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Experiments and Modeling of Fire Spread in Shrubs in a Wind Tunnel

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Abstract: Current operational fire spread models are based on experimental results from dead, low moisture fuels and thus do not perform well when modeling fire behavior in live, high moisture fuels. In this work, fire spread in live shrubs was measured in a wind tunnel in Riverside, CA and used to validate the fire spread model being developed at Brigham Young University (BYU). A 200 g excelsior bed upwind of the fuel bed was used as the ignition source. The fuel bed was designed to contain two shrubs in their natural arrangements (nominally 2 m long x 1 m wide x 1 m high). The shrub closest to the excelsior bed was used as an ignition shrub and the fire was allowed to propagate to the second shrub. The goal was to measure fire behavior without the influence of the excelsior bed. Wind speed was held constant at 1.4 m/s while fuel density and moisture content varied across natural levels. The effect of understory fuel was also explored in some experiments. Mass, fuel surface temperature, gas temperature, radiative heat flux and total heat flux data were collected throughout each experiment. Combustion characteristics and time-dependent fire behavior were measured continuously using three digital camcorders at different locations around the fuel bed. After the experiment, the terminal end diameter of burned branches was measured as an indicator of fire intensity. Results indicate fire behavior under these conditions is highly dependent on species and fuel moisture content as well as local fuel density fluctuations rather than on overall fuel bed density. Radiative pre-heating accounted for approximately one-third of the temperature rise prior to ignition; this result was not affected by moisture content. Simulations using the BYU Bush Model were compared to the shrub combustion experiments performed in the wind tunnel.
Keywords: wildland fire, shrub combustion

1. Introduction

Operational models can be used to predict the spread of wildland fires and prescribed burns. Most current models (e.g. BehavePlus, FARSITE, FlamMap) [1-7] are based on the empirical spread model by Rothermel [8], which was developed for dead and low-moisture fuels that are contiguous to the ground. These models do not adequately describe fire spread in live fuels such as those found in shrublands and tree crowns. Since much of the western United States is covered by sparsely growing shrubs and small trees [9], it is imperative that fire models be developed that can describe fire spread in live fuels. Development of a next-generation model is hindered by the lack of fundamental understanding regarding fire behavior in live fuels [10, 11].

Computational fluid dynamics models (CFD) have also been developed, including FIRETEC and WFDS [12-14]. These models solve the governing equations for mass and energy balances rather than using empirical relationships and thus provide insight into the physics and chemistry that influence fire spread. However, these models are computationally expensive and are generally constrained to 1 to 2 m^3 grid cells for landscape-scale simulations, oversimplifying the combustion process. Additionally, CFD models are restricted by inadequate knowledge regarding solid fuel physical properties (e.g. heat capacity) and surface reactions [15].

This paper describes a semi-empirical, multi-leaf shrub combustion model was developed to fill the gap between current operational models and CFD models. This model is based on individual leaf sample combustion behavior measured with a flat-flame burner [16, 17]. Flames are simulated using equations based on individual leaf properties and combustion behavior; fire spread is accomplished via flame-fuel overlap. This model is computationally efficient while maintaining the essential components of fire spread models [15]. The current model has several fuel models but has only been validated for manzanita.

2. Experimental Methods

Shrub Combustion Experiment

Multi-shrub combustion experiments were performed in the wind tunnel (see Figure 1) at the USDA Forest Service Pacific Southwest Research Station in Riverside, CA. The fuel bed was designed to contain two shrubs in their natural arrangements (nominally 2m long x 1m wide x 1m high). A 200-g, triangular shaped bed of excelsior placed just upwind of the first shrub was used as the ignition source. The shrub closest to the excelsior bed was used as an ignition shrub and the fire was allowed to propagate to the second shrub, with the goal of measuring fire behavior without the influence of the excelsior bed. Continuous mass data were collected using a Sartorius CPA34001s mass balance (< 2 s response time, 0.1 g resolution). Fuel surface temperature was measured using a FLIR A20M infrared camera; gas temperature was measured using K-type thermocouples spaced throughout the fuel bed. Radiative and total heat flux downwind of the fuel bed was measured using a Hukseflux SBG01-200 heat flux sensor. The terminal end diameter of burned branches was measured as an indicator of fire intensity. The wind tunnel is open-roofed with doors on both sides. The doors on one side were open for video camera and FLIR camera recording. Shrub fuels were collected in the mountains near Riverside, CA.

Fuel density was varied between high and low values to explore the effect of local and overall fuel density on fire spread. Moisture content was also varied between high and low values by performing a set of experiments immediately after fuel collection and again after allowing the fuel to dry for approximately 48 hours in ambient air or one hour in a drying oven at 95 °C. Combustion characteristics and time-dependent fire behavior were measured using three digital camcorders at different locations around the fuel bed. For example, flame angle, fire propagation path, time to burnout and flame length were determined by processing the video image frames by a MATLAB code routine developed. Wind speed was held constant at 1.4 m/s. Ambient temperature and relative humidity were recorded before each experiment. The effect of understory fuel was also explored in some experiments.

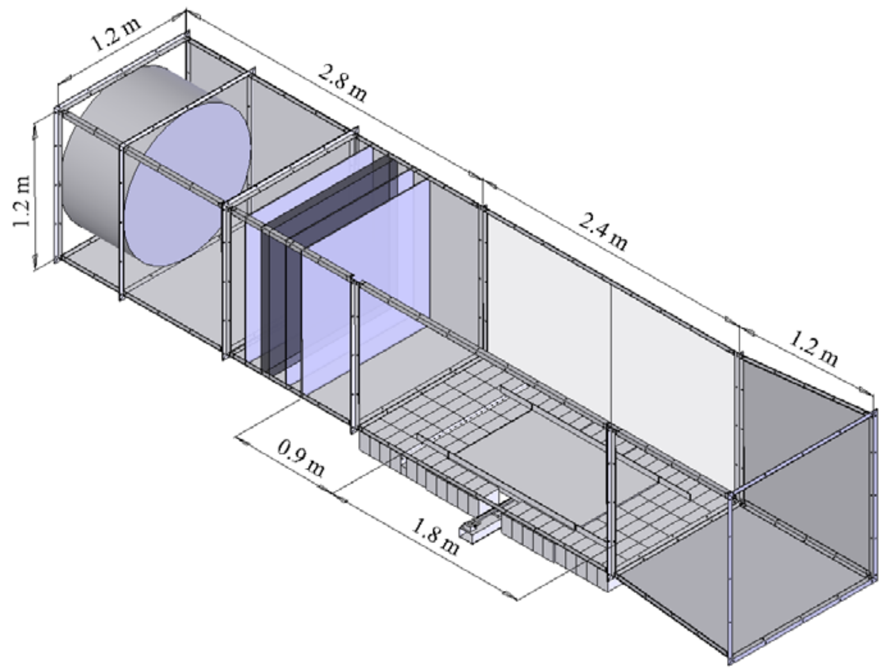

Figure 1: Schematic illustration of the wind tunnel at the Pacific Southwest Research Station of Forest service in Riverside, CA [18]

Individual Leaf Combustion Experiment

Individual live fuel sample combustion experiments were conducted for various species on a flat-flame burner (FFB) system [15, 16, 19-24]. The FFB has a porous surface and produces a 1 mm thin premixed flame (CH_4, H_2 and air). A glass cage surrounding the FFB prevents entrainment of ambient air. The fuel samples were placed 5 cm above the burner surface and ignited by the post-flame convective gases (1000°C, 10mol% O_2). Moisture content and geometric dimensions of each fuel sample were measured. The sample is held above the burner by a holding rod connected to a Mettler Toledo XS204 Cantilever mass balance; mass data are continuously measured using National Instruments Labview 8.6 Software. A K-type thermocouple (0.013 mm diameter, 0.05 s response time) was used to measure the gas temperature. Leaf sample combustion from ignition to burnout was recorded by a video camera. Combustion characteristics (e.g. flame height and time to ignition) were determined by image analysis using an automated MATLAB code routine. The results of individual live fuel combustion experiments were used to develop statistical, species-specific correlations for combustion characteristics which describe the single flame growth behavior of each fuel element. These correlations were embedded in the semi-empirical, multi-leaf shrub combustion model.

3. Shrub Combustion Modeling

The semi-empirical multi-leaf shrub combustion model developed at BYU includes following sections: fuel element locations, fuel element physical properties, fuel element combustion behavior, individual flame volume simulation and flame merging submodel. Pickett [16] developed the first-generation of this shrub combustion model in two dimensions for Manzanita shrubs. The flame merging was based on the two-leaf combustion experiments by Pickett [16] and was treated as the expansion of each individual flame height when two flames overlapped.

An individual leaf is ignited, and the flame height and flame angle is calculated from correlations developed from observations of burning individual leaves. As a neighboring leaf is contacted by a flame, the ignition sequence for that leaf commences, and that leaf ignites. The flames then merge and contact surrounding leaves until burnout occurs. The shrub combustion model was extended to three dimensions and improved through consideration of flame coalescence and wind effects on flame angle and size [25, 26]. Shen [21] expanded fuel types and modified the individual flame volume simulation method to be capable of handling larger fuel sample flame. More species-specific shapes of fuel element placement were also developed.

Figure 2 is an example of a manzanita shrub from the southern California and the associated model shrub constructed using an image recognition method. Fuel element detail properties, including total dry mass and number of stems, were determined by empirical correlations developed from either literature data or measurements in the field. Prince [15] initiated an image recognition method to place the fuel elements. Fuel element placement was random within the project outline of the shrub. Prince also upgraded the flame interaction submodel to include semi-empirical correlations (shown in Equations 1-3) based on 2D flame merging experimental results reported in the literature. However, he considered both horizontal and vertical separation between leaf flames in three dimensions to approximate the merging flame height in shrub combustion model.

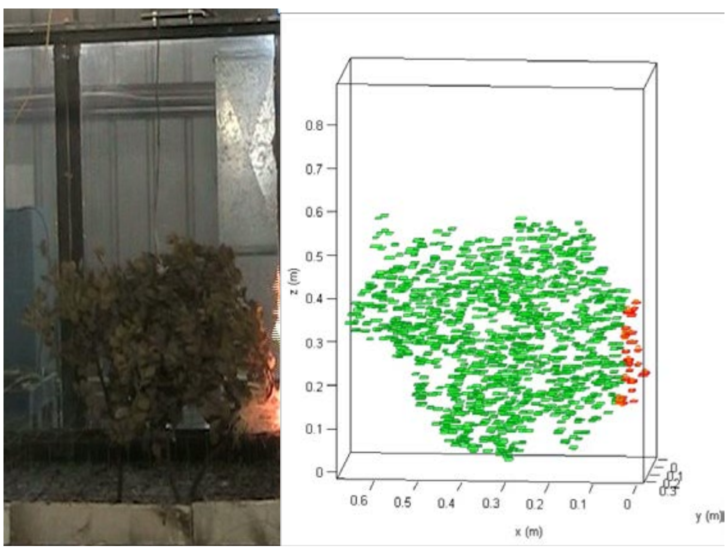

Figure 2: Comparison of (a) picture of a manzanita shrub and (b) manzanita shrub simulated.

$$\left(\frac{L_m}{L_1}\right)_{N_2} - \left(\frac{L_m}{L_1}\right)_{N_1} = c_1 \ln\left(\frac{N_2}{N_1}\right) \tag{1}$$

$$\hat{S}_{i,j} = \sqrt{\left(\frac{s_{i,j}}{r_{f,i}+r_{f,j}}\right)^2 + \left(\frac{z_i - z_j}{L_{f,j}}\right)^2} \tag{2}$$

$$\frac{L_{f,i}}{L_{1,i}} = \left(\frac{v}{v_0}\right)^{c_3} \sum_{j=2}^{N^*} \left(\frac{c_1 \ln\left(\frac{j}{j-1}\right)}{1+c_2 \hat{S}_{i,j}}\right) + 1 \tag{3}$$

In Equations 1-3, N_1, N_2 are number of fuel sources in two groups of flames; i,j are two different leaves (fuel sources); $\hat{S}_{i,j}$ is the dimensionless separation distance; r denotes radius of leaf; and c_1, c_2 are coefficients obtained via literature data.

Prince [15] established a physics-based submodel for scaling flame parameters. This submodel provided a mechanistic description of heat transfer to the leaf surface, tracked the temperature-dependent mass release and held the energy balance of the leaf. A multi-component one-step devolatilization model was used to compute the mass release of the dry matter components from the manzanita leaf. Water release was tracked by a diffusion-limited model. The mass transfer were dependent on the leaf temperature as well. Both convection and radiation were used to determine the elevated temperature of leaf. Finally, the heating of a leaf with the moisture evaporation was solved and the temperature history of a leaf was obtained. Based on this physics submodel, flame parameters (end time of mass release, flame height, etc.) were scaled to match the observed fire spread conditions.

4. Results and Discussion

Shrub Combustion Experiments

In total, 45 multi-shrub combustion experiments studying chamise and sagebrush were performed over a two-year period from 2012 to 2014. The experimental results presented here are for sagebrush only. Table 1 shows the average results for 16 experimental runs (2 runs at each condition). In the table, runs that were considered low bulk density are in italics. The average density for no understory experiments was 17.8 kg/m^3 for the high bulk density experiments and 13.3 kg/m^3 for the low bulk density experiments. None of the low density, no understory experiments (four runs) spread successfully. This suggests a spread, no-spread condition corresponding to a critical density. While the local fuel density measurements are still being analyzed, preliminary observations indicate that local fluctuations in fuel density also affected fire spread behavior. These results agree with those published by Parsons [27]. The excelsior understory was meant to approximate grasses and dead fuels found near the base of wildland shrubs and was found to significantly increase flammability. Shrubs burned with an excelsior understory exhibited no "critical density" point, i.e., fire spread successfully in all experiments with an understory.

Table 1: Experimental data for 16 big sagebrush shrub combustion experiments.

Shrub Age (days)	**Understory (Y/N)**	**MC (%)**	**Bulk Density (kg/m^3)**	**Fraction Burned**	**Spread Success (Y/N)**	**Propagation Speed (cm/s)**
4	*N*	*14*	*14.5*	*0.156*	*N*	--
4	N	14	19.1	0.523	Y	1.3
4	*Y*	*10*	*12.1*	*0.701*	*Y*	*2.4*
4	Y	10	16.5	0.574	Y	2.0
1	*N*	*38*	*13.8*	*0.214*	*N*	--
1	N	37	21.0	0.790	Y	1.2
1	*Y*	*52*	*15.1*	*0.532*	*Y*	*2.2*
1	Y	38	15.5	0.594	Y	2.1

Age of the shrub had little effect on burn behavior under these conditions. Propagation speed, defined as the length of the fuel bed divided by the time of active fire spread, showed no difference between 1-day and 4-day shrubs. Propagation speed doubled with the addition of understory fuels, but the speeds themselves were the same between age groups. It is generally accepted that higher moisture content slows fire propagation, but that is not seen here. More work must be done to understand this result.

For analysis purposes, the bush data were divided into four equal, vertical sections and the maximum solid temperature was recorded from each frame for each section, as shown in Figure 3 for a manzanita shrub burned with no wind. Area 1 was the upwind slice of the bush and area 4 was ignited last. Fuel surface temperatures showed a slow temperature rise until immediately before the fire reached the unburned fuel. Based on this, it was concluded that radiative pre-heating accounted for approximately one-third of the temperature rise prior to ignition.

Chamise stems smaller than ¼ inch diameter burned at almost the same rate as the rest of the chamise shrub. In contrast, it was found that sagebrush stems burned more readily and longer than stems in other species (e.g., chamise). Figure 4 is an example of burning big sagebrush stem after the leaf element fuel burnout.

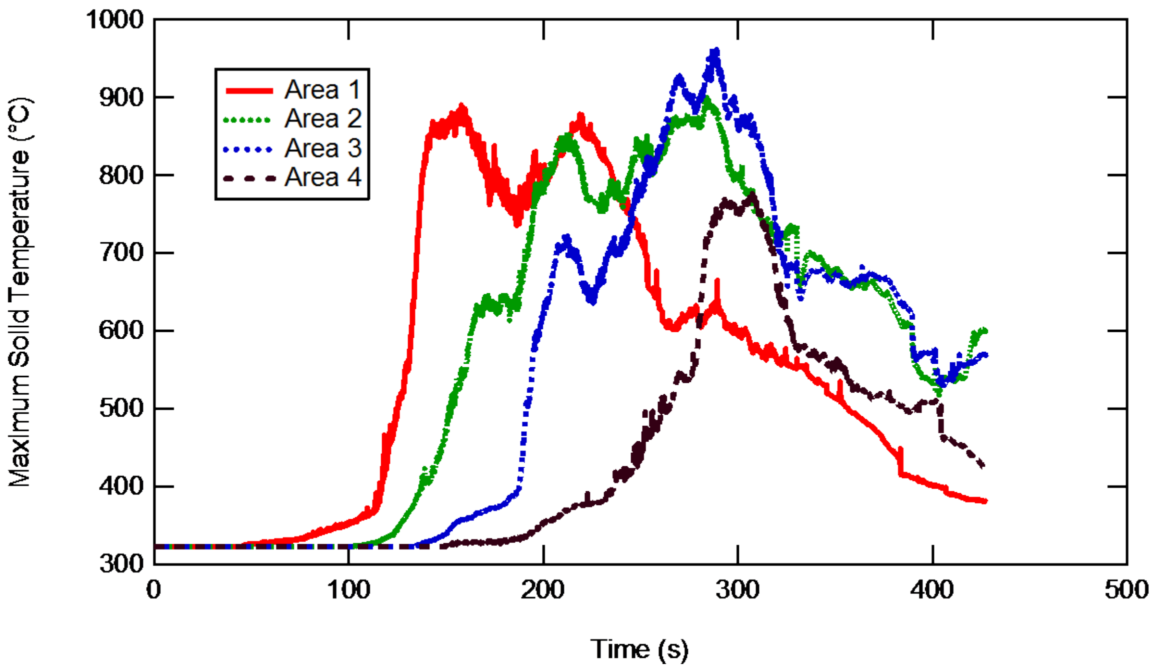

Figure 3: Maximum solid temperature of each area with respect to time for a manzanita shrub combustion experiment with no wind.

Figure 4: Burning big sagebrush stems after the foliage burnout.

Shrub Combustion Modeling

The semi-empirical, multi-leaf shrub combustion model was constructed to model flame propagation through a user-defined manzanita shrub. Species-specific correlations and flame behavior submodels for burning behavior of individual manzanita leaves were incorporated into this model. A few of the flame merging and combustion parameters were tweaked to give good agreement with measured shrub flame behavior [15]. The calculated flame height above the shrub ($\Delta z_{f,max}$), fraction of shrub burnt (X_s), burn time (t_{burn}) as well as flame propagation speed and flame path were all compared with experimental results.

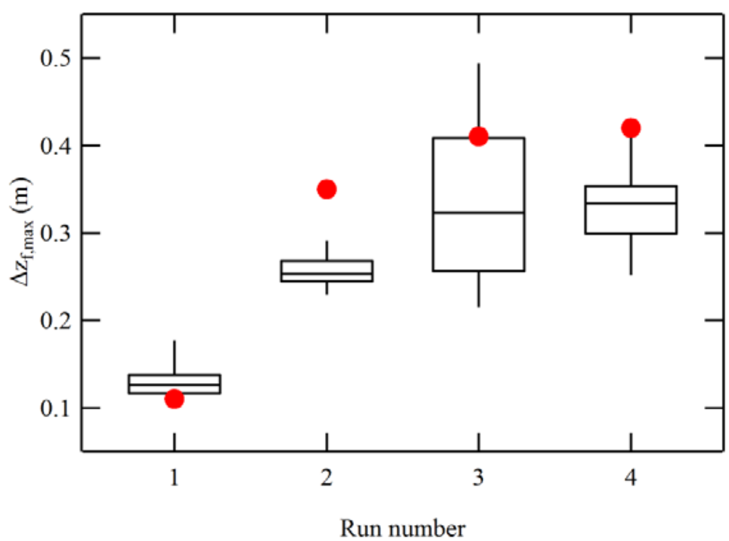

Figure 5: $\Delta z_{f,max}$ comparison of current model (box plots of minimum, first quartile, median, third quartile and maximum) and wind tunnel experiments (dots) [15]

The calculations of $\Delta z_{f,max}$ was underestimated and decreased with increasing wind speed in the previous shrub combustion model [16], which contradicted experimental observations. The predicted burn times also did not match the measurements from the wind tunnel experiment well. The current shrub combustion model managed to match the trend of $\Delta z_{f,max}$ obtained from experiments, as shown in the box plot (Figure 5). The spread in the calculations was due to 30 different realizations with random placement of fuel elements within the project shrub volume. Predicted t_{burn} also agreed with the measured values, which was largely due to the physics-based scaling efforts by Prince [15]. The comparison is shown in Figure 6. Flame merging was improved in the current shrub model by simulating group flames rather than separate individual flames. The flame simulation compared with flame behavior for a manzanita shrub is shown in Figure 7.

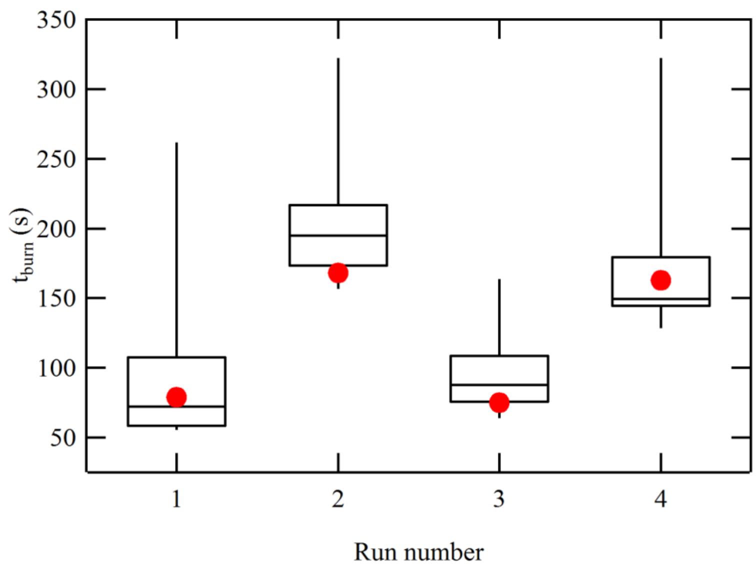

Figure 6: Burn time comparison of model simulations (box plots of minimum, first quartile, median, third quartile and maximum) and wind tunnel experiments (dots) [15]

5. Future Work

Fuel element placement was found to be critical to this model. Methods to better incorporate image recognition for fuel placement are being explored. Models for chamise and sagebrush are currently being developed as well. The image recognition will be combined with an L-systems fractal theory approach for chamise [28].

6. Conclusions

Multi-shrub combustion experiments were performed in a wind tunnel facility at the Pacific Southwest Research Station in Riverside, CA. Bulk density and local fuel density were found to be two major factors in shrub flame propagation. Shrubs with high moisture content were usually observed to burn slower. Infrared observations of solid temperatures ahead of the flame front indicated that radiation heat transfer contributed about one-third of the temperature rise for pre-heating the fuel element prior to ignition. Calculated shrub flame propagation behavior agreed well with observed flame height, flame tilt, flame path, and extent of burnout. More accurate 3D fuel placement development is currently in progress. Furthermore, a better flame merging submodel is being developed based on 3D flame merging experiments and correlations.

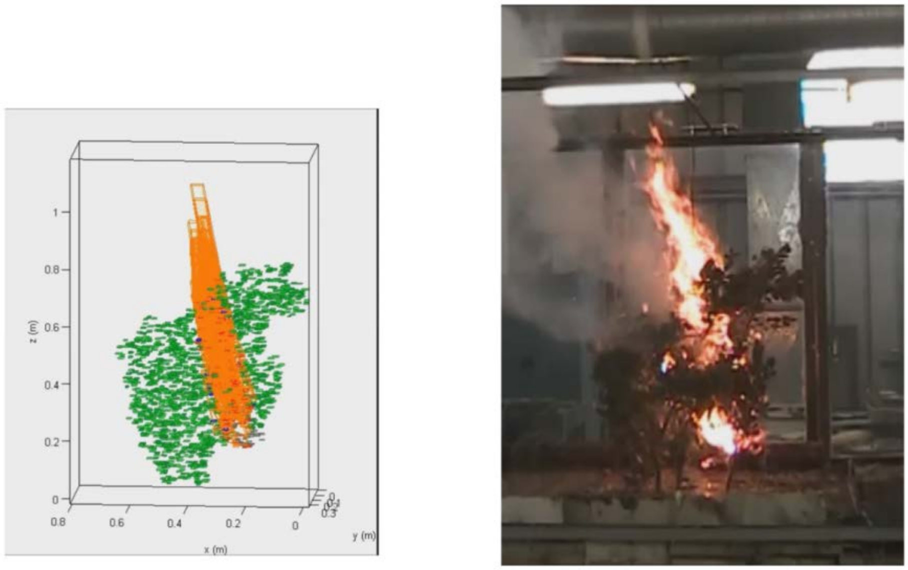

Figure 7: Comparison of predicted flame behavior in a manzanita shrub (left) using the semi-empirical shrub combustion model vs. the measured flame behavior in a wind tunnel

7. Acknowledgements

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