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Wind Tunnel Experiments to Study Chaparral Crown Fires

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Abstract:	The present protocol presents a laboratory technique designed to study chaparral crown fire ignition and spread. Experiments were conducted in a low velocity fire wind tunnel where two distinct layers of fuel were constructed to represent surface and crown fuels in chaparral. Chamise, a common chaparral shrub, comprised the live crown layer. The dead fuel surface layer was constructed with excelsior (shredded wood). We developed a methodology to measure mass loss, temperature and flame height for both fuel layers. Thermocouples placed in each layer estimated temperature. A video camera captured the visible flame. Post-processing of digital imagery yielded flame characteristics including height and flame tilt. A custom crown mass loss instrument developed in-house measured the evolution of the mass of the crown layer during the burn. Mass loss and temperature trends obtained using the technique matched theory and other empirical studies. In this communication, we present the detailed experimental procedures with used instrumentation. The representative results for the fuel mass loss rate and temperature filed within the fuel bed are also included and discussed.
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Riverside, July 20, 2017

Alisha DSouza
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Dear Dr. DSouza,

Please find enclosed the revised manuscript entitled "Wind Tunnel Experiments to Study Chaparral Crown Fires" by Cobian, Aminfar, Chong, Burke, Zuniga, Weise, and Princevac.

As requested, all changes are tracked. Also, a separate document with replies to each of reviewers' comments is included.

I hope you will find everything in perfect order. Please do not hesitate to contact me if I can be of any assistance.

Hope you and the reviewers will find the manuscript ready for publication in JoVE and we can schedule the filming.

We are finalizing the manuscript with the experimental results to be submitted to the Journal of Combustion and we look forward to have this manuscript and video available to the community soon so we can refer to JoVE for experimental procedures and setup.

Thank you very much for your consideration.

Sincerely yours,

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TITLE:
Wind Tunnel Experiments to Study Chaparral Crown Fires

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KEYWORDS:
Chaparral, wind tunnel, surface fire, crown fire, fuel mass loss, flame height

SHORT ABSTRACT:
This protocol describes wind tunnel experiments designed to study the transition of a fire from the ground to the canopy of chaparral shrubs.

LONG ABSTRACT:
The present protocol presents a laboratory technique designed to study chaparral crown fire ignition and spread. Experiments were conducted in a low velocity fire wind tunnel where two distinct layers of fuel were constructed to represent surface and crown fuels in chaparral. Chamise, a common chaparral shrub, comprised the live crown layer. The dead fuel surface layer was constructed with excelsior (shredded wood). We developed a methodology to measure mass loss, temperature, and flame height for both fuel layers. Thermocouples placed in each layer estimated temperature. A video camera captured the visible flame. Post-processing of digital imagery yielded flame characteristics including height and flame tilt. A custom crown mass loss instrument developed in-house measured the evolution of the mass of the crown layer during the

burn. Mass loss and temperature trends obtained using the technique matched theory and other empirical studies. In this study, we present detailed experimental procedures and information about the instrumentation used. The representative results for the fuel mass loss rate and temperature filed within the fuel bed are also included and discussed.

INTRODUCTION:

In 2016, the state of California experienced a total of 6,986 wildland fires, consuming 564,835 acres[1], costing millions of dollars in damage, and risking the wellness of hundreds of people. Because of the regional Mediterranean climate, a major fuel source for these fires are chaparral vegetation communities[2]. Fire spread in chaparral can be considered a crown fire since the main fuel that burns is elevated[3]. Co-existing with the predominantly live crown layer, is the dead surface fuel layer, which consists of cast foliage, branches, and herbaceous plants which grow under and between the individual shrubs. Fire will more easily initiate in the dead surface fuel layer. Once the surface fire ignites, the fire may transition to the crown layer where the energy released by the fire increases dramatically. While chaparral fires have typically been modelled as a fire spreading in deep surface fuels[4], there has been limited study of chaparral fires as crown fires.

Crown characteristics in chaparral, including foliage particle shape, differ from boreal coniferous forest, where most of the research has occurred. Numerous laboratory and field scale studies have investigated various aspects of wildfire dynamics[6,5,7,3,8–12]. Within the realm of laboratory experiments, several studies have examined the influence of parameters such as wind and fuel properties on chaparral crown fire behavior. Lozano[7] examined characteristics of crown fire initiation in the presence of two discrete crown fuel beds. In Tachajapong *et al.*[3], discrete surface and crown layers were burned inside a wind tunnel and the surface fire was characterized. Only crown fire initiation was fully described leaving full analysis of spread for future work. Li *et al.*[11] reported on the propagation of a flame though single chaparral shrubs. In related work, Cruz *et al.*[10,9] developed a model to predict the ignition of coniferous foliage above a spreading surface fire. Burn characteristics of chaparral fuels have been explored in experimental studies of bulk fuels and individual leaves[13–16]. Dupuy *et al.*[13] studied the burning characteristics of *Pinus pinaster* needles and excelsior by burning the fuels in cylindrical baskets. They observed that in these fuels, flame height was related to heat release rate via a two-fifths power law as has been reported previously in the literature[17,18]. Sun *et al.*[14] burned chaparral fuels in similar cylindrical baskets to analyze the burning characteristics of three chaparral fuels: chamise (*Adenostoma fasciculatum*), ceanothus (*Ceanothus crassifolius*), and manzanita (*Arctostaphylos glandulosa*).

Motivated by results from the aforementioned laboratory studies, our purpose here is to present a methodology to characterize spread in both surface and shrub crown layers. Furthermore, we aim to clarify some of the key characteristics that dictate the degree of surface-crown layer interaction. To this purpose, we developed an experimental laboratory methodology to study the vertical transition of a fire burning in a wildland surface fuel to a fire spreading in an elevated shrub fuel. In these types of fires, translation of the fire to the shrub crown, known as crowning, may be followed by sustained spread under the right conditions. In general, chaparral fire behavior is dictated by topography, weather, and fuel[19]. It has been shown that wind affects energy release rate in the fuels[5,3,8,20].

Fire spread in porous fuels can be viewed as a series of transitions or thresholds that must be crossed to be successful[21]. Energetically, a fuel particle ignites if the amount of heat that it receives results in a mixture of gases that successfully react with oxygen. The resulting flame spreads if the heat from the burning particle ignites an adjacent fuel particle. The fire spreads across the ground if it is able to cross gaps between combustible fuel elements. If the flame of a surface fire is able to propagate vertically into the crown of shrubs and trees, a significant change in fire behavior, including increased heat release rates, is often observed due to a greater availability of fuel. Thermal energy dynamics in wildland fires encompass several scales, from the very large scale, such in mega-fires which often require climatological modeling, to the small scale requiring chemical scale kinetic modeling. Here, we deal with laboratory wind tunnel scale behavior modeling; for chemical scale cellulose combustion studies, the reader is referred to works such as Sullivan *et al.*[22]

Since 2001, we have conducted a variety of experiments examining some of the laboratory scale energy thresholds[23,8,24–27], with an emphasis on live fuels associated with chaparral. While outdoors measurements of fire may provide more lifelike results, the controlled environment of the wind tunnel allow for delineation of the impact of various parameters. Controlling wind, for example, is especially important for chaparral crown fires occurring in regions such as Southern California where foehn type winds, known as Santa Ana winds, are typical drivers of fire events. Because a major motivator for the methodology described here is to study the effect of wind and other controlled parameters on chaparral fire spread, this study was performed in a laboratory scale wind tunnel. The reader is directed to the work by Silvani *et al.*[28] for field measurements of temperature in chaparral fires similar to the ones presented here. For field measurements on the effect of wind on fire spread, please see Morandi *et al.*[29]

Several parameters influencing the spread in chaparral fuels have been experimentally analyzed by quantifying the probability of fire spread success in elevated fuel beds[8]. The current experimental study involves a methodology developed to study chaparral crown fire spread by modeling surface fuels and crown fuels inside the test section of a low speed wind tunnel. The surface fuel is modeled with excelsior (dried shredded wood). The surface fuel bed is placed on the ground level of the wind tunnel over a standard scale (see **Figure 1**). Representing the crown fuel bed, a fuel bed with chamise was placed over the surface fuel bed by suspending the fuel from a platform mounted on the wind tunnel frame (see **Figure 1**). Both fuel beds are instrumented for temperature and mass loss measurements; flame geometry is obtained from video recordings of experiments. Parameters measured include mass loss rate, fuel moisture content and the relative humidity of the air. Parameters controlled were wind presence, distance between surface fuel bed and crown fuel bed, and the presence of surface fuel. The measured mass loss rate can be used to calculate the heat release rate, which is defined as:

$$Q = -h\frac{dm}{dt} \qquad (1)$$

where *h* is the heat of fuel combustion, *m* is the fuel mass, and *t* is time.

[Figure 1 here]

Experiments have focused on understanding the behavior of chaparral crown fires, particularly ignition, mechanisms of flame propagation and spread, flame front velocities, and fuel consumption rates. To study the interaction between a surface fire and a crown fire, six configurations of surface and crown fuel beds with and without applied wind flow, have been burned in the wind tunnel: crown fuel only with and without wind (2), crown and surface fuel beds separated by two distances with and without wind (4). **Table 1** summarizes the experimental configurations with the 6 experimental classes. In the table, the surface fuel bed parameter denotes whether surface fuel was present during the experiment, the wind parameter refers to the presence of wind and crown height refers to the distance between the bottom of the crown fuel bed and the bottom of the surface fuel bed. Fuel moisture was measured for each experiment but not controlled, average fuel moisture content was 48%, whereas the minimum and maximum values were 18% to 68%, respectively.

[Table 1 here]

An electronic scale measured surface fuel mass and we developed a custom mass loss system for the crown layer. The system consisted of individual load cells connected to each corner of the suspended fuel bed. Consumer-grade video cameras recorded the visual flames; image processing of the visual data using a custom script generated flame characteristics including height and angle. A program was developed to convert video frames from RGB (red/green/blue) coding to black and white through a process of light intensity thresholding. The edge of the flame was obtained from the black and white video frames. Maximum flame height was defined as the highest point of the flame edge, instantaneous flame heights were also obtained. In an image, flame height was measured from the base of the fuel bed to the maximum vertical point of the flame. All processing codes as well as the instrument control interface designed for this protocol have been made available by the authors here through their software access site. Harvesting the live fuel locally and conducting the experimental burns within 24 h minimized moisture loss. A thermocouple array recorded fuel bed temperature in the wind stream-wise direction enabling the calculation of spread rate. **Figure 1** shows a diagram of the fuel bed setup along with the thermocouple arrangement. Details of the experimental protocol follow.

PROTOCOL:

Caution: As several steps in the following protocol involve activities that have the potential to cause injury, ensure that the proper personal protective equipment (PPE) is used following established safety protocols including fire grade lab coats and goggles.

1. Crown Fuel Bed Load Cell Instrumentation Setup

1.1. Modify 4 C-clamps by attaching dual spring gate carabiners (see **Table of Materials**) through the pin hole at the clamp's screw end (see **Figure 2**). Use the carabiners to suspend the crown fuel bed.

1.2. Using a different set of C- clamps, affix each load strain gauge cell to the top portion of the wind tunnel frame (see **Figure 2**).

1.3. Attach modified C-clamps to the free end of the strain gauge cells, with the carabiners hanging down. Attach chains to the platform for the crown fuel bed.

1.4. To suspend the crown fuel bed platform from the wind tunnel frame, connect each of the crown fuel bed chains to a carabiner.

1.5. Once each of the four load cells are fully mounted and connected to the fuel bed, connect their wires to the Wheatstone bridge which will be used for data acquisition. Cover the load cells with fire insulating material, such as the kind used for fire shelters.

[Figure 2 here]

2. Load Cell Calibration

Note: The signal produced by the load cells is converted to an equivalent mass through:

$$m = A \cdot V + B \qquad (2)$$

where *V* is the signal, typically in millivolts, *A* and *B* are constants to be determined through calibration, and *m* represents the mass in grams. All the parameters in equation (2) are obtained through the custom instrument control interface developed for the crown mass instrumentation in this protocol. When first using the system, precision weights are used to calibrate the load cell signal. Calibration constants *A* and *B* will be obtained based on the signal produced when measuring the load of these precision weights. The constant *A* is calculated from:

$$A = \frac{\mathrm{m_t}}{\mathrm{a_w} - \mathrm{a_{w,o}}} \qquad (3)$$

where m_t is a the mass of trial precision weight, a_w is the signal produced with the weight loaded on the load cell, whereas $a_{w,o}$ corresponds to the signal produced when no weight is applied on the load cell.

2.1. To obtain the calibration constant *A*, hook precision weights (a good range would be 200–500 g) to the first load cell. Use the mass of the precision weights as parameter m_t in equation (3).

2.2. Set the load cell gain to 128 using the Input # field as shown in **Figure 3b**, i.1. This corresponds to the maximum value allowed by the device.

2.3. Read the signal output at Output 0 from the instrument interface (See **Figure 3b**, i2). This is parameter a_w in equation (3).

2.4. Unhook the weight and read the new value displayed in the instrument interface (**Figure 3b**, i2). This is parameter $a_{w,o}$.

2.5. Calculate *A* based on the parameters (m_t, a_w, $a_{w,o}$) obtained in steps 2.1 to 2.4 and the equations presented.

2.6. In the controller interface, fill in the Ch 0-M value for each sensor with the *A* value obtained in the previous step.

2.7. To find the offset value, *B*, remove all weights, read the value in the 'Outputs Calibrated (g)' box (See **Figure 3c, i2**), multiply this value by -1. The resulting number is constant B, type this number in the "Addition" Ch 0-A box (See **Figure 3c**, i.3).

2.8. Repeat steps 2.3–2.8 for each load cell (0, 1, 2, 3), the system is now completely calibrated; proceed to load the fuel beds with the fuels.

[Figure 3 here]

3. Preparation of Chaparral and Excelsior Fuel Beds

Note: Each experiment uses 2 kg of live chamise and 0.5 kg of excelsior (shredded aspen wood).

3.1. From the pile of fuel collected for burning, collect several 1-pint bottles of fuel (3-4 bottles).

3.1.1. Follow the procedures delineated by Countryman and Dean to oven dry samples and obtain fuel moisture content[30].

3.2. Trim individual branches from a bundle of recently harvested chamise to remove dead material and branch material greater than ¼ inch diameter. Place the remaining live fuel material in the container for weighing.

3.3. Select 2 kg of the trimmed chamise and 0.5 kg of excelsior using an electronic scale. Load 2 kg of trimmed chamise onto the platform hanging from the load cells to create the elevated fuel bed. Evenly spread the chamise branches over the entire platform to produce a uniform fuel bed.

3.4. Pull apart (fluff) the compacted excelsior to decrease its bulk density so it will burn readily. Place 0.5 kg of excelsior onto the surface fuel bed platform on the wind tunnel floor, ensuring that the bulk density is as uniform as possible. Do this by placing a known amount of excelsior over a known area to a constant depth.

4. Thermocouple Arrangement

Note: K-Type thermocouples are used to measure temperature of both fuel beds. Data is collected through a data acquisition system controlled with a custom graphical user interface (see table of materials for controller design software). The thermocouples recommended for use are 24 AWG thermocouples with a response time of 0.9 s.

4.1. Connect an array of sixteen 24 AWG thermocouples (conductor diameter: 0.51054 mm) to a data logger (response time: 0.9 s).

4.2. Insert 6 thermocouples into the crown fuel layer. Place these thermocouples 20 cm apart and avoid contact of thermocouples with branches. Insert 10 thermocouples into the surface fuel layer. Place these surface fuel thermocouples 10 cm apart and avoid contact of thermocouples with branches (See **Figure 4**).

4.3. Activate data logging by clicking the "Start" button in the thermocouple control software interface.

5. Image Acquisition Setup

5.1. Mount the visual reference target that has red marks at 10-cm-intervals above the wind tunnel window. Use this target as a reference to determine flame height from the experiment video.

Note: Sample flame heights are presented in **Figure 5**.

5.2. Setup photographic data collection. Focusing on the wind tunnel test area, adjust the camera focus so as to capture the entire vertical reference target as well as the fuel bed area.

5.3. Setup video camera data collection. Mount the video camera with a universal camera wall mount on the wall to provide a full view of the wind tunnel test section.

6. Flow Setup

Note: The wind tunnel is equipped with a variable speed fan. The air flow in the wind tunnel has been previously calibrated to the fan speed. To achieve the desired wind velocity, the fan rotational speed (in Hz) is selected. In the present experiments, no wind and 1 m/s wind flow cases were studied.

6.1. Set the fan speed to 1 m/s on the speed controller. Turn on the fan to ensure that it is functioning properly.

6.2. Turn off the fan. It is now ready for use.

Note: The burn building is designed to conduct fire experiments safely while evacuating smoke from the working space. Notify local fire authorities that experiments are being conducted to eliminate the occurrence of false alarms.

6.3. Close all doors in the building to ensure that the roof vents are the only possible exit for smoke evacuation.

6.4. Turn on the air supply fans to bring in fresh air from outside the building at floor level. Turn on the exhaust fans to evacuate smoke through the roof vents.

Note: This will establish a low velocity, high volume air flow from outside the building that rises vertically due to the slight pressure difference and the roof openings.

6.5. Prior to each experiment, use a wet-bulb hygrometer to measure the relative humidity and temperature of the ambient air.

7. Ignition (Implement Simultaneously with Step 8)

Note: The ignition process should be conducted as follows by the ignition crew member. For increased safety, it is recommended that a second crew member remain near the test area during ignition.

7.1. When instructed to 'ignite', soak the leading edge of the excelsior surface fuel bed with denatured ethyl alcohol. Place the alcohol bottle away from the ignition zone and using a butane torch, ignite the end of the surface fuel bed in a line parallel to leading edge of the fuel bed. Be observant as the alcohol-soaked fuel will readily ignite.

7.2. Once the fuel bed has been ignited, step out of the test section and close the tunnel door. If wind is required for the experiment, turn on the wind tunnel fan.

8. Initiate Experimental Run

Note: Upon verifying the experiment is correctly setup, the cameras should be started.

8.1. Turn on the video camera to record.

8.2. Speak aloud the experiment number/code, the date, and experimental configuration so the microphone on the video camera records this information.

8.3. Instruct the computer crew to begin data logging by ticking the "Enable data logging" option in the instrument control interface (see **Figure 3d**, i.1). Instruct the ignition person to ignite the fuel. Once the ignition crew member exits the wind tunnel, instruct the wind crew member to start the wind tunnel fan. This will be the start of the experiment where time is zero (t = 0).

REPRESENTATIVE RESULTS:

Crown and surface flame height data were obtained from the video data. Typical flame height trends for experiments is presented in **Figure 6**. Flame height behavior followed that found in Sun *et al.*[14]

[Figure 6 here]

The evolution of flame height in **Figure 6** was chosen because it shows typical flame height behavior for experiments with wind. In these types of experiments, the flames start small, get large close to the middle of the fuel bed, then will decay with time as flames get closer to the end of the fuel bed. The experiment in the presented figure is Case F (wind at 1m/s and distance between crown and surface fuel at 70 cm). In this case, the wind helps the flame to tilt. Because of the flame tilt, radiative heat transfer of the flame to the fuel bed is enhanced[31]. As the flame travels through the fuel bed it will pre-heat the fuel ahead of it. The mid fuel bed seems to be an optimum location where sufficient preheating has occurred over a large amount of fuel to create a large flame. The end of the fuel bed is also pre-heated, however, the amount of fuel becomes limited so that less pyrolysis gases are released which results in decreased flame height.

Fuel consumption rates were obtained for the entire extent of both fuel beds. The evolution of mass loss for selected experiments is presented in **Figure 7**. The non-dimensional parameter M is the ratio of instantaneous mass m and the initial mass m_0. Dimensionless time T is the ratio of the experimental time t and the total burn time t_f, where total burn time is defined as the time when flaming ignition has stopped. The evolution of mass loss throughout experiments followed expected behavior. Three general regions were identified from the characteristics of the mass loss curve: ignition, flaming, and smoldering, see **Figure 7**. This was a Case F experiment (wind at 1 m/s, distance between surface and crown of 70 cm). The fuel moisture content was 45%, relative humidity was 66%, and the total burn time was 2.5 min. Overall mass loss and mass loss rate trends matched those presented by Rothermel[32] and Freeborn *et al*.[33]

[Figure 7 here]

To illustrate mass loss trends for both the surface and crown layers obtained from experiments described through this methodology, the results for four experiments are presented in **Figure 8** and **Figure 9**. Average burn times for experimental categories represented by **Figure 8** were as follows: Class C and D averaged 4.5 minutes and class E and F averaged 2.5 minutes. As can be observed, wind enhanced the rate of mass loss and the total burn time.

[Figures 8 & 9 here]

Gas phase temperatures were measured for both fuel beds using sixteen thermocouples within the fuel beds. Thermocouples are labeled T0–T15, **Figure 4** depicts the thermocouple arrangement. Thermocouples T0–T09 were placed inside the surface fuel bed, while T10–T15 were placed inside the crown fuel bed. Crown fuel bed temperatures for a selected experiment are presented in **Figure 10**.

[Figure 10 & 11 here]

It is important to note that if the thermocouples are not properly inserted in the fuel bed, temperature readings will be inaccurate. For instance, upon examining temperature readings in the experiment represented by **Figure 11**, it was noted that temperatures for one of the crown fuel bed thermocouples (T15) was below normal for burning conditions. These temperatures were closer to ambient conditions than to the gas phase temperatures of burning chamise. Thus, it was inferred that in this case, thermocouple T15 remained outside the fuel bed through the experiment.

FIGURE AND TABLE LEGENDS:

Figure 1: Wind tunnel experimental setup. Locations of the crown fuel bed, the surface fuel bed, and the tunnel fan have been labeled for convenience. The surface fuel bed is placed on the ground level of the wind tunnel over a standard scale. Representing the crown fuel bed, a fuel bed with chamise was placed over the surface fuel bed by suspending the fuel from a platform mounted on the wind tunnel frame.

Figure 2: Wind tunnel crown fuel bed load cell instrumentation. (**a**) Wind tunnel front view (**b**) Modified C-clamp with carabiner and crown fuel bed chain which supports the crown fuel bed. (**c**) Load cell attached to the wind tunnel frame using a C-clamp.

Figure 3: Instrument control interface data input steps for load cell calibration. (**a**) Bridge initial setup window with gain setup and enable box (**b**) Window for first stage of load cell calibration (**c**) Window for second stage of load cell calibration (**d**) Window for last stage of load cell calibration, file is saved here and data logging was started.

Figure 4: Diagram of surface and crown fuel beds with thermocouple array location. Here 6 thermocouples were inserted into the crown fuel layer 20 cm apart from each other. 10 thermocouples were inserted into the surface fuel layer 10 cm apart.

Figure 5: Photograph of sample flame heights from a typical experiment. The blue visual target with red marking serves as a reference to determine flame height from the experiment video.

Figure 6: Estimated crown flame height. Here U = 1 m/s, surface-crown separation d = 70 cm. This corresponds to a representative Class E experiment. Flame height is obtained by processing images from the experiment video.

Figure 7: Fuel consumption trend. Depicted is a representative Class F experiment, where U = 1 m/s and surface-crown separation d = 70 cm. Combustion regions are labeled in the plot (ignition, flaming and smoldering). The generalized trend with these three regions was observed for most experiments.

Figure 8: Surface fuel bed mass loss for representative experiments. Data are shown from experiments with wind at 1 m/s and without wind, as well as the two surface-crown distances tested: d = 60, 70 cm. Mass loss data here are obtained from the digital scale used for the surface fuel bed.

Figure 9: Crown fuel bed mass loss for representative experiments. Data show experiments with wind and without wind as well as the two surface-crown distances tested. Mass loss data here is obtained from the load cell instrumentation used for the crown fuel bed.

Figure 10: Fuel bed gas temperatures crown fuel bed. Thermocouple arrangement is indicated in **Figure 4**. Shown is a Class B experiment without surface fuel bed and a wind speed of 1 m/s.

Figure 11: Temperature readings resulting from improper placing of thermocouples. Thermocouple arrangement is indicated in **Figure 4**. Depicted are data for crown fuel bed temperature where the thermocouples were improperly placed as is apparent by the abnormally low temperatures.

Table 1: Experiment configurations. Here the surface fuel bed parameter denotes whether surface fuel was present during the experiment, the wind parameter refers to the presence of wind and crown height refers to the distance between the bottom of the crown fuel bed and the bottom of the surface fuel bed.

DISCUSSION:

The ability to measure the elevated fuel mass throughout the experiment was one of the main advantages of the technique presented here. Previous studies addressing chaparral fire have focused on either only crown fire initiation or only on surface spread, but not both. Such studies have quantified the possibility of ignition in the crown layer and have left study of spread for future work[23]. Our methodology allows for measurement of mass loss, temperature distribution, and flame geometry for both layers involved in shrub crown fire ignition and spread. It provides a means for indirectly inferring energy flux from the rate of mass loss. Other studies have shown the advantages of directly measuring heat flux in fire spread experiments. Finney *et al.* presented several examples of heat flux measurements in wildfire spread experiments[34]. Through such work, they were able to make important observations on the roles convective and radiative heat transfer play in wildfire spread. The methodology presented here allowed for baseline observations of energy dynamics in wildfire spread in the chaparral. A beneficial next step would involve a more in-depth analysis of the particular contributions of radiative and convective heat transfer. For future studies, we recommend exploring the direct measurement of heat fluxes.

To ensure accuracy in the measurements there are several critical steps. The calibration of the load cells measuring crown mass loss is perhaps the most critical step and the step that takes the most time. This is because at the end of each experiment day, the crown fuel bed must be unmounted, and slight movement in the configuration may cause alterations in the mass readings. Hence, calibration must be done at the beginning of each experiment day. For future experiments, a more permanent configuration would be ideal. In this future configuration, the individual load cells would be affixed to the experimental setup.

In addition to the calibration step, another critical step in the protocol is the preparation of the fuels. The intent of the entire experimental program is to develop a better understanding of combustion in live fuels for the purpose of improving our ability to predict prescribed fire behavior. While live branches up to ½ inch (1.27 cm) can be consumed in the flame front of a high intensity prescribed burn in chaparral (see Green[35]), larger diameter fuels are typically not burned in the flame front. Laboratory burns using chaparral fuels have focused on using fuels that would generally be consumed by a prescribed burn's spreading flame front (see Cohen and Bradshaw[36], Weise *et al.*[37]). Major chaparral species include chamise (Adenostoma fasciculatum), while other chaparral fuels include manzanita (Arctostaphylos glandulosa) and hoaryleaf ceanothus (Ceanothus crassifolius). Here chamise was the fuel chosen because it is the most flammable of these species. The protocol can be modified to include other species as long as the branch size is maintained below ¼ inch.

In general, regardless of the species chosen as fuel, branches should be trimmed such that all branch diameters are < ¼ inch (0.63 cm) in order to maintain uniformity. Not performing this step or performing it incorrectly would negatively affect the reproducibility of the results. Over trimming the branches may also be disadvantageous because fuel beds with very small branch sizes tend to have greater packing density and hence also burn differently. In the procedure described here, following Omodan[38], the packing density was maintained at an average of 9.2 kg/m^3.

It is worth noting that because of the scale of this experiment, a crew of 4 or more people is required to ensure efficiency during the experiment. Having a person in charge of the crew with the protocol visible at all times is important to ensure all steps are followed correctly. This person is in charge of the safety of the crew as well as the coordination of the experiment. It is important that this person and the rest of the crew pay attention to their safety and that of the environment, which means having visibility of fire extinguisher, ensuring exhaust vents are on and the doors are closed during the experiment.

Additionally, it would be advantageous to synchronize all the instruments with a single trigger button. This would make data analysis and processing more efficient. Finally, a natural progression after the technique here is mastered would be to integrate some of the remaining wind tunnel capabilities such as temperature control which has been shown in other studies to be another important factor to consider. This would enable a wider range of control of environmental conditions. The results presented here are from experiments conducted during the summer months when fuels are typically drier; this period also corresponds to a portion of the year when wildland fires occur. If, however, a large range of seasons are to be analyzed during one experimental period, the wind tunnel temperature control may be employed. Similarly, variation of fuel moisture content would provide insight on the influence of this parameter on chaparral crown fire transition and spread. In designing an expanded study to include fuel moisture content and bulk density as controlled parameters, error analysis such as the one provided by Mulvaney *et al.* would aide in designing a methodology with experimental uniformity[39].

The technique described here enables an examination of crown fire behavior that integrates measurements of mass, temperature, and flame geometry for both layers of fuel involved. Analysis resulting from this methodology may lead to an increased understanding of chaparral fire as a crown fire specially within the bounds of independent, passive or active crown fire behavior as presented by Van Wagner[5], thus providing knowledge to aid in fire prediction and control.

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The authors have nothing to disclose.

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Figure 1


Fan
Crown Fuel Bed
Surface Fuel Bed

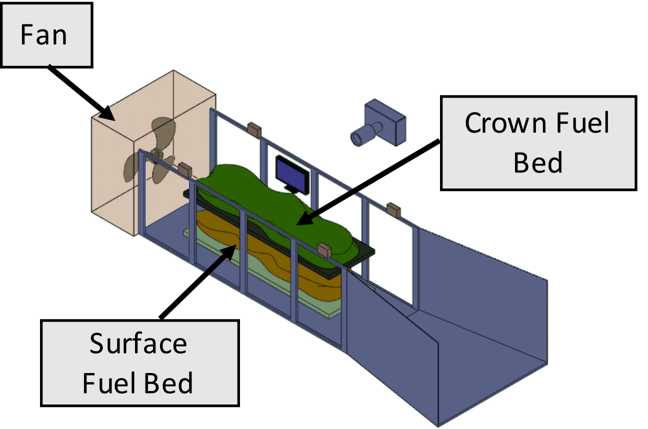
Fan
Crown Fuel Bed
Surface Fuel Bed

Figure 2

Click here to download Figure Figure2.pdf

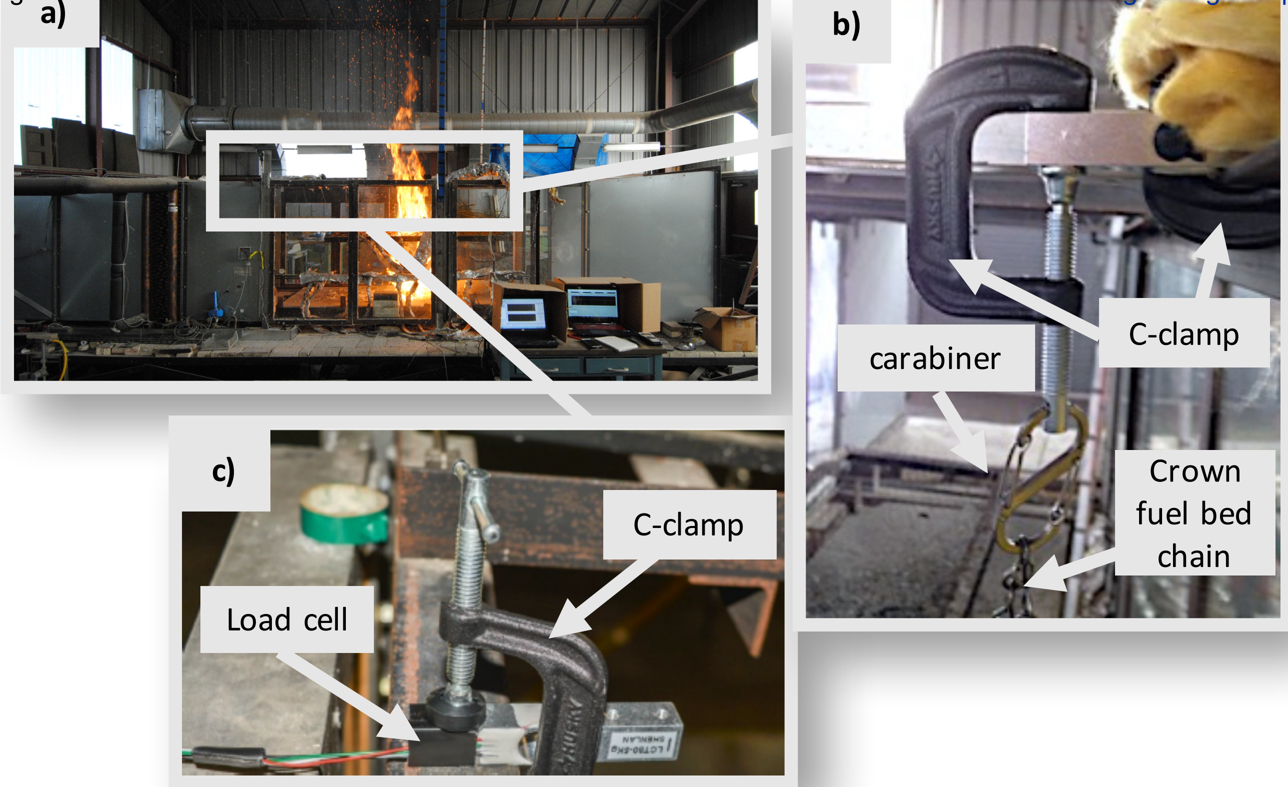

Figure 3

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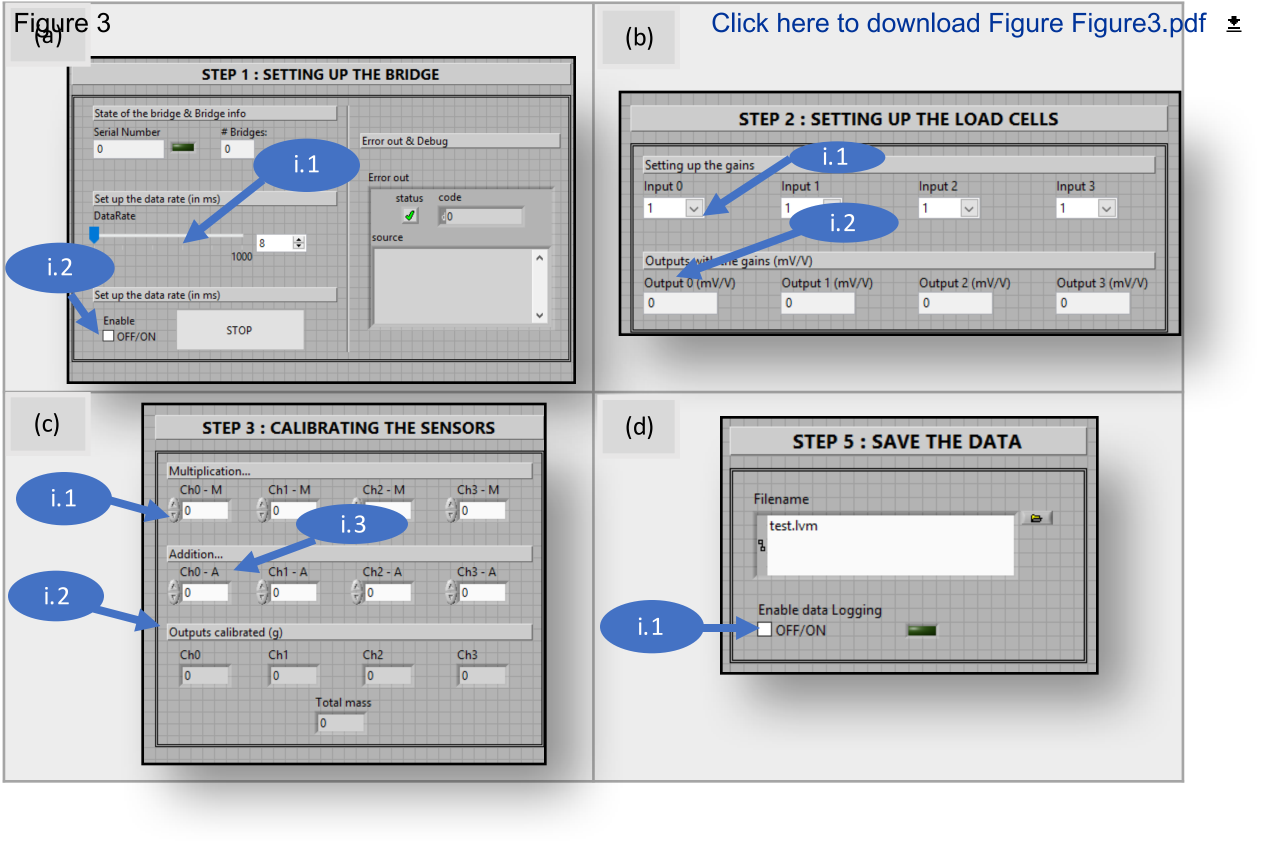

Figure 4

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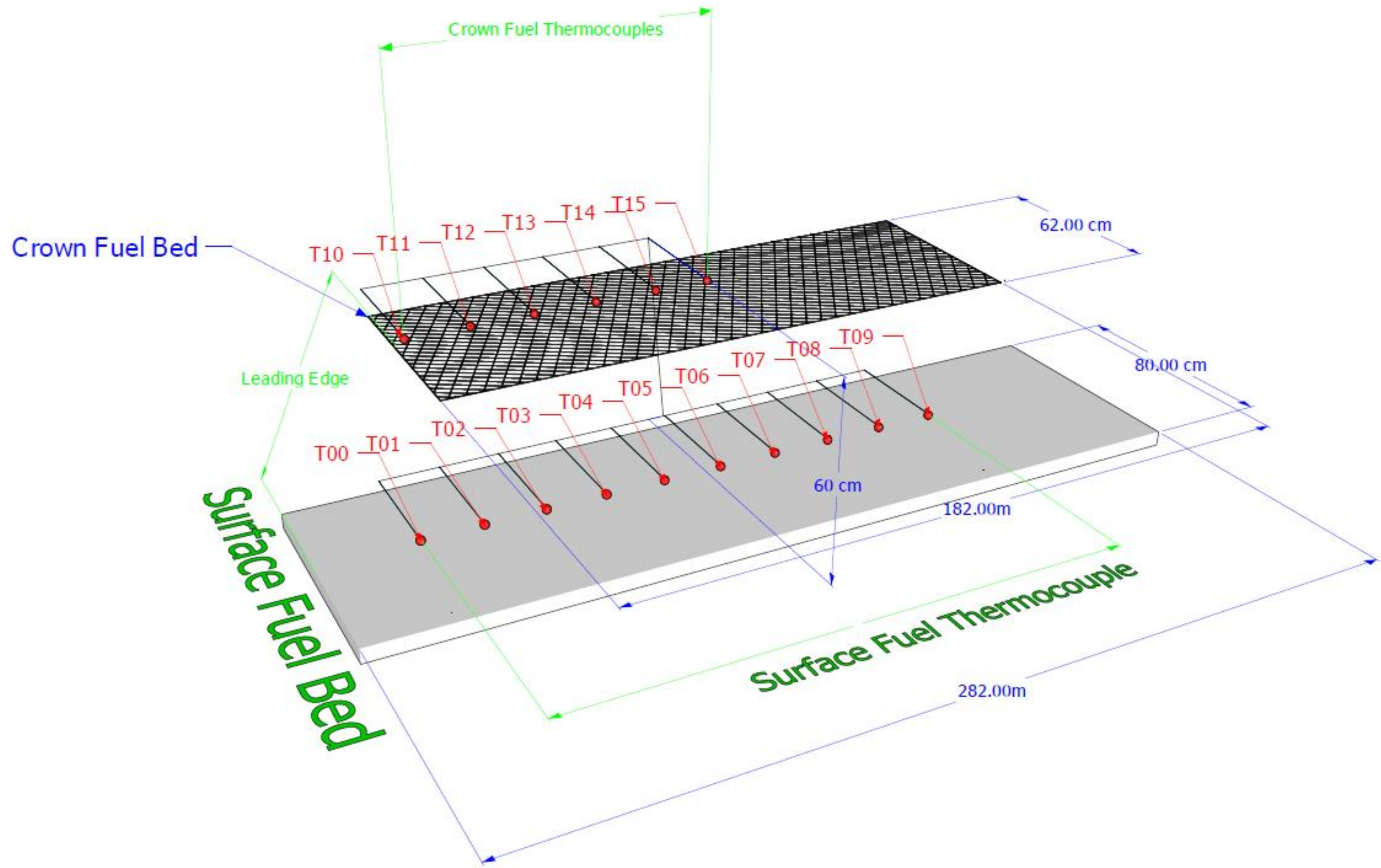

Figure 5

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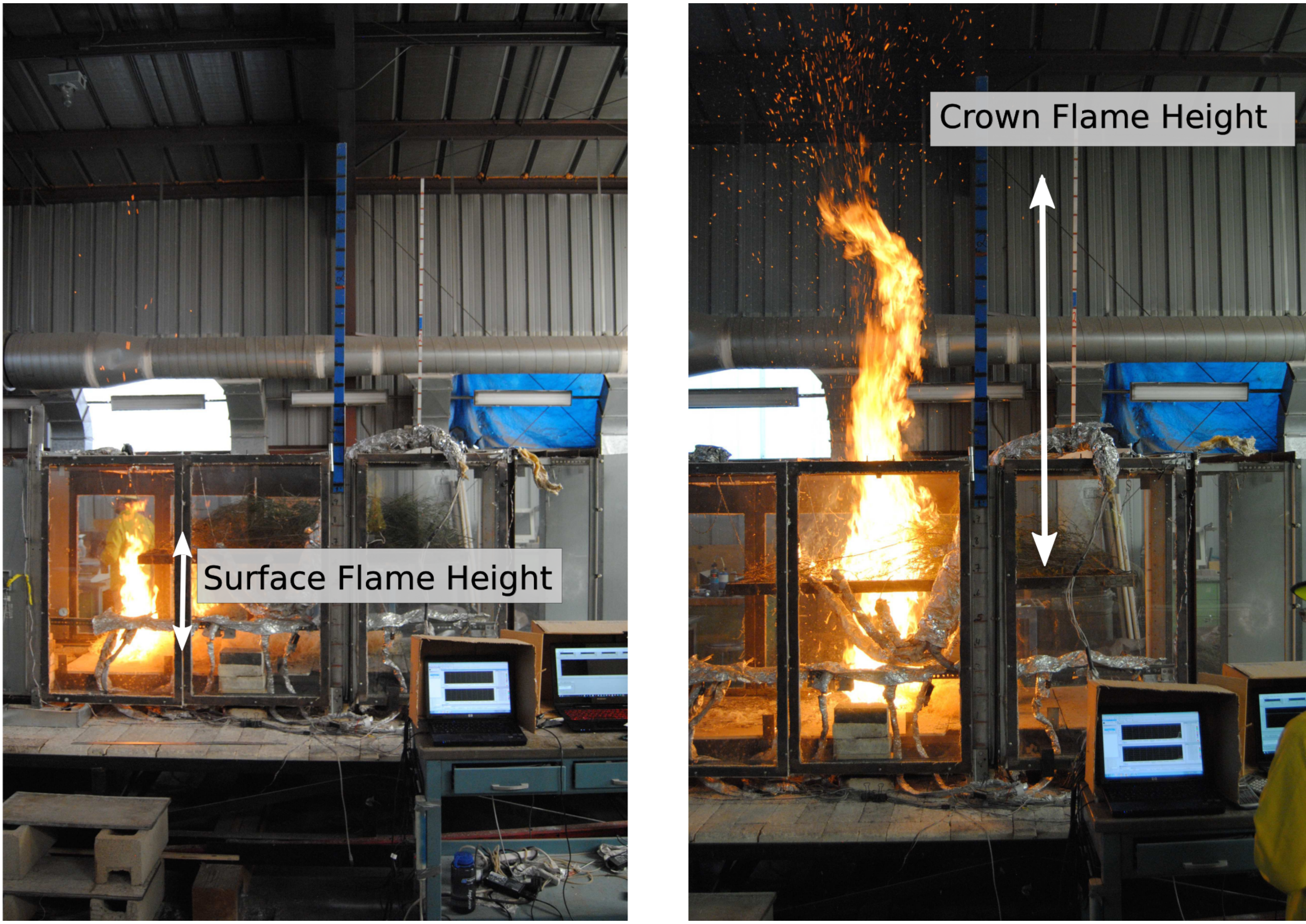

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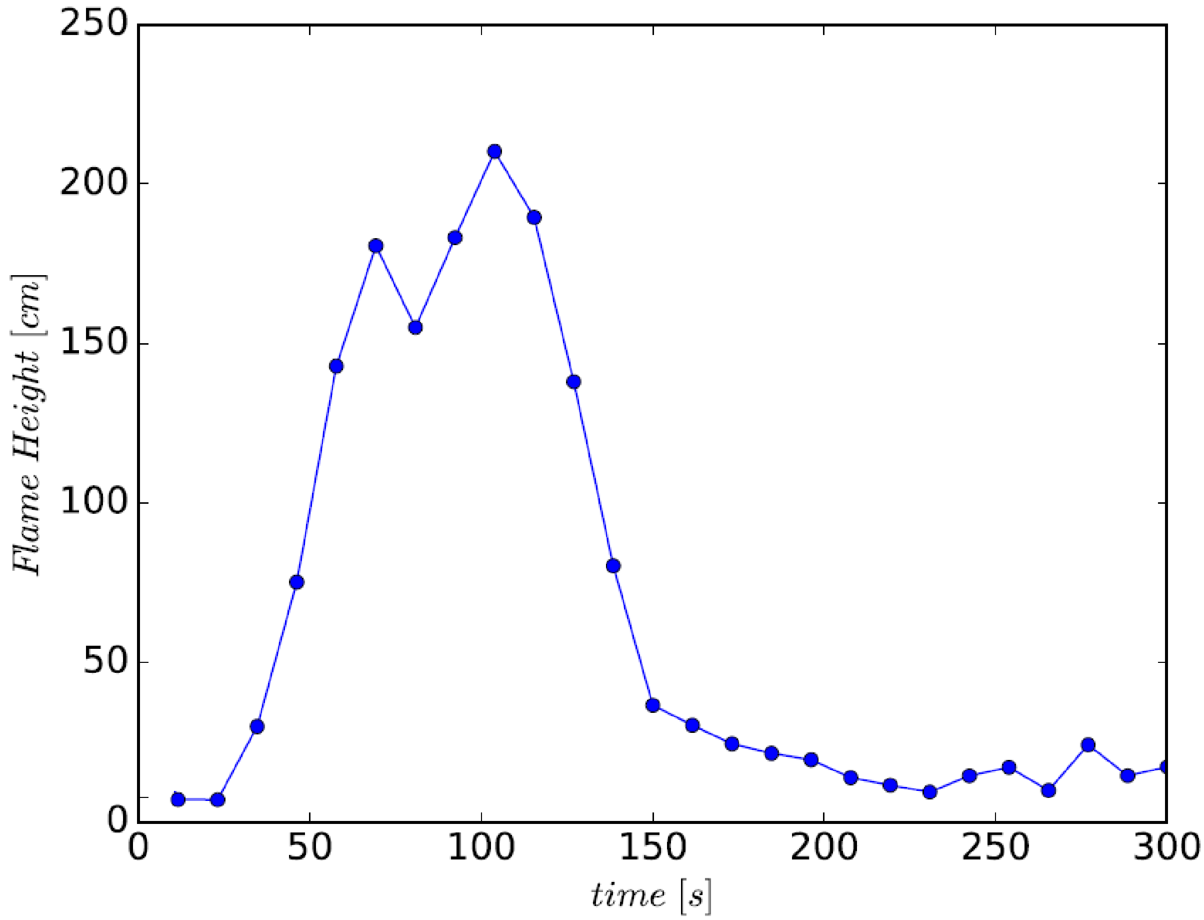
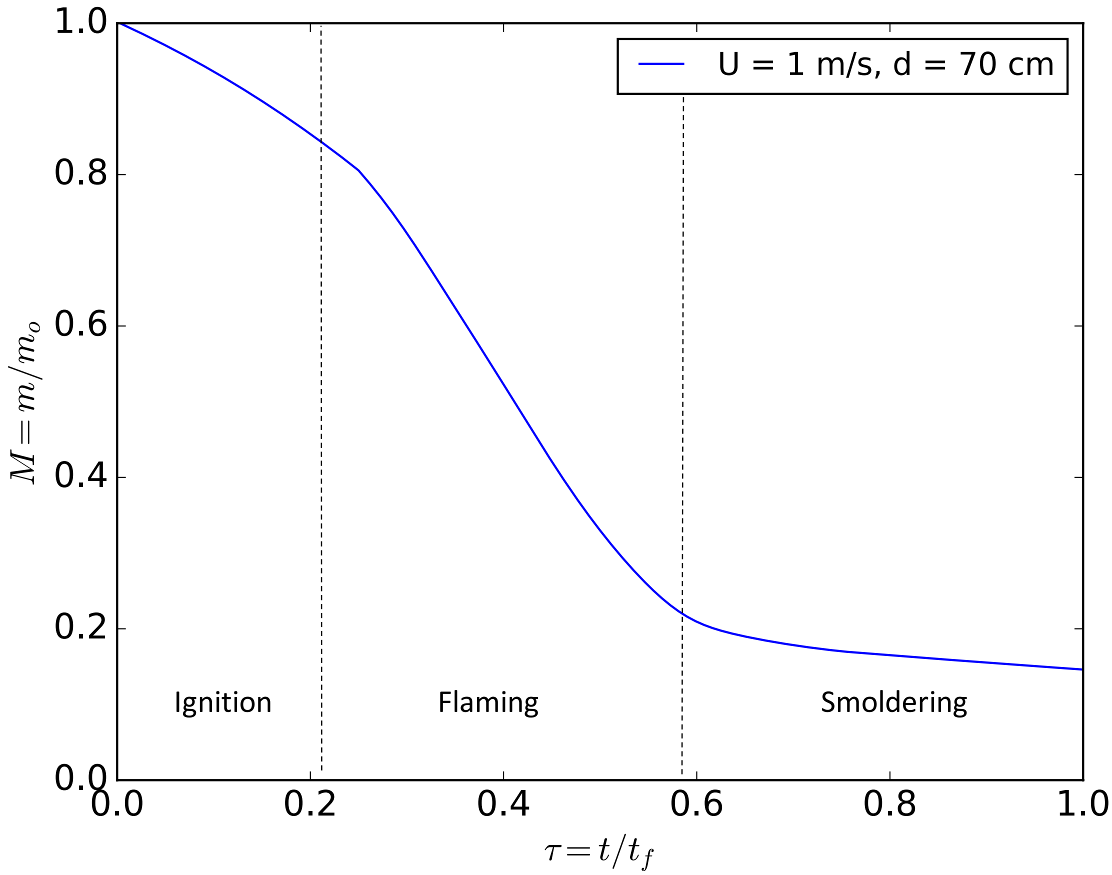


Figure 7


U = 1 m/s, d = 70 cm
Ignition
Flaming
Smoldering
$M = m/m_o$
$\tau = t/t_f$
1.0
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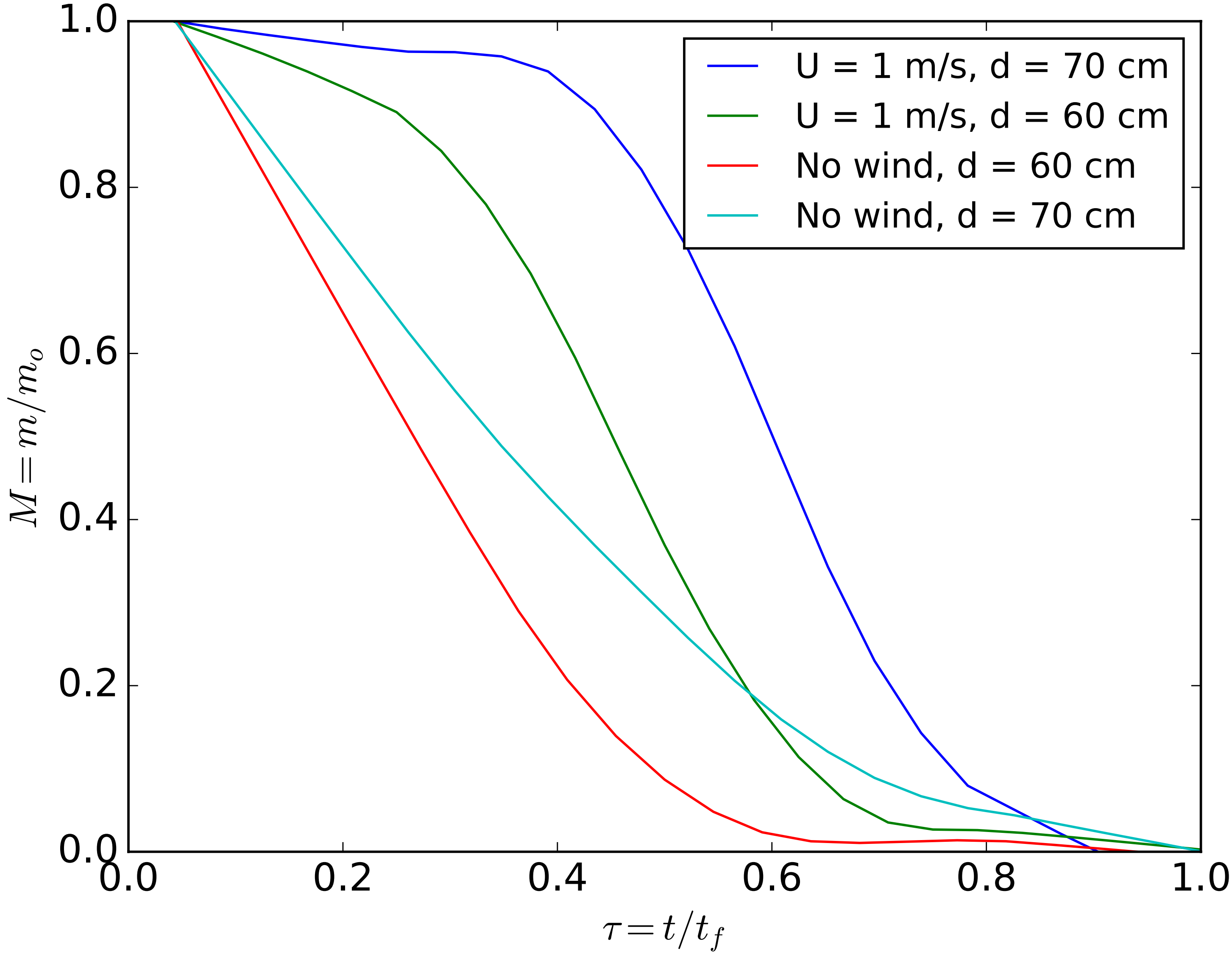
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0



1.0
0.8
0.6
0.4
0.2
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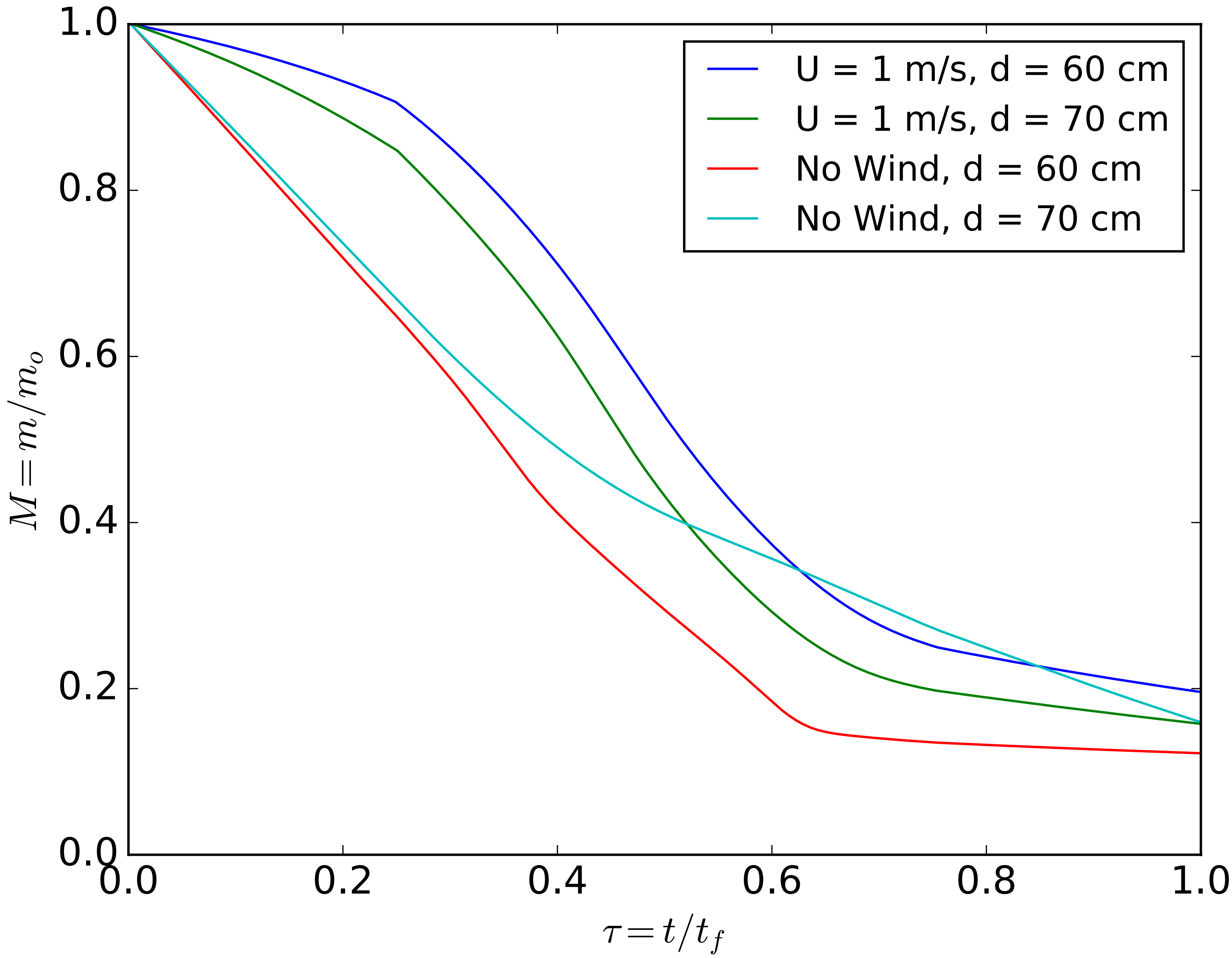
0.0
0.2
0.4
0.6
0.8
1.0
$M = m/m_o$
$\tau = t/t_f$
U = 1 m/s, d = 70 cm
U = 1 m/s, d = 60 cm
No wind, d = 60 cm
No wind, d = 70 cm



1.0
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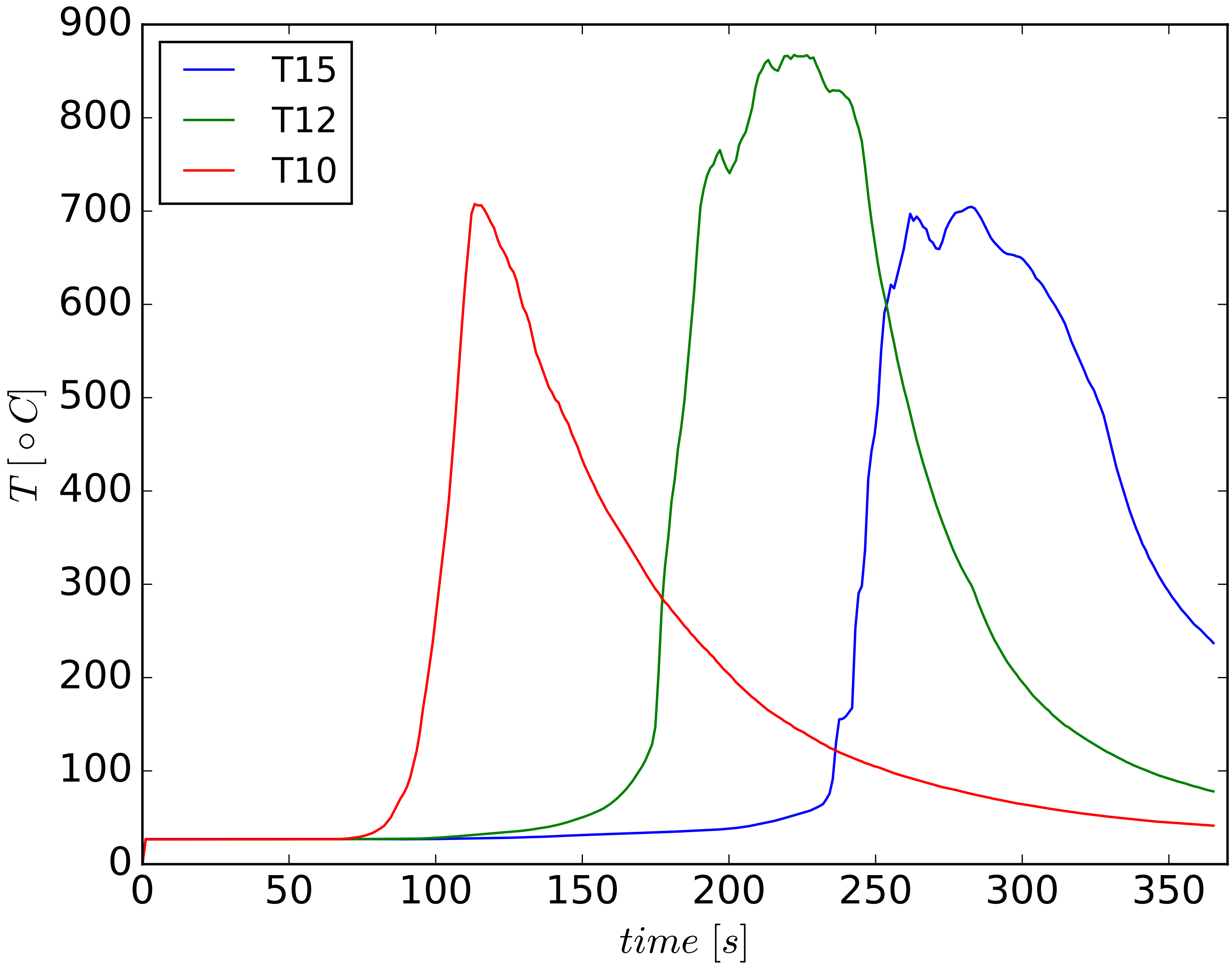
0.0
0.0
0.2
0.4
0.6
0.8
1.0
$M = m/m_o$
$\tau = t/t_f$
U = 1 m/s, d = 60 cm
U = 1 m/s, d = 70 cm
No Wind, d = 60 cm
No Wind, d = 70 cm

Figure 10


T15
T12
T10
$T\ [\circ C]$
$time\ [s]$
0
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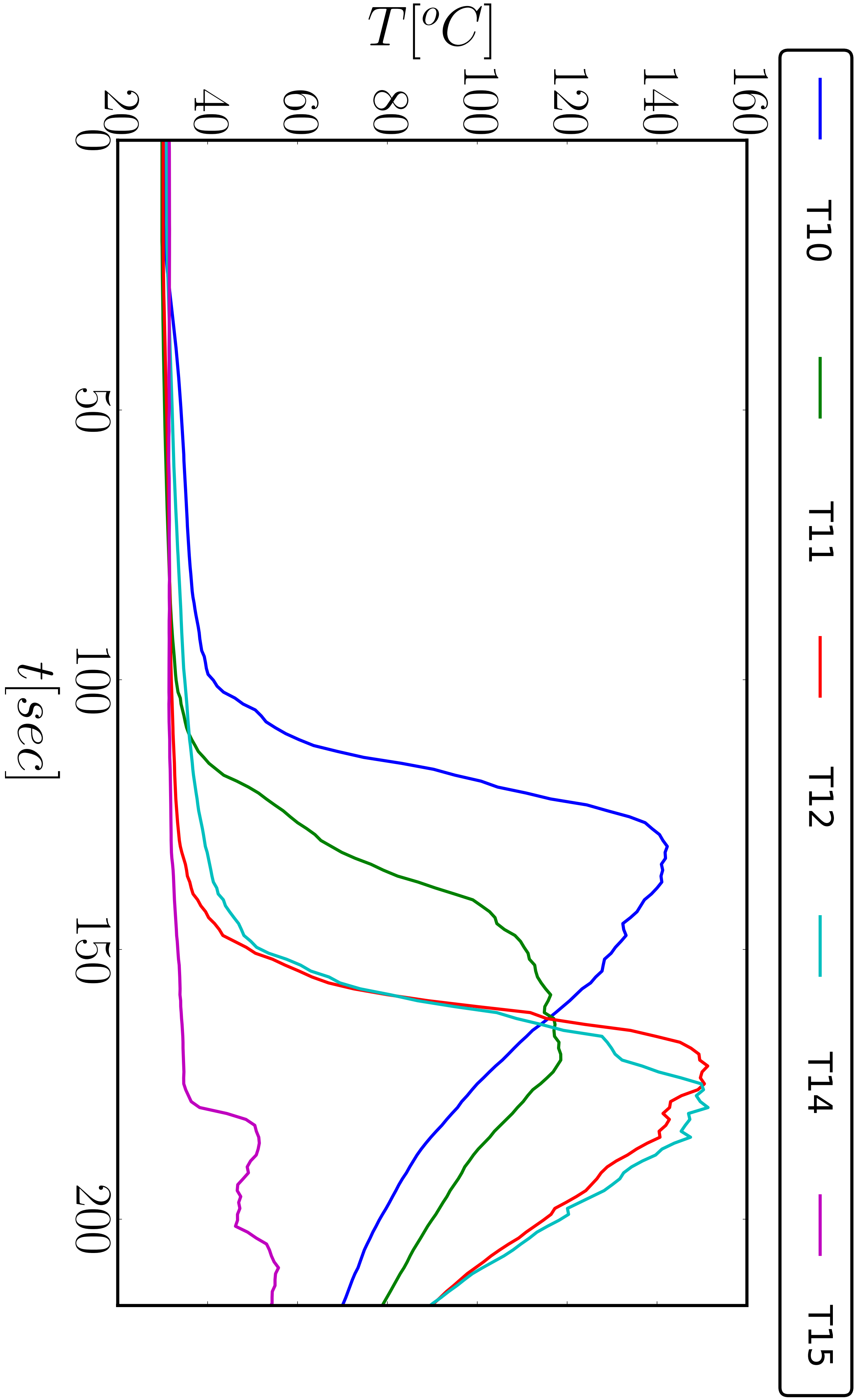
350

Figure 11



Class	Surface Fuel Bed	Wind	Crown Height
A	Absent	No wind	60 or 70 cm
B	Absent	1 ms^{-1}	60 or 70 cm
C	Present	No wind	60 cm
D	Present	No wind	70 cm
E	Present	1 ms^{-1}	60 cm
F	Present	1 ms^{-1}	70 cm

MATERIAL

Wind Tunnel Instrumentation

cDAQ-9178 CompactDAQ Chassis

NI-9213 C Series Temperature Input Module

NI SignalExpress for Windows

High Temperature Nextel Insulated Thermocouple Elements

Thermocouple Extension Wire with Polyvinyl Coated Wire and Tinned Copper Overbraid

Ultra High Temperature Miniature Connectors

CompuTrac MAX 2000XL

Kestrel 3000 Pocket Weather Meter

Satorius CPA 34001S

5 Kg Micro Load Cell (X4)

Phidget PhidgetBridge Wheatstone Bridge Sensor Interface

#2 Stainless S-Biner (X4)

2 in. Malleable Iron C-Clamp

Personal Protective Equipment

Wildland Firefighter Nomex Shirt

Fireline 6 oz Wildland Fire Pants

Fuels

Chamise

Natural Shredded Wood Excelsior – Natural Coarse 50 lbs bail

Bernzomatic UL100 Basic Propane Torch Kit

Isopropyl alcohol

Video and Photography

Nikon D3000 10.2-MP DSLR camera with DX-format sensor and 3x 18x55mm Zoon-NIKK(

Sony Handycam Camcorder DCR-SX85

Software

NI LabView

MATLAB Student Version (MATLAB_R2014a)

VENDOR	CATALOG NUMBER	COMMENTS
National Instruments	781156-01	
National Instruments	785185-01	
National Instruments	779037-35	Newest version, older version used for exper
Omega	XC-24-K-18	
Omega	EXPP-K-24S-TCB-P	
Omega	SHX-K-M	
Arizona Instruments	MAX-2000XL	Discontinued, Newer Model Out
Nielsen-Kellerman	0830	
Sartorius	25850314	Discontinued Model
Robotshop.com	RB-Phi-118	Strain Gauge Load Cell
Robotshop.com	RB-Phi-107	Interfaces with 4 load cells, performs signal a
Home Depot	SB2-03-11	Dual spring gate carabiners used to mount lo
Home Depot	# 4011	Used to mount load cells
GSA Advantage	SH35-5648	
GSA Advantage	139702MR SEV16	
Collected in situ	N/A	
Paper Mart	21-711-88	
Home Depot	UL100KC	
Convenience store	N/A	
OR VR Image Stabilization Lens		
Amazon.com	DCR-SX85	
National Instruments	Student Version	Used for instrument control and interfacing
Mathworks	Student Version	Used for data post-processing including imag

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amplification
oad cells

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Response to reviewers' comments on the "Wind Tunnel Experiments to Study Chaparral Crown Fires"

We wish to thank the reviewers for thorough reading of our manuscript and comments that lead to the significant manuscript improvement. Each comment is addressed below and the appropriate changes are incorporated in the manuscript. We hope that the reviewers will find the revised manuscript suitable for publication in JoVE.

Editors Comments

Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammatical errors.

Response:

The manuscript is now thoroughly proofread and changes and corrections are implemented.

Comment

Please avoid use of the pronouns "you" and "your" throughout the manuscript.

Response

Instances of "you" and "your" have been removed

Comment

The JoVE format style does not allow footnotes, please merged any footnotes into the text.

Response

Trademarks for products replaced by generic product name thus footnotes are no longer in text.

Comment

Please re-word the Short Abstract to more clearly state the goal of the protocol. For example, "This protocol/manuscript describes…". Please re-word the Long Abstract to more clearly state the goal of the protocol.

Response

Short and long abstracts have been modified to more clearly state the goal of the protocol.

Comment

Please ensure that all text in the protocol section is written in the imperative tense as if you are telling someone how to do the technique (i.e. "Do this", "Measure that" etc.) Any text that cannot be written in the imperative tense may be added as a "Note", however, notes should be used sparingly and actions should be described in the imperative tense wherever possible.

Response

All protocol language has been updated to the imperative tense.

Comment:

Protocol Detail: Please note that your protocol will be used to generate the script for the video, and must contain everything that you would like shown in the video. Please add more details to the following protocol steps. There should be enough detail in each step to supplement the actions seen in the video so that viewers can easily replicate the protocol.

1.11: How do you choose the values?

Response:

These values correspond to the signal outputs from the load cell. That is, when calibrating precision weights are added to the load cells, the signal produced by the load cell when measuring the mass can be obtained from the instrument interface. The Load Cell Calibration step in the protocol has been re-structured in order to improve clarity in the methodology. We hope the updated protocol section addresses the inquiry.

Comment:

2) 3.3,6.3: Please mention what button is clicked on in the software to do this, or which menu items need to be selected.

Response:

To clarify the software interface an additional figure (Figure 3) is now in the manuscript. Also, the text is modified for clarity.

Comment

Protocol Numbering: All steps should be lined up at the left margin with no indentations. There must also be a one-line space between each protocol step.

Response

Steps have been lined up at the left margin with no indentations and a one-line space between each step has been added.

Comment

Protocol Highlight: After you have made all of the recommended changes to your protocol (listed above), please re-evaluate the length of your protocol section. There is a 10-page limit for the protocol text, and a 3- page limit for filmable content. If your protocol is longer than 3 pages, please highlight ~2.5 pages or less of text (which includes headings and spaces) in yellow, to identify which steps should be visualized to tell the most cohesive story of your protocol steps.
o The highlighting must include all relevant details that are required to perform the step. For example, if step 2.5 is highlighted for filming and the details of how to perform the step are given in steps 2.5.1 and 2.5.2, then the sub-steps where the details are provided must be included in the highlighting.
o The highlighted steps should form a cohesive narrative, that is, there must be a logical flow from one highlighted step to the next.
o Please highlight complete sentences (not parts of sentences). Include sub-headings and spaces when calculating the final highlighted length.
o Notes cannot be filmed and should be excluded from highlighting.

Response

We have highlighted ~2.5 pages of the protocol for the filmable content. Please see the updated manuscript.

Comment

Discussion: JoVE articles are focused on the methods and the protocol, thus the discussion should be similarly focused. Please ensure that the discussion covers the following in detail and in paragraph form: 1) modifications and troubleshooting, 2) limitations of the technique, 3) significance with respect to existing methods, 4) future applications and 5) critical steps within the protocol.

Response

Several updates have been made to the discussion section. Items 1) – 5) required for this section are included as requested. Please see the manuscript.

Comment

Figure/Table Legends:: Please expand the legends to adequately describe the figures/tables. Each figure or table must have an accompanying legend including a short title, followed by a short description of each panel and/or a general description.

Response

All figures and tables now have expanded legends followed by short descriptions.

Comment

References:Please make sure that your references comply with JoVE instructions for authors. Citation formatting should appear as follows: (For 6 authors or less list all authors. For more than 6 authors, list only the first author then *et al.*): [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. *Source*. Volume (Issue), FirstPage – LastPage, doi:DOI (YEAR).]
1) Please abbreviate all journal titles.

Response

References have been updated and journal titles have been abbreviated.

Comment

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Response

Trademarks for products replaced by generic product name thus footnotes no longer in text.

Comment

Please define all abbreviations at first use. Please use standard abbreviations and symbols for SI Units such as µL, mL, L, etc., and abbreviations for non-SI units such as h, min, s for time units. Please use a single space between the numerical value and unit.

Response

Abbreviations and symbols have been updated.

Reviewer 1

Comment:

1st half of paper very well written paper. Did not think the Protocol section was a good way to get the information across on the experimental set up and how the instrumentation worked. As written, I couldn't recreate the experiment, nor do I know how to interpret the results and apply it to the real world. Some significant experimental details missing (see below).

Response:

The protocol section is now modified to enable reader to recreate the experiment.

Comment:

No figure captions were attached to the article. Better images of experimental setup and flame video processing. Discussion of the figures needs to be improved.

Response:

We have added figure captions, better images of experimental setup, sample frames from experiment video and discussions of the figures. Please see the updated manuscript.

Additional Comments to Authors:

Comment

Table 1. Is the Crown Height, the distance between the bottom of the crown and the ground?

I would suspect it's not the top height of the crown relative to the ground surface, right?

Response

In Table 1, Crown Height represents the distance between the bottom of the crown fuel bed and the bottom of the surface fuel bed. The text introducing Table 1 has been updated to define all table parameters including the crown height.

____]’

Comment:

-could you include starting fuel moisture content in the table for fuel bed and crown canopy?

Response:

The fuel moisture was measured for each experiment but it was not controlled. This is now clarified in the manuscript. Range of fuel moisture across the experiments is now included in the text.

Comment:

*Protocol:

-This section is strange. Like a recipe for how to set things up? It reads like an undergrad lab class, listing to-do steps. I'd rather just learn how the instrumentation works and how the experiment was conducted.

Response:

It was our intention to enable the reader the reproduce the experiments in their labs as per the JoVE's editorial instructions.

Comment:

-Fig. 2 is hard to see what is going on. I just see some C clamps.

Response:

The figure is enhanced and the additional legend added for clarity.

Comment

-lines 165 to 178 - could you provide the density of the fuel load too. 2 kg of chamise is placed on a hanging platform, but how deep is the material, over what area is the material spread, etc. same with excelsior. 500 g over what depth and what area? over what downwind distance does the fuel cover?

Response:

Density is now given in the manuscript and updated diagrams provide more insight on the fuel bed configurations.

Comment

What is the geometric relationship between the surface fuels and the crown fuel? is there crown fuel immediately above all surface fuel? Lines 179-184 - where were the thermocouples actually placed (with respect to the fuels)?

Response

The crown fuels are immediately above the surface fuel. The manuscript has been updated with a description on the geometric relationship between both fuel layers and Figure 1 has been updated to depict the fuel bed arrangements. Also, new figure, Figure 4, is included to present the thermocouple arrangement.

Comments

Representative Results: (249-253) having a figure showing a frame from the video with notation showing flame height and angle would be nice.

Response

A new figure (Figure 5) showing a frame with flame geometry notation has been added.

Comments

-Are there captions that go with figures???

Response

Now we have included the figure captions in the body of the ms.

Comment

-some explanation of Fig. 3 is needed in text. this is not a pdf, correct? since it's frame number, it implies that the flames start small, get large, then decay with time? is that because the 500 g of surface fuel or the 2kg of crown fuel has been completely consumed? something else?

Response

For greater clarity the original time replaced the frame number in the x-axis of the flame height figure. Indeed, in a typical experiment the flames start small, the flame will get large close to the middle of the fuel bed then will decay with time as it gets closer to the end of the fuel bed. The experiment in the figure is Case F (wind at 1m/s and distance between crown and surface fuel at 70 cm). In this case, the wind helps the flame to tilt. Because of the flame tilt, radiative heat transfer of the flame to the fuel bed is enhanced, Albini (1985)31. As the flame travels through the fuel bed it will pre-heat the fuel ahead of it. The mid fuel bed seems to be an optimum location where sufficient preheating has occurred over a large amount of fuel to create a large flame. The end of the fuel bed is also pre-heated, however, the amount of fuel becomes limited so that less pyrolysis gases are released which results in decreased flame height. This is now clarified in the manuscript.

Comment

-Fig. 4. is this the average from many repeated experiments (if so how many)? or just one experiment? For what case (with or without wind, etc.)? Moisture content? What is the total burn time tf? it seems like this would be useful information, in addition to the normalized curve provided. just to be clear, this is for surface fuel only?

Response

The mass loss rate depicted in the figure represents data for the crown fuel bed. This was a Case F experiment (Wind at 1m/s, distance between surface and crown at 70cm). The fuel moisture content was 45%, relative humidity was 66% and the total burn time was 2.5 minutes. The manuscript has been updated with this information.

Comment

Fig. 5. Moisture content of fuel (are you assuming that fuel equilibrates with RH, that's why you are listing RH) Is that appropriate for live fuel? Just to be clear, no surface fuel, so instead of soaking the excelsior surface fuel bed (as explained in the Protocol section), you instead soaked the crown fuel directly? And what is the actual value of tf?

Response

We are listing fuel relative humidity to show environmental conditions at the time of the experience. Not necessarily indicating that the fuel moisture will equilibrate within the short experimental period. Regarding the surface fuel, the reviewer is right that no surface fuel was present, which means that instead of soaking the excelsior surface fuel bed we soaked the crown fuel directly. The actual value of tf for the mass loss curves are now listed in the manuscript.

Comment

-Fig. 6 What should I learn from Fig. 6 (as compared to Fig. 4, the other surface fuel plot)? Wouldn't information on tf help the reader understand what is going on better?

Response

We agree that information on tf would help the reader understand what is happening in the experiment, therefore we have now included this information in the manuscript. Thank you for bringing this to our attention.

Comment

Fig. 7: where are T10 through T15 located relative to the ignition location? why is T12 much hotter and T14 cooler? is the fuel inhomogeneous? For this no wind case, how does the fire move in this case. From the numbering of the T sensors, one could surmise that the fire is moving in a preferred direction. But should it, for a no wind case?

Response

Figure 4 with experimental setup has been added to clarify the thermocouple arrangement. Thermocouple T10 is placed in the leading edge of the crown fuel bed, T15 is near the back of the fuel bed. Thus, T12 is closer to the ignition location than T14. The temperatures in the crown are consequence of preheating from the surface fire from beneath and the crown fire development itself. Since in most of our experiments the surface fire would propagate faster than the crown fire, the superposition of the flames would occur only at the leading edge of the crown. This superposition would lead to higher temperature. However, this is not sufficient to explain the observed large variations in the crown temperature. Although, we would place the fuels as homogeneously as possible, the vicinity of individual thermocouples and their orientations relative to fuel branches was never the same. This radiative heating from the burning branches would introduce additional disparities in measured temperature at each thermocouple. This is now discussed briefly in the manuscript.

Comment

Fig 8. Where are the T sensors, how are they arranged? Why does the max Temperature decrease for T04, T08, T09?

Response

Figure 4 with experimental setup has been added to clarify the thermocouple arrangement.

Comment:

-Fig. 7 & 8: is there any rhyme or reason for choosing U=0 for Fig. 7 and U = 1 m/s for Fig. 8? i.e., they have different fuel "geometries", so no real way to compare the two cases.

Response:

Data in the original manuscript was presented as representative data as can be obtained through the methodology described. For Fig. 7 and 8, two separate cases were included as typical trends that can be obtained through different configurations of the experiment. We now realize that it is advantageous to show results that can be cross referenced such as mass loss for both the surface and crown layers for the same experiments. Per your comment and with this in mind, we have re-structured the way mass loss data is presented. Four representative experiments were selected, crown mass loss and surface mass loss data is now included for these experiments. Please see the updated manuscript.

Comment

-Could you show an overlay of surface fire and crown fire fuel mass vs. time and for for the same case with T sensors located at the same (x, y) location, as well as temperature vs. time?

Response

As an example of temperature vs time and mass loss vs time please see Figure 1 below. The representative experiment in the figure is a Class B experiment, that is an experiment modeling independent crown spread where no surface fuel bed was present. The arrangement of the thermocouples is presented in Figure 2. For brevity we did not include both plots in the manuscript.

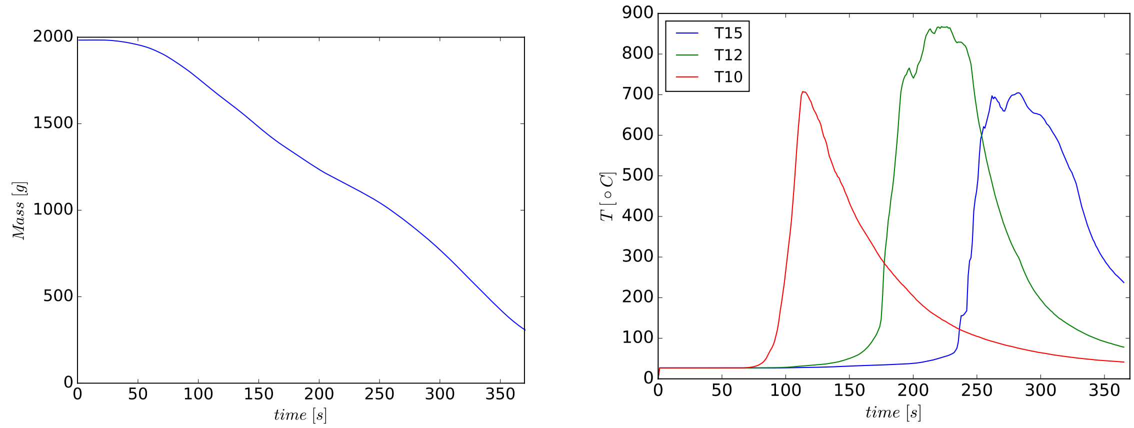

Figure 1 – Representative Class B experiment (a) crown mass loss trend (b) crown fuel bed temperature.

Comment

-Discussion section indicates that your results help us understand fire spread, but without some idea of where the T sensors are located, we can't figure that out from the information provided.

Response

Thank you for bringing this to our attention, to better navigate the reader through thermocouple location a CAD drawing of the fuel beds with thermocouple location labels has been added. For your reference that diagram is presented here as Figure 2 and in the manuscript as Figure 4.

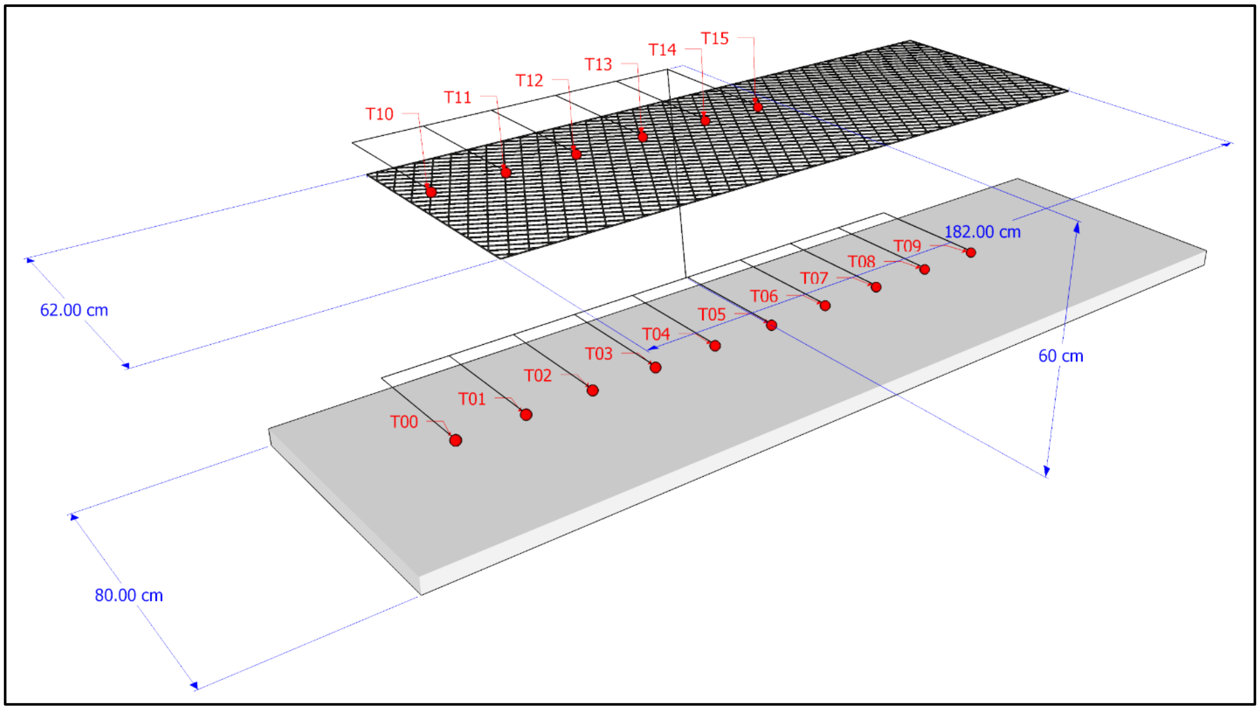

Figure 2 – Fuel bed diagram with thermocouple arrangement.

Comment:

You also mention importance of packing density in discussion, but this information is not provided in the document.

Response

The value of packing density is now included as 9.2 kg/m^3 per Omodan reference 30 (Omodan, Sunday. *Fire Behavior Modeling-Experiment on Surface Fire Transition to the Elevated Live Fuel*. University of California, Riverside, 2015)

Comment:

-Good list of references.

Response:

Thank you!

Reviewer 2

Comment:

This is an interesting, laboratory-based technique to study transition and spread for surface and crown fuels. It's useful to have this information in the literature. I have several comments, mostly relating to benefits and drawbacks of the technique that should be included for its broadest applicability and future work.

Response:

We are glad that the reviewer finds the manuscript informative.

Comment:

Major Concerns:

I would suggest stressing this is a laboratory technique. There are other techniques that focus on prescribed fires, etc. in the outdoors. There is a benefit for this being indoors that should be mentioned. I also suggest noting this in the title and the abstract, for instance "A laboratory technique to study chaparral fuels…". I would argue both laboratory and field measurements are worthwhile, but you will capture more measurements in the lab like this, they're just not necessarily 100% realistic.

Why isn't heat flux measured, particularly convective/radiative? Many papers have shown this to be important (e.g. Finney et al., PNAS). Should this be suggested as something that can be added in the future?

Response:

We agree with the reviewer that both laboratory and field measurements have advantages and shortcomings. This is now further stressed in the manuscript. Also, the abstract now clarifies that this is about laboratory techniques.

We also agree with the reviewer that having the heat flux measurements would definitely be advantageous. In the revised manuscript we added explanation of the relevance of directly measured heat fluxes (Finney, 2015) or indirectly inferring them (Tachajapong, 2009, 2014). At the initiation of the present study we did not have technical capability for heat flux measurements and had to proceed with the study by indirectly estimating heat release through fuel mass loss rate. Definitely, adding heat flux capabilities in the future is recommended. This is now added to the manuscript.

Comment

Regarding thermocouple measurements, details appear missing. What is the size, response rate, specific location, type, etc. Were radiation corrections applied? Can you include error estimates in the figure caption or figure itself? This is important if convective heating is important, which I assume is at this small scale with these fine fuels.

Response

Thank you for your comment. We agree that our manuscript benefits from a better description of the thermocouple array system we used in order to obtain temperatures. Thus, we have updated the manuscript with thermocouple specification including size, response rate, thermocouple location and type. We have also added a diagram with the thermocouple placement within the fuel bed configurations (Figure 2 here, Figure 4 in the manuscript).

Comment

Minor Concerns:

1. How do Mediterranean fuels differ from traditional canopy fuels? You cite Van Wagner, which has a theory for transition, but little mention is made. As far as I'm aware, there is no direct theory for spread in crown fuels, only rough correlations by M. Alexander that extend Rothermel's equations by a constant factor with a low R^2. So this additional data is very useful. This could help further motivate your paper and distinguish it from other crown fires.

Response

We agree that crown fire theory as the one presented by Van Wagner is quite relevant to our work. Following Van Wagner's crown fire categories, we observed that our experiments displayed some active and passive crown fire behavior but rarely did we see independent crown fire. For this manuscript we have added a brief discussion on Van Wagner's fire categories and we wish to continue our data analysis in the future in order to provide a bit more insight into how and why we observed these categories of fire and what is the significance of this. We hope this contribution will increase the body of knowledge on chaparral crown fire.

Comment

Other crown fires in tree stands also are ~100 feet + while yours are smaller. What is a typical height for chaparral fuels and how do your experiments compare with that?

Response

Typical chaparral crown height is anywhere between 3 and 6 ft (Countryman and Philpot, 1970). In our experiments distance from the surface fuel to the bottom of the crown was 2 ft to 2.3 ft. We selected crown-surface distance to address two different flame regions of interest: continuous flame and intermittent flame.

Comment

There are a number of outdoor measurements in the literature in similar types of fuel beds I think are worth citing. Some discussion of differences and advantages would be worthwhile.
a. https://doi.org/10.1016/j.firesaf.2006.01.006
b. https://doi.org/10.1016/j.firesaf.2008.06.004

Response

Thank you for bringing to our attention the works by Silvani *et al.* (2008) and Morandi *et al.* (2006). Indeed, such studies involved fuel beds similar to the ones in our study with the difference that their experiments were performed in the field whereas ours are laboratory scale. There are many advantages to both field and laboratory scale fire experiments including the ability to control wind speeds in laboratory studies and the ability to more precisely replicate the natural environment for field experiments. It is beneficial that the reader is aware of these differences and we have thus updated the manuscript with a brief discussion on laboratory versus field chaparral fire experiments.

Comment

Can other fuels than the ones you mention be used and tested in the same way?

Response

Yes, aside from chamise chaparral other types of chaparral fuels can be used and tested in the same way. In addition to chamise (*Adenostoma fasciculatum*), other chaparral fuels include manzanita (*Arctostaphylos glandulosa*) and hoaryleaf ceanothus (*Ceanothus crassifolius*). In the protocol chamise was the fuel chosen because as per Sun *et al.* it is the most flammable of these species. The protocol can be modified to include other species as long as the branch size is maintained below ¼ inch for uniformity. The manuscript has been updated to include this information.

Comment

How was moisture content of the fuels determined?

Response

Fuel moisture content was obtained by oven drying. Samples of fuel are collected prior to experiments and taken to an oven to be dried, fuel moisture is calculated from the initial sample weight and the final weight after drying. The manuscript has been updated to include fuel moisture calculation procedures.

Comment

Is the MATLAB script for flame height mentioned available with this document or based on previous work, e.g. Audoin et al?

Response

It is in house developed matlab script. We will be working with the editor to make the script available with the manuscript and the video.

Comment

Reference 24 appears to be incomplete.

Response

The reference is now completed.

Comment

Page 3, line 68-69 - what do the basket results have to do with spreading results, how do they compare? It was not clear by the tests.

Response

The basket experiments dealt with the burning characteristics of chamise as a chaparral fuel which we thought it would be useful for the reader since we also use chamise fuel. We indeed agree that these studies did not address spread but we hope that the spread studies we included by Tachajapong et al., Lozano et al., and Li et al., help illustrate works focusing on fire spread for chaparral fuel.

Reviewer #3:

Manuscript Summary:

The ms details a method for studying the behaviour and spread of fires burning through model fuels representing chaparral shrubs over litter in a small combustion wind tunnel

Comment

Major Concerns:

While the ms provides many details about the methodology used, it is rather poor in its presentation of results. Those presented do not allow direct comparison of the different components, seemingly selected at random instead of attempting to illustrate any particularly interesting point. Deficiencies in the methodology in regard to providing a consistent and uniform experimental design (i.e. fuel moisture content and fuel bulk density variations do not appear to have been identified by the authors but have been found to be quite important in fire behaviour studies elsewhere.

Response

Thank you for reviewing our manuscript and for the comments provided. In order to address the major concerns, we have re-formatted part of the representative results section as to allow comparison between datasets. The protocol section has also been updated. Please see the updated version of the manuscript. Detailed answers to comments in the PDF are provided below.

Comment

Minor Concerns:

Numerous comments and suggestions have been entered into the PDF of the ms for the consideration of the authors.

Response

The authors would like to express their gratitude for the comments on the PDF of this manuscript. Many improvements were made and references added based on these comments. Below are responses to those comments.

Comments

"Because of the regional Mediterranean climate…" Causality? Does chaparral occur in the Mediterranean region?

Response

This part is now rephrased.

Comment

"…which cover 5% of the land in the state…" Is this a large component of the vegetation? If not, why is it important here? Provide some bounds for your studies.

Response

Thank you for your question. Indeed, this information is not relevant from the methodology presented and it has been thus removed. Please see the updated manuscript.

Comment

All shrubs fit this criteria--is that enough to consider fires in this fuel a 'crown fire'? This statement needs a supporting reference.

Response

Thank you for your question. Chaparral fires are typically characterized as crown fires in the literature, a reference indicating this information has been added to the manuscript.

Comment

On "dynamics[3-11]": What is the purpose of this non-exhaustive list?

Response

We agree with the reviewer that the body of work on laboratory scale modeling of wildfires is vast. We believe these references are a good starting point for the reader interested in learning about laboratory

---

Comment

On "Lozano[5]" This work was carried out before reference 6, thus the narrative linking the two is incorrect. Lazy writing.

Response

Thank you for bringing this to our attention. We reworded this sentence in the manuscript.

Comment

On "…fire conditions.." Do you mean behaviour?

Response

Yes, we have updated the manuscript.

Comment

On "…topography, weather and fuel.." Provide a reference. See

Response

Reference has been added.

Comment

On "It has been shown that wind affects energy release rate in the fuels" Do you mean combustion rate?

Response

Yes, in this context energy release rate refers to the energy released through combustion.

Comment

This repeats lines 66-67 from the previous paragraph.

Response

Thank you for bringing this to our attention, we have corrected this in the manuscript.

Comment

On "Energetically, a fuel particle ignited if the amount of heat that it receives results in a mixture of gases that successfully react with oxygen". There needs to be initiation of thermal degradation reactions first that produce these gases--see Sullivan and Ball (2012).

Response

Thank you for providing this information on the thermal reactions producing the reaction gases described here. We have now included the Sullivan and Ball (2012) in the manuscript in order to direct readers to literature on chemical scale processes involved in cellulose burning.

Comment

On “Since 2001, we..”

Response

Thank you for your comment, this has been re-phrased in the updated manuscript.

Comment

On “Parameters measured include mass loss rate, fuel temperature, flame height, fuel moisture content and relative humidity of the ambient air.” What about air speed if, as per L77, wind is critical?

Response

Correct, we controlled for air speed. The manuscript has been updated in order to better clarify this.

Comment

On “..induced” applied? Induced would be that created by the fire.

Response

Thank you for bringing this to our attention, we have re-worded in the manuscript.

Comment

On “…the suspended fuel bed…” This aspect of the experiment needs to be introduced and discussed prior to this. It seems to relate to the previous work utilising 'baskets' which also were not properly explained for the uninitiated.

Response

The manuscript has been updated with an expanded description of the experimental setup.

Comment

Protocol comments

Response

There were several comments on the protocol, in order to address them and for greater clarity, we reformatted this section, added new figures and included new supplemental information.

Comment

On Representative Results “A custom MATLAB script…” This is all methods, not results.

Response

Thank you for bringing this to our attention, we agree that this should not be part of the results section. We have moved information about our processing script to the introduction section.

Comment

On “Fuel consumption rates were obtained for both fuel beds.” Where are these measurements in relation to the ignition line?

Response

Fuel consumption rates were calculated for the entirety of both fuel beds. The manuscript has been updated to clarify this.

Comment

On “…experimental time t and the total burn time t_f…” How are these determined? t_f needs to be defined.

Response

The total burn time is defined as the time when flaming combustion has stopped. We have updated the manuscript to clarify this.

Comment

On “…conducted on August 14th, 2015…” Why is this important?

Response

Based on your question, we re-evaluated the need for this information and realized that it is not relevant in the context presented. We have thus removed it and all similar calendar date information for experiments throughout the manuscript.

Comment

On "Figure 6 – Surface fuel mass loss for U = 1, surface-crown separation d = 60 cm (Class E)" How are these two figures meant to comparable if they are totally different conditions. What is the point of these two graphs if they are not meant to be compared? Can Figure 4, 5 and 6 be combined?

Response

The purpose of the data in the original manuscript was to show typical trends in the data obtained through the methodology described. We now realize it is advantageous to provide data that will allow for comparison between data sets. To address this issue we have presented the data in a new form on the updated manuscript. Mass loss for both the surface layer and crown layer for the same experiments are now presented, this allows for cross examination of the mass loss for both layers.

Comment

Comments on "Discussion"

Response

The authors would like to thank the reviewer for comments throughout the Discussion section. The new version of the discussion addresses comments.

Comment

There are a number of aspects of this methodology for which experimental uniformity does not appear to have been controlled and which would have significant effect on ability to replicate experiments. These include controlling or limiting effect of fuel moisture content (both of surface and crown fuels), and bulk density of fuel beds. These two factors have been found to be the most important after air speed in determining the behaviour of fire in a large range of fuels. Considering the variables that you have controlled, have you investigated the residual error in fire spread to identify whether these are capturing the bulk of the factors influencing the behaviour of your fires? See Mulvaney et al (2016).

Response

We agree that fuel moisture content and bulk density are important parameters for fire spread for both the crown fuel bed and surface fuel bed. In the protocol described by the ms, fuel moisture content (FMC) is measured for each experimental set but FMC was not one of the controlled parameters. Instead, we focused on the influence of wind, fuel bed separation and surface fuel bed presence on chaparral crown fire behavior. Indeed in the future, the methodology should be expanded to include fuel moisture content and fuel bulk density variations. We believe this is an important next step in the methodology described by the manuscript. In addition, experimental design of a study that includes fuel moisture and bulk density as controlled parameters would benefit from the analysis presented by Mulvaney *et al.* as this approach quantifies the variation of experiments which include fuel moisture, fuel particle diameter and fuel load as varied parameters.

References:

Countryman CM (1966) The concept of the fire environment. Fire Control Notes 27, 8-10.
Mulvaney JJ, Sullivan AL, Cary GJ, Bishop GR (2016) Repeatability of free-burning fire experiments using heterogeneous forest fuel beds in a combustion wind tunnel. International Journal of Wildland Fire 25, 445-455. doi:10.1071/WF15068.
Sullivan AL, Ball R (2012) Thermal decomposition and combustion chemistry of cellulosic biomass. Atmospheric Environment 47, 133-141. doi:10.1016/j.atmosenv.2011.11.022.