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Fuel Element Combustion Properties for Live Wildland Utah Shrubs

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Current field models for wildfire prediction are mostly based on dry or low-moisture fuel combustion research. To better study the live fuel combustion behavior and develop the current semi-empirical bush combustion model, a laminar flow flat-flame burner was used to provide a convection heating source to ignite an individual live fuel sample. In this research project, four Utah species were studied: Gambel oak (*Quercus gambelii*), canyon maple (*Acer grandidentatum*), big sagebrush (*Artemisia tridentata*) and Utah juniper (*Juniperus osteosperma*). Leaf geometrical parameters measured included individual leaf total mass (m_0), thickness (Δx), leaf width (W), leaf length (L), and moisture content (MC). Time-stamped images of combustion behavior along with time-dependent mass data were recorded via LabVIEW system. Combustion characteristics were determined by an automated MATLAB routine modified for analyzing Utah species images of experimental runs, including time to ignition (t_{ig}), time of flame duration (t_{fd}), time to maximum flame height (t_{fh}), time to burnout (t_{brn}), and maximum flame height ($h_{f,max}$).

Qualitative results included various combustion phenomena like bursting, brand formation and bending. Sparks accompanied with leaf material bursting out were observed for Utah juniper sample combustion mostly before ignition, especially for segments cut from top of the branch. Quantitative results included exploration on best prediction equations for leaf geometrical properties (individual leaf dry mass (m_{dry}), Δx , W and L) and combustion characteristics. A beta distribution was used to predict the distribution of m_{dry} . Multiple linear regressions were performed on other leaf geometrical properties and combustion characteristics. Minimized Bayesian information criterion (BIC) value models were achieved by stepwise regression analysis and compared to the previous empirical prediction models. A linear correlation between flame area (determined by images) and flame height was observed. Leaf placement and bush structure were based on observations of wildland shrubs. A correlation between crown diameter and total bush dry weight was developed based on the data measured in the field. A new fractal-based L-systems approach was used for the segment fuel placement of Utah juniper. A semi-empirical bush combustion model was adapted to simulate combustion of Gambel oak, canyon maple and Utah juniper shrubs.

1. Introduction

In order to improve the suppression of wildfires (unwanted and uncontrolled) and the prediction of prescribed fire (ignited intentionally to decrease the amount of live and dead fuel accumulation in forest), it is important to better understand wildland fire propagation (USDA/USDI, 2005). Weber (1991) and Sullivan (2009a, b, c) performed comprehensive reviews of wildfire modeling and classified types of fire propagation models. The Rothermel model (1972) is a *semi-empirical model* that was further developed into wildfire *field operational models* (FARSITE

(Finney, 1998) and BEHAVE (Andrews, 1986)). Moreover, some computational fluid dynamic (CFD) models for wildfire modeling have been developed, such as FIRETEC and WFDS (Linn, 1997; Mell et al., 2006; Clark et al., 2010). Besides CFD models and the Rothermel model (1972), many other wildland fire propagation models were developed based on experimental data from dead or dry fuel beds, which might be inappropriate for predicting live wildland fuel combustion, especially at high moisture content (Fletcher et al., 2007; Pickett, 2008). There is a need for better methods to simulate combustion of live wildland fuels, especially for shrubs. Various kinds of live fuel combustion experimental studies have been conducted previously (Dimitrakopoulos and Papaioannou, 2001; Smith, 2005; Weise et al., 2005; Pickett, 2008; Pickett et al., 2010).

More than 2200 combustion experiments were conducted on single live fuel samples of various species common in California and Utah (Engstrom et al., 2004; Smith, 2005; Fletcher et al., 2007; Pickett, 2008). Both Smith (2005) and Pickett (2008) performed combustion experiments on four fuels from Utah (canyon maple, Gambel oak, big sagebrush, and Utah juniper) and developed empirical correlations between leaf properties and combustion characteristics. Pickett (2008) developed a first-generation two-dimensional model of Manzanita shrub combustion, based on empirical correlations developed from single leaf experiments. This bush model was capable of predicting overall burn times and amount of fuel unburned. This model was later extended to three dimensions (Prince et al., 2010), including effects of flame coalescence and the effects of wind on flame angle and size (based on the findings of (Cole et al., 2011)). However, improved combustion data on live Utah shrub fuels must be obtained to expand the bush model.

2. Methods

Experimental Apparatus

A flat-flame burner (FFB) was used as the heat source, which can be moved directly under the leaf (see Figure 1). Fuel gases (CH_4 and H_2) and oxidizer (air) were premixed and introduced into the FFB, providing a 1 mm thick flame at a height of 1 mm above the sintered bronze burner surface. The vertical distance between the FFB and the leaves was typically 5 cm, a point where the gas temperature was 1200 K. This premixed FFB surface was 7.5" x 10". A cage with glass panels was placed above the FFB to avoid indraft of surrounding air, which introduced natural convection flow recirculation, leading to decreased effective flame area. This glass cage ensured 10 mol% O_2 in the post-flame gases and a laminar flow environment. The live fuel sample (leaf or twig) was placed horizontally or vertically, according to experimental purpose, on a rod connected to a mass balance. The FFB was placed on a cart, which could be pulled and stopped exactly under the sample.

A bare fine-wire type-K (chromel-alumel) thermocouple was used to measure the gas temperature close to the leaf sample during each experimental run. The diameter of the thermocouple was 0.003 inches and the length was 12 inches. A Sony CCD-TRV138 camcorder or a Panasonic SDR-S50P digital camcorder was used to record video images. The images were collected and digitized by a National Instruments PCI-1411 IMAQ device. A National Instruments LabVIEW 7.1 program was used for data collection, which simplified data collection and minimized human error. Video images, temperature, and mass data (from a Mettler Toledo XS204 analytical mass balance) were collected simultaneously with a time-stamp at 18 Hz. Video images were digitized and stored as jpeg files along with the datasheets for each experimental run.

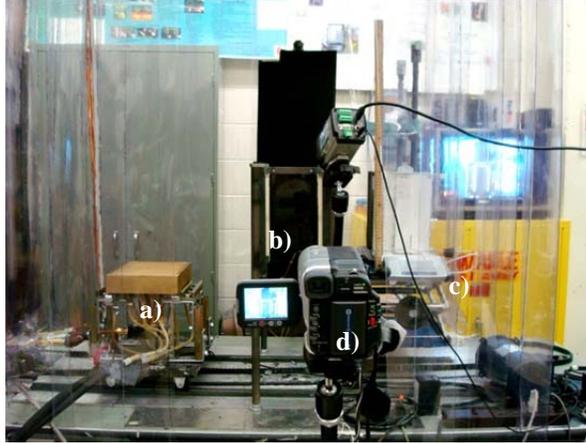


Figure 1. Flat-flame burner experimental set-up, including a) large flat flame burner, b) cage with glass panel on each side, c) mass balance, d) video camera.

Previously, a CompuTrac moisture analyzer was used to measure the moisture content (MC) of each sample on a dry mass basis. Moisture content in the forest products industry is defined on a dry basis (m_{H_2O}/m_{dry}). Values of MC were measured before and after the combustion experiments, and the two values were averaged together to provide an average MC for all the experimental runs. Since July 29 2011, a new method was used to determine the MC . For every three samples, a fourth sample was prepared and measured for MC . This representative sample was cut from the original plant at the same part of the plant as the other three samples. The mass of each of the four samples (m_0) was measured prior to running the experiment. After all the experimental runs were completed, the representative sample was dried and then weighed to measure for the dry mass (m_{dry}). Then MC can be calculated from:

$$MC = \frac{m_{H_2O}}{m_{dry}} = \frac{m_0 - m_{dry}}{m_{dry}} \quad (1)$$

where m_{H_2O} is leaf moisture mass.

Leaf length (L) and width (W) were measured with a ruler to accuracy of 0.1 mm for each sample prior to each experimental run. Length was defined as the longest distance from top to bottom of a leaf sample. Width was defined as the widest distance from side to side of a leaf sample. Thickness (Δx) was determined by a Chicago Brand digital caliper with an accuracy of 0.01 mm. Thickness was measured at different positions of the sample (excluding leaf vein) and determined by taking an average of all measurements. For non-broadleaf samples, measurement of the diameter was treated as equivalent to thickness. Initial total single leaf mass (m_0) was also measured by a Mettler Toledo AB104 mass balance.

Experimental Fuels

Experiments were performed on four kinds of Utah species: Gambel oak (*Quercus gambelii* Nutt.), canyon maple (*Acer grandidentatum* Nutt.), big sagebrush (*Artemisia tridentate* Nutt.) and Utah juniper (*Juniperus osteosperma* (Torr.) Little). The samples of Gambel oak, canyon maple and big sagebrush were primarily collected from Rock Canyon, Provo, Utah. Utah juniper samples were collected from Diamond Fork Canyon near Spanish Fork, Utah. Samples were selected and detached from the branches at random. Samples were collected in no less than five days and are referred to as live fuels. Once the samples were collected, samples were kept moist by watering the stems until

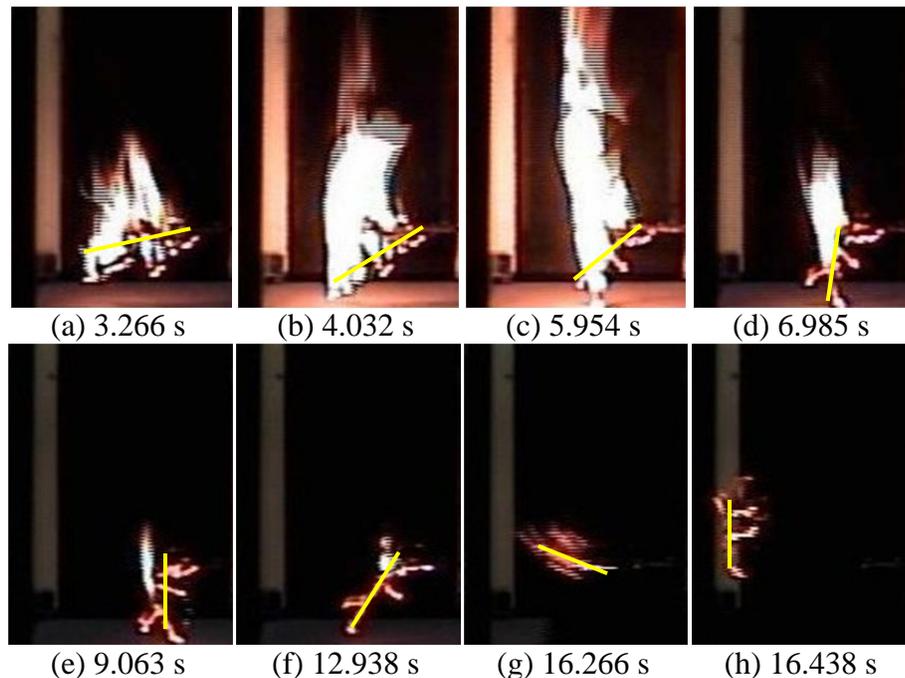
testing began if testing was on another day. Combustion experiments were performed on live samples with various moisture contents.

3. Results and Discussion

Qualitative Results

Ignition Behavior

Because of the shape of the Gambel oak leaves, ignition normally started at the tips of the samples when they were placed horizontally. Several sustained local ignitions from the tips would finally merge into a sustainable flame. On the other hand, for vertical leaf placement, the ignition normally started from the bottom edge closest to the FFB. Generally, these bottom edge ignition flames were intense enough to sustain and propagate towards the center of the leaf. When placed vertically, the maple leaf sample mostly ignited from the bottom big saw-tooth tip or edge. The horizontal-placed maple sample showed random local ignition sites on the saw-tooth tip. When juniper was burned as a segment, ignition occurred at different tips of the small needles. These small flames with local ignition eventually merged into a sustainable flame and engulfed the entire sample. Sagebrush samples ignited from the trident tip of the leaf for both single leaf combustion runs and segment combustion runs. Segment samples ignited more easily than single leaf samples, which could be explained by larger surface area per volume of leaf exposed to the convective gases.



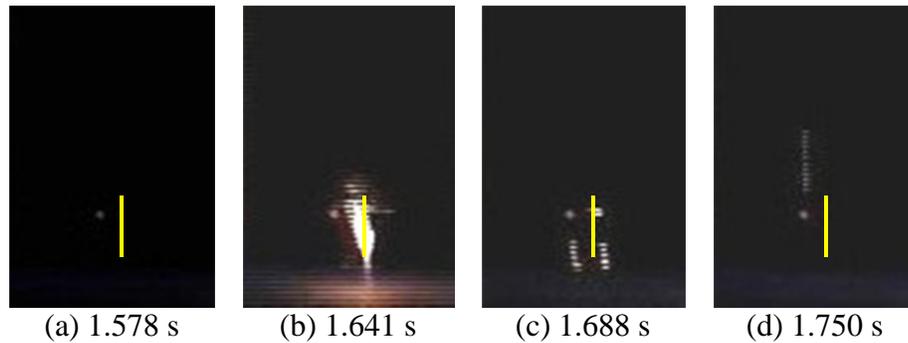
Numbers indicate the time stamp from the initial time of the experimental run and a yellow line was showing the position of leaf sample.

Figure 2. Bending behavior of Gambel oak sample placed vertically. The yellow line shows the leaf orientation.

Combustion Behavior

Leaf bending was observed for most of the broadleaf (Gambel oak and canyon maple) sample runs with horizontal or vertical placements. Figure 2 is an example of bending behavior for Gambel oak burning when the sample was placed horizontally. The sample bent towards the burner against the convective heating gas flow until maximum flame height was achieved (shown as Figure 2a-d). The sample bent backwards till its original horizontal placement (shown as Figure 2e-g). Brand formation was also observed during four Utah species sample combustion. Figure 2g and 2h show that the sample was eventually detached from the clip as a brand.

Sparks were often observed before the complete ignition of the sample (shown in Figure 3 as consecutive frames). These pictures showed the sparks appeared on frame (b) of Figure 3 and disappeared suddenly in next frame. Accompanying the sparks, there were usually small leaf materials burst out. These behaviors were always observed for the segments cut from the top section of a juniper branch. Characteristics identified for the top section of juniper included lighter surface color and different surface structure.



Numbers indicate the time stamp from the initial time of the experimental run and a yellow was showing the position of leaf sample.

Figure 3. Spark and bursting behavior of Utah juniper sample. The yellow line shows the leaf orientation.

Quantitative Results

Leaf Properties

Single leaf dry mass (m_{dry}), leaf thickness (Δx), leaf width (W) and leaf length (L) were cross-correlated to obtain a distribution of physical leaf parameters from experimental measurements. The order of predictions for each leaf parameter is shown in Figure 4, meaning that Δx can depend on m_{dry} , W can depend on both m_{dry} and Δx , etc..

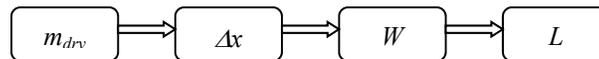


Figure 4. Flowchart of leaf physical parameters prediction order.

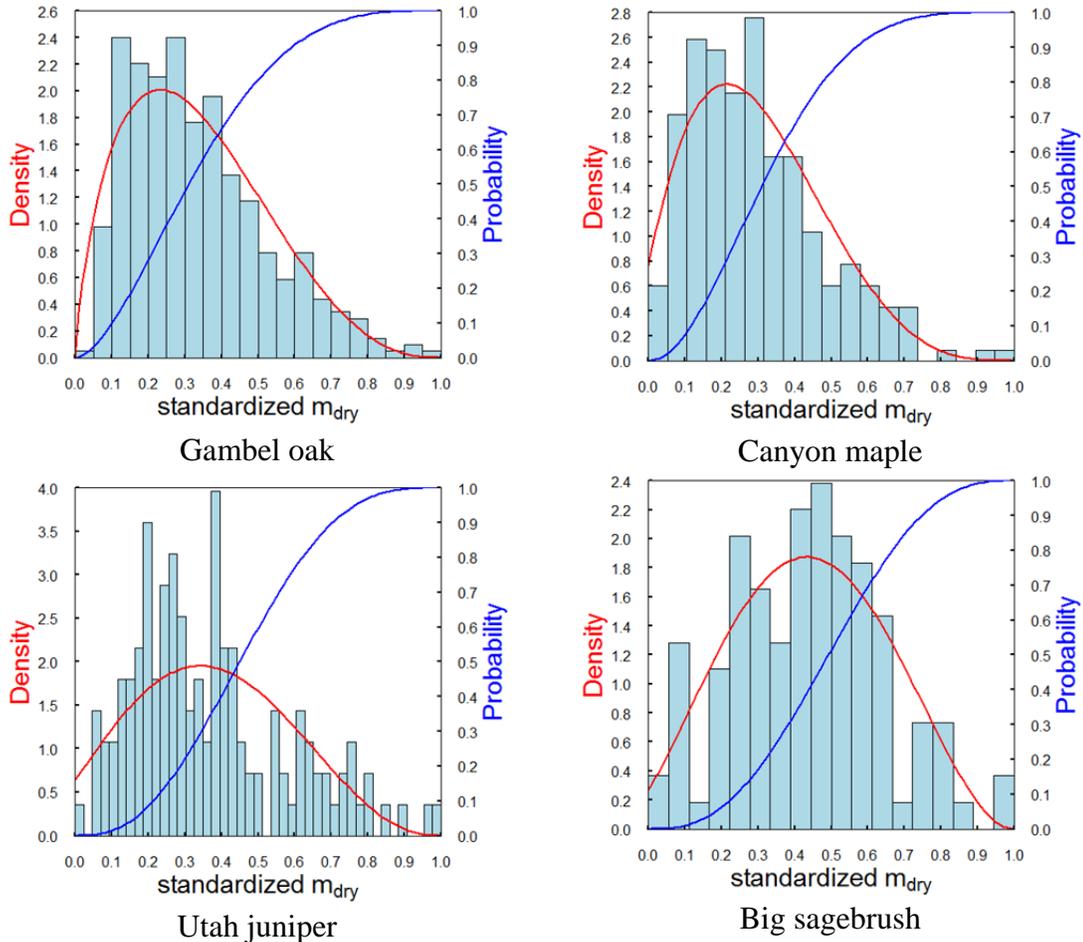


Figure 5. Histogram of the experimental leaf dry mass versus the fit to a beta distribution (probability density function (PDF) and the corresponding cumulative distribution function (CDF)).

Single leaf dry mass (m_{dry} , in gram) was utilized as the base indicator for all leaf parameters, and it was well represented by a beta distribution. The goodness of the fit is shown in Figure 5. A single leaf was the unit sample for the broadleaf species (Gambel oak and canyon maple) and small segments were used for the non-broadleaf species (Utah juniper and big sagebrush). Further regressions with stepwise analysis to minimize the Bayesian information criterion (BIC) values were performed to predict the Δx , W and L (all in cm). The results of predictive equation are showing in Table 1.

Table 1. Summary of regression analysis on leaf geometrical properties for Utah species.

Species		Predictive Equation	MSE	R ²
Gambel Oak	W	$W = 3.51 - 7.68 \cdot \Delta x + 11.96 \cdot m_{dry} + 3.76 \cdot m_{H2O}$	0.63	0.73
	L	$L = 10.16 + 0.26 \cdot W + 1.56 \cdot \ln(m_{dry}) + 0.50 \cdot \ln(m_{H2O})$	0.76	0.77
	Δx	$\Delta x = 0.27 + 0.052 \cdot MC + 0.035 \cdot \ln(m_{dry})$	0.0012	0.35
Canyon maple	W	$W = 11.72 - 0.81 \cdot MC - 10.66 \cdot \Delta x + 9.51 \cdot m_{dry} + 1.67 \cdot \ln(m_{H2O})$	0.45	0.81
	L	$L = 6.82 - 1.19 \cdot MC + 0.30 \cdot W + 1.01 \cdot \ln(m_{H2O})$	0.37	0.74
	Δx	$\Delta x = 0.067 + 0.046 \cdot MC + 0.21 \cdot m_{dry}$	0.0006	0.37
Utah juniper	L	$L = 5.54 + 1.01 \cdot \ln(m_{dry})$	0.21	0.46
	Δx	$\Delta x = 0.88 + 0.50 \cdot MC + 0.62 \cdot m_{dry}$	0.033	0.21
Big sagebrush	L	$L = 5.54 - 4.92 \cdot \Delta x + 8.66 \cdot m_{H2O}$	0.72	0.49
	Δx	$\Delta x = 0.24 + 0.59 \cdot m_{dry}$	0.0043	0.14

The leaf apparent dry density (ρ_{leaf}) is defined as the dry mass of a single leaf over the leaf volume, as shown in Equation (2). The value of ρ_{leaf} is calculated for broadleaf species (Gambel oak and canyon maple).

$$\rho_{leaf} = \frac{m_{dry}}{L \cdot W \cdot \Delta x} \quad (2)$$

Combustion Characteristics

Multiple linear regression was performed to achieve the models for prediction of combustion characteristics, including time to ignition (t_{ig} , in seconds), time to maximum flame height (t_{fh} , in seconds), time of flame duration (t_{fd} , in seconds), maximum flame height ($h_{f,max}$, in cm), time to maximum flame height (t_{fh} , in seconds), etc. Time to ignition (t_{ig}) is defined as the time difference between exposure to heat flux and ignition. The time of flame duration (t_{fd}) is the time difference between the moment of ignition and the moment of burnout. A maximum flame height ($h_{f,max}$) during combustion of each live fuel sample was determined from the video images processed by the MATLAB routine developed in wildfire lab at BYU.

The time to maximum flame height (t_{fh}) was defined as the amount of time from the moment of ignition to the moment of reaching the maximum flame height. The width of the flame area determined from the video image was assumed to be constant during individual sample combustion. This flame width is named FW_{β} . The values of FW_{β} for different species were also expected to be a function of physical leaf properties. The stepwise regression with bidirectional elimination was used to achieve the statistical best models based on Bayesian information criterion (BIC). Best statistical models used in the semi-empirical bush combustion model are showing in Table 2.

Table 2. Summary of regression analysis on combustion characteristics for Utah species.

Species	Predictive Equation	MSE	R ²
Gambel Oak	$t_{ig} = -1.15 + 1.59 \cdot MC - 0.094 \cdot W + 7.13 \cdot \Delta x$	0.32	0.58
	$t_{fd} = 3.05 + 1.02 \cdot \ln(MC) + 22.82 \cdot m_{dry}$	3.11	0.61
	$h_{f,max} = 2.24 - 9.15 \cdot MC + 2.04 \cdot W + 1.54 \cdot L + 24.55 \cdot \Delta x$	15.93	0.65
	$t_{fh} = 3.02 - 0.31 \cdot L + 14.28 \cdot m_{H2O}$	0.61	0.57
	$FW_{\beta} = 1.42 + 0.14 \cdot L + 5.30 \cdot m_{dry} - 3.70 \cdot m_{H2O}$	0.13	0.65
Canyon maple	$t_{ig} = 0.92 + 0.86 \cdot \ln(MC)$	0.15	0.40
	$t_{fd} = 1.44 + 12.44 \cdot \Delta x + 6.78 \cdot m_{dry} + 4.49 \cdot m_{H2O}$	0.57	0.71
	$h_{f,max} = -21.55 + 2.68 \cdot W + 1.37 \cdot L + 62.14 \cdot \Delta x - 27.42 \cdot m_{H2O} + 29.72 \cdot \rho_{leaf}$	10.98	0.75
	$t_{fh} = 10.79 + 1.07 \cdot \ln(MC) - 0.54 \cdot W + 2.05 \cdot \ln(m_{dry})$	0.38	0.48
	$FW_{\beta} = 0.95 - 0.48 \cdot MC + 0.36 \cdot W$	0.23	0.61
Utah juniper	$t_{ig} = 4.24$	1.84	NA
	$t_{fd} = 5.21 + 3.24 \cdot \Delta x + 53.00 \cdot m_{H2O}$	6.01	0.51
	$h_{f,max} = 5.47 - 4.21 \cdot MC + 1.00 \cdot L + 33.90 \cdot m_{H2O}$	3.58	0.45
	$t_{fh} = 6.23 + 2.75 \cdot \ln(MC) + 14.78 \cdot m_{dry}$	6.41	0.10
	$FW_{\beta} = 1.26 + 5.35 \cdot m_{dry}$	0.06	0.43

Modeling Results

The semi-empirical bush model developed in the wildfire lab at Brigham Young University was expanded to adapt to Utah species in this research project. In this model, the number of leaves and MC were defined by user. Then leaf properties are assigned to each leaf based on the prediction equations discussed in the previous section. With leaf properties assigned, leaves were placed in the bush space which was specific to species. A rectangular box with a hollow middle space was used as the shape of Gambel oak and canyon maple bushes. The proportion of the hollow space was decided by studying bushes in the field. A hemi-ellipsoid shape with a hollow middle space was also used for Gambel oak bushes. A fractal-based L-systems approach was adapted for modeling the branching structure of Utah juniper (Fletcher and Fletcher, 2013). The fuel elements were evenly placed onto the primary and secondary branches generated by this L-system approach.

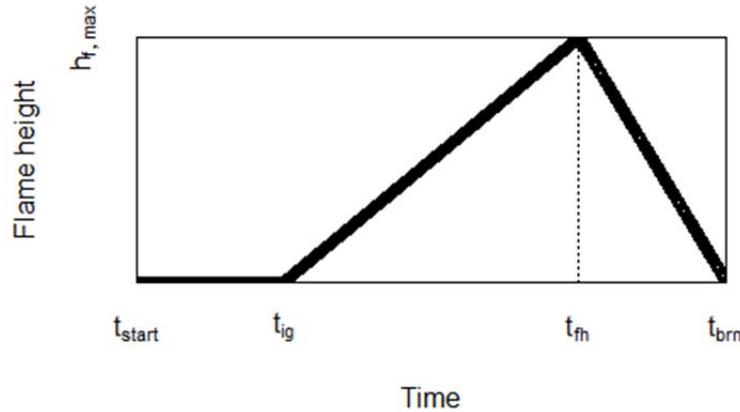


Figure 6. Flame zone history for individual leaf combustion (distances not to scale).

A corner of a bush was manually set to be burning as ignition source. FW_{β} and leaf flame height (h_f) were used to create the rectangular flaming zone. The flame height h_f of the ignited horizontal leaf was linearly increased from zero to $h_{f,max}$ (at t_{fh}) and then decreased to zero (at t_{brn}) (as shown in Figure 6).

It was assumed that flame widths of the front and the side were equal. A sketch for this flame volume simulation method is shown in Figure 7. This new method effectively improved the flame volume simulation by preventing the unrealistic large flame for Gambel oak and canyon maple bushes combustion simulations.

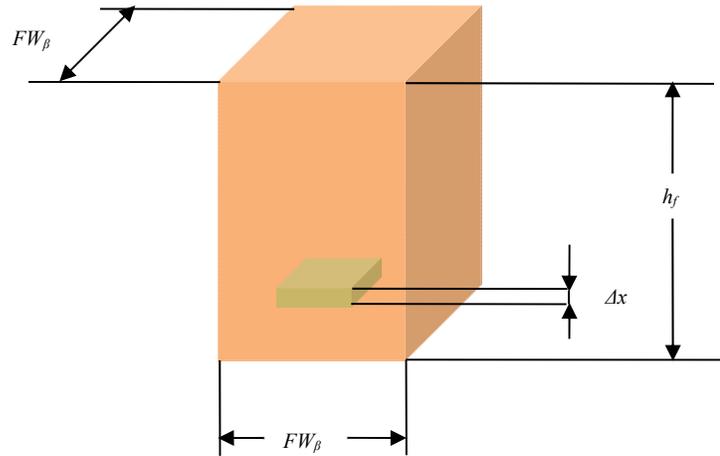


Figure 7. 3-D representation of leaf flame volume via current modified method. (The orange shaded rectangle represents the flame and the green shaded rectangle represents the leaf. Distances are not to scale.)

Parametric runs were performed on the semi-empirical bush combustion model with different configuration inputs to study the effect of the following factors: bush shape, bush size, leaf properties, MC , bulk density, local density and wind speed. The maximum bush flame height ($h_{f,bush}$) was defined as the maximum value of the flame height above the bush during flame propagation, which could be zero if there was no flame above the bush. The bush burnout time ($t_{brn,bush}$) was defined as the time difference between the moment that flame stopped propagation and the moment first ignition happened. The extent of burnout (X_s) was defined as the percentage of the total number of leaves that were completely burned. Bulk density (ρ_{bulk}) was defined as the number of leaves divided by the total volume of the bush. Local density (ρ_{local}) was referred to the number of leaves in the bush volume without counting the inside hollow space.

The rectangular box shape seemed to provide more accessible fuel above the initial flame for fire propagation than the hemi-ellipsoid shape. The bush size and leaf number of bushes estimated from the field were scaled down by 1/8 or 1/27 while other inputs were keeping the same. It was observed that the X_s did not change significantly, which indicated that bush size would not influence the burning behavior significantly if the change of scale was less than 27 times. For different bush species, not only density affected predicted fire propagation, but also leaf properties had an impact on burning time and maximum flame height above the bush. This semi-empirical model was able to

embed the bush species characteristics separately from the geometrical aspects, and it was therefore concluded that canyon maple bush burned much faster than Gambel oak bush.

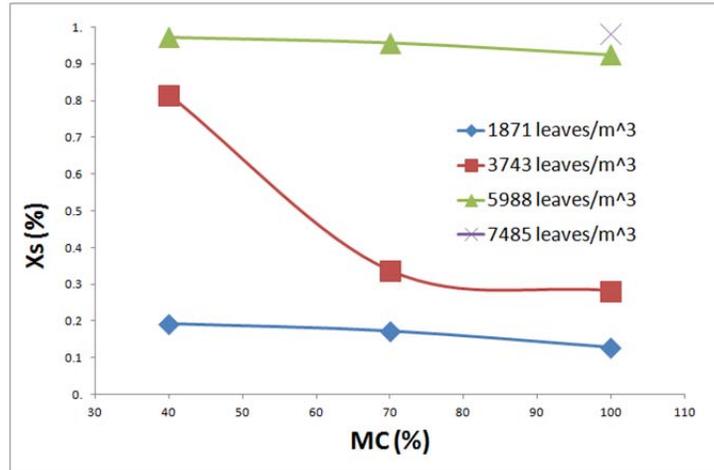


Figure 8. Percentage burned versus moisture content at different levels of local density for large-hollow-space rectangular box Gambel oak bush.

Both density and MC affected X_s significantly in the bush model. Different species also resulted in a different range of X_s . It appears that the flame might not propagate in bushes vigorously unless a high enough density and low enough MC were present. Decreased moisture content and increased bulk density caused the extent of burnout for the bush to increase. Figure 8 is an example of X_s versus MC rectangular box Gambel oak bushes combustion in the semi-empirical model at different levels of local density.

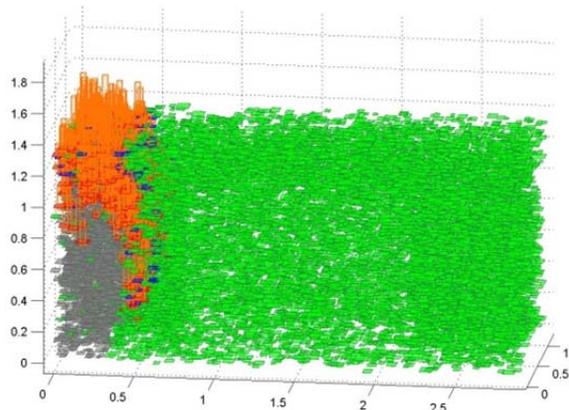
When wind was introduced and wind speed increased, the extent of burnout did not necessarily increase. However, when wind speed was larger, the flame extended further away from the ignition source as predicted by this semi-empirical model. This effect of wind could increase the possibility of flame propagation between bushes in wildfire. Figure 9 is an example of rectangular box Gambel oak bush combustion in the semi-empirical model with and without wind.

As for Utah juniper bush combustion in the semi-empirical model, a correlation (shown as Equation (3)) was developed to predict total Utah juniper bush dry weight (W_{dry}) and was also embedded in the bush model.

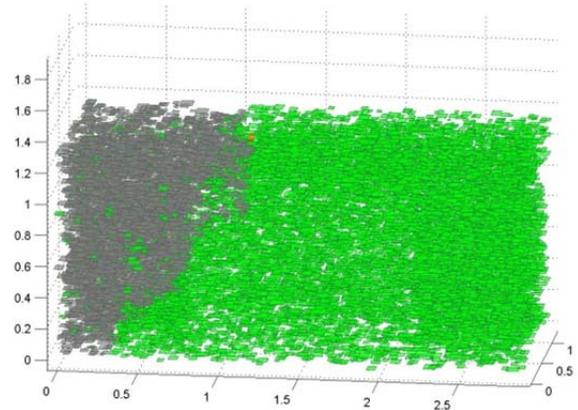
$$W_{dry} = 30.05 \cdot D_{crown} - 1763.33 \quad (3)$$

where D_{crown} is the crown diameter of Utah juniper bush in cm and W_{dry} is in grams. The regression to this equation was based on the measurements of Utah juniper bushes at Diamond Fork Canyon near Spanish Fork, Utah. Parametric runs were performed and based on the geometrical measurements in the field. The flame propagation and X_s might depend on the ratio of bush height to crown diameter and bulk density as well. However, bush size did not influence the X_s significantly for this semi-empirical bush combustion model. When MC decreased, the X_s increased as expected. It was observed that flame propagation was worse when wind was introduced. This could be the reason that there was less chance for flame to ignite the fuel above when wind tilted the flame as predicted by this semi-empirical bush model. Figure 10 is an example of the Utah juniper bush combustion history from the semi-empirical model.

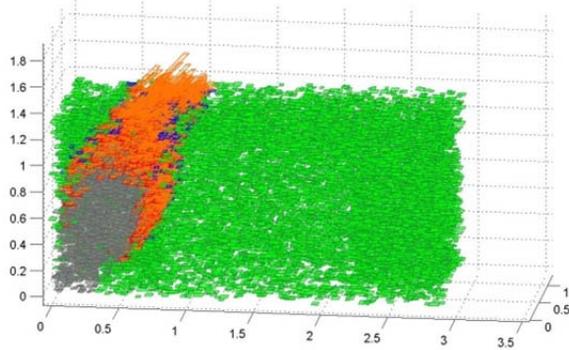
For simulated bushes matching geometrical measurements in the field, flame propagation and extent of conversion in this semi-empirical bush model were not as intense as expected, especially for the semi-ellipsoid Gambel oak bush and rectangular box maple bush. Since density and moisture content influenced the extent of burnout significantly, more precise estimation of the leaf number of a bush and the moisture content appear to be necessary for improved predictions.



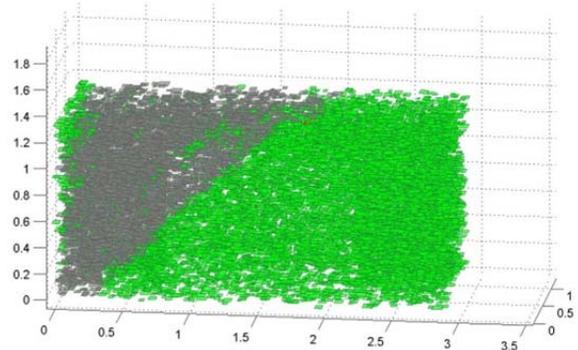
(a) at 28.5 s, wind speed at 0 m/s



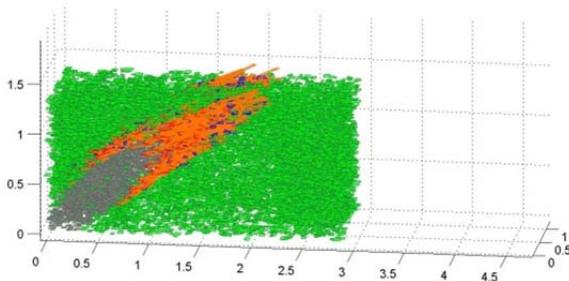
(b) at burnout, wind speed at 0 m/s



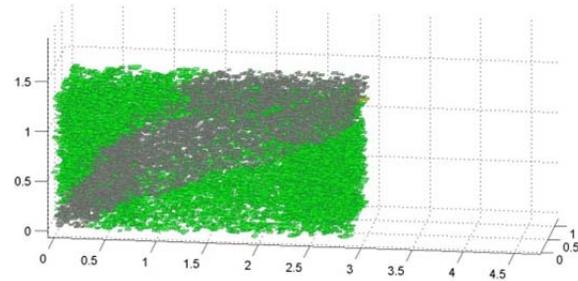
(c) at 28.5 s, wind speed at 1 m/s



(d) at burnout, wind speed at 1 m/s



(e) at 28.5 s, wind speed at 3 m/s



(f) at 28.5 s, wind speed at 3 m/s

Figure 9. Bush combustion modeling results of rectangular box Gambel oak bush at different wind speed (0, 1 and 3 m/s).

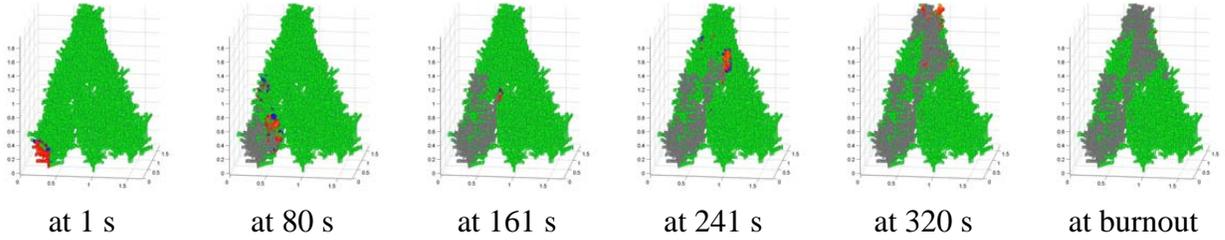


Figure 10. Combustion behavior in the semi-empirical model for Utah juniper bush.

4. Conclusions

Observations of combustion experiments on live leaves showed that ignition was initiated at the tip of the leaf, where local surface area was relative large. Bending behavior was observed during combustion experiments of Gambel oak and canyon maple. Brand formation was mainly observed for combustion of light leaf samples. Some samples detached from the clip after burnout and some samples detached from the clip when samples were still flaming, especially for canyon maple. Sparks and bursting behavior were observed usually before Utah juniper sample ignition, which occurred particularly for juniper segments cut from the top of the branch.

Statistical analyses were performed on both leaf geometrical properties and combustion characteristics. A beta distribution was used to describe individual leaf dry mass (m_{dry}). Multiple linear regressions were performed to correlate leaf thickness (Δx), leaf width (W), leaf length (L) (in this order). Multiple linear regression correlations for combustion characteristics (time to ignition (t_{ig}), time of flame duration (t_{fd}), time to maximum flame height (t_{fh}), time to burnout (t_{brn}), maximum flame height ($h_{f,max}$) etc.) were also developed. Minimized BIC value models were achieved by stepwise regression analysis and recommended to be used in the semi-empirical bush model.

An existing semi-empirical bush combustion model was improved to treat Gambel oak, canyon maple and Utah juniper. Bush structure and leaf placement were determined for different species. A rectangular box shape with a hollow middle was used to simulate both Gambel oak and canyon maple shrubs. A hemi-ellipsoid shape with a hollow center was also used to simulate a Gambel oak shrub. A fractal-based L-systems approach was adapted to model branching structure for Utah juniper bushes (Fletcher and Fletcher, 2013). Total bush dry weight (W_{dry}) for Utah juniper was correlated to bush crown diameter (D_{crown}) and the correlation was embedded in the semi-empirical bush model. A new flame width approach was used to build flaming zone in the modified semi-empirical bush combustion model, which improved the simulation of bush flame height prediction especially for large broadleaf bushes (Gambel oak and canyon maple). Prediction equations of leaf geometrical properties and combustion characteristics were integrated into the bush model for Utah species.

Parametric runs of different configurations were conducted on the semi-empirical bush combustion model. Both density and species properties affected burning time and maximum flame height above the bush. Decreased moisture content and increased bulk density caused the extent of burnout (X_s) for the bush to increase. When wind was introduced and wind speed increased, X_s did not necessarily increase though the distance that the flame propagated from the ignition source increased. For simulated bushes matching geometrical measurements in the field, flame propagation

and X_s were not as intense as expected, especially for the semi-ellipsoid Gambel oak bush and rectangular box maple bush. Since density and moisture content influenced the extent of burnout significantly, more precise estimation of the leaf number of a bush and the moisture content appear to be necessary for improved predictions. A better flame coalescence algorithm in the bush combustion model seems necessary as well.

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