CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire* **2011**, *20*, 657–667

The effects of wind on the flame characteristics of individual leaves

Wesley J. Cole[A], *McKaye H. Dennis*[A], *Thomas H. Fletcher*[A,C] *and David R. Weise*[B]

[A]Chemical Engineering Department, Brigham Young University, Provo, UT 84602, USA.
[B]USDA Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, Riverside, CA 92507, USA.
[C]Corresponding author. Email: tom_fletcher@byu.edu

Abstract. Individual cuttings from five shrub species were burned over a flat-flame burner under wind conditions of 0.75–2.80 m s^{-1}. Both live and dead cuttings were used. These included single leaves from broadleaf species as well as 3 to 5 cm-long branches from coniferous and small broadleaf species. Flame angles and flame lengths were determined by semi-automated measurements of video images. Additional data, such as times and temperatures corresponding to ignition, maximum flame height and burnout were determined using video and infrared images. Flame angles correlated linearly with wind velocity. They also correlated with the Froude number when either the flame length or flame height was used. Flame angles in individual leaf experiments were generally 50 to 70% less than flame angles derived from Froude number correlations reported in the literature for fuel-bed experiments. Although flame angles increased with fuel mass and moisture content, they were unaffected by fuel species. Flame lengths and flame heights decreased with moisture contents and wind speed but increased with mass. In most cases, samples burned with wind conditions ignited less quickly and at lower temperatures than samples burned without wind. Most samples contained moisture at the time of ignition. Results of this small-scale approach (e.g. using individual cuttings) apply to ignition of shrubs and to flame propagation in shrubs of low bulk density. This research is one of the few attempts to characterise single-leaf and small-branch combustion behaviour in wind and is crucial to the continued development of a semi-empirical shrub combustion model.

Additional keywords: flame angle, flame geometry, live fuels, wildfire.

Introduction

Flame angle and flame length are important characteristics of wildland fires. The angle and length of a flame will largely determine how radiant heat is transferred to unburned fuel. Flame length is important in fire modelling because it is strongly correlated with fireline intensity (Byram 1959; Albini 1981; Weise and Biging 1996; Fernandes *et al*. 2002). Additionally, flame length and fireline intensity have been used to predict the height that foliage within a forest canopy can be killed by heating from a surface fire (Van Wagner 1973; Michaletz and Johnson 2006).

The Brigham Young University (BYU) leaf combustion facility has compiled a database with several thousand measurements of single-leaf, no-wind experiments to measure flame height (note that here and throughout the remainder of this paper 'single-leaf' refers to individual cuttings of either leaves or branches) (Engstrom *et al*. 2004; Pickett *et al*. 2005, 2010; Fletcher *et al*. 2007; Pickett 2008). These experiments provide the basic data for a semi-empirical shrub combustion model already under development at BYU (Pickett 2008; Cole *et al*. 2009). Other single-leaf combustion experiments have also been performed (Montgomery and Cheo 1969; Burrows 2001; Nelson 2003). However, none of these single-leaf experiments were conducted with wind.

Numerous empirical studies have been performed in order to determine the effects of wind on flame geometry (Thomas 1963; Putnam 1965; Welker *et al*. 1965; Nelson and Adkins 1986; Weber and De Mestre 1990; Beer 1995; Sinai and Owens 1995; Weise and Biging 1996; Fernandes *et al*. 2002; Morandini *et al*. 2002; Mendes-Lopes *et al*. 2003; Morvan 2007). These empirical studies were carried out using laboratory-size fuel beds or cribs (1–3 m wide and 2–3 m long) placed inside a wind tunnel or outdoor forest plots ($\sim 10 \times 10$ m). The convection number (N_c) is commonly used to correlate the effects of wind on flame geometry (Byram 1959; Albini 1981; Nelson 1993; Weise and Biging 1996; Sullivan 2007; Morandini and Silvani 2010). However, N_c is a function of the rate of spread, and no rate of spread could be determined in the single-leaf experiments. Many of these studies presented power-law correlations between the flame angle and the Froude number ($U^2/(gL_f)$ or $U^2/(gH_f)$, where U is wind speed, g is the acceleration as a result of gravity, L_f is flame length and H_f is flame height). Theoretical analyses have also been performed demonstrating the effect of the Froude number on flame geometry (Thomas *et al*. 1963; Albini 1981). The flames observed in these studies ranged from 20 cm to over 2 m long at wind speeds of 0–4 m s^{-1} for heading fires, yielding Froude numbers of 0–1. Single-leaf experiments with no wind yielded flame lengths of 3–9 cm (Pickett 2008).

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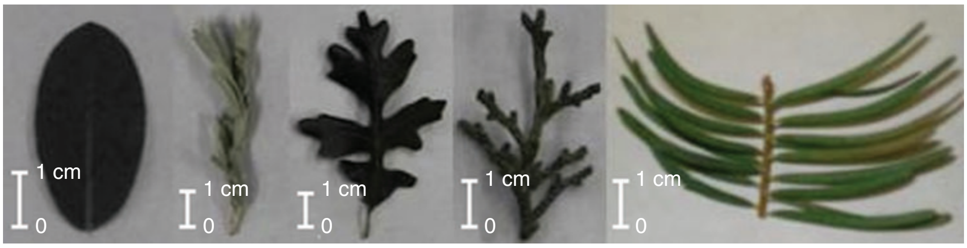

Fig. 1. Fuel samples: (left to right) Eastwood's manzanita, big sagebrush, Gambel oak, Utah juniper, Douglas-fir.

Table 1. Sample characterisation

Values are ±standard deviation. Species listed are: Manzanita, *Arctostaphylos glandulosa* Eastw.; Gambel oak, *Quercus gambelii* Nutt.; Big sagebrush, *Artemisia tridentata* Nutt.; Utah juniper, *Juniperus osteosperma* (Torr.) Little; Douglas-fir, *Pseudotsuga menziesii* (Mirbel) Franco. Terms are defined in the Nomenclature

Species	Sample type	*n* of samples	Length (cm)	Width (cm)	Thickness (mm)	m_0 (g)	*MC* (wet ÷ dry)
Big sagebrush	Cutting	50	5.4 ± 1.0	3.4 ± 0.9	n.a.	0.46 ± 0.32	120 ± 42%
Douglas-fir	Cutting	70	3.3 ± 0.6	5.6 ± 1.2	1.2 ± 0.3	0.69 ± 0.24	86 ± 2%
Gambel oak	Leaf	100	5.6 ± 0.8	3.5 ± 0.6	0.15 ± 0.04	0.17 ± 0.08	84 ± 38%
Manzanita	Leaf	330	3.4 ± 0.5	1.9 ± 0.3	0.45 ± 0.09	0.24 ± 0.11	63 ± 33%
Utah juniper	Cutting	120	4.7 ± 0.8	3.4 ± 1.0	1.9 ± 0.3	0.72 ± 0.35	76 ± 5%

If such flame lengths occurred with a wind speed of 2.75 m s^{-1}, the resulting Froude numbers would be between 8 and 26. Thus, single-leaf Froude numbers often fell outside the range of previous correlations.

The objective of this research was to determine the combustion behaviour of single leaves and small cuttings in the presence of wind in order to improve a current model of shrub ignition and combustion. The relationship of flame behaviour at the single-leaf scale and at the shrub scale is not well described. Scale has long been recognised as an important factor in flame and combustion modelling (Williams 1969; Quintiere 1989). If flame behaviour at leaf scale is not well described by correlations derived at larger scales, then new correlations must be developed in order for them to be implemented into the shrub model under development.

Methods

Fuel samples

The experimental fuels used were big sagebrush (*Artemisia tridentata* Nutt.),[A] Gambel oak (*Quercus gambelii* Nutt.), Utah juniper (*Juniperus osteosperma* (Torr.) Little) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), harvested from areas in or around Provo, Utah, and Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.), harvested near Riverside, California, and shipped overnight to the Provo facility (see Fig. 1). Live and dead samples of each species were burned. Large broadleaf species (manzanita and Gambel oak) were burned as individual leaves. Big sagebrush, juniper and Douglas-fir were burned as small cuttings, 3 to 5 cm in length, because the individual leaves or needles were too small to handle. Characteristics of the samples are summarised in Table 1.

The moisture content (on an oven-dry basis) for each experimental run was determined using a Computrac MAX1000 Moisture Analyzer[B] (Chandler, AZ). A sample of ~2 g was loaded into the analyser and heated to 104°C. The sample remained at that temperature until its mass changed by less than 0.01% min^{-1}. The mass lost during drying divided by the dry mass was the moisture content *MC* (i.e. $MC = m_{H_2O}/m_{dry}$ where m_{H_2O} is the initial mass of the water in the sample and m_{dry} is the initial dry mass of the sample). For large broadleaf samples, the length, width, thickness and mass of each leaf were recorded. For coniferous and big sagebrush samples, the thickness of the stem and the sample mass were recorded.

Experimental apparatus

The experimental apparatus described here (Fig. 2) is a modified version of the one used by Fletcher *et al*. (2007). Fuel samples were loaded horizontally into an alligator clip that was centred 5 cm above a flat-flame burner. The alligator clip was attached to a horizontal rod and counterweight that were supported by a mass balance (Mettler Toledo cantilever XS204, Columbus, OH). The fuel sample was kept stationary while the burner was pulled on a moveable cart until it came to a stop under the sample. The post-flame gases of the flat-flame burner were maintained at 987 ± 12°C with 10 mol% O_2.

The apparatus was modified in that a 7.9 cm (3.125 inch) wide 12 V DC Rotron square fan (San Ysidro, CA) was placed into a 45 cm (17.75 inch) long, 9.5 cm (3.75 inch) wide square duct in order to simulate wind. A honeycomb mesh was placed

[A]Source for common and scientific plant names – USDA plants database: http://plants.usda.gov, accessed 2 June 2011.

[B]Trade names are presented for informational purposes only and do not constitute endorsement by the US Department of Agriculture.

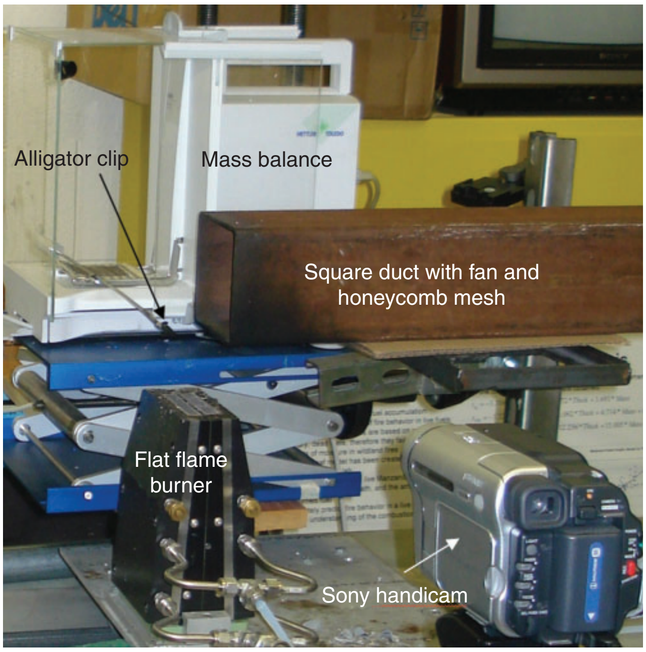

Fig. 2. Experimental apparatus.

in the duct 6.4 cm (2.5 inch) from the fan in order to smooth the air flow. The duct exit was placed 1 to 2 cm from the sample such that the air would flow across the top of the sample. A BK Precision DC Power Supply (model 1610A, Chicago, IL) was used to vary the voltage to the fan, allowing for wind speeds of 0.75–2.80 m s^{-1}. The wind speed for each run was measured in the centre of the open end of the square duct over 1 min by a 7.6-cm (3-inch) diameter Extech AN 100 anemometer (Waltham, MA). The anemometer had a reported accuracy of ±3%.

Data collection

The times corresponding to ignition, maximum flame height and burnout were obtained using video images as described by Pickett *et al*. (2010). Mass data were accurate to within 0.1 mg. Pickett's method for compensation for buoyancy effects from the flat-flame burner was used. Temperatures of the upper side of the leaf were measured using a FLIR thermal imaging (IR) camera (model A20M, Boston, MA) that used wavelengths of 7.5–13 µm. A surface emissivity of 0.8 was used to estimate the temperature for all of the runs (Fletcher *et al*. 2007; Pickett 2008).

Ignition time was defined as the time when a flame first appeared and was sustained. This precluded some brief flamelet events on some species where an edge or barb ignited and quickly extinguished. Flame height time was defined as the time of the largest flame area as determined from captured video images using an automated routine in MATLAB (Pickett 2008). Burnout time was defined as the time when the flame had visually extinguished. The temperature of ignition was defined to be the maximum temperature of the leaf surface at the time of ignition. The temperature at maximum flame height was the maximum temperature of the leaf surface at the time of maximum flame height. The burnout temperature was defined as the maximum temperature of the leaf surface at the time of burnout.

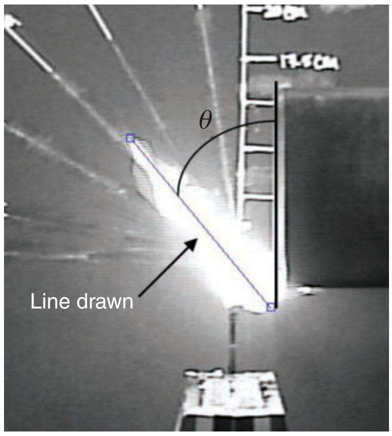

Fig. 3. Method for manually reducing the flame angle (θ).

Flame angle measurements

For each experimental run, the flame angle (θ) and flame length (L_f) were determined by analysing the video images. The flame height (H_f) was computed from the measured θ and L_f values (i.e. $H_f = L_f \cos\theta$).

Flame height measurements

After video images of the experimental run were collected, the image with the maximum flame height was determined, and both the nine images immediately before and after that image were selected for further analysis (Pickett 2008). The 19 images represented a 1-s interval centred on the image with maximum flame height. A line from the base of the flame to the tip of the flame was drawn manually on each of the 19 images (see Fig. 3), the flame angle was calculated assuming the image was 2-D, and the mean of the 19 flame angles of the 19 images was reported as the flame angle for that experimental run. The maximum flame length was calculated from the maximum flame height image as $L_f = H_f/\cos\theta$, converting the pixel distance to a physical distance. Similar computer processing of fire imagery has been commonplace since its inception (Quintiere 1989; Morandini and Silvani 2010).

The semi-automated process described above to obtain flame length in each experiment was somewhat subjective. Flame angles determined by individual researchers differed on average by 5%. An automated technique was also developed to determine flame angle using a prescribed flame geometry. The automated technique gave similar flame angle and flame height results to the semi-automated technique but had slightly greater error statistics. When the regression analysis (discussed in the Results section) was applied to the data produced from the automated process, all the regression coefficients were within the 95% confidence intervals of the regression coefficients from the data from the semi-automated process. The subjectivity in the flame angle measurements therefore did not appear to have a significant effect on the results. The results reported here, however, are only from the semi-automated process.

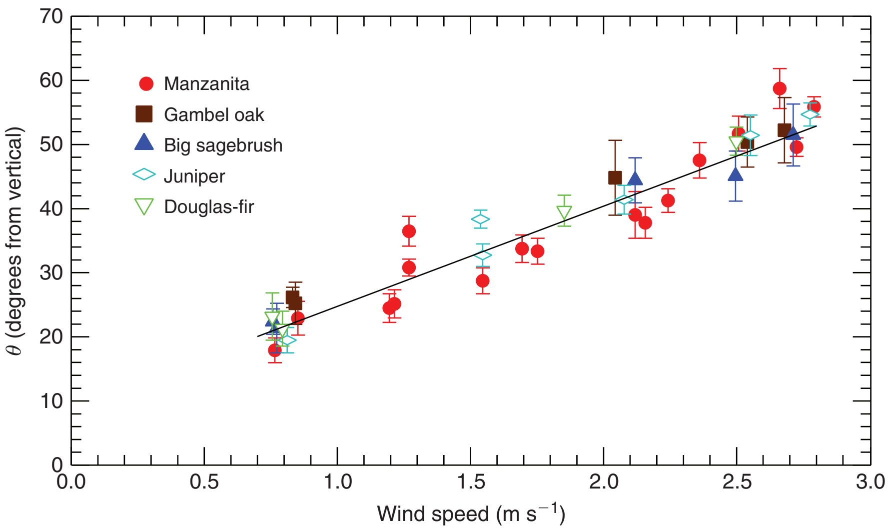

Fig. 4. Average flame angle of each run plotted against wind speed. Error bars represent 95% confidence intervals. Solid symbols are broadleaf species and open symbols are coniferous species. Solid line is a linear correlation of all data.

Table 2. Coefficients for Eqns 2–7, along with their corresponding 95% confidence intervals (CI), standard errors and *t* values
Terms are defined in the Nomenclature

Equation	Coefficient	Variable	Value	95% CI	s.e. coefficient	*t* value
1 (θ)	*a*	U	15.635	±0.777	0.346	45.16
	b	–	9.124	±1.501	0.668	13.66
2 (θ)	*c*	U	14.050	±1.022	0.455	30.90
	d	m_0	5.406	±2.119	0.943	5.74
	e	H_f	−0.757	±0.281	0.125	−6.06
	f	MC	−6.797	±1.577	0.702	−9.68
	h	–	19.133	±3.451	1.536	12.45
3 (L_f)	*i*	U	−1.832	±0.249	0.111	−16.52
	j	m_0	−14.788	±2.092	0.931	−15.88
	k	m_{dry}	35.214	±4.157	1.850	19.01
	l	–	8.414	±0.553	0.246	34.26
4 (H_f)	*m*	U	−2.565	±0.218	0.0969	−26.47
	n	m_0	−11.457	±1.828	0.814	−14.08
	p	m_{dry}	27.102	±3.635	1.618	16.75
	q	–	8.774	±0.482	0.215	40.89

Statistical analysis

Stepwise linear regression was used to fit simple linear models to estimate θ, H_f and L_f. Stepwise regression is an iterative process in which predictor variables are entered into and removed from the regression based on their partial correlation coefficient (Montgomery *et al*. 2006). Linear regressions of up to three predictor variables were developed using *Minitab 15*, a statistical software package (Minitab, Inc., State College, PA, USA). For Froude number correlations, fits were determined using the least-squares method.

Results and discussion

Raw data

Mean flame angles for each experimental condition, distinguished by species, are presented in Fig. 4. As can be seen, there is a significant amount of scatter in the data. The average standard deviation for a single species at a single wind speed was 5.0°. The mean data with the greatest amount of scatter had a standard deviation of 8.5°, occurring with a wind speed of 2.7 m s^{-1}.

Linear predictions

Results of the regression with wind speed (Eqn 1) are shown in Fig. 4 ($R^2 = 0.76$), where a and b are regression coefficients. Coefficients for this and subsequent regressions (c through u) are shown in Table 2, along with statistical criteria. P values were less than 5×10^{-4} for each coefficient listed.

$$\theta = aU + b \quad (1)$$

Variables that were significant in various combinations with U included initial mass (m_0), m_{dry}, m_{H_2O}, MC, thickness (Δx), H_f

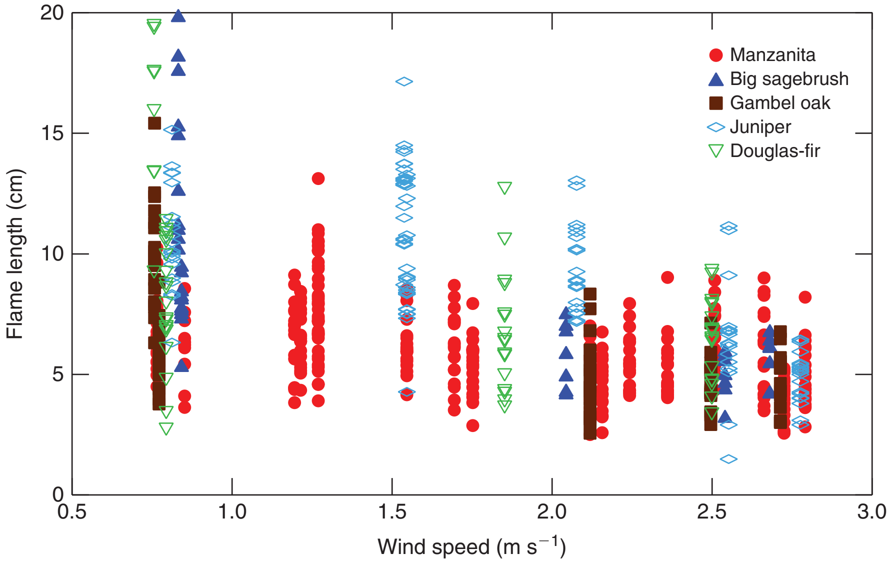

Fig. 5. Flame length *v.* wind speed. Solid symbols are broadleaf species and open symbols are coniferous species.

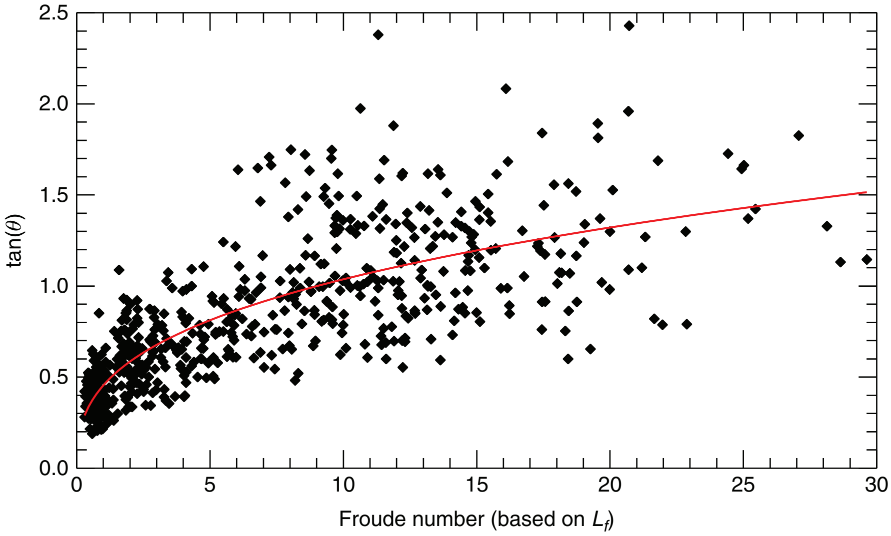

Fig. 6. Froude number (based on L_f) *v.* tan(θ). The fitted curve is Eqn 7.

and L_f. The regression that gave the highest R^2 value is shown in Eqn 2 ($R^2 = 0.80$). However, this relationship accounts for only 4% more variation than the one with U only (Eqn 1).

$$\theta = cU + dm_0 + eH_f + fMC + h \qquad (2)$$

Of interest in Eqn 2 is that m_0 has a positive coefficient, implying that larger samples produce a greater θ. More mass, however, means that the edges of the leaf are farther apart, decreasing the heat release per unit volume. It is possible that this spatial spread of the heat release could cause the decrease in the buoyant effects of the flame at this scale.

Flame lengths varied from 1.5 to 19.8 cm; however, 80% of the runs had flame lengths between 3 and 9 cm (see Fig. 5). When the effect of species was ignored, the best linear fit for L_f was obtained with Eqn 3 ($R^2 = 0.55$):

$$L_f = iU + jm_0 + km_{dry} + l \qquad (3)$$

Although not found in the best-fit correlation (Eqn 3), MC, Δx and m_{H_2O} were also found to be significant variables; however, correlations in which these variables were significant yielded a lower R^2. The coefficients relating to each variable retained the same sign (positive or negative) regardless of variable combination. MC and m_{H_2O} both had negative coefficients, demonstrating that moist samples generally have shorter flames than dry samples (this can also be observed in the positive coefficient of m_{dry}). U also had a negative coefficient, indicating that higher

Table 3. Summary of results for Froude number correlations
n.r., not reported

Researchers	Experimental fuels	U (m s^{-1})	*MC*	c_1	c_2	*Fr*	H_f (cm)
Putnam (1965)	Natural gas jets	0–4.0	N/A	1.4	0.5	0.1–1	n.r.
Albini (1981)	Theory			1.22	0.5		
Nelson and Adkins (1986)	Fuel beds of: (1) Fresh slash pine needles; (2) Slash pine needles and Palmetto fronds	0.57–2.3	11% 90–125%	0.89	0.29	0.6–18	33–75
Weise and Biging 1996 (H_f)	Fuel beds of vertical birch sticks and aspen excelsior	0–1.1	11–35%	2.35	0.57	0.2–0.28	8–169
Weise and Biging 1996 (L_f)	See above	0–1.1	11–35%	2.67	0.57		
Fernandes *et al*. (2002)	Maritime pine stands in plots 10–15 m wide	0.28–6.4	82–158%	1.41	0.28	n.r.	10–430
Single leaf (H_f)	See Experimental fuels section	0.75–2.80	1–193%	0.41	0.35	0.1–30	2–20
Single leaf (L_f)	See Experimental fuels section	0.75–2.80	1–193%	0.46	0.35		

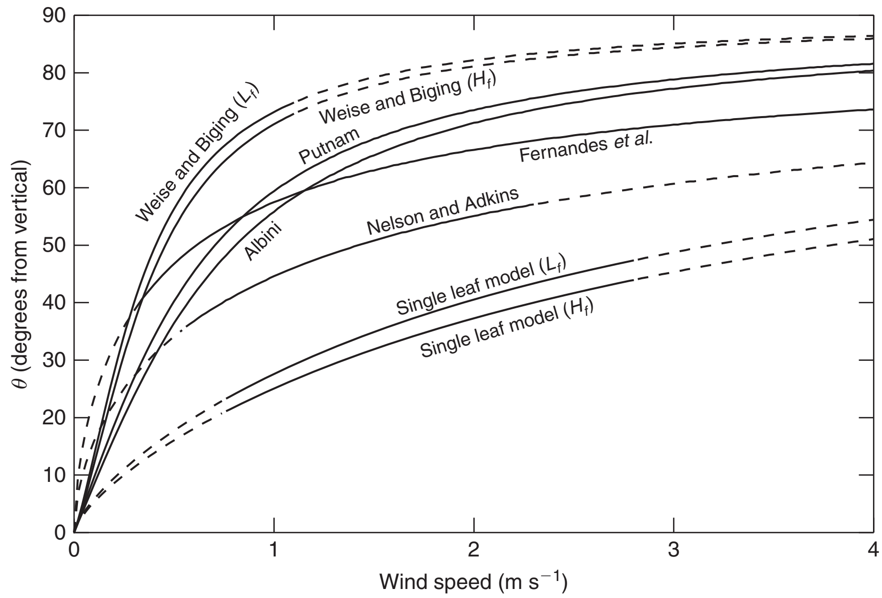

Fig. 7. Flame angle model comparisons using a constant flame height or length of 7 cm. This graph is for general comparisons only because flame height or length is dependent on wind speed. Dashed lines represent ranges of wind speed where data were not gathered.

wind speeds tend to shorten the flame length. The coefficient for Δx was positive, so thicker samples tended to have longer flames.

Flame height correlations followed the same trends as those for L_f and therefore are not discussed here. The best fit linear correlation for H_f ($R^2 = 0.64$) was:

$$H_f = mU + nm_0 + pm_{dry} + q \tag{4}$$

The signs for the coefficients for m_0 and m_{dry} in Table 2 are of opposite sign for Eqns 3 and 4. As m_0 includes m_{dry}, this indicates a strong negative influence of the moisture portion of m_0, which tends to decrease L_f and H_f.

Froude number

Existing flame angle prediction models are generally correlated with the dimensionless Froude number (*Fr*), in the form of

$$\theta = \tan^{-1}(c_1 Fr^{c_2}) \tag{5}$$

(see Weise and Biging 1996). When the data were fitted using this model, the R^2 values were lower than those of the linear models. A strong correlation nonetheless existed (see Fig. 6). Resulting Froude number correlations are as follows:

$$\theta = \tan^{-1}(0.46(U^2/gL_f)^{0.35}) \quad (R^2 = 0.67) \tag{6}$$

$$\theta = \tan^{-1}(0.41(U^2/gH_f)^{0.35}) \quad (R^2 = 0.75) \tag{7}$$

The values of c_1 presented here are considerably lower than those reported in literature and the values of c_2 are lower than all but two values. Comparative results are summarised in Table 3. Nelson and Adkins (1986) reported a c_2 of 0.29, with a c_1 value of 0.89 that correlated two different experiments with different

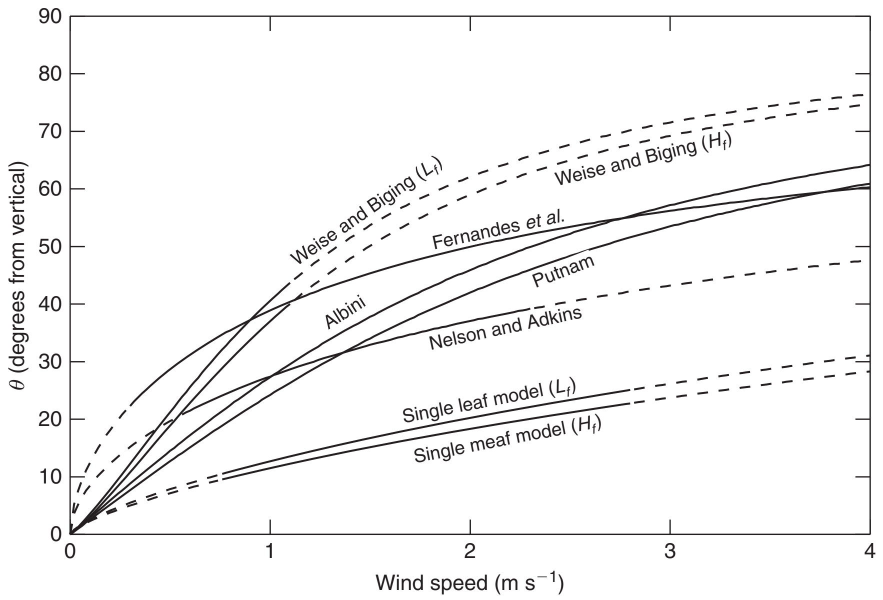

Fig. 8. Flame angle model comparisons using a constant flame height or length of 75 cm. This graph is for general comparisons only because flame height and length are dependent on wind speed. Dashed lines represent ranges of wind speed where data were not gathered.

Table 4. Linear regression equations of each species for predicting flame height and length (see Eqn 9)
Abbreviations are defined in the Nomenclature. Species listed are as in Table 1

Species	Flame characteristic variable	*r* (*U*)	*s* (*MC*)	*t* (m_{dry})	*u* –	R^2
Manzanita	Length	−1.19	−2.35	9.07	8.366	0.38
Manzanita	Height	−1.90	−1.18	7.74	7.881	0.56
Gambel oak	Length	−0.63	−5.00	15.07	9.94	0.69
Gambel oak	Height	−1.18	−4.51	7.81	10.016	0.77
Big sagebrush	Length	−2.89	−3.00	0	16.41	0.75
Big sagebrush	Height	−3.32	−2.71	0	15.37	0.78
Utah juniper	Length	−2.64	−4.66	5.50	15.20	0.67
Utah juniper	Height	−3.55	−2.88	3.19	14.52	0.77
Douglas-fir	Length	−1.16	−7.37	0	16.51	0.60
Douglas-fir	Height	−2.23	−6.64	0	16.10	0.70

moisture contents. Fernandes *et al*. (2002) found a similar value of c_2 at 0.28, but reported a higher value of c_1 (1.41). Both Albini (1981) and Putnam (1965) derived c_2 to be 0.5, with c_1 values of 1.22 and 1.40 respectively. Weise and Biging (1996) obtained values of $c_1 = 2.35$ and $c_2 = 0.57$ when H_f was used in the Froude number and $c_1 = 2.67$ and $c_2 = 0.57$ when L_f was used in the Froude number. The low values of c_1 and c_2 presented here are likely due to the lower heat releases of the individual leaf samples versus the heat release of fuel beds.

Comparisons of the different correlations are shown in Figs 7 and 8 for different characteristic lengths. In these figures, L_f and H_f were held constant at the specified flame length over the range of wind speeds, even though in reality L_f and H_f change with wind speed. Fig. 8 shows an extrapolation of the correlation developed in this research, as flame lengths of 70 cm were not observed. The reasons for the differences between the correlations shown in Figs 7 and 8 are unknown. However, the results suggest that flame angle is more than a function of just the Froude number. The vertical momentum of the gases from the flat-flame burner likely reduces the influence of the wind in the horizontal direction. The difference of air entrainment for small-leaf samples versus larger fires could also cause a difference in heat release per unit volume, reducing the buoyant effects of the flame. These possibilities should be explored in future research.

Species effects

As expected, flame angle did not appear to vary between species (see Fig. 4). Flame lengths and heights cannot easily be compared between species because of the nature of the samples. Differences in combustion behaviour between species may be masked by the effects of differences in mass, orientation or surface area. Analysis of individual species does indicate that flame height and length are strong functions of wind speed and

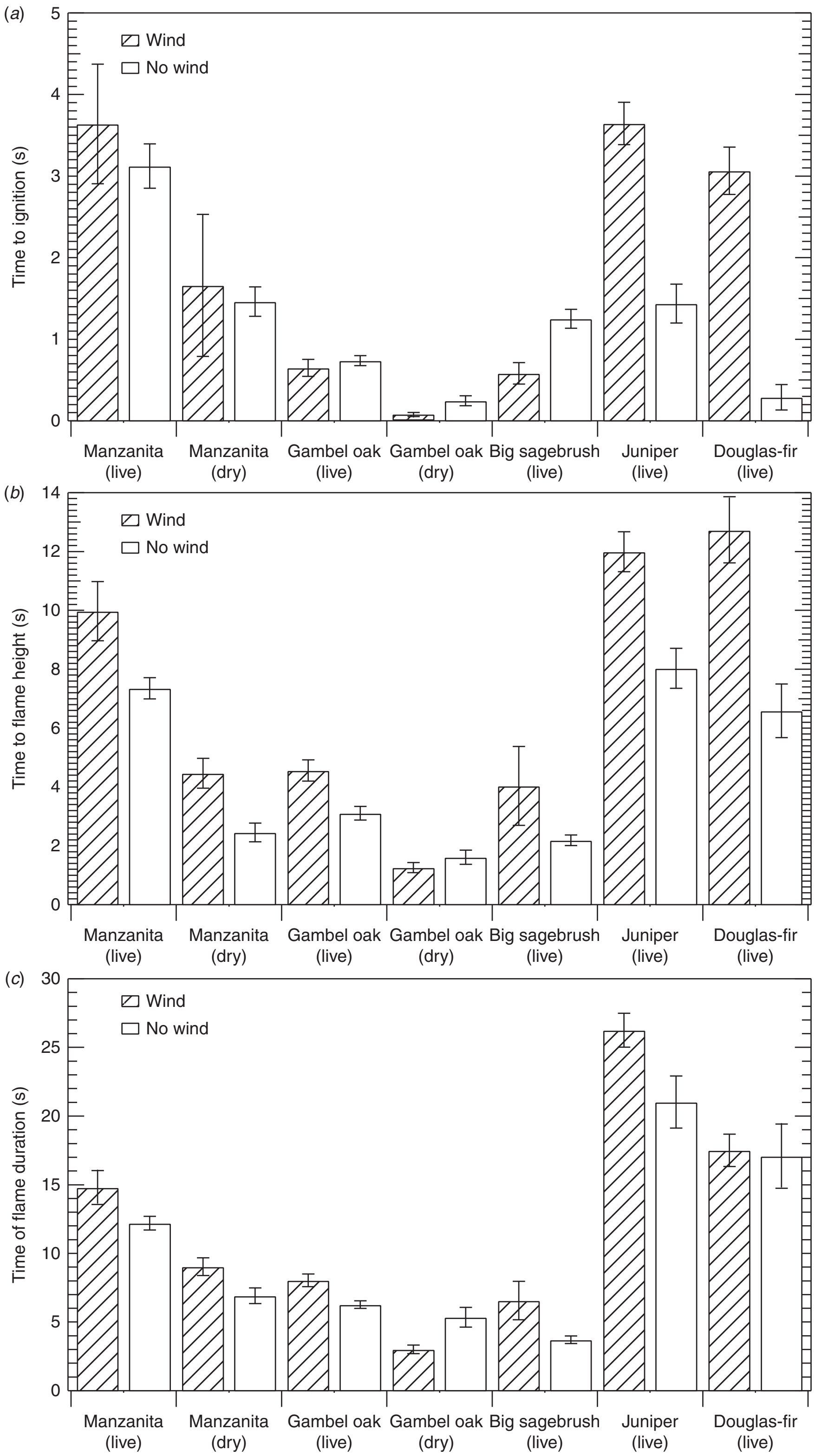

Fig. 9. (*a*) Effect of wind on time to ignition; (*b*) time to maximum flame height; and (*c*) flame duration time. Error bars represent 95% confidence intervals.

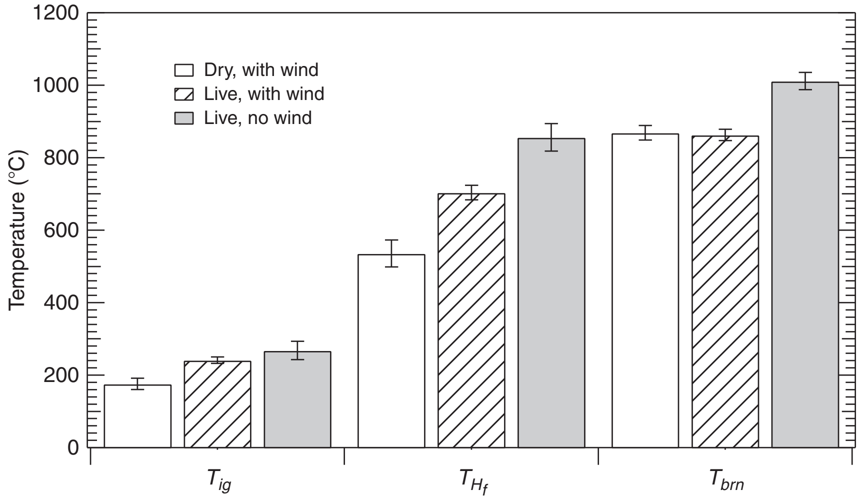

Fig. 10. The effects of wind on fuel temperature at time of ignition (T_{ig}), maximum flame height (T_{H_f}), and burnout (T_{brn}). Although this particular figure is for juniper, it is characteristic of the other four species that were examined. Error bars represent 95% confidence intervals.

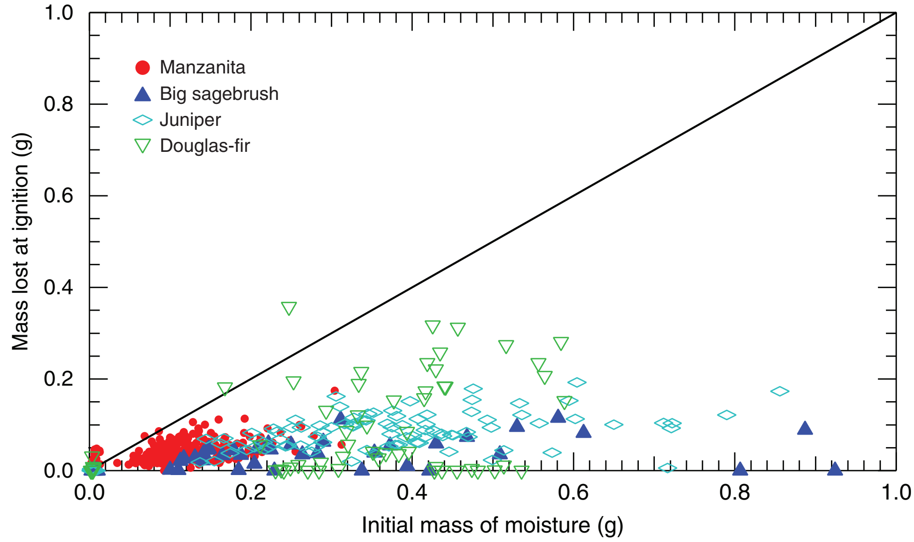

Fig. 11. Initial mass of water in sample *v.* mass lost at ignition for wind experiments. If all the moisture in the sample were to have evaporated by ignition, the points would lie on or above the parity line.

moisture content. Linear regression was performed for flame length and flame height using only one species at a time, yielding significantly improved correlations than Eqns 3 and 4. These correlations have the form of Eqn 8 (see Table 4 for coefficients). For example, big sagebrush has R^2 values of 0.75 when wind speed and moisture content are correlated with flame length and 0.79 when wind speed and moisture content are correlated with flame height.

$$H_f \text{ or } L_f = rU + sMC + tm_{dry} + u \qquad (8)$$

Time and temperature data

The data from experiments with wind were compared with thousands of previous leaf combustion experiments performed without wind (Engstrom *et al.* 2004; Pickett *et al.* 2005, 2010; Fletcher *et al.* 2007; Pickett 2008). These comparisons were separated into 'dry' and 'wet' groups. Dry samples had moisture contents 3–15%, and wet samples had moisture contents of 16–200%. In most cases, the samples burned with wind had longer times of ignition, maximum flame height and burnout (see Fig. 9), as well as lower temperatures at ignition, maximum flame height and burnout (see Fig. 10). The only exceptions to these trends were that big sagebrush and Gambel oak both exhibited shorter times to ignition with wind, and the dry Gambel oak had a shorter time to maximum flame height and flame duration with wind than without wind. The wind convectively cooled the samples, causing the longer ignition times and lower temperatures. The wind caused some movement of the sample as it curled, causing uncertainty in the local gas conditions. Future work includes examining the role of incoming air temperature in more detail. No regression analyses were performed on the time and temperature data because variations in leaf movement, shape, surface area and orientation significantly influenced both the time and temperature data.

Moisture at ignition

According to many traditional combustion models (Montgomery and Cheo 1969; Lu *et al*. 2008), all of the moisture in a fine fuel sample should evaporate before ignition. However, Pickett *et al.* (2010) found that there can still be significant amounts of moisture in a leaf sample when it ignites. The leaf burns from the perimeter towards the middle and moisture remains in the middle of the leaf when the perimeter ignites, which is consistent with the findings of Pickett *et al*. The amount of mass lost at the time of ignition (m_{ig}) *v*. m_{H_2O} is shown in Fig. 11. If all the water in the leaf evaporated before ignition, the points in Fig. 11 would fall on or above the parity line. Most of the points in the figure fall below the parity line, indicating that the large majority of samples still contained some amount of moisture at the time of ignition. At the time of ignition, samples burned with wind retained more moisture than those burned without wind. The average mass loss at ignition was 13% for wind experiments versus 25% for no-wind experiments. As the wind cools the leaf, one portion of the leaf may ignite while another portion remains at a significantly lower temperature, whereas in no-wind experiments, the leaf will have a more uniform temperature.

Conclusion

A total of 670 individual samples of five different species were burned using a flat-flame burner with wind speeds of 0.75 to 2.80 m s^{-1}. Flame angles, lengths and heights were determined from video images using a semi-automated procedure. Flame angles were correlated linearly with wind speed. A new Froude number correlation for small samples was developed from the flame angle data. Flame angles in these experiments were generally 50 to 70% less than those computed from Froude number correlations in the literature.

Flame length and height were found to correlate linearly with wind speed, initial mass, and initial mass of dry material. Greater wind speeds and higher amounts of moisture in the leaf tended to decrease flame length and height, whereas greater values of thickness and sample mass tended to increase flame length and height.

Compared with leaf samples burned without wind, samples burned with wind in these experiments generally took longer to ignite, reach maximum flame height and burn out. The temperatures corresponding to ignition, maximum flame height and burnout with wind were significantly lower than in the experiments without wind.

A significant amount of moisture remained in most samples from the wind experiments at the time of ignition. This finding is consistent with the work of Pickett *et al*. that leaf samples in no-wind experiments retained some amount of moisture at the time of ignition.

The results of this research may be applicable to the ignition of shrubs and to flame propagation in shrubs of low bulk density. In particular, correlations developed in this research are being incorporated into a semi-empirical model of flame propagation through shrubs (Pickett 2008; Cole *et al*. 2009). These correlations are also being investigated with further experiments examining leaf-to-leaf flame propagation within a shrub and the role of fuel moisture in pyrolysis gas flame structure.

Nomenclature

a–u, regression coefficients
c_1, constant in the Froude number correlation
c_2, constant in the Froude number correlation
Fr, Froude number ($U^2/(gL_f)$ or $U^2/(gH_f)$)
g, acceleration due to gravity
H_f, flame height (cm)
L_f, flame length (cm)
m_0, initial mass of sample (g)
MC, moisture content (m_{H_2O}/m_{dry}) (%)
m_{dry}, initial mass of dry material in sample (g)
m_{H_2O}, initial mass of water in sample (g)
m_{ig}, mass lost at ignition (g)
T_{brn}, temperature of sample at burnout (°C)
T_{ig}, temperature of sample at ignition (°C)
T_{H_f}, temperature of sample at maximum flame height (°C)
U, wind speed (m s^{-1})
Δx, thickness of sample (mm)
θ, flame angle (degrees from vertical)

Acknowledgements

This research was funded by the USDA and USDI National Fire Plan administered through a Research Joint Venture Agreement (no. 06-JV-11272166-060) with the Forest Fire Laboratory, Pacific Southwest Research Station, USDA Forest Service, Riverside, CA. Special thanks go to Dr David Lignell for his assistance in developing the code used for automated flame angle analysis. We would also like to thank Joey Chong for the collection and shipping of live samples from California to Brigham Young University.

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Manuscript received 9 February 2010, accepted 29 November 2010