Project Title: Deriving fundamental statistical shrub fuel models by laser scanning and combustion experimentation

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1. Abstract:

We exploited the measurement capacity of a terrestrial laser scanner to precisely characterize shrub fuel matrices in a laboratory setting, to abstract fuel elements for fire behavior modeling, and to identify strengths and limitations of TLS for these purposes. Simultaneously, we produced statistical distributions of combustion parameters for individual fuel elements by burning hundreds of individual chamise and sagebrush samples. Finally, we imaged and burned whole-shrub fuel beds in a wind-tunnel and used measurements from these experiments to further develop and validate a semi-empirical shrub model. The project was based on the principle that developing dynamic fuel models for shrub lands requires tiered experiments starting with burning of individual leaves in the laboratory, followed by combustion of whole shrubs in a wind tunnel, and culminating in burning of field plots of representative fuels. This project focused on the latter two elements.

Our experiments showed that TLS-derived 3-D shrub models can be used to detect changes in volume and biomass following combustion across a range of losses on a per shrub basis. Near constant variance across the range of mass losses showed that the TLS can detect changes in the fuel bed effectively even when only parts of the fuel bed are consumed. Although the model did not numerically depict where the loss was occurring in the shrub fuel bed due to data gaps in shrub interiors, ocular assessment of change showed that the TLS correctly identifies the locations of mass loss. The primary shortcoming of shrub geometries obtained from TLS is the shadowing that occurs interior of shrub hulls. We explored statistical methods for filling in these voids and developed L-systems fractal models for chamise and sagebrush from geometric measurements of actual shrubs to predict the locations of fuel elements.

LiDAR scan data were used as evidence to represent the local fuel density, which were combined with L-systems fractal theory during the fuel placement development in the semi-empirical shrub combustion model. The LiDAR scan data guided the L-systems approach by pointing the shrub branches to the highest possible density position, which resulted in a better combustion modeling outcome when compared to the shrub constructed by L-systems approach only. This result emphasizes the need to accurately describe fuel placement in shrubs when modeling combustion behavior. Calculated flame heights above the shrub, fraction of shrub burned, burn time, and flame propagation speed and flame path were all compared with experimental results. The modeling results suggested that the combustion behavior predicted was too intense compared to the wind tunnel experiments. One of the reasons that the simulations predicted higher combustion intensity was that individual fuel element experiments were conducted at a higher gas temperature than the local combustion zone temperature in the wind tunnel shrub experiments. Methods to correct for the effect of local temperature are currently underway.

2. Background and Purpose:

Rothermel's (1972) semi-empirical equations remain the basis for fire behavior prediction in the US through a suite of model platforms developed over the past 20 years (Finney, 2004; Heinsch & Andrews, 2010). Although constrained by the characteristics of the experiments from which they were derived, the equations continue to serve wildfire operations due to their rapid application and ease of use. Limitations inherent to experimentally-derived fire behavior prediction systems have led to development of alternative models free of empiricism. Researchers have incorporated fundamental laws of heat transfer in lieu of experimentally-derived fire behavior in these prediction systems (Albini, 1985; Weber, 1991; Mell, et al., 2007). These so-called physics-based models are beginning to prove useful in the study of fire propagation in critically important environments such as the wildland urban interface, fuel treatments, and insect-attacked timber stands (Mell, et al., 2009; Hoffman, et al., 2012).

However, application of computational fluid dynamics models remains constrained in several ways. For example, the spatial heterogeneity of fuels has been shown to strongly influence fire behavior in these model environments (Parsons, et al., 2011), and lack of knowledge about fuels variability is now limiting advancement of the models. Further, the inherent downfall of fully physical models remains the vast amount of computational power and time necessary to model a fire environment, making them useful in research but rarely beneficial for timely, on-the-ground model projections (Mell, 2013). Consequently, fire modelers are attempting to validate these models on smaller domains (sub-grids) such as individual shrubs and are combining physics-based simulations with observational data (Fletcher et al. 2007) with the goal of developing computational short-cuts intended to speed up modeling on larger grids.

Considerable effort has been expended in pursuit of the latter approaches through measurement of combustion characteristics of individual fuel elements that make up a plant structure (Fletcher, et al., 2007; Pickett, et al., 2009). By incorporating fire behavior measurements from individual leaves, researchers have produced hybrid empirical-physics based models that simulate propagation of flames from one fuel element to another at leaf scale (Pickett, et al., 2010). These modelers have typically described the spatial characteristics of fuel elements by randomly distributing individual leaves within volumetric arrays roughly the size of an individual plant (Prince, 2014; Shen et al. 2015). The method of describing an entire plant from statistical distributions of leaves requires each fuel element to retain combustion characteristics derived from empirical probability density functions (Prince, 2014). While current multi-leaf combustion models are beneficial for understanding combustion interaction and heat transfer, the generation of whole shrubs in a model environment currently lacks a basis in the actual geometry of real shrubs.

The motivation for our research, then, stemmed from the need to improve characterization of fuel models for fire behavior simulations and to develop shrub fire models that consider spatial heterogeneity of fuel elements. Precise 3-D models of fuels form the basis for accurate, replicable inputs to a variety of models, yet the state of science for fuel models is statistical distributions of fuel elements within simple volumes such as cubes and spheres. Terrestrial Laser Scanning (TLS) provides a source of data for spatially representing fuels more precisely, yet application of the technology to this problem is limited. For shrubs common to fire-prone Mediterranean and high-desert environments of the western US, treating discrete fuel elements presents additional complications for fire and fuel modelers.

In this project, we developed methods to represent shrub fuel matrices of chamise (*Adenostoma fasciculatum* Hook. & Arn.) and sagebrush (*Artemisia tridentata* Nutt.) in 3-dimensions using laser scanning, then simulated fire propagation through the shrubs, and validated simulations against measurements of shrub fires in a burn chamber. Developing models of shrub fuels as the basis for accurate and replicable inputs to a variety sub-grid models used in physic-based fire spread simulations is a vital step in producing more computationally efficient, widely applicable fire models for shrub fuels. By creating inputs to sub-grid models from laser point clouds and testing them against measurements of actual fire behavior, the project aimed to describe the complexity of shrub fuel beds for fire behavior modeling and provide scale integration from leaf to shrub.

Our research approach was five-fold: 1) to make multiple leaf-scale measurements of fire behavior; 2) to map ‘leaves’ (fuel elements) in 3-D using TLS; 3) to simulate fire behavior in TLS-derived shrubs; 4) to combust TLS-imaged fuel beds in a wind-tunnel under controlled conditions; and 5) to compare and refine fire behavior simulations with actual measurements of fire from the laboratory combustion experiments. Along the way, we developed alternative ways to build fuel models (fractals) and tested the influence of fuels variability on fire behavior as depicted by TLS, fractals, and statistical distributions of leaves.

3. Study Description and Location:

This study progressed in four overlapping phases: 1) laser scanning of foliage elements, clumps, and shrubs in controlled laboratory experiments at University of Montana; 2) combustion experiments using individual fuel elements in a flat-flame burner at Brigham Young University; 3) experimental burns in a wind tunnel at PSW Fire Sciences Lab in Riverside, CA; and 4) integration of 3-D fuel models and a semi-empirical shrub fire model.

3.1 Materials:

The study focused on two western USA shrub species. Chamise (*Adenostoma fasciculatum*) and sagebrush (*Artemisia tridentata*) are both prevalent species in areas where wildfires commonly occur. During critical fire weather conditions, both shrub types can produce flame lengths of greater than 20 feet, thereby placing fire activity above the threshold of standard suppression efforts (NWCG, 2006; Missoula Fire Sciences Laboratory, 2011). The widespread occurrence of these fuels adjacent to populated areas in southern California and the Great Basin make them the subject of much interest in the fire community.

The collection site for chamise was located on the North Mountain Experimental Area, a BLM-administered land reserved for fire research, at 33.84° N by 116.88° W with elevation ranging from 3600-3900 feet ASL. Samples were subject to a typical Mediterranean climate pattern of cool, wet winters with hot and dry summers. Collection of sagebrush samples occurred on the San Bernardino National Forest at 34.28° N by 116.78° W elevation ranging from 6900-7200 feet ASL. Neighboring species were typical of a high-desert ecotype with pinyon pine (*Pinus edulis*) and California juniper (*Juniperus californica*). Ground species were sparse, but small patches of annual grasses were found growing in the microclimates located under and around shrub specimens. The climate on the site is typical of high elevation, Mojave desert, receiving little rainfall with moderate winters and hot summers.

3.2 Laser Scanning

The instrument used was an Optech Intelligent Laser Ranging and Imaging System (ILRIS™) 36D-HD[1] Terrestrial Laser Scanner (TLS). This scanner uses a class I laser (1535 nm wavelength) and has a range of 3 to 1500 m with 0.17-mrad divergence (17.6 mm spot spacing at 100 m). This instrument allows the user to specify the spot spacing and focus distance for each scan. For each scan throughout this research, spot spacing was held at 1.0mm with a focus distance specified as the range from the instrument head to the target of the scan. Four experiments were conducted to develop a methodology for application of TLS to shrub fuel modeling. They were: 1) assess the occurrence of geometric error in TLS point clouds and describe its causes; 2) quantify the range effect on laser intensity at short scan distances; 3) relate discrete fuel elements (‘leaves’) to laser response; and 4) test the effects of rotational geometry on laser intensity and density. The results from these experiments were used to inform the methods for scanning whole shrub fuel beds in a wind tunnel. For whole shrub experiments, the TLS was placed at 4 meters range from the leading edge of the fuel bed and was set at a height of 1.4 m above the ground, approximately equivalent height to the middle of each shrub. Scan locations were marked with tape on the floor of the wind tunnel facility and the scanner was fixed on the tripod for the duration of the experiments to ensure nearly identical geometry between scans. Focus distance for the collected data was set at 4.0 m and the spot spacing was held at 1.0 mm. Fifty-eight 3-D fuel bed models were produced from opposing pairs of laser scans. Half of these were pre-burn scans and half were post-burn scans. Scan pairs were stitched together and extraneous reflections from objects around the shrubs were removed. The scans were stitched together using highly reflective control points placed around the fuel bed for this purpose. For each fuel bed, volume elements (voxels) were created by establishing a volume grid around the shrub structure and filling each voxel with information from the point cloud, (e.g., average intensity and number of points). The voxel dimension was 8 cm^3, or 2x2x2 cm. The voxel dimensions corresponded with the size of the fuel elements used for combustion experimentation in the flat-flame burner facility of collaborators at BYU.

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[1] The use of trade or firm names in this publication is for reader information and does not imply an endorsement by the U.S. Department of Agriculture of any product or service.

3.3 Flat-flame Burner Combustion and Measurement Apparatus

Components of our experimental apparatus to collect combustion data include a mass balance, a Sony Handcam video camera[1], a FLIR A20M IR camera, a flat-flame burner on a moveable cart, and a square duct with fan and honeycomb mesh. Fuel samples are suspended horizontally in the air by attaching to a horizontal rod that connects to the mass balance. The flat-flame burner is positioned on a cart pulled by a motor and pulley to simulate an advancing fire. The distance between the burner (in its stationary position) and a fuel sample is typically 5 cm. The fuel for the flat-flame burner is natural gas and hydrogen. Techniques have been developed to extract measurements of flame properties automatically from video using programs in Matlab®, yielding data such as flame height, tilt angle, and flame duration. The equipment and techniques described here were also used to characterize fire behavior in the wind tunnel experiments.

3.4 Leaf Combustion Experiments

Physical and combustion characteristics of individual fuel elements were measured. Measured physical characteristics were width (w, in cm), length (l, in cm) and thickness (Δx, in mm). Measured combustion characteristics were (a) time to ignition (t_{ig}, the time between when the FFB stops under the leaf and when the first visible flame occurs, in s), (b) time to maximum flame height (t_h, time between ignition and maximum flame height, in s), (c) time of flame duration (t_{fd}, time between ignition and burnout, in seconds (s), (d) maximum flame height ($h_{f,max}$, in cm), and (e) flame tilt angle (θ), the angle that a flame deviates from its otherwise vertical position, in degrees).

3.5 Bush Model

The Bush Model models shrub geometry and the propagation of fire through the shrub (Prince, 2014). Flame propagation occurs by direct flame contact with an adjacent particle (leaf or fuel segment) for the pre-ignition time specified through experiments. Particle combustion characteristics are based on data from the experiments described above. The fuel combustion characterization provides a framework that can accommodate inconsistent, discontinuous, heterogeneous, and even multi-layer fuel complexes. The shrub structure is defined by the unique locations and properties of the fuel elements. The physical description of each fuel element is based on the mean and standard deviation determined from the measurements made during experiments. Flame parameters are based on correlations based on the physical properties of each fuel element. Wind speed (U, in m/s) and moisture content (MC) are included in the correlations, providing some response to the local environment.

3.6 L-Systems Fractal Models

L-systems fractal models of live chamise and sagebrush were developed from geometric measurements of shrubs (Figure 1). In these models, crown diameter was specified, target mass was used to determine the number of primary branches, branch angles and starting locations were set, branch geometry was determined by L-systems, and fuel parameters were specified (Prince et al. 2014). The result was a realistic shrub that fit within specified dimensions and was composed of spatially-explicit fuel elements with empirically-derived fuel characteristics.

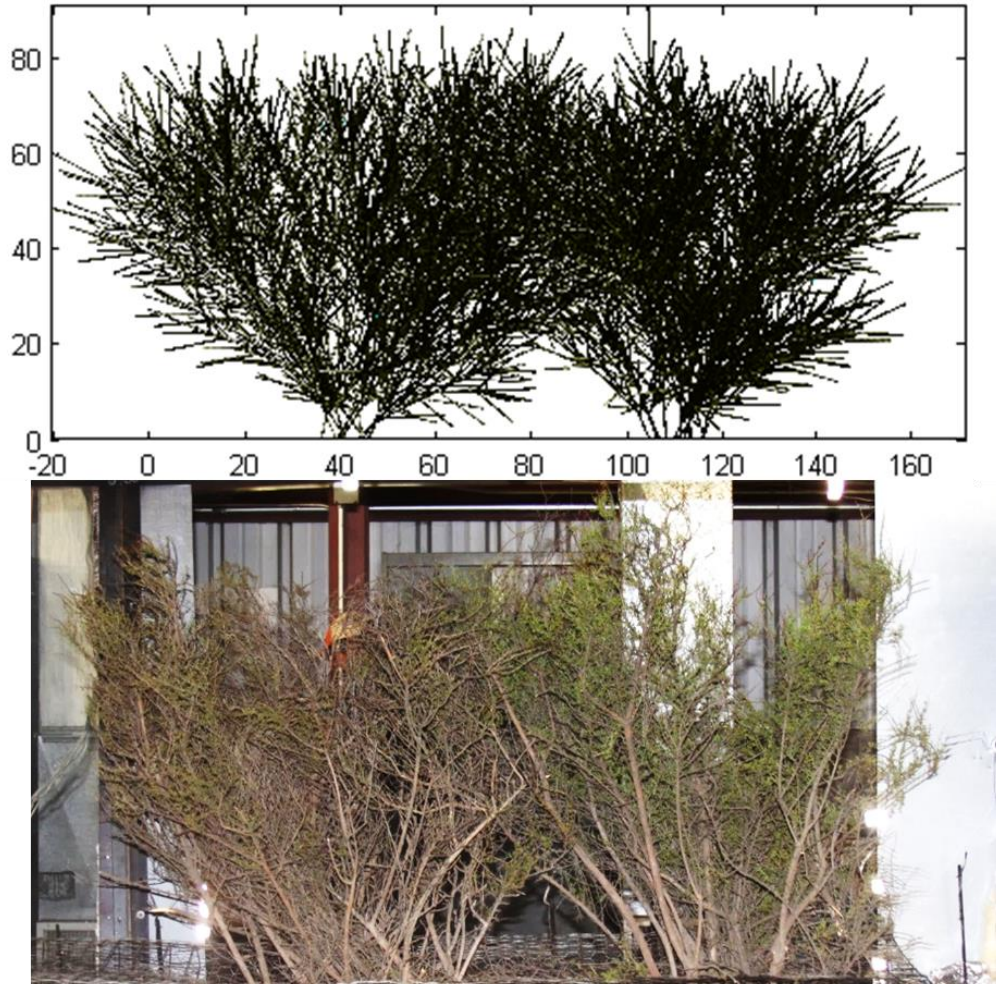

Figure 1. L-systems fractal model of chamise fuelbed (top). Actual fuel bed (bottom).

3.7 Wind Tunnel Experiments

In total, 55 multi-shrub combustion experiments studying chamise and sagebrush were performed from 2012 to 2015 (Figure 2 for example). Fuelbeds were placed on a scale for mass measurement before, during, and after combustion. Our fuel beds were limited to 2 m lengths to avoid shadowing caused by the structure of the tunnel. A mesh was created using Jackson fencing and chicken wire where stems of samples could be placed and held stationary during scanning and burning. Samples were assembled in the wind tunnel to create a variety of different burning conditions. The density of biomass in each replication was constructed to represent a range of fire behavior, rather than to re-create natural shrub structures explicitly. The mass and density of shrubs was varied from run to run in order to simulate high and low fuel load conditions. Chamise shrubs were conditioned for fuel moisture in a drying oven prior to some runs. For sagebrush, half of the runs utilized a homogenous excelsior fuel bed beneath the sagebrush, and total sagebrush mass/density was varied from high to low from run to run. Fuel moistures were from ambient conditions, ranging from 60-85 percent, which is on the dry end of field-observed live fuel moisture for the shrub.

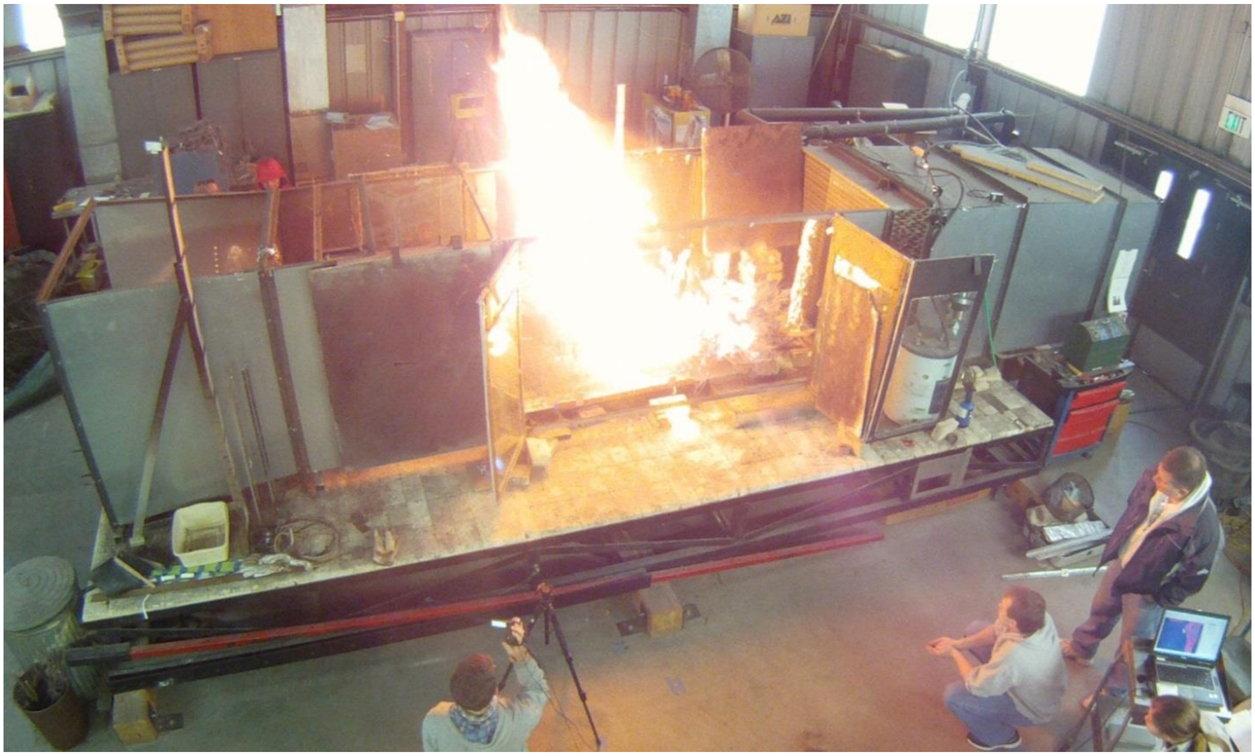

Figure 2. Shrub combustion experiment (chamise) in Riverside Fire Lab wind tunnel.Flaming area is approximately 2 meters long

3.8 Bush Model Refinement and Validation

Fire spread in live shrubs (chamise and big sagebrush) was measured in a wind tunnel and used to validate a semi-empirical shrub combustion model. 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). Shrub geometry dimensions were measured manually or determined from images. LiDAR scanning was also performed in most experiments to establish a 3-D voxel data matrix for potential fuel placement. Wind speed was held constant at 1.4 m/s while fuel density and moisture content varied across natural levels. 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 experiments, the terminal end diameter of burned branches was measured as an indicator of fire intensity.

4. Key Findings

4.1 Geometric Artifacts of Laser Scanning at Close Range

4.1.1 Haloing

The 'halo' effect, occurs when the laser footprint partially intersects the edge of an object. The result is the filling in of gaps smaller than the diameter of the laser footprint and the creation of halos around objects (Figure 3). Although the laser scanner correctly identifies the occurrence of matter within its footprints, it translates that occurrence to the center of each footprint and thus represents objects as slightly larger than they actually are. The halo phenomenon is very consistent, occurring in every scan. It can be mitigated by removing low intensity values from the data sets, but at the cost of also removing returns from small branches. Because the intensity of halo returns is lower than that of returns centered on objects, laser metrics that average intensity by volume are down-weighted relative to fully occupied volumes. The result is canopy gaps within the shrubs that contain low intensity returns.

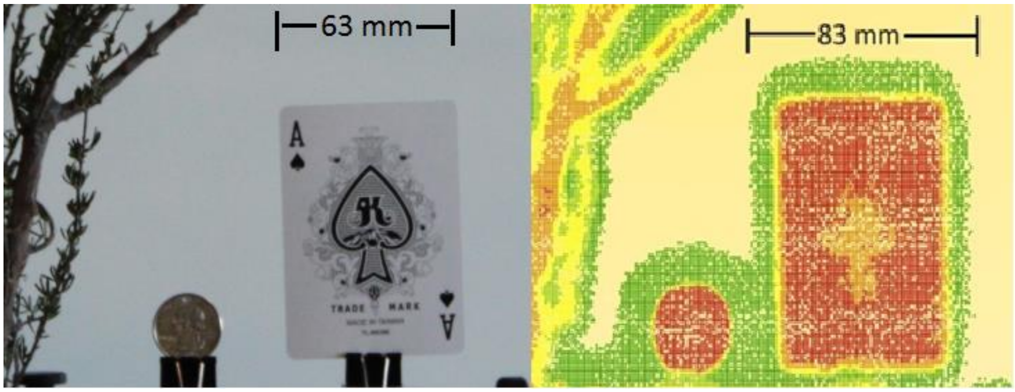

Figure 3. Photograph on left of shrub, US quarter, and playing card; TLS point cloud on right. Green points are 'halo'.

4.1.2 Ghosting

When reflective material occurs at different depths within a single laser footprint, the laser scanner can produce a range error in which target location is erroneously placed in the space between the reflective materials. The result is the apparent presence of material in spaces where none actually occurs. Experiments were performed to quantify the relationship between the occurrence of ghosting and the proximity of diffuse targets to discrete backgrounds. Ghost points comprise a large proportion of total returns when a discrete background is positioned close behind the target. Beyond a distance of 2.5 meters between the target and the background, the number of ghost points becomes negligible. A logarithmic regression applied to the number of ghost points in each scan was significantly related to the range of background to the target at 1-5 m range. Ghosting can be avoided by scanning without a background proximate to the target. For this project, pairs of scans were made of each shrub fuel bed from opposite sides of the wind tunnel with all windows removed to prevent ghosting artifacts.

4.1.3 Shadowing

Laser scans of whole shrubs in the wind tunnel revealed canopy gaps in shrub interiors where laser energy was not able to penetrate the shrub hulls. The depth of laser energy penetration averaged 5.45 ± 2.27 voxels (10.9 ± 4.54 cm) . Interior of this depth is mostly void except in cases where total shrub width was less than ~24 cm. When expressed as a proportion of total width of shrub, the void space ranged from none to more than 75% of the total width (Figure 4). In more than a quarter of the lines sampled, the length of the data was fully described and there were no voxels left unfilled in the model. In about half of the data lines, one third of the shrub was not described. At the least descriptive data line, the filled voxels represented 18% of the length sampled. The statistical distribution that best fit the proportion histogram was a logistic distribution. The resulting logistic model had a location of 0.305 with a scale of 0.156 with corresponding standard errors of 0.027 and 0.012. The Akaike information criterion (AIC) for the model fit was 25.9.

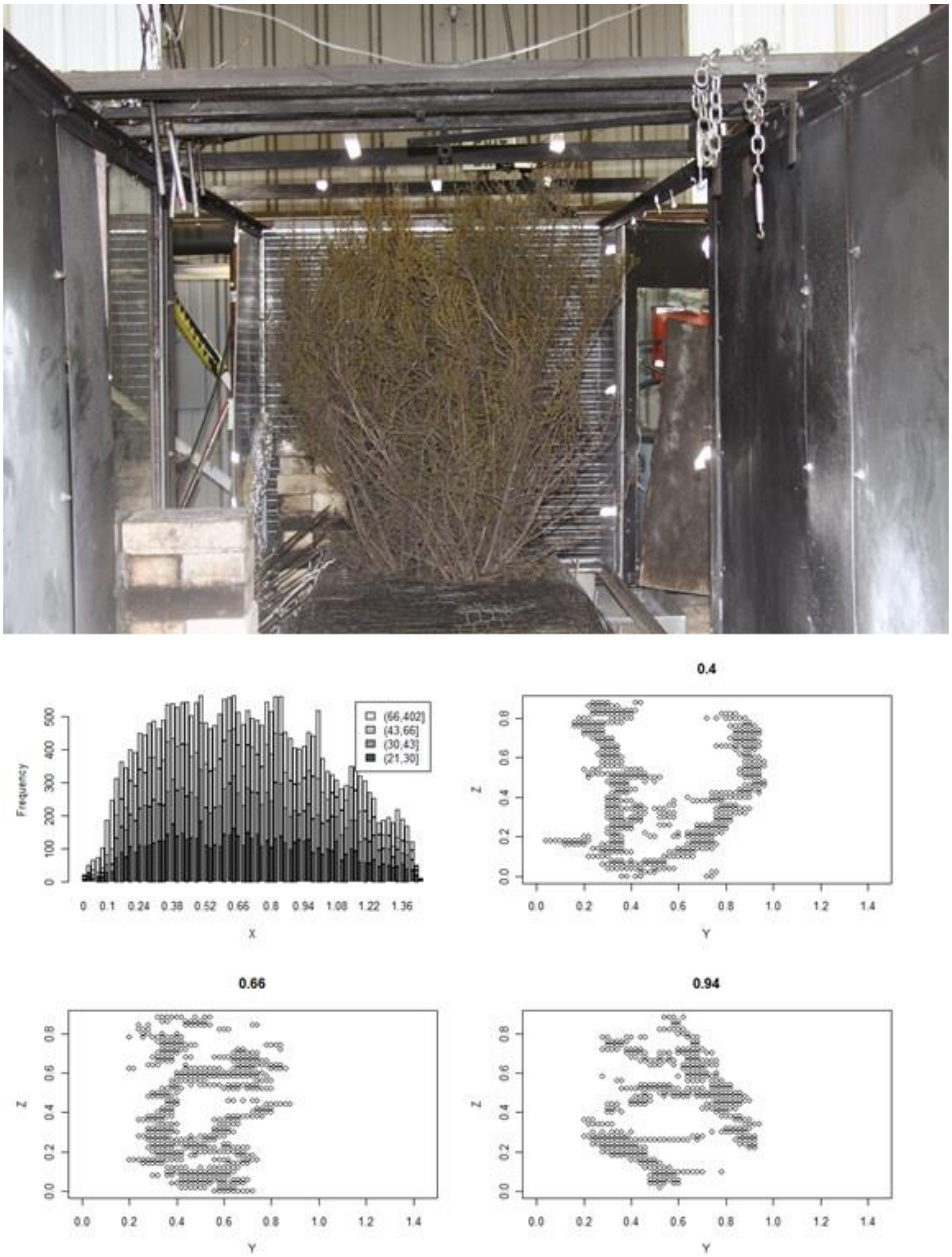

Figure 4. Chamise fuel bed pictured on the z-plane (top). Upper left histogram shows sideview frequency of filled voxels by height. Remaining plots depict cross-sections of fuel bed (side-to-side) at 0.4m, 0.66m, and 0.94m from edge of fuel bed. Note absence of filled voxels in shrub interior (gaps).

4.1.4 TLS Range Correction

A range correction was developed for intensity of laser reflection. This correction was necessary because intensity does not follow an inverse-square distance function at ranges <5 m due to the compressed geometry of the laser, target, and receiver. The relationship between intensity and range was consistent for all sample types, shapes, and sizes. The smallest, most-diffuse fuel samples exhibit the lowest intensities while the larger branches produce brighter reflections. Intensity increases with range out to 5.5 m. A mixed effect linear regression model produced the following equation (slope t-value: 11.9, p-value: <0.001; intercept t-value: 20.1, p-value: <0.001): $I = 7.73(r) + 117.8$, where I is mean intensity and r is range from instrument to sample in meters.

4.1.5 Biophysical Characterization of Fuel Elements Using TLS

Samples of shrub fuels were clipped from branches to span the observed range of variability. Samples were selected systematically from the bottom to the top of the branch, including larger branches (bottom), forks (middle), and terminal ends (top). Each sample was cut to a length of 2 cm so that TLS point clouds would be contained within 2 cm voxels after data collection. Multiple linear regression models were created to examine the ability of laser metrics to predict a biophysical trait of the scanned samples. Independent variables were the laser-derived metrics (point count, average intensity, and sum of intensities). Dependent variables were physical traits of the scanned samples thought to be best interpreted by the laser metrics based on surface area exposed to the laser energy. Those variables were dry weight, diameter of the sample, and diameter factored by branch type (branch, terminal end, fork). The results from regression modeling showed that the laser metrics are each statistically capable of discerning variations in the biophysical traits (P-Values: <2.2 e-16 to 2.63 e-08). The predictive capability of each model varied greatly (Adj. R^2: 0.29 to 0.67), but all showed a positive association between the selected laser metric and associated biophysical trait (Slope: 2.20 e-05 to 0.238). The strongest relationship identified was between average intensity and the natural log of the dry weight (P-value: <2.2 e-16, Adj. R^2: 0.6716) (Table 1; Figure 5).

Table 1. Descriptive statistics and linear regression model parameters from TLS metrics and biophysical traits (Chamise)

Dependent Variable	Independent Variable	Intercept	Slope	RSE	Adj. R^2	P-value
Natural Log of Dry Weight	Point Count	-4.05 ± 0.240	4.17 e-03 ±4.261 e-04	0.872	0.5189	1.07 e-15
Natural Log of Dry Weight	Average Intensity	-9.86 ± 0.598	0.0498 ± 3.70 e-03	0.720	0.6716	<2.2 e-16
Natural Log of Dry Weight	Sum of Intensities	-3.79 ± 1.90 e-06	2.20 e-05 ± 1.96 e-06	0.807	0.588	<2.2 e-16
Diameter	Point Count	0.0447 ± 0.615	6.67 e-03 ± 1.09 e-03	2.23	0.2928	2.63 e-08
Diameter	Average Intensity	-8.70 ± 1.78	0.076 ± 0.011	2.14	0.3483	6.929 e-10
Diameter	Sum of Intensities	0.446 ± 0.508	3.55 e-05 ± 5.24 e-06	2.16	0.3378	1.412 e-09
Diameter, Factored by Type	Point Count	-3.51 ± 1.51	0.0236 ± 2.69 e-03	5.51	0.4627	1.374 e-13
Diameter, Factored by Type	Average Intensity	-29.4 ± 4.74	0.238 ± .0.293	5.70	0.4243	2.882 e-12
Diameter, Factored by Type	Sum of Intensities	-1.86 ± 1.24	1.23 e-04 ± 1.28 e-05	5.26	0.5104	2.314 e-15

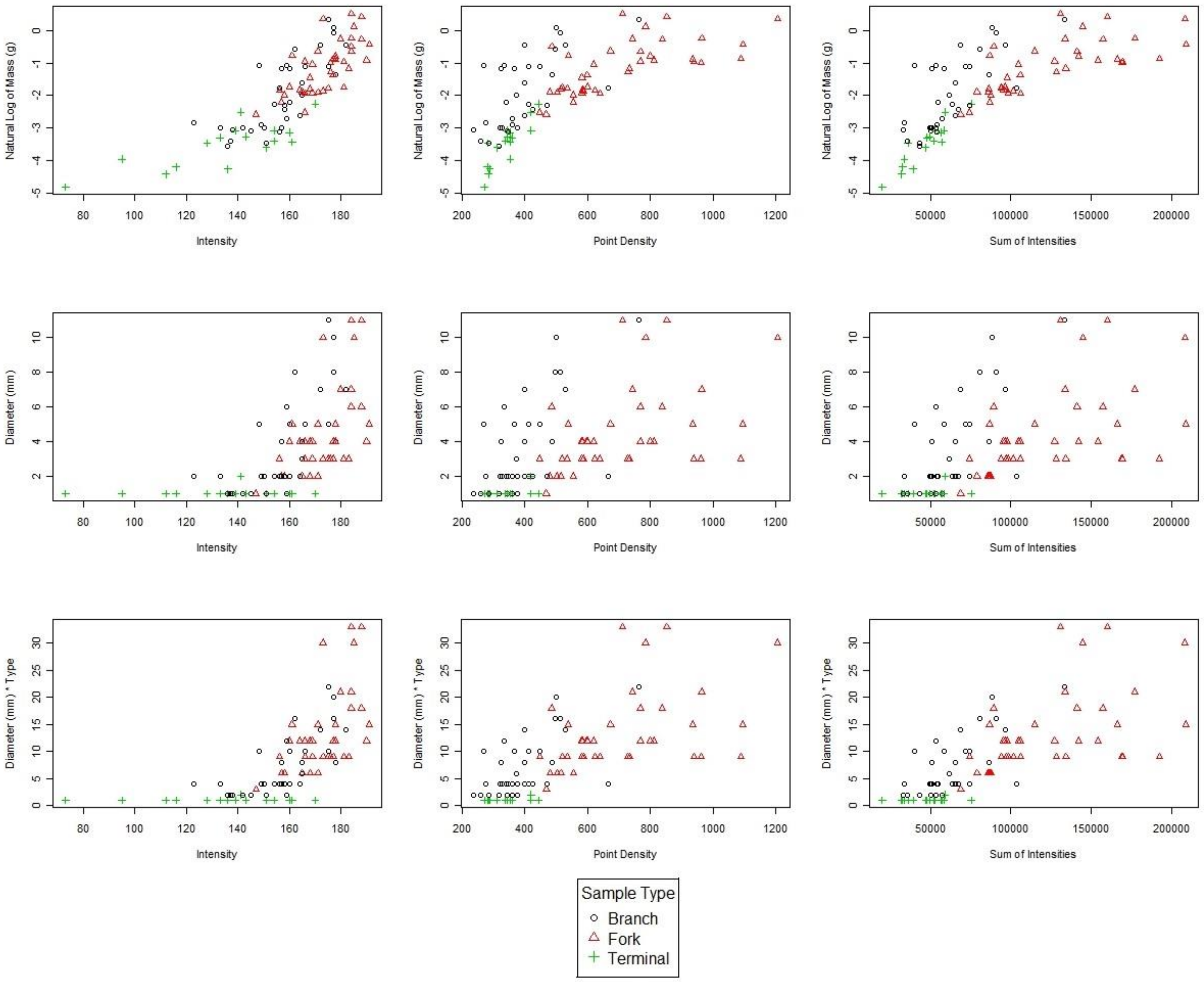

Figure 5. Laser metrics plotted against biophysical characteristics for chamise samples for branches, forks and terminal ends.

4.1.6 Rotation-Effects

The samples and design for this experiment were the same as the biophysical characterization above. Shrub specimens were rotated horizontally at random angles and scanned a second time (n=59). Angles between 0° and 180° were achieved throughout this process and no changes were made to the structure or composition of each sample. Statistical analysis performed on the data was to compare the sum of intensity for each sample to its corresponding twisted value using a linear regression. The sum of intensity was used to account for the entire value of the sample, rather than classifying by point count or intensity alone. Rotation had little effect on laser characterization. The slope of the regression line relating samples viewed from different perspectives was 1.027, very near to a 1:1 relationship. The intercept for the line was -0.002, very close to zero, and the adjusted R^2 was 0.93. We conclude that leaf elements look the same to the laser independent of viewing perspective.

4.2 Individual Leaf Experiments on the Flat Flame Burner

Combustion experiments were performed on chamise and big sagebrush to develop burn correlations for the semi-empirical shrub combustion model developed at BYU. Chamise experiments were performed using nominally 4 cm branch tips with the needles attached as the basic fuel element. The basic sagebrush fuel element used was a 2 cm branch tip with the leaves attached. Fuel element properties were measured prior to burning, including mass, moisture content, relative moisture content, length, and stem diameter. Experiments were performed each month from May 2012 to March 2013 to account for natural variation in fuel element properties. Transient mass, surface temperature and flame data were collected during every run. Flame characteristics were extracted from these data for use in the semi-empirical shrub combustion model, including ignition time, maximum flame height, time to maximum flame height and burn out time. The surface temperature at ignition was extracted from the temperature data obtained by FLIR infrared camera. Both average surface temperature at ignition and maximum surface temperature at ignition were reported because ignition is known to be a local phenomenon (corresponds to maximum temperature) but reported ignition temperature values are often average temperatures.

No statistically significant relationships were found between moisture content and the listed flame and temperature characteristics. However, large changes in flame characteristics throughout the year indicate seasonal changes within the plant have an impact on burning behavior.

Combustion models were developed to predict the flame and temperature characteristics listed above. While no significant correlations were found between the fuel element properties and the burning characteristics, significant multi-parameter models were found that account for much of the variability in the data (average $R^2 > 0.5$). These models can be used in operational fire models like the semi-empirical shrub combustion model to more accurately describe fire spread in live shrub fuels.

4.3 TLS-derived Volume and Mass Loss

TLS-derived 3-D shrub models can be used to detect changes in volume and biomass following combustion across a range of losses on a per shrub basis. Near constant variance across the range of mass losses shows that the TLS can detect changes in the fuelbed effectively even when only parts of the fuel bed are consumed. Although the model does not numerically depict where the loss is occurring in the shrub fuel bed, ocular assessment of change shows that the TLS identifies the locations of mass loss (Figure 6). This is an important consideration for fire modelers wishing to track propagation of fire through the shrubs. The ability to accurately model mass loss using voxel volumes suggests that the application of TLS in diffuse-form shrub may be useful to fire modelers despite shortcomings identified previously (primarily shadowing). The regression also showed a significant difference between mass loss in chamise compared with sage (Figure 8, top). The mass removed during combustion was different between the two species and this was represented in the voxel volumes. The linear regression fit the same slope to both species, showing that the same mass loss to volume loss relationship was significant. However, the different intercepts show that sagebrush volumes are denser and account for more mass loss with less volume than those of chamise.

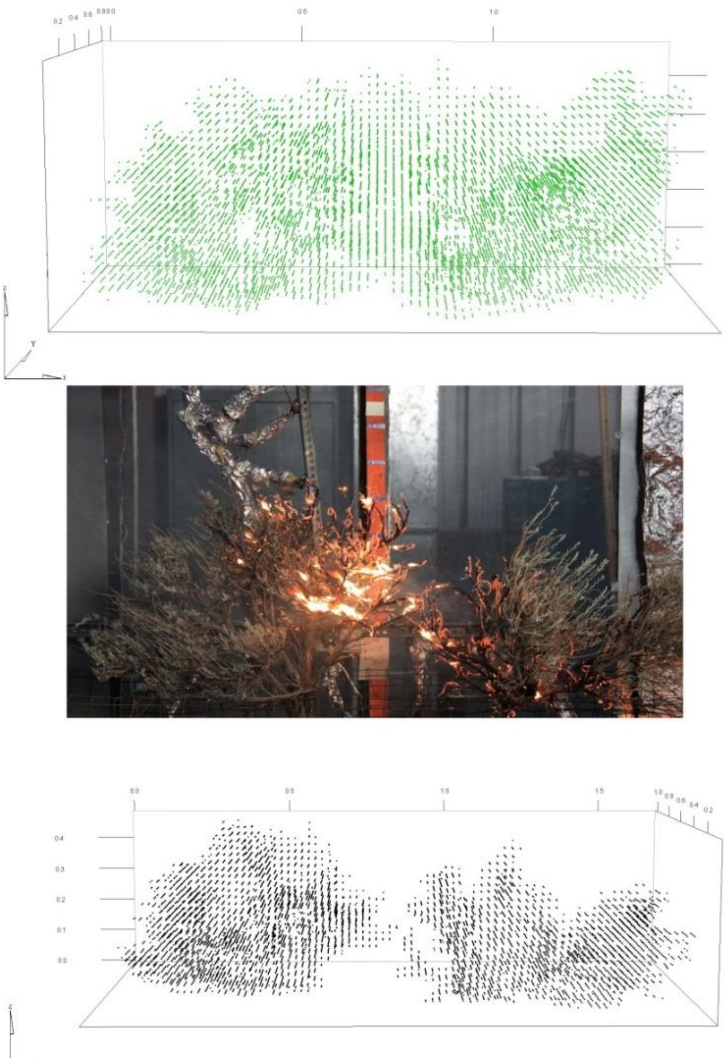

Figure 6. Pre-(top) and post-combustion (bottom) voxel arrays showing removal of fuels. Photo (middle) from near end of combustion process.

4.4 Shrub Combustion in a Wind Tunnel

In total, 55 multi-shrub combustion experiments studying chamise and sagebrush were performed from 2012 to 2015 (Figure 7 shows a typical arrangement of two sagebrush shrubs in the wind tunnel). It was observed that low density shrub arrangement experiments without understory did not spread successfully. This suggests a spread, no-spread condition corresponding to a critical bulk density, which also indicated that local fluctuations in fuel density likely affect fire spread behavior. The excelsior understory was meant to approximate grasses and dead fuels found near the base of wildland shrubs and were found to significantly increase flame spread behavior. Shrubs burned with an excelsior understory exhibited no “critical density” point, i.e., fire spread successfully in all experiments with an understory.

Figure 7. Sagebrush samples placed in the wind tunnel. Wind is from right to left. Horizontal scale is about 2 meters.

The length of time since the shrub was harvested (up to 4 days) had little effect on burn behavior in this experiment. For example, 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-old shrubs. Another observation was that the flame propagation speed almost doubled with the addition of the excelsior understory. A curious result was that the flame propagation did not seem slower for the higher moisture content experiments; more work must be done to understand this result.

It was observed that all chamise stems smaller than ¼ inch diameter burned. In contrast, it was observed that sagebrush stems burned more readily and longer than stems in other species (e.g., chamise). This resulted in the complete combustion of some sagebrush stems larger than ¼ inch diameter. For example, many sagebrush stems were observed to burn for an average of 109 seconds after the leaf material finished burning. A few chamise stems burned an average of 48 seconds after the main flame extinguished.

4.5 Simulated Mass Loss

Following combustion experiments, a test was conducted to determine whether TLS could detect changes in mass associated with removal of different kinds of material (e.g.top down foliage-and-branches, branches-by-size-class, random). This experiment was conducted for chamise only. Its purpose was two-fold: first to examine the sensitivity of volume loss to mass loss of different types of material; second to test whether random removals of material were detectable by laser-measured volume loss. Volume was iteratively removed from six branches, with a TLS scan between each removal. Foliage was removed systematically from top of branch to bottom, randomly, and by size class (smallest pieces first). The TLS tracked mass and volume loss in each case (Figure 8, bottom). Eighty-five percent of the variability of mass is explained by the amount of volume determined from TLS irrespective of the type of removal.

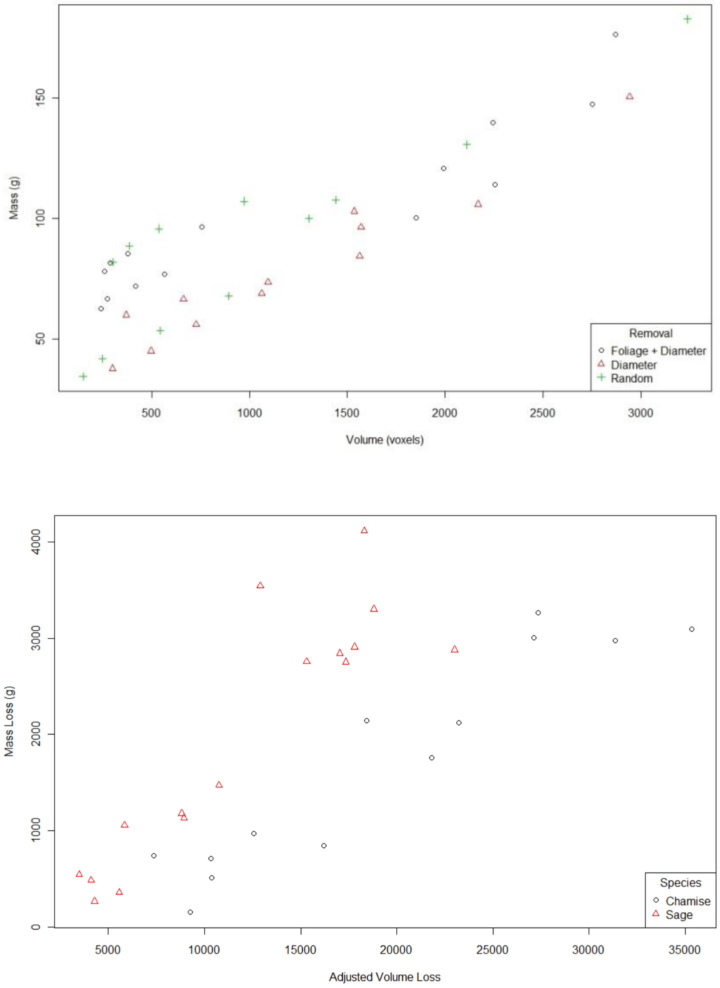

Figure 8. Mass versus volume across a range of manual systematic and random removals from chamise branches (top). Observed mass loss versus volume loss for sagebrush and chamise following combustion (bottom).

4.6 Semi-Empirical Shrub Combustion Model

LiDAR scan data were used as evidence to represent the local fuel density, which were combined with L-systems fractal theory during the fuel placement development in the semi-empirical shrub combustion model. The calculated flame height above the shrub ($\Delta_{zf,max}$), fraction of shrub burned (X_s), burn time (t_{burn}) as well as flame propagation speed and flame path were all compared with experimental results. Figure 9 shows measured and predicted flame behavior for chamise shrubs in the wind tunnel. The initial modeling results suggested that the combustion behavior predicted was too intense compared to the wind tunnel experiments. One of the reasons that the simulations predicted higher combustion intensity was that individual fuel element experiments were conducted at a higher gas temperature than the local combustion zone temperature in the wind tunnel shrub experiments. Methods to correct for the effect of local temperature are currently underway. The LiDAR scan data did not completely resolve the interior of the shrubs, and hence an L-systems approach was used in conjunction with the LiDAR data. The LiDAR scan data guided the L-systems approach by pointing the shrub branches to the highest possible density position, which resulted in a better combustion modeling outcome when compared to the shrub constructed by L-systems approach only. This result emphasizes the need to accurately describe fuel placement in shrubs when modeling combustion behavior.

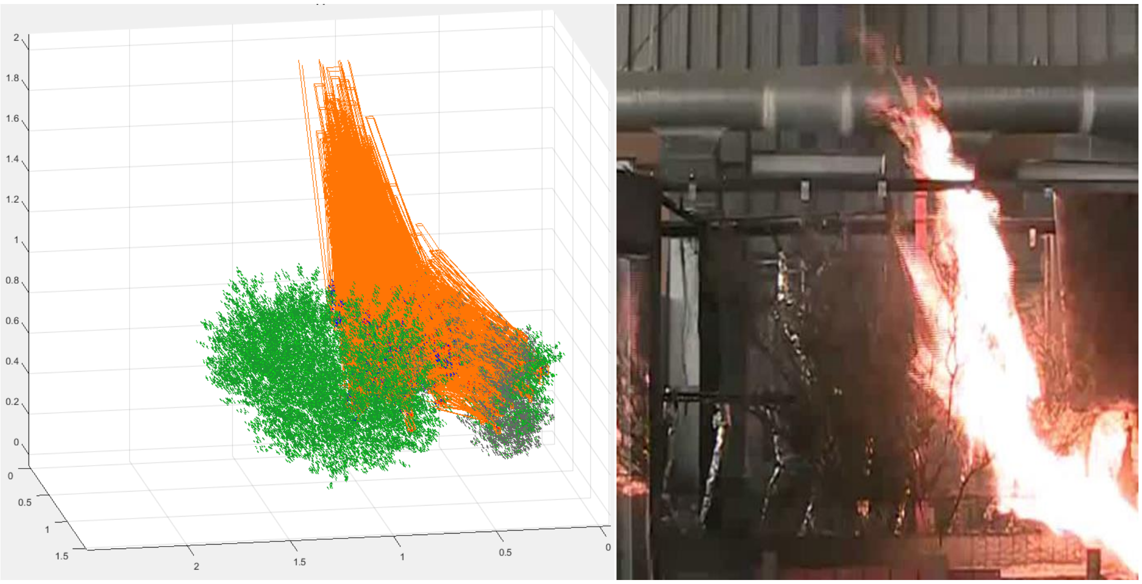

Figure 9. Comparison of predicted flame behavior in chamise shrubs (left) using the semi-empirical shrub combustion model vs. the measured flame behavior in a wind tunnel (right). Figure taken from Shen et al. (2015).

5. Management Implications

The amount of ongoing research focused on better understanding fire behavior and developing new wildland behavior models is unprecedented. Much of this research is basic, with few immediate management implications. Our research falls into this category. The promise of new operational fire models that improve fire forecasting drives this research, which is proceeding on two primary fronts. The first is in developing sound theories of wildfire spread. For example, Finney et al. (2015) have recently shown that fire spread depends on buoyancy produced by the flame zone. Parallel convective vortices force hot gases down into fuel particles resulting in flame-length dependent saw-toothed patterns of flaming edge across many scales. Finney et al.’s (2015) research and work like it feeds into the second research front of incorporating physical processes into models of fire propagation. Several models are being developed and tested that directly handle variability in environmental inputs and that directly provide heat fluxes, winds, and firebrand transport (Linn et al., 2002; Mell et al. 2007; Tachajapong et al. 2008; Morvan et al. 2009). These models depend on heat transfer research to correctly handle heat transport processes.

Limitations to model development remain shortcomings in fire theory along with high computational and data demands and difficulty in model validation. Our shrub model is attempting to resolve some of these limitations by incorporating observations of leaf combustion and flame merging using a semi-empirical approach. Our research is part of a larger body of work that will eventually lead to improvements in operational fire forecasting. How much empiricism will be necessary in future operational models is uncertain at this time. However, we have observed some of the limitations of physical models in this project. For example, simulations of fire spread in our sagebrush fuel models using NIST’s Fire Dynamics Simulator (FDS6) (2-cm grid fuel particles with constant attributes) produced 7 seconds of output in 48 hours of computer run-time using a 100-core processor. Further, the model runs were plagued with numerical instability issues, highlighting the complexity of the models for users. We think it is fair to say that parameterizing the models effectively with fuels data is not intuitive, and only a handful of users currently exist worldwide with the experience necessary to do this effectively. This is not an indictment of the models themselves- rather, it points to the need for continued research across a continuum of modeling approaches (e.g., empirical, rule-based, cellular, semi-empirical, physical) if a long-term goal remains improved operational forecasting tools for managers.

6. Relationship to Other Recent Findings and Ongoing Work on this Topic

6.1 Fractal –TLS Assessment

The primary shortcoming of shrub geometries obtained from TLS is the shadowing that occurs interior of shrub hulls. As noted above, we explored statistical methods for filling in these voids. We also developed L-systems fractal models for chamise and sagebrush from geometric measurements of actual shrubs. A shortcoming of the fractal approach is in constraining shrub models within the dimensions of actual shrubs. In our experiments, the actual shrubs were intended to resemble natural shrubs but their geometries ultimately fell short of ‘natural’. Therefore, it was difficult to reconcile the fractal model to the actual shrubs. We are currently using the TLS data to determine overall shrub shape and primary branch structure in order to inform the fractal models (Figure 10). More specifically, we are using TLS hulls to constrain the outer dimensions of the fractal models and using intensity density to link basal branch nodes to upper points within the shrub structures.

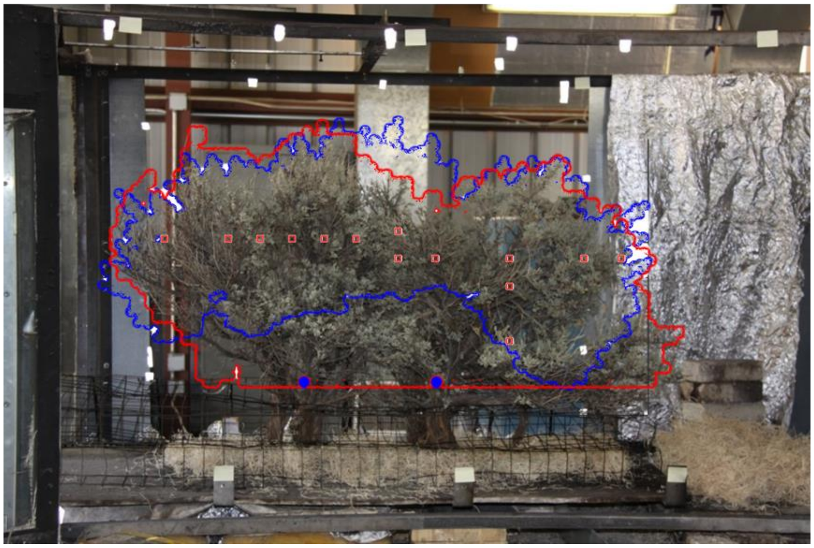
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Figure 10. Red polygon depicts TLS derived sagebrush hull. Red squares indicate branch nodes from laser intensity-density. Blue polygon indicates fitted fractal hull, and blue circles are basal nodes. L-systems fuel mass is within 2.5% of observed mass.

6.2 Flame Merging

Research is ongoing to better understand flame interaction and merging. A lack of fundamental understanding of flame interactions is a limitation to current performance of the Bush Model. We are using various types of fuel sources and arranging multiple flames in three-dimensional geometries to formulate useful flame merging correlations. So far, 2-jet and 3-jet flame experiments have been conducted using a low-speed methane jet and varying horizontal and vertical separation distances. Some preliminary findings are counter-intuitive. For example, when flames are merged at different heights, the lower flame appears to drag the merged flame downward.

6.3 Fire Intensity

There was evidence in the wind tunnel combustion experiments that the flame intensity was related to the bulk density of the fuel. The individual fuel experiments conducted in the FFB facility at BYU were performed at one temperature (1000C), but the temperature of the actual fuel in the wind tunnel experiments varied with fire intensity. Therefore the correlations developed from the small-scale experiments must be corrected for the temperature in the wind tunnel. Methods to perform this correction are ongoing.

7. Future Work

7.1 Terrestrial Laser Scanning and Plant Models

We highlight two results from this research that will direct future work. First, the placement of fuel elements affects fire behavior at shrub scale. Second, TLS provides detailed but incomplete images of fuel bed geometry and the translations necessary to convert geometry to fuel attributes (mass, surface area, etc.) are confused by variability in range, footprint size, scan angle, and associated haloing, ghosting, and shadowing. The first result emphasizes the need to understand the *actual* variability of fuel beds in addition to statistical abstractions. The second result supports additional investigation into methodologies such as L-systems fractal theory to exploit the advantages of TLS and overcome some of its weaknesses.

TLS is an excellent tool for characterizing the dimensions of fuel bed hulls at very fine spatial resolution. The quality of TLS-based predictions of fuel attributes such as mass then depend on correlations with dimensions of objects (e.g., shrubs; trees) , as is shown in our research and others (Hosoi and Omasa 2006; Van der Zande et al. 2006; Hosoi and Omasa 2009). The primary advantage of TLS for characterizing fuels appears to be mapping the height, structure, and arrangement of vegetation. Translating these metrics into conventional fuel attributes requires statistical modeling and associated simplifying assumptions.

One promising area of future research related to L-systems fractal theory is the application of parametric plant modeling systems to fuel bed design. Such systems use model generators to build plant elements (grasses, shrubs, cones, logs, needles, leaves) that can be distributed within virtual fuel beds. Resultant fuel beds can then be used to explore the 3-D arrangement of fuel characteristics in mixed fuel beds and to simulate laser point clouds using ray-tracing algorithms. We expect these approaches to improve the utility of laser scanning for predicting fuels and to help provide a different context for describing fuels that may facilitate improved approaches to fire behavior modeling.

7.2 Whole Shrub Models

A logical next step in development of our Bush Model is migration from leaf-element to shrub-element simulation. TLS is ready-made for mapping the locations and dimensions of individual shrubs on landscapes (Olsoy et al. 2014; Greaves et al., 2015), and biomass estimations for these shrubs (sagebrush; arctic birch and willow) are relatively robust. In the same way that leaf combustion experiments have been used to develop probability density functions of fire behavior, similar shrub experiments (or simulations) could be used to develop pdfs at shrub resolution. Quantifying the fuel matrix between shrubs will be an important consideration in this effort and work is ongoing in this arena (Rowell et al., in press).

7.3 Improved Methods for Building Fuel Beds for Model Validation

One shortcoming of our TLS- mass loss work was inability to produce a spatially explicit comparison of pre- and post- combustion scans when most of the biomass was removed by fire. In such cases, the structural integrity of the shrubs was lost during combustion and the remaining branch butts shifted and fell. The movement of branch stalks during combustion made it unfeasible to directly compare post-fire voxel arrays to pre-fire arrays in the context of creating constant geometry between scans. It would be worthwhile to develop improved methodologies for creating fuel beds for wind tunnel experiments that are more realistic – for example, growing shrub specimens in pots and burning them directly.

7.4 Semi-Empirical Shrub Combustion Model

The semi-empirical shrub model has been applied to chamise and sagebrush, but current work is focusing on (a) correcting the lab-scale data for temperature and (b) using the proper correlations that capture the effects of moisture. Initial correlations of flame height with moisture content did not work well for the low moisture contents of fuels used in the wind tunnel experiments. The resulting calculations of flame height in the wind tunnel were five times too high. We recently performed some lab-scale combustion experiments on low moisture chamise samples, and the corresponding analysis is underway.

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Appendix A – Project Deliverables

Project presentations, publications, and reports are listed below. Their alignment with proposed deliverables is detailed in Table A-1.

Conference Presentations (8)

[1] Adams,T. and C.A. Seielstad,"Using terrestrial LiDAR to describe fuel elements in a diffuse-form shrub," presented at the 4th Fire Behavior and Fuels Conference, International Association of Wildland Fire, Raleigh, NC (Feb. 18-22, 2013).

[2] Fletcher, M. E. and T. H. Fletcher, "Application of L Systems to Geometrical Construction of Chamise and Juniper Shrubs," presented at the 4th Fire Behavior and Fuels Conference, International Association of Wildland Fire, Raleigh, NC (Feb. 18-22, 2013).

[3] Prince, D. R. and T. H. Fletcher, "Semi-empirical Fire Spread Simulator for Manzanita, Utah Juniper and Chamise Shrubs," presented at the 8th US National Combustion Meeting, The Combustion Institute, Park City, Utah (May 19-22, 2013).

[4] Prince, D. R. and T. H. Fletcher, "A Combined Experimental and Theoretical Study of the Combustion of Live vs. Dead Leaves," presented at the 8th US National Combustion Meeting, The Combustion Institute, Park City, Utah (May 19-22, 2013).

[5] Shen, C. and T. H. Fletcher, "Combustion Properties of Fuel Segments for Live Wildland Utah Shrubs," presented at the 8th US National Combustion Meeting, The Combustion Institute, Park City, Utah (May 19-22, 2013).

[6] Adams, T. and Seielstad, C. Using Terrestrial LiDAR to Model Shrub Fuel Beds for Fire Behavior Simulation, IAWF-AFE Large Wildland Fires: Social, Political and Ecological Effects Conference, Missoula, Montana (May 19-23, 2014).

[7] Shen, C. Fletcher, M., Gallacher, J., Prince, D., Fletcher, T., Seielstad, C. Weise, D. 2015. Experiments and modeling of fire spread in big sagebrush and chamise shrubs in a wind tunnel, Meeting of the Western States Section of the Combustion Institute , Provo, Utah, (Oct. 5-6, 2015).

[8] Shen, C. Fletcher, M., Gallacher, J., Prince, D., Fletcher, T., Seielstad, C. Weise, D. 2015. Experiments and modeling of fire spread in big sagebrush and chamise shrubs in a wind tunnel, 6th International Fire Ecology and Management Congress, San Antonio, TX (Nov. 16-20, 2015).

Conference Posters (2)

[9] Prince, D. R. and T. H. Fletcher, "Semi-empirical Fire Spread Simulator for Utah Juniper and Chamise Shrubs," poster presented at the 4th Fire Behavior and Fuels Conference, International Association of Wildland Fire, Raleigh, NC (Feb. 18-22, 2013).

[10] Shen, C. and T. H. Fletcher, "Fuel Element Combustion Properties for Live Wildland Utah Shrubs," poster presented at the 4th Fire Behavior and Fuels Conference, International Association of Wildland Fire, Raleigh, NC (Feb. 18-22, 2013).

Peer-Reviewed Publications (3; 1 in progress)

[11] Shen, C. and T. H. Fletcher, Fuel Element Combustion Properties for Live Wildland Utah Shrubs. 2015. Combustion Science and Technology, 187, 428-444. dx.doi.org/10.1080/00102202.2014.950372

[12] Prince, D. R. and T. H. Fletcher. 2014. The Fundamental Burning Behavior of Live and Dead Leaves: Part 1. Measurements. Combustion Science and Technology, 186, 1844–1857. dx.doi.org/10.1080/00102202.2014.923412

[13] Prince, D. R., M. E. Fletcher, C. Shen, and T. H. Fletcher. 2014. Application of L-Systems to Geometrical Construction of Chamise and Juniper Shrubs, Ecological Modelling, 273, 86- 95.

[14] Adams, T. and Seielstad, C. in progress. Measurement and Modeling of Individual Shrubs Using Terrestrial Laser Scanning, Ecological Modeling and Software (2016).

Graduate Dissertations and Theses (3; 2 in progress)

[15] Shen, C., Application of Fuel Element Combustion Properties to a Semi-Empirical Flame Propagation Model for Live Wildland Utah Shrubs, M.S. Thesis, Chemical Engineering Department, Brigham Young University (April, 2013).

[16] Adams, T. Using Terrestrial LiDAR to Model Shrubs for Fire Behavior Simulation, M.S. Thesis, College of Forestry and Conservation, University of Montana (May, 2014).

[17] Prince, D. R., Measurement and Modeling of Fire Behavior in Leaves and Sparse Shrubs, Ph.D. Dissertation, Chemical Engineering Department, Brigham Young University (July, 2014).

[18] Gallacher, J. Experiments and Modeling of Fire Propagation in Shrubs, Chemical Engineering Department, Brigham Young University (in progress)

[19] Shen, C. Flame Interaction and Merging in Live Shrub Fuel Elements, Chemical Engineering Department, Brigham Young University (in progress)

Table A-1. Proposed deliverables and present status; references in brackets index project communications above.

Proposed Deliverable	**Status**
Document Sampling Protocols and laboratory methodologies – *non-refereed publication*	**Complete** [1] [3][4][5][15][17]
Present leaf experiment results; TLS scanning results – *conference presentations*	**Complete** [9][10]
Report on shrub combustion results, shrub fuel characterization – *refereed publication*	**Complete** [11]
Present TLS shrub measurement methodology & results; bush model development and results – *conference presentations*	**Complete** [2] [6] [7] [8][9][10]
Report on laser enumeration of shrubs – *refereed publication*	**Manuscript in preparation** Expected completion March 2016 [14]; but see also [13] [17]
Report on fire behavior equations and model – *refereed publication*	**Complete** [12]
Gridded 3-D shrub datasets for Bush Model, WFDS, & FIRETEC - *data*	**Complete & to be published** Data collected as part of this study will be made available upon publication of peer-reviewed manuscripts. Contact authors for specific requests.
Measurement of shrub canopies using TLS – *M.S. thesis*	**Complete** [16]
Fundamental statistical shrub model for fire propagation – *Ph.D. dissertation (3 chapters)*	**Complete** [17][18]
Validated bush model for chamise/sagebrush – *model*	**In Progress** 2 pending dissertations on model refinement [18] [19]