burnout (flaming) along with the corresponding mass and temperature. Ignition was determined to be the time that the first sustainable visible flame from the collection of video images.

Leaf parameters which affect temperatures and mass release rates for these individual fuels may include initial mass (m_0), amount of moisture in the sample (m_{H_2O}), surface area (SA) and perimeter (P). The geometric parameters (SA and P) were not easily measured by hand for lobed leaves such as canyon maple or gambel oak, so an image analysis technique was used to estimate these parameters. This technique is discussed in detail by Pickett (2008); the imaging (calculated) values of SA and P were found to be comparable to the measured values (performed by hand).

Data analysis

Buoyancy correction

As the hot convective gases from the FFB created a large buoyancy force on the leaf, the raw mass history data showed a large discontinuity when the FFB passed under the leaf sample (Fig. 1). This discontinuity yielded negative mass values at the end of the experiment. To correct this unrealistic mass history curve, a constant buoyant force was assumed throughout the run, allowing the mass to shift to a final realistic value (positive mass). Originally, the mass was assumed constant through the time of the discontinuity (i.e. time when buoyancy was first observed in the raw history data to when it levelled off). Because mass was released during this short discontinuity interval, this constant

[C]Trade names are not an endorsement by the USDA.

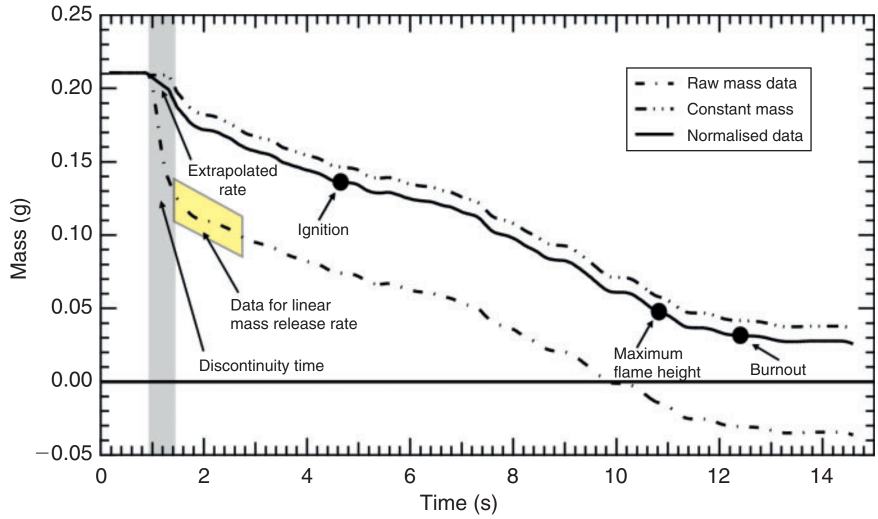

Fig. 1. Raw mass history data for a canyon maple leaf compared with constant mass through the discontinuity time (dotted line) and extrapolated mass release rate through the discontinuity time (normalised data, solid line).

mass assumption was not accurate. To improve this assumption, a linear regression determined from the data ~1 s (20 time-steps) directly after the discontinuity interval (data in parallelogram of Fig. 1), yielding a mass release rate. This rate was then extrapolated through the discontinuity time interval, which yielded realistic mass values (i.e. no longer constant) during the time of discontinuity.

One test of applicability of the buoyancy correction is to check the final mass measured at the end of flaming combustion. Using this buoyancy correction, values of the final mass after combustion were 5–20% of the original wet mass, depending on the moisture content of the original sample. These fuels had a volatile matter content of ~80% on a dry basis (Fletcher *et al*. 2007), giving a combined ash and char content of ~20% on a dry basis, which was consistent with the observed upper bound for final mass. When moisture was present in the original sample, the overall remaining percentage decreased (e.g. with a moisture content of 100%, the final mass should be 10% of the original). Because of the agreement between the measured final mass (after buoyancy correction) and the theoretical final mass (remaining ash and char), the constant buoyant force assumption was deemed acceptable (Pickett 2008). From this corrected mass history profile, specific times for ignition, maximum flame height and burnout could be determined from video images (Fig. 1).

Mass release rate

Fire spread rate is directly related to how much heat is released from the fuel bed (Drysdale 1999). This heat release rate is also related to the mass release rate of the volatiles during combustion since all forest fuels have similar chemical makeup (i.e. cellulose, hemicellulose and lignin content). Understanding mass release rates can help estimate flame intensity and flame height for any given species.

To determine the mass release rate at any point during the experimental run, the derivative of the normalised mass history data was taken by the point-to-point derivative (finite difference method) of the tabulated data. However, this derivative method yielded large amounts of scatter in the mass release rate curve (MR, derivative of mass with respect to time (dm/dt) *v.* t as shown in Fig. 2) due to the small acquisition frequency (18–19 Hz), the sensitivity of the mass balance and the overall noise of the data. Because of this scatter, values of mass release rate at times of interest (ignition, flame height, burnout) obtained by the point-to-point method were not considered reliable.

To smooth the scatter, the normalised data were fit in a piecewise-manner to a cubic polynomial regression since a single regression did not account for the large number of observed discontinuities. The piece-wise regression consisted of fitting the desired data point and a pre-determined number (25) of time-steps in each direction to a cubic polynomial. A regression was performed for each data point (time-step) and the derivative was taken at each time step using the regressed cubic coefficients to obtain the smoothed overall mass release rate. The number of regression time-steps was determined arbitrarily; more time-steps smooth the data until no discontinuities are observed (single cubic regression to all the data), while fewer time-steps augment the number and magnitude of the discontinuities (cubic spline function that fits each data point exactly). Fig. 2 shows the normalised mass data along with the two methods to determine the mass release rate (finite difference and piecewise-cubic regression) for various experimental runs. These results were consistent for all species. The piece-wise-cubic method gave more reliable mass release rates at times of interest than the point-to-point difference method; this method can also help to better identify regions of evaporation or pyrolysis or both.

Results and discussion

Over 1500 individual samples were burned in the FFB apparatus with ~650 experiments on freshly cut species or humidified excelsior performed with accurate mass measurements. Results of the experiments with measured mass histories are presented below.

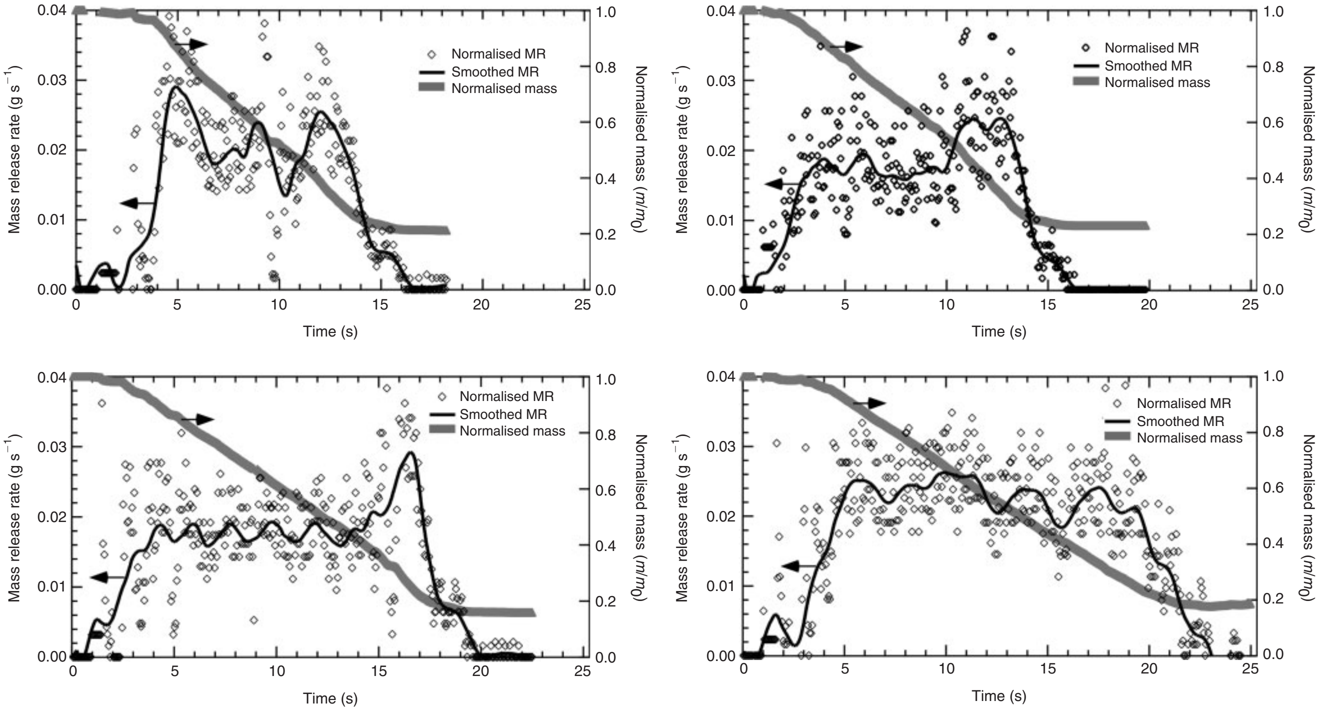

Fig. 2. Mass release rate data with corresponding mass data for a multiple manzanita runs at varying levels of moisture content. The normalised mass release data was obtained by a finite difference of the normalised mass data method while the smoothed data was obtained by a piecewise-cubic regression of the normalised mass data.

Mass at ignition

One of the main purposes of this research is to characterise the effects of moisture of live fuels during combustion. It is therefore expedient that evaporation of moisture during combustion of these individual samples be studied. The classical combustion model assumes that all moisture will first evolve from the sample at a temperature near the boiling point of water. Ignition (according to the classical model) occurs when a combustible mixture of pyrolysis gases is obtained and follows shortly after moisture evaporation is complete.

To better analyse the effects of evaporation of moisture from the fuel sample, the mass released at ignition (m_{ig}) was compared to the original mass of moisture (m_{H_2O}) for several fuel samples, as shown in Fig. 3. Assuming a classical model, if ignition occurred at the moment evaporation ended, the data points should lie on (or close to) the parity line. The majority of the data fell below the parity line, indicating that ignition did not occur at the end of global evaporation but possibly at the end of local evaporation. Regardless, a significant amount of moisture (30–60%) remained in the sample for most species at the time ignition occurred.

One reason moisture remained in the sample is due to local ignition, showing that combustion and evaporation occur simultaneously on a global scale. Ignition could occur on a tip or needle while the bulk of the moisture remained in the inner layers of the sample. Another reason for moisture remaining could be due to the physical nature of live samples. Moisture could not escape the outer boundaries of the sample, thus the structure of the sample (e.g. exterior cell walls such as the epidermis) must first be pyrolysed before the moisture can escape. Thus, even 'free' moisture (Simpson and TenWolde 1999) can require some pyrolysis of the fuel material before interior moisture escapes from the sample. This pyrolysis requires a higher temperature than required for evaporation alone. Qualitative phenomena such as interior bubbling and bursting (Fletcher *et al*. 2007) are examples of moisture escaping before the structure can completely devolatilise.

A linear regression of the data in Fig. 3 was performed for each species. The slope (a or dm_{ig}/dm_{H_2O}) for each regression is shown in Table 1 along with a 95% confidence interval for the estimate of the slope. The intercept was set to zero assuming that ignition would occur immediately if no moisture were in the sample. A classical model would show data having a slope of 1 (on the parity line); however, each species has a slope significantly lower than 1.

The magnitude of the slopes may be inversely related to the flammability (i.e. propensity to ignite) for a given species. The species with lower slopes (juniper, chamise, Douglas-fir, etc.) are more flammable than those with higher slopes (ceanothus and manzanita). Dimitrakopoulos and Papaioannou (2001) performed flammability analyses on live Mediterranean fuels and found a linear relationship between MC and time to ignition (t_{ig}), with species with lower slopes (dt_{ig}/d_{MC}) being more flammable. The data shown in Fig. 3 are consistent with the findings of Dimitrakopoulos and Papaioannaou (Fig. 4), although these data are on a mass basis (m_{ig} *v.* m_{H_2O}) instead of time (t_{ig} *v.* MC).

Individual excelsior samples are distinctly different from live species. First, single excelsior samples are long, thin and

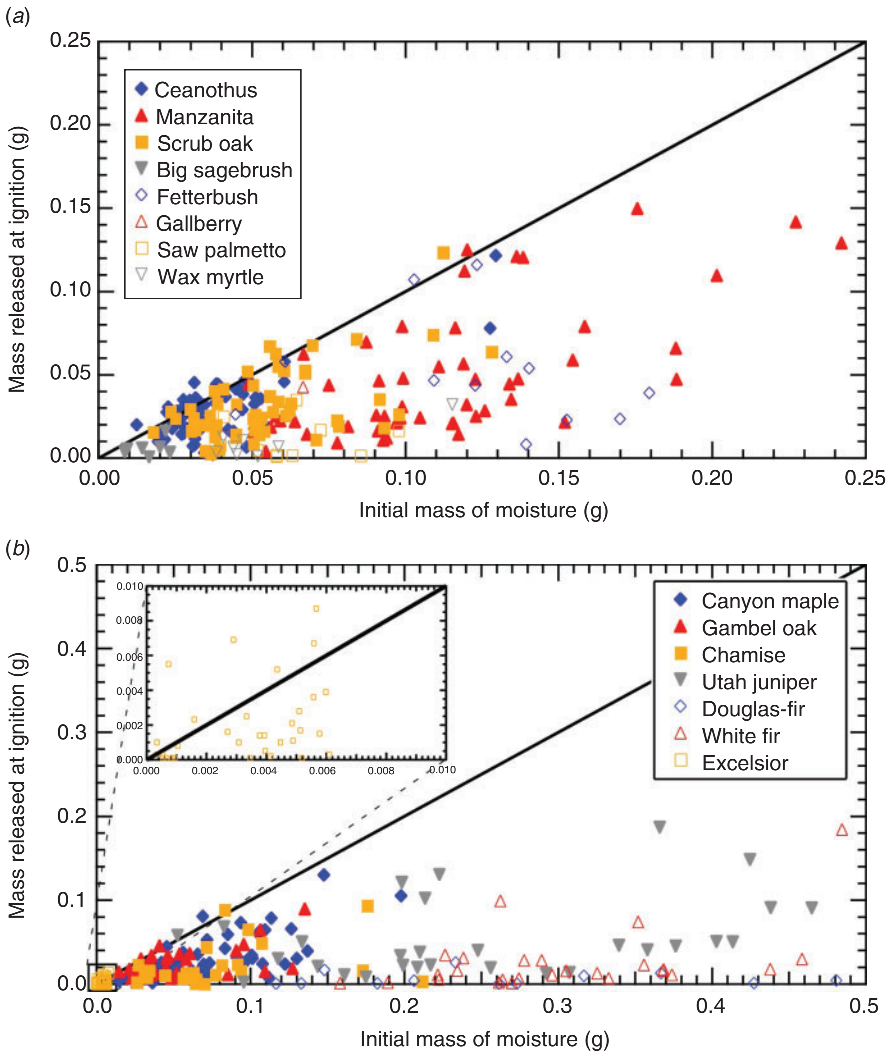

Fig. 3. Data of the mass released at ignition *v.* the initial mass of moisture for all species.

cylindrical (single needle) while non-broadleaf species (e.g. juniper, chamise, etc.) have clusters of needles at multiple directions or orientations. Second, moisture is introduced to the excelsior samples by diffusion (i.e. water treatment in a humid environment) and not by an active biological process. The fibre saturation point, which is typically ~30% MC for wood (Simpson and TenWolde 1999), was possibly achieved from this diffusive process but not exceeded. Therefore, all moisture within the excelsior samples was 'bound' to the wood-like material. Since the water treatment process was relatively short (2–4 h) as compared to live fuels, the 'bound' moisture in excelsior may not have as strong of physical or chemical bonds with the wood fibre (Simpson and TenWolde 1999) as do live fuels. In addition, the cellular structure of a live leaf is different than for dead wood. The slope of m_{ig} *v.* m_{H_2O} (Table 1) for excelsior is 0.729 ± 0.248, which was higher than most other live species, meaning that it behaved more like the classical combustion model (moisture is driven off first before ignition occurs) than the live species. This may be due to the lack of mass transfer resistance in the thin, cylindrical sample; allowing the moisture to release easily from the sample. This lack of mass transfer resistance may also be due to the water treatment process. Also, due to the low MC (<30%) and lower initial mass (m_0 ~0.02 g), the mass of moisture in the sample (m_{H_2O}) is low compared to all other species (excelsior shown in insert of Fig. 3*b*).

Temperature history

Classical combustion modelling assumes that evaporation occurs at a constant temperature of 100°C (Rothermel 1972; Albini 1980). Temperature profiles from both thermocouple and IR measurements show no plateau at 100°C, but rather at 200°–300°C for most broadleaf species, as in Fig. 5*a*. This plateau at higher temperatures is more prominent in thicker leaves (i.e. ceanothus, manzanita, gallberry).

This plateau at higher temperatures is thought to be delayed moisture evaporation due to moisture transfer resistance in the leaf. In the absence of light (e.g. during shipment), stoma on the leaf tend to close (Sadava *et al*. 2008), thus limiting moisture passage out of the leaf. Also, cell walls may first need to be broken down (devolatilised at these higher temperatures) before moisture within that cell can be released. Because of the 2-D nature of leaf combustion and the complicated mass and heat transfer involved inside and around the leaf, no plateau was observed at 100°C.

Temperature histories for excelsior showed no plateau at either 100° or 200°–300°C, but a slight plateau at 350°–425°C (Fig. 5*a*). This plateau was normally observed well after ignition and was usually observed near the time of the maximum flame height. The plateau may be due to the heat of pyrolysis for the excelsior at 350°–425°C; this is not observed in live species.

Table 1. Slope (α) of linear regression of mass released at ignition *v.* mass of moisture data shown in Fig. 3

Values indicated with ± are the 95% confidence interval

Species	m_{ig} (g) *v.* m_{H_2O} (g)		
	α	R2	Significance
Manzanita	0.408 ± 0.039	0.7033	+
Ceanothus	0.794 ± 0.075	0.8622	+
Scrub oak	0.491 ± 0.076	0.6819	+
Chamise	0.128 ± 0.057	0.4807	+
Gambel oak	0.326 ± 0.072	0.6288	+
Canyon maple	0.443 ± 0.062	0.7866	+
Big sagebrush	0.296 ± 0.152	0.4246	+
Utah juniper	0.115 ± 0.027	0.5022	+
Douglas-fir	0.042 ± 0.060	0.0743	
White fir	0.146 ± 0.090	0.2899	+
Fetterbush	0.453 ± 0.224	0.5737	+
Gallberry	n.a.	n.a.	
Wax myrtle	0.192 ± 0.089	0.7871	+
Saw palmetto	0.180 ± 0.131	0.4854	+
Excelsior	0.729 ± 0.248	0.5201	+

The IR profile was determined from an area selected near the location of the thermocouple (near the perimeter of the leaf) and the maximum temperature within that area was reported. It was of interest to determine the temperature in a location away from the original area such as in the middle of the leaf away from the perimeter. To do this, another area was selected that remained within the leaf boundaries during the experimental run, away from the perimeter. It was observed that the centre or middle temperature was significantly lower than the original or perimeter temperature; Fig. 6 shows the average values of perimeter and middle temperature for multiple manzanita runs. This centre temperature profile showed a plateau at 140°C, lower than the 200°–300°C plateau from the perimeter profile, but still higher than evaporation. The centre profile had a much longer plateau than the perimeter profile. Temperature variations across the leaf were sometimes up to 350°C, which was observed for most broadleaf species.

This lower temperature plateau (140°C) and the large temperature variation across the leaf, as well as the understanding that a significant amount of moisture remains in the leaf, indicate that both evaporation and combustion occur concurrently. The perimeter ignites and burns while the centre or interior is still evaporating. The actual temperature (140°C) may be higher than 100°C because the moisture would be a mixture of water and carbohydrates or other volatile organic compounds (VOC), which would increase the boiling temperature of the moisture. Also, surface tension of the moisture inside the leaf (e.g. capillary action) could prohibit the water boiling at the normal 100°C.

Mass release rate

The average mass release rates (with confidence intervals of 95%) at ignition (MR_{ig}) and at maximum flame height (MR_{FH})

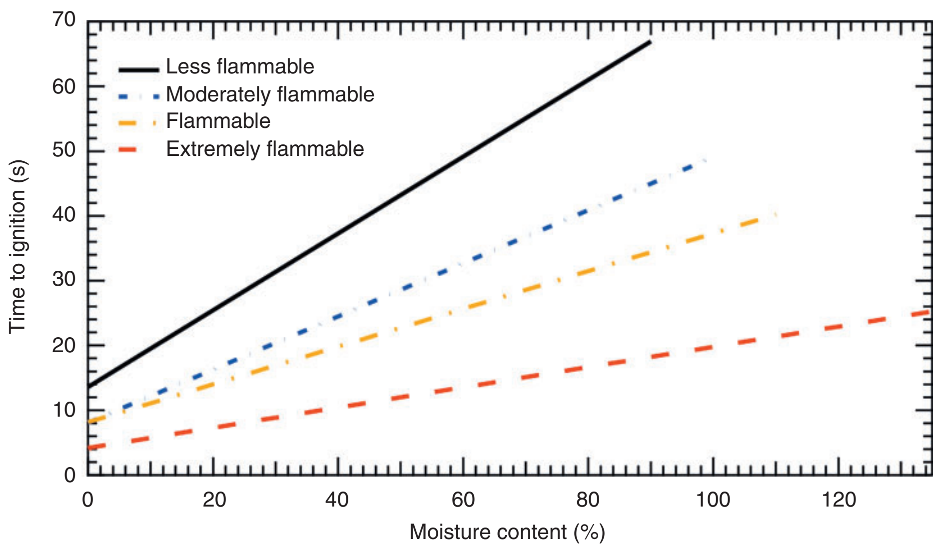

Fig. 4. Flammability based on regressions of time to ignition *v.* moisture content taken from Dimitrakopoulos and Papaioannou (2001). Each line represents a flammability level determined by the aforementioned authors where the average slope and intercept for each level are shown in the figure.

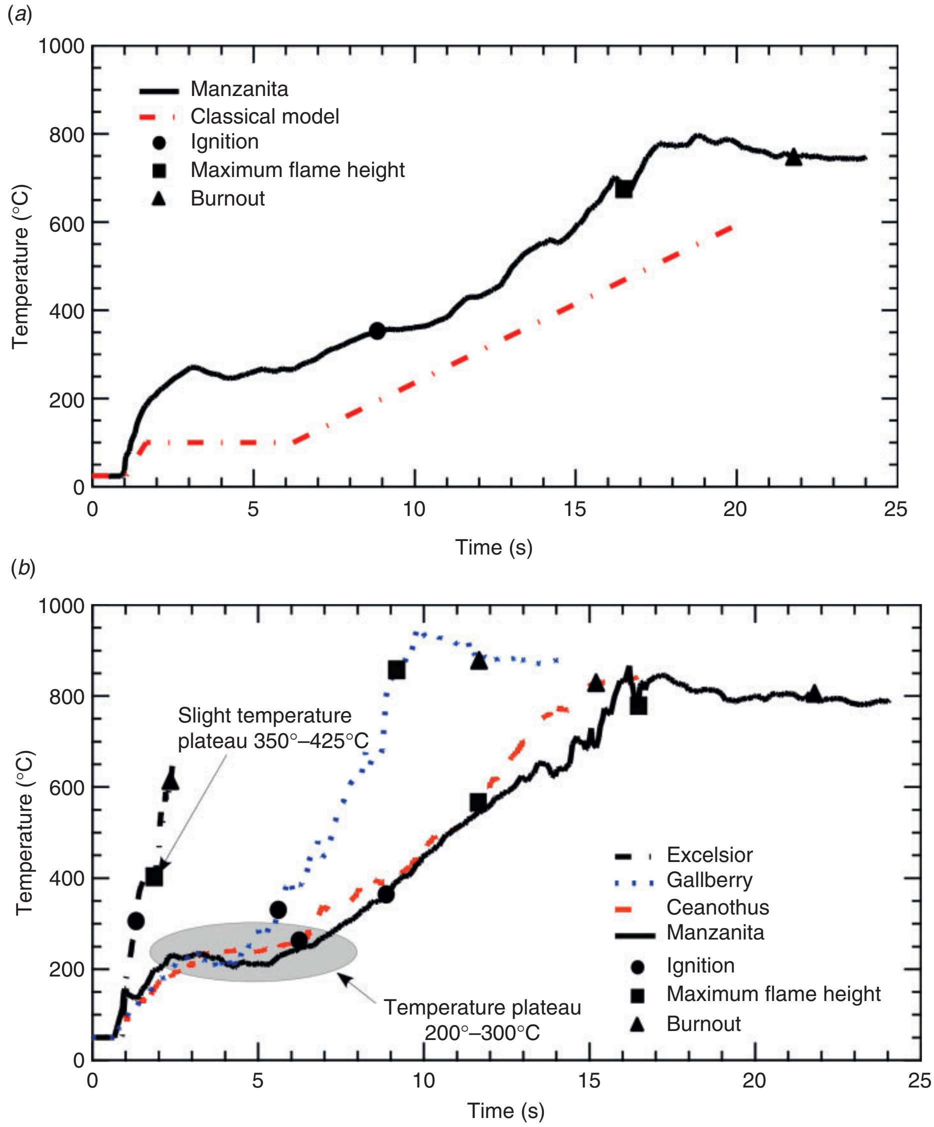

Fig. 5. Comparison of a thermocouple temperature history of a manzanita leaf with the classical combustion model (*a*) (e.g. Rothermel 1972). Representative IR temperature histories for a variety of samples (*b*). A temperature plateau was observed at 200°–300°C for live species. A slight temperature plateau was observed at 350°–425°C for excelsior.

are in Fig. 7. Some broadleaf species with nearly elliptical shape (i.e. ceanothus, scrub oak, wax myrtle) exhibited similar mass release rates at ignition and maximum flame height ($MR_{ig} \approx MR_{FH}$ for that species). Other species such as manzanita, fetterbush and gallberry exhibited significantly different mass release rates at these two conditions (ratio of MR_{ig}/MR_{FH} different than unity). Since moisture remains in the leaf before ignition, as discussed in the previous section, mass release at ignition is assumed to be primarily due to moisture release. This assumption indicates that manzanita (where $MR_{ig} < MR_{FH}$) has the ability to retain moisture (even while igniting) better than fetterbush and gallberry (where $MR_{ig} > MR_{FH}$). Broadleaf species with non-elliptical shape (i.e. gambel oak, canyon maple, big sagebrush, saw palmetto), which generally ignited locally, exhibited different mass release rates at ignition than at maximum flame height. Ignition occurred on the dry or dead tips of the saw palmetto leaf, then nearly extinguished before igniting the bulk of the leaf. This local tip ignition of saw palmetto may have more impact on moisture retention than on the other non-elliptical species.

Non-broadleaf species (i.e. chamise, juniper, Douglas-fir, white fir) exhibited much higher mass release rates (both at ignition and at maximum flame height) than most broadleaf species (note scale difference in Fig. 7), which is consistent with the high surface-to-volume ratio in the non-broadleaf species (i.e. more surface for gases to escape the leaf surface). There was also a large difference observed within the same species between MR_{ig} and MR_{FH}, which can be attributed to jetting (high mass transfer away from the sample; see Pickett 2008) that occurred in the non-broadleaf samples. Excelsior, being small and cylindrical

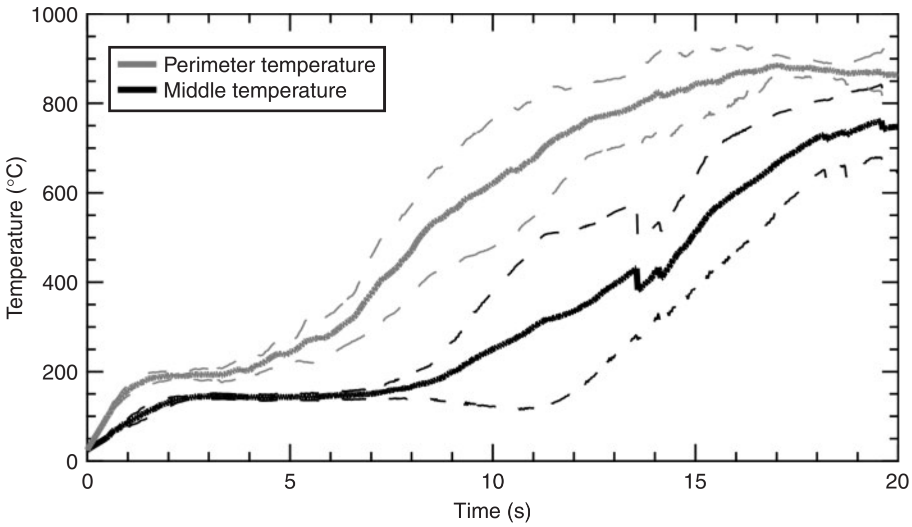

Fig. 6. Comparison of IR temperature profiles determined at the perimeter and middle of manzanita leaves.

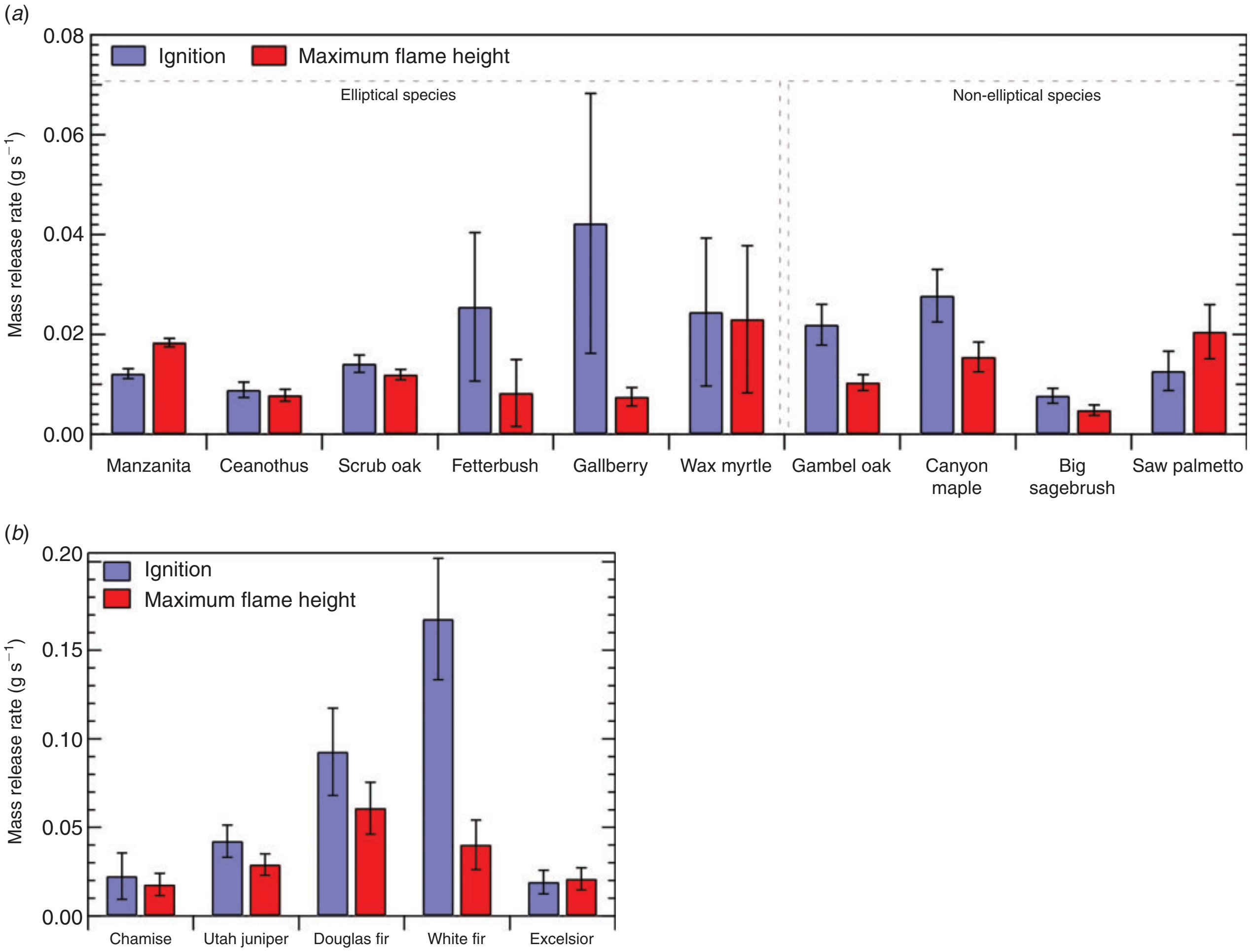

Fig. 7. Average mass release rates for each species at ignition and maximum flame height for broadleaf species (*a*) and non-broadleaf species (including excelsior) (*b*). Note that the scale is twice as small for broadleaf species. Error bars indicate the 95% confidence intervals.

Table 2. Mean values for all species along with the number of samples and the range of moisture contents (dry weight basis)
MC, moisture content; SA, surface area; P, perimeter; m_0, initial mass; m_{H_2O}, moisture mass in sample; MR_{ig}, mass release rate at ignition; MR_{FH}, mass release rate at the maximum flame height. Values indicated with ± are the 95% confidence interval

Species	n	MC (%)	SA (cm^2)	P (cm)	m_0 (g)	m_{H_2O} (g)	MR_{ig} ($g\,s^{-1}$)	MR_{FH} ($g\,s^{-1}$)
Manzanita	91	44–107	5.62 ± 0.39	8.82 ± 0.31	0.2197 ± 0.0127	0.0760 ± 0.0060	0.0121 ± 0.0010	0.0184 ± 0.0009
Ceanothus	85	35–106	1.54 ± 0.09	4.71 ± 0.17	0.0856 ± 0.0058	0.0336 ± 0.0029	0.0089 ± 0.0015	0.0078 ± 0.0012
Scrub oak	70	37–98	4.31 ± 0.45	8.52 ± 0.48	0.1852 ± 0.0170	0.0644 ± 0.0075	0.0141 ± 0.0017	0.0119 ± 0.0011
Chamise	55	48–90	n.a.	n.a.	0.8035 ± 0.5388	0.1735 ± 0.0818	0.0225 ± 0.0131	0.0177 ± 0.0063
Gambel oak	85	52–126	14.92 ± 2.42	21.96 ± 1.53	0.1983 ± 0.0175	0.0751 ± 0.0086	0.0220 ± 0.0041	0.0104 ± 0.0016
Canyon maple	15	55–159	13.79 ± 1.19	34.9 ± 4.03	0.1694 ± 0.0144	0.0823 ± 0.0072	0.0278 ± 0.0053	0.0155 ± 0.0030
Big sagebrush	10	113–197	1.36 ± 0.49	3.56 ± 0.49	0.0309 ± 0.0023	0.0185 ± 0.0015	0.0077 ± 0.0015	0.0048 ± 0.0010
Utah juniper	77	41–99	n.a.	n.a.	0.9438 ± 0.1964	0.3611 ± 0.079	0.0422 ± 0.0091	0.0290 ± 0.0061
Douglas-fir	40	78–144	n.a.	n.a.	0.6809 ± 0.1013	0.3732 ± 0.0651	0.0926 ± 0.0247	0.0609 ± 0.0147
White fir	35	81–100	n.a.	n.a.	0.6143 ± 0.0773	0.2951 ± 0.0368	0.1677 ± 0.0342	0.0402 ± 0.0139
Fetterbush	19	80	6.29 ± 1.16	11.05 ± 1.21	0.2598 ± 0.0444	0.1152 ± 0.0197	0.0255 ± 0.0149	0.0083 ± 0.0067
Gallberry	15	96	2.52 ± 0.38	7.30 ± 0.45	0.1170 ± 0.0154	0.0574 ± 0.0075	0.0422 ± 0.0260	0.0075 ± 0.0019
Wax myrtle	12	103	5.69 ± 1.02	13.45 ± 1.2	0.1311 ± 0.0412	0.0666 ± 0.0209	0.0245 ± 0.0148	0.0230 ± 0.0147
Saw palmetto	15	71	3.37 ± 0.7	14.88 ± 1.41	0.1536 ± 0.0245	0.0636 ± 0.0101	0.0127 ± 0.0039	0.0205 ± 0.0054
Excelsior	55	4–31	n.a.	n.a.	0.0216 ± 0.0021	0.0032 ± 0.0006	0.0191 ± 0.0067	0.0209 ± 0.0063

in shape, showed similar rates at ignition and maximum flame height, and the magnitude of the rates was higher than in other smaller broadleaf species such as ceanothus, scrub oak and sagebrush. However, when normalised to the original mass (MR/m_0), smaller samples (e.g. sagebrush and excelsior) had significantly higher values than most other species in their respective categories (i.e. sagebrush compared to other broadleaf species, excelsior compared to other non-broadleaf species). Excelsior had normalised mass release rates at ignition (MR_{ig}/m_0) approximately 2.5 times higher than white fir, which had the highest non-normalised mass release rate.

Mass release rate data at ignition and maximum flame height were correlated with a variety of variables such as SA, P, m_0 and m_{H_2O} (SA and P were only estimated on broadleaf species). Linear regressions were performed on the mass release rate as a function of the dependent variable (MR_{ig} (SA) $= \alpha \cdot SA + \beta$ or MR_{FH} $(m_0) = \alpha \cdot m_0 + \beta$). Although some species exhibited a significant positive correlation (positive slope for α) for a particular dependent variable, no variable proved significant for all species. The most significant independent variables (i.e. significant for the most number of species) for both MR_{ig} and MR_{FH} were m_{H_2O} and P (Pickett 2008). Average data for these variables are in Table 2 for all species as well as the average mass release rate at ignition and maximum flame height.

Conclusions

Experiments were performed on 14 species of live (high moisture) samples as well as humidified excelsior, focusing on the effects of moisture during combustion. It was observed that moisture remains in the leaf after ignition occurs for all live species, which is contrary to the classical combustion model; excelsior showed behaviour closest to the classical model. Flammability of individual samples can be expressed as the slope of the mass released before ignition (m_{ig}) *v.* the initial mass of moisture (m_{H_2O}), where the more flammable species have a lower slope. Temperature histories for most live species showed a plateau at 200°–300°C on the leaf perimeter and not at 100°C. A plateau of 140°C was observed for interior areas of the leaf. The combination of spatial temperature variations and mass transfer resistance in the leaf is believed to cause the delayed evaporation. Humidified excelsior showed no evaporation plateau but showed a slight plateau at 350°–425°C due to pyrolysis.

The ratio of the average mass release rate at ignition to the mass release rate at the maximum flame height was near unity for all elliptical broadleaf species except fetterbush and gallberry, while the ratio for non-elliptical broadleaf species differed from unity. Saw palmetto had higher rates at maximum flame height than ignition due to local ignition near the tip which nearly extinguished before flaming of the bulk leaf occurred. Non-broadleaf species had higher mass release rates than most broadleaf species. Attempts were made to correlate mass release rates with variables such as surface area, perimeter, initial mass and mass of moisture. However, none of these variables correlated well with the mass release rate for every species.

Because of the presence of moisture still in the live samples at ignition and the observed evaporation delay of the temperature profile, the classical model (constant evaporation temperature at 100°C until all moisture has evolved) may need to be altered to show a delayed moisture plateau. Also, Excelsior burned differently than live species in these experiments. This variation from live species may need to be addressed when applying excelsior correlations to fire spread models for live vegetation.

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