Hindawi
Journal of Combustion
Volume 2022, Article ID 5630594, 13 pages
https://doi.org/10.1155/2022/5630594

*Research Article*

# The Transition and Spread of a Chaparral Crown Fire: Insights from Laboratory Scale Wind Tunnel Experiments

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Received 5 November 2021; Revised 1 April 2022; Accepted 10 June 2022; Published 20 July 2022

Academic Editor: Benjamin Shaw



Fire occurring in the chaparral behaves as a crown fire, a dual-layer fire that typically ignites in a dead surface fuel layer and transitions to an elevated live crown layer where it continues to spread. In chaparral fuels including chamise, a dominant species in southern California, flame transition to live crown fuels is associated with higher spread rates and greater fire intensity. Despite the relative importance of surface-to-crown transition and crown fire spread, most fire models represent chaparral fire as surface fire, therefore omitting key behavior processes driving this fire system. The purpose of this study was to characterize transition and spread behavior in chaparral fires modeled experimentally as crown fires. We examined heat release rate in the surface and crown fuel layers, time to transition, flame height, and rate of spread in wind-driven and nonwind-driven fires at two crown base heights. Our results showed that wind increased heat release rate, rate of spread, and flame height. A marked increase in heat release rate was observed in wind-driven fires, where adding wind produced an increase from 328 kW to 526 for a crown base height of 0.6 m and from 243 kW to 503 kW for a crown base height of 0.7 m. Further, crown base height served to decrease heat release rate and rate of spread for wind-driven and nonwind-driven fires.

## 1. Introduction

Southern California is a naturally fire-prone region where fire and people have coinhabited the landscape for thousands of years [1]. The natural propensity for wildfire is shaped by harsh winds, highly flammable fuels, dry ambient conditions, and the presence of homes near the wildland [2]. In this region, fire propensity is coupled with rapid population growth which pushes human settlements closer to the wildland placing people and their property at risk in the event of a fire. Despite the endemic nature of fires, recent catastrophic megafires are potential indicators of shifts in the fire regime, which some would argue will continue to increase the occurrence and frequency of intense large fires [3].

The mechanisms shaping wildfire behavior in southern California are shaped in part by the fuel regime where due to the Mediterranean climate, the wildland is primarily dominated by chaparral shrubbery [4] which acts as the primary fuel for wildfires. Chaparral fires are typically categorized as crown fires [5], dual-layer fires which originate in dead surface fuels and subsequently transition to live crown fuels. The establishment of a crown fire potentially reduces the ability to control a fire [6] as crown fires are likely to spread much faster than surface fires [7]. Because a fire may intensify upon transition to crown fuels, the ability to identify conditions under which a fire will transition and spread in crown fuels is an important prerequisite for fire management and prediction.

Much of the work and fundamental knowledge on crown fire behavior has been developed by studying crown fire in coniferous fuels. Thus, works on fires in coniferous systems provide some guiding insights into the behavior of crown fires in chaparral fuels. In the case of drivers shaping transition behavior, early work by Van Wagner [8] proposed that a surface fire would bring crown fuels to ignition when supplying the minimum energy required to attain crown fuel ignition temperature at the crown base height. In this formulation, wind plays an important role as it can lead to surface fire intensity enhancement. Recent work has highlighted the importance of crown base height and surface fire burning zone conditions in driving a successful transition to the crown fuel layer [9]. Once a fire transitions, it may or may not spread through crown fuels. Spread behavior in the crown is completely or partially dependent on the surface fuel layer for the supply of energy and fuel mass for spread; special cases of crown fires will spread regardless of surface layer energy and mass supply [8].

Understanding the local chaparral fire problem involves integrating regional characteristics into the broader set of crown fire behavior principles. In the southern California case, wildfires are often paired with strong Foehn-type winds known locally as Santa Ana winds [10]. The role of wind as a fire driver is known from classical models of surface fire behavior [11–13]. In crown fires, wind affects flame transition [14] and spread. Recent works have addressed wind effects on chaparral fire behavior. Weise et al. [15] conducted experiments aimed at predicting successful flame propagation in elevated live chaparral fuel beds under the influence of slope and wind. Their results showed that wind is a strong predictor of spread success. Tachajapong et al. [16] built on such experimental work by modeling chaparral fires using discrete surface and crown fuel layers. They reported on the influence of wind on transition, surface fuel layer mass loss rate, and flame heights as surface fire behavior diagnostics. Li et al. [17] observed that wind speed influenced maximum fuel consumption and flame geometry in single shrub fuel beds modeled in a wind tunnel.

In addition to the influence of wind, thorough consideration of the regional fire problem involves attention to fuel properties. For instance, some studies have shown the importance of modeling chaparral fuels as live fuels in fire behavior analysis. Laboratory scale work by Sun et al. [18] found differences in mass loss rate, flame height, and heat release rate while burning chaparral fuels modeled as live fuels versus when modeling as dead fuels. This accentuated the need to model chaparral fuels as live fuels. Furthermore, perhaps one of the less studied parameters in chaparral crown fire behavior is crown fuel bed structure. Although it is known from classical crown fire theory that physical properties such as crown base height affect transition and spread behavior, there has been little experimental or analytical work done to study this for chaparral fire. Wind tunnel scale work has shown that placing the crown fuel bed within the continuous or intermittent surface flame regime may affect crown fire behavior. Tachajapong et al. [19, 20] and Lozano [21] investigated the effects of placing the crown fuel bed within the continuous or intermittent surface flame regimes on chaparral fires modeled as crown fires in a wind tunnel. Moreover, recent studies have examined the effects of changing the horizontal distance between adjacent crown fuel beds [21, 22] on transition and fluid flow behavior. These investigations showed that altering crown fuel bed configurations induced the formation of circulating vortices between fuel beds and increased vertical flow velocity.

Although various studies have examined chaparral fire behavior [23–25], most have modeled these fires as surface fires. However, when considering crown fire behavior, assuming a single fuel layer may not capture important energy and fuel mass exchange between the surface and crown fuel layers as is thoroughly exemplified in the Van Wanger model. This has motivated recent works that have experimentally modeled chaparral fires as dual-layer systems [16, 20, 21]. Findings there have shown that fuel structure and wind affect surface fire spread and crown fire ignition but have left characterization of crown fire spread for future work. Thus, the objective of this work was to model chaparral crown fires as dual-layer fires and examine spread behavior in both the surface and crown fuel layers. By studying chaparral fires as crown fires, we capture thermal energy and mass exchange influencing fire spread behavior in addition to the process of flame transition from the surface to the crown layer. In this way, the aim here is to study the effect of wind and crown base height on transition and crown behavior in order to obtain an improved understanding of the fire spread behavior and the degree of thermal interaction between fuel beds.

## 2. Methods

Experiments were conducted in a specialized wind tunnel located at the USDA Forest Service Pacific Southwest Research Station (see Figure 1).

Chamise chaparral was used to model the crown fuel layer. Chamise (*Adenostoma fasciculatum*) is a heterogeneous fuel consisting of branches and foliage. The shrubs have numerous branches covered by groups of small slender leaves 6 mm to 1.2 cm long; they are known to grow in single-species colonies or mixed with other chaparral [26]. For chamise chaparral, the thermal and physical properties are specific to the branch and foliage components. For the foliage, fuel particle density, surface-to-volume ratio, and heat of char combustion are $500\,\mathrm{kg\,m^{-3}}$, $8000\,\mathrm{m^{-1}}$, and $31.35\,\mathrm{MJ\,kg^{-1}}$, respectively [27]. The same properties for the chamise branches are $600\,\mathrm{kg\,m^{-3}}$, $1143\,\mathrm{m^{-1}}$, and $31.35\,\mathrm{MJ\,kg^{-1}}$, respectively [28]. The fuel bulk density was measured for the crown fuel bed during early testing [29]; the measured value was $9.2\,\mathrm{kg\,m^{-3}}$.

In the natural environment, when chamise sheds, it produces a litter layer [26]. This litter layer composed of dead fine fuels creates the surface fuel layer. A common fuel used to model dead surface fuels in chaparral fire studies (e.g., Morvan and Dupy [23], Dahale et al. [30], and Padhi et al. [22]) is excelsior (*Populus tremuloides*). Surface fuel beds constructed using excelsior have been used as alternatives for wind tunnel studies because they are typically uniform and thus offer fuel bed repeatability between experiments [31]. Thermal and physical properties of excelsior relevant to our analysis include fuel bulk density, fuel particle density, surface-to-volume ratio, and heat of char combustion which were assumed to be $3.13\,\mathrm{kg\,m^{-3}}$,

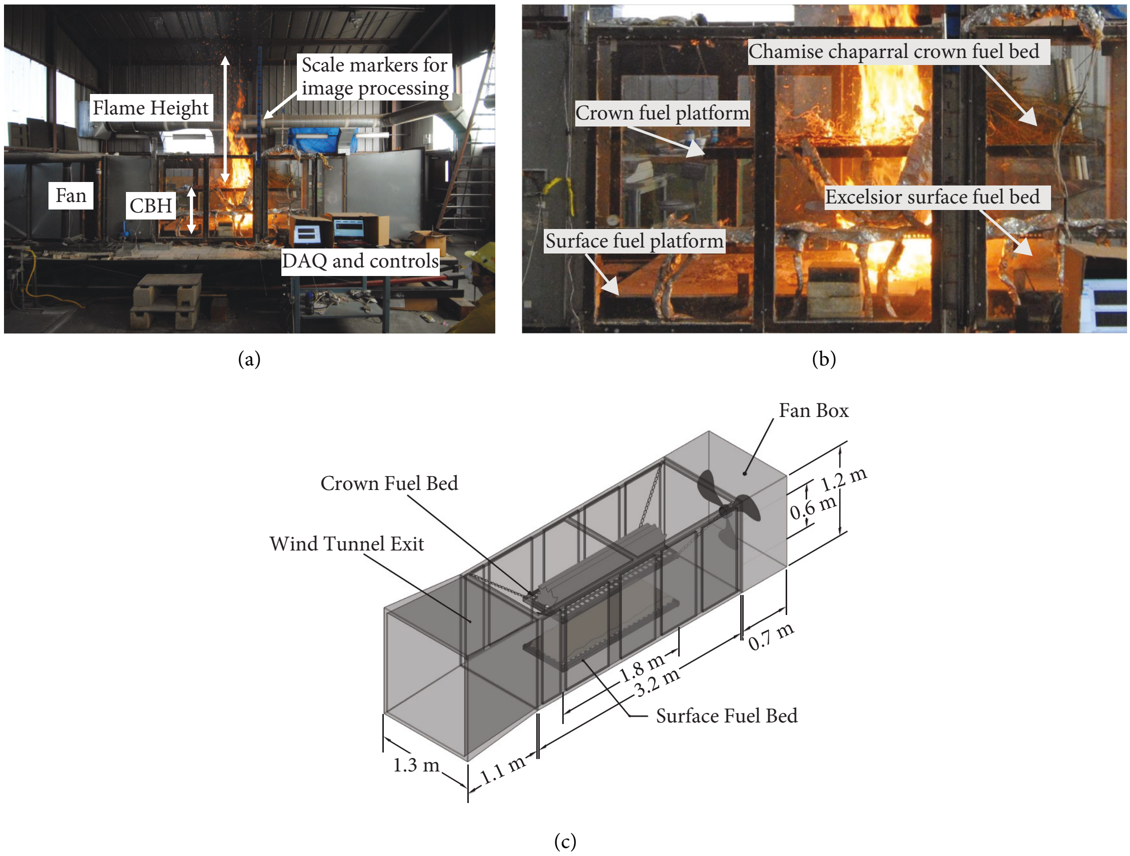



Figure 1: Experimental setup for wind tunnel experiments, from top to bottom: (a) complete experimental setup showing the location of the wind tunnel fan, data acquisition system (DAQ) and controls, crown base height (CBH) distance, flame height, and metal bar with markers used as a scale during image processing, (b) a close-up view of the test section showing the location of the crown fuel bed platform, chamise chaparral fuels, surface fuel bed platform, and excelsior surface fuels, and (c) schematic with part labels and dimensions.

$400\,kg\,m^{-3}$, $3092\,m^{-1}$, and $32.37\,MJ\,kg^{-1}$ respectively [27, 32].

To model chaparral fire as crown fire, some simplifying assumptions were made. First, as in Tachajapong et al. [19], no vertical continuity between the surface fuel bed and the base of the crown fuel bed was assumed, thus neglecting the existence of ladder fuels and generating a vertical distance between the surface fuel bed and the crown fuel bed, as in Albini [33]. The crown base height (CBH) was then the lowest height from the surface fuel bed where there was enough crown fuel to promote vertical movement of the fire to the crown fuels Scott and Reinhardt [6].

Fuel beds were constructed by using two distinct fuel beds, one for the crown fuel bed and one for the surface fuel bed (See Figure 1). The surface fuel bed was constructed by evenly spreading 0.5 kg of excelsior on a $0.80 \times 2.82$ m ceramic platform. The platform holding the surface fuel bed was placed over a Sartorius CPA 34001S (the use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service) scale to measure surface mass loss. Crown fuels were loaded on a $0.62 \times 1.82$ m platform built using a solid aluminum frame for the exterior perimeter and a hexagonal wire mesh for the interior area. The thin wire mesh allowed for flame contact as well as energy and fuel mass exchange. The crown fuel platform was mounted by suspending each corner from a load cell attached to the wind tunnel test section. The platform was centered over the surface fuel bed allowing approximately 0.5 m of space between the front and rear of the surface fuel bed. A custom load cell system was built to measure mass loss in the elevated crown fuel platform. The system consisted of four load cells with a resolution of 2.5 grams, a Wheatstone bridge for data acquisition, and a LabView program designed for controls and data preprocessing.

All experiments utilized 2 kg of chamise. Because chamise is a live fuel that will quickly lose water once the fuels are cut from the plant, it was harvested no more than 24 hours prior to an experiment and stored in a cool, dark place to minimize moisture loss. Fuel moisture was measured but not controlled for both the surface and crown fuel layers. Thus, this work did not examine the effects of fuel moisture on transition and crown fire behavior. Moreover, when preparing crown fuels for burning, we trimmed and disposed of branches larger than 6 mm in diameter. Thus, the fuel bed consisted of live branches and foliage less than 6 mm. Fuel moisture content (dry mass basis) was determined by drying samples in forced convection to a constant mass [34].

An experimental run was ignited by first soaking the excelsior fuel bed leading edge, defined as the edge closer to the wind tunnel inlet, with denatured ethyl alcohol. Once the excelsior fuel bed was soaked with alcohol, a butane torch was used to ignite a line fire along the fuel bed leading edge. Upon igniting, the surface fire would be allowed to spread. As the surface fire would spread, the flame would eventually move vertically and transition to the crown fuel bed. The fire was allowed to continue spreading in both layers until both the crown and surface fuels were extinguished at which point the experiment was deemed finished.

Ambient temperature and relative humidity were measured prior to each experiment using a wet bulb hygrometer. Four experiment treatments were used to quantify the effect of wind and surface-crown base height. Table 1 summarizes the experimental parameters in each treatment. In these experiments, the crown fuel bed was placed in two locations, the continuous or the intermittent surface flame region. The continuous and intermittent flame region heights were previously determined for this experimental setup by Omodan [29]. The procedure followed there was built upon works by Lozano et al. [35] and Tachajapong et al. [20] in which the intermediate and continuous regions were determined for previous versions of the setup by examining experiment videos. The continuous region was defined as the region from the surface fuel to the minimum surface flame height whereas the intermittent flame region was determined as the region from the minimum surface flame height to the maximum surface flame height (Lozano et al. [35], Omodan [29]). For this experimental setup, the resulting continuous and intermittent regions corresponded to heights of 0.6 m and 0.7 m, respectively. These two heights were used as the crown base heights.

Each experiment was repeated 4–6 times on average. Of the treatments, only experiments that exhibited sustained ignition and spread in the crown fuel layer were used in the analysis of crown flame height and crown mass loss rate.

*2.1. Image Processing.* Flame height is defined as the total height of the crown flame, from the base of the crown fuel bed to the tip of the crown flame. The surface flame height is the height of the surface flame, from the base of the surface fuel bed to the tip of the surface flame. The surface fuel flame height is limited by the crown base height, which is set to 0.60 or 0.7 m depending on the experiment. In most experiments, the surface flame quickly achieved a maximum flame height equal to CBH, for this reason, and because of the minimal amount of variation in this parameter, it is not further discussed in the results sections of this work. A MATLAB algorithm developed in-house and described in [36] was used to obtain flame height from experiment videos. Furthermore, an algorithm was developed to calculate the surface fire rate of spread from experiment videos by identifying and tracking the leading edge of the surface flame. Flame tilt was obtained via the image processing software ImageJ. The steps in the algorithm developed to obtain the rate of spread are now briefly described and depicted in Figure 2.

Image processing for the rate of spread calculation was done using the OpenCV library in Python. Before processing, the video is cropped to only show the view of the surface flame; the area of interest is shown in Figures 2(a) and 2(b). After cropping, RGB images are converted to black and white intensity images through a process of masking which isolates a specific color range between white (HSV: 0°, 0%, 100%) and light orange (HSV: 20°, 29%, 100%). Any pixels in that range will be masked. Once the image is converted to a black and white image, we calculated the bounding rectangle of the mask. The bounding rectangle is obtained with the contours of the mask. Contours of the mask are obtained with OpenCV's find contours function. To avoid sporadic jumps in the leading-edge detection, contour bounding rectangles over 40 pixels in the area will be counted toward the final bounding rectangle of the flame. The final bounding rectangle, Figure 2(d), of the mask can be derived from finding the minimum and maximum coordinates of the edges out of all the contour bounding rectangles that are over 40 pixels in the area. Since the leading edge is ultimately the right-most bottom point of the fire—and the video is already cropped toward the bottom of the fire—the leading edge of the fire can be tracked with the right side of the bounding rectangle. The red line in Figure 2(e) represents the fire's leading edge. Each video is run through the algorithm and exported to a CSV file. The file contains how far the leading edge was on the $x$-axis in pixels, paired with the frame number of the video.

For instances where a full view of the flame was obstructed or there were issues with camera orientation, manual cropping of each video was conducted. Moreover, to compensate for cases with overexposure to the camera, interpolation was conducted using autoregressive modeling. Times where the view of the fire was distorted or blocked were recorded. Recorded leading-edge values during the problematic range of time were replaced with null values during postprocessing. To predict the fire's leading edge even if it was blocked from view, autoregressive modeling is used to predict the null values. Concisely, data before and after the problematic range of time are used for prediction. Smoothing was performed to remove noise. Pixel values were converted to centimeters by using a scale placed in all videos. The result of this image processing routine was the rate of spread of the surface flame throughout the experiment (the flame's leading-edge speed) in centimeters per second.

## 3. Results and Discussion

*3.1. Time to Transition.* A surface-to-crown transition was considered successful and recorded if it led to sustained ignition followed by flame spread through the crown fuel bed. Instances where transition did not lead to sustained ignition and fire spread thereafter were considered unsuccessful and were not included in the analysis. For most experimental classifications, only a single transition moment was observed. Only for the classification of experiments without wind and a crown base height of 0.7 m, over 50% of experiments in that category exhibited multiple ignition points.

Table 1: Summary of experimental parameters for the four experimental treatments considered.

| Experimental parameters | | | | |
|---|---|---|---|---|
| Wind condition | Wind at 1 m/s | | No wind | |
| Crown base height (CBH) | CBH1 = 0.6 m | CBH2 = 0.7 m | CBH1 = 0.6 m | CBH2 = 0.7 m |

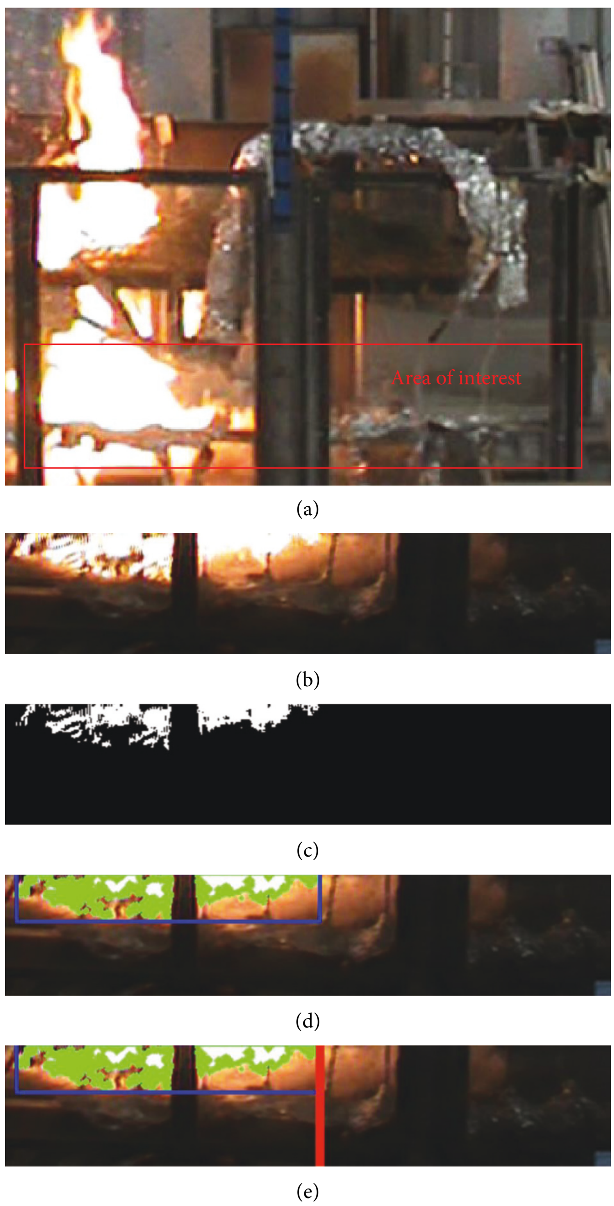



Figure 2: (a) Raw flame image. (b) Cropped flame region of interest. (c) Binary image. (d) Final bounding rectangle. (e) Identification of leading edge.

As can be observed in Figure 3, when comparing transition behavior for cases at the same crown base height, it was found that at CBH = 0.6 m, on average, the presence of wind decreased the time to transition, whereas in the cases at CBH = 0.7 m, the presence of wind increased the time to transition. For experiments where the crown fuel bed was placed closer to the surface fuel bed, (CBH = 0.6 m), adding wind decreased the time to transition. On the other hand, in experiments where the crown fuel bed was placed further away from the surface fuel bed, (CBH = 0.7 m), adding wind increased the time to transition.

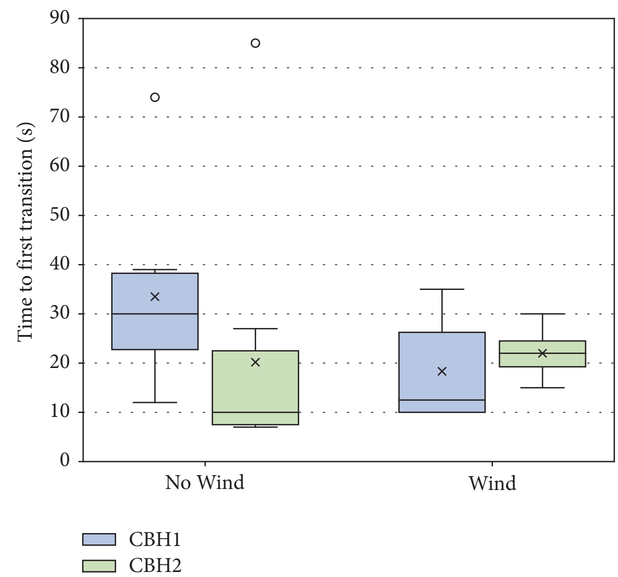



Figure 3: Time to first sustained surface-crown transition for nonwind-driven and wind-driven fires at the two examined crown base heights, where CBH1 = 60 cm and CBH2 = 70 cm; the symbols outside of the box plots for the nonwind cases are outliers.

*3.2. Heat Release Rate.* The heat release rate was obtained from the mass loss rate by using the equation in

$$\text{Heat release rate} = \text{mass loss rate} * H. \tag{1}$$

For fuel where $H$ is the heating value for each fuel, the heat of combustion value or heating value for chaparral or chamise fuel is used 14.71 kJ/g and for surface or excelsior is used 14.20 kJ/g. Heat release rates in the crown fuel layer for nonwind-driven experiments are presented in Figure 4. In nonwind-driven fires conducted under a crown base height of 0.6 m, the maximum heat release rate was 328 kW. In experiments conducted under a crown base height of 0.7 m on the other hand, the maximum heat release rate was 243 kW. Overall, it can be observed that the heat release rate for nonwind-driven fires was lower than for wind-driven fires, and the peak heat release rate occurred later in the fire than for wind-driven fires. For instance, in wind-driven fires conducted under a CBH1 = 0.6 m, the maximum heat release rate was 526 kW. In experiments conducted under CBH2 = 0.7 m on the other hand, the maximum heat release rate was 503 kW.

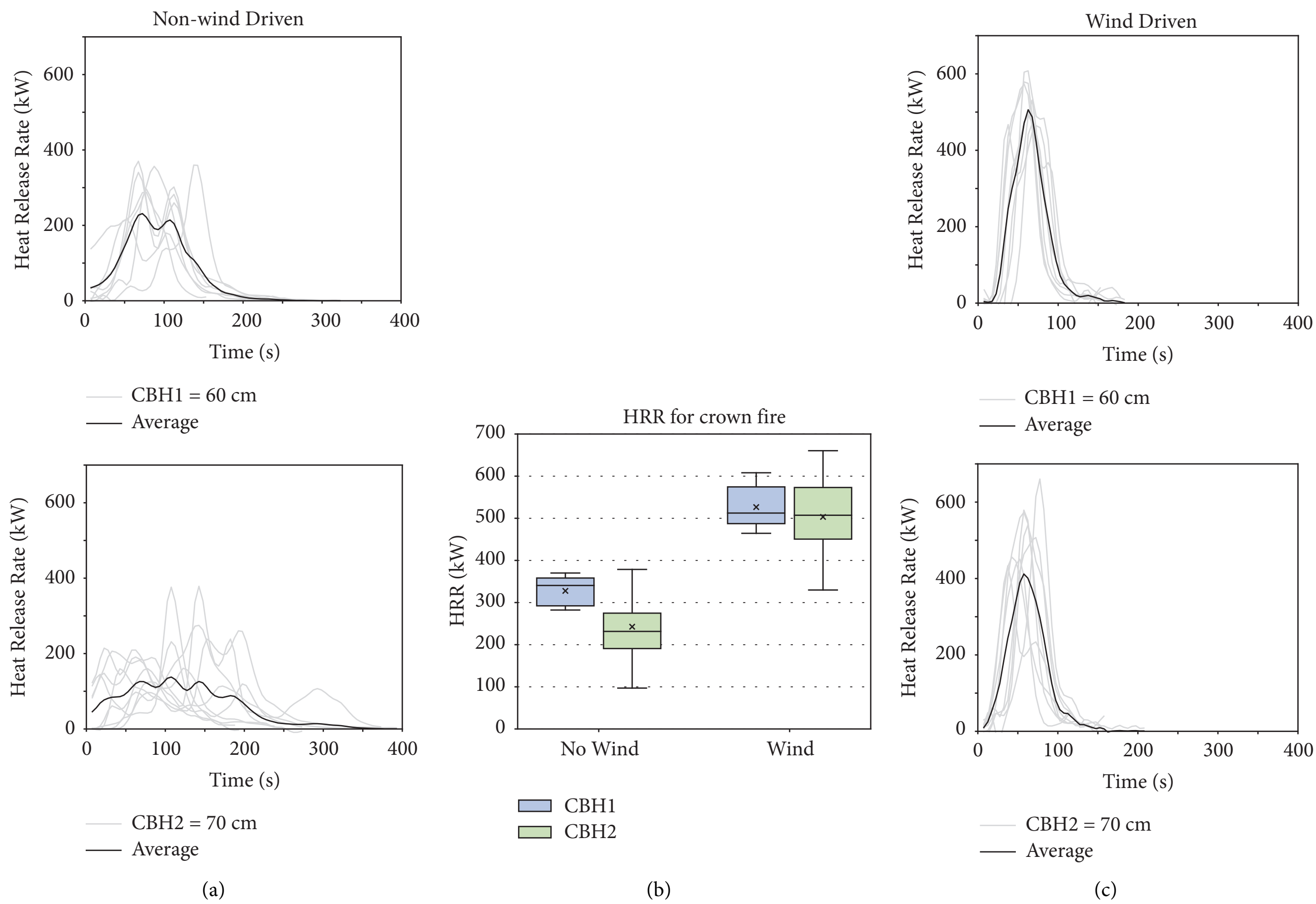


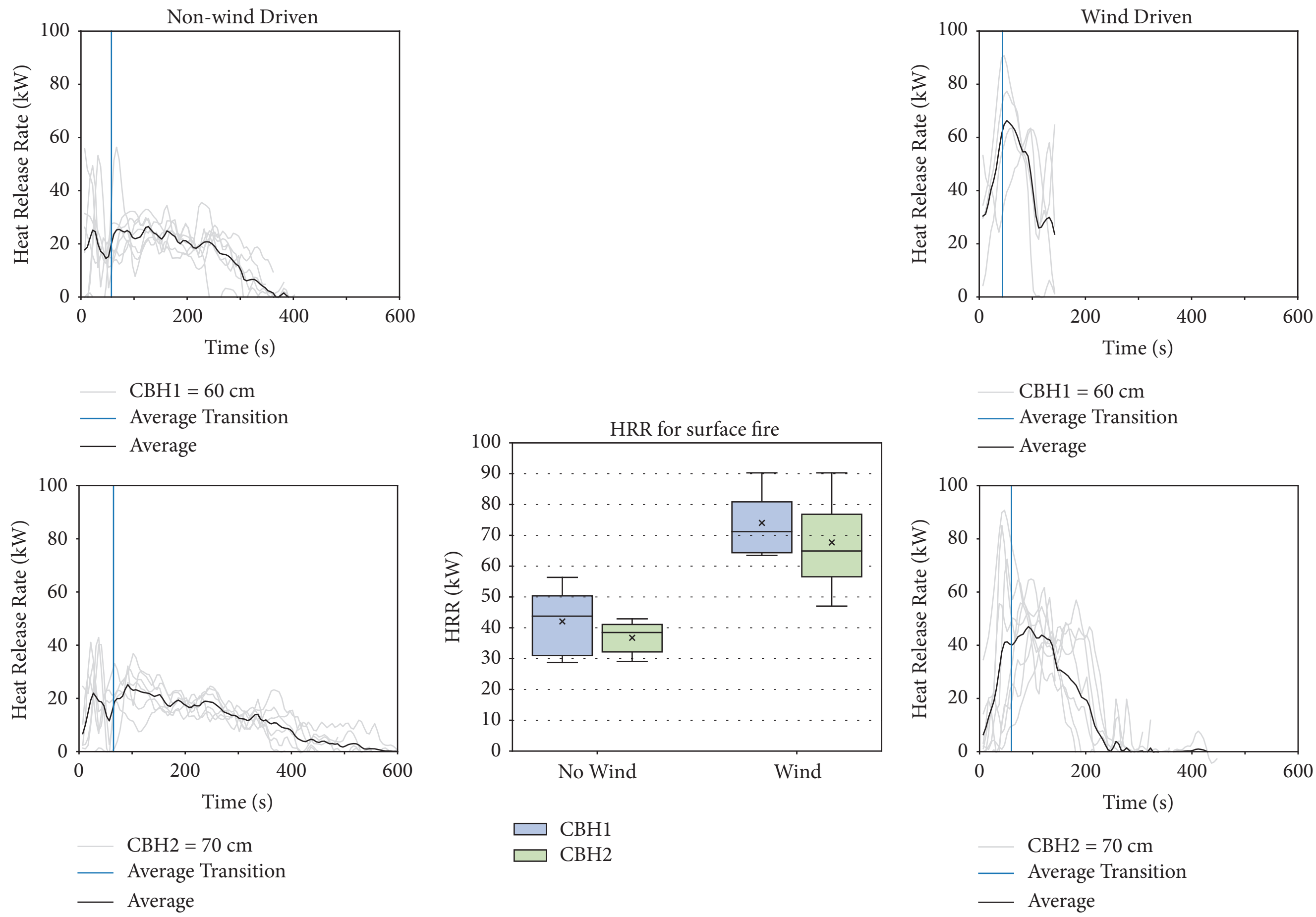

Figure 4: Crown fire heat release rate in nonwind-driven fires (a), wind-driven fires (c), and the box and whisker plot with average heat release rate for all experiments (b). For the box plot, the cross represents the mean, the horizontal bar represents the median, the bottom of the box represents the 25th percentile, the top of the box represents the 75th percentile, the bottom of the whisker is the minimum data point, and the top of the whisker is the maximum data point.

Heat release rates exhibited by surface fires were lower than those in crown fuel fires for all cases. The peak heat release rate achieved by all surface fires was 77 kW whereas the peak heat release rate by crown fire was 526 kW. Much like in fires spreading through the crown fuel layer, the maximum heat release rate in surface fuel layer fires varied for wind-driven and nonwind-driven fires. In nonwind-driven surface fires, the maximum heat release rate in fires conducted at a CBH1 = 0.6 m was 42 kW whereas for those conducted at 0.7 m was 35 kW (Figure 5). In wind-driven fires, on the other hand, the maximum heat release rate was 74 kW and 67 kW for fires conducted at a surface-to-crown distance of 0.6 m and 0.7 m, respectively.

*3.3. Rate of Spread.* The rate of spread was measured using the computer vision algorithm described in the Methods section. Results from the surface rate of spread calculations are presented in Figure 6(a). There, it can be observed that wind-driven fires exhibited the largest rate of spread for the duration of the fire. In nonwind-driven fires, the rate of spread was an average of 1.121 cm/sec for experiments conducted at a CBH1 = 0.6 m and 0.915 cm/sec for experiments conducted at a CBH2 = 0.7 m. In the case of wind-driven fires, the average rate of spread was 2.969 cm/sec for experiments conducted at a CBH1 = 0.6 m and 1.687 cm/sec for the experiment conducted at a CBH2 = 0.7 m.

Results from the crown flame rate of spread calculations are presented in Figure 6(b). Wind-driven fires exhibited higher spread rates than nonwind-driven fires. The crown spread rate of nonwind-driven fires at CBH = 0.6 m was an average of 1.08 cm/sec whereas at CBH = 0.7 m the spread rate was 1.03 cm/sec. In the case of wind-driven fires at CBH = 0.6 m, the average spread rate was 3.58 cm/sec while at CBH = 0.7 m the spread rate was 2.45 cm/sec.

As can be observed in the results here, increases in crown base height served to decrease both heat release rate and rate of spread in all fuel beds. Insight into this behavior can be achieved by comparing the results to the results in Tachajapong et al. [20] where a similar dual-layer chaparral fire system was tested. By experimentally measuring and modeling conditions at the base of the crown fuel bed, they established that gas temperatures decreased with increasing crown base height. In such study, the dampening of temperature and convective heating led to a reduction of




(a) (b) (c)

FIGURE 5: Surface fire heat release rate in nonwind-driven fires (a), wind-driven fires (c), and the box and whisker plot with average heat release rate for all experiments (b). For the box plot, the cross represents the mean, the horizontal bar represents the median, the bottom of the box represents the 25th percentile, the top of the box represents the 75th percentile, the bottom of the whisker is the minimum data point, and the top of the whisker is the maximum data point.

successful surface-to-crown flame transition. In the experiments here, although transition did occur, we postulate that the same physical phenomenon served to decrease the heat release rate in the crown fuel layer. This is because gases emerging from the surface fire likely decreased in temperature when the crown base height increased. As the thermal energy delivery to the crown decreased so did fuel bed preheating and overall thermal energy flux required for flame advancement, thus producing a reduction in the rate of spread and heat release rate. In addition, the lower heat release rate and spread rate measured in the surface fire further explain the reduction in thermal energy supplied by the surface fire to the crown at this configuration.

The results showed that, overall, the rate of spread increased with the wind as expected according to classical spread theory [11–13]. Moreover, wind acted to promote flame tilt angles more favorable for enhanced radiative heat transfer where previous models [37–40] have effectively applied classical heat transfer principles to show the correlation between radiative heat transfer in fire spread to flame tilt angle. We propose that in the experiments here, the enhancement in radiative heat transfer to unburned fuels served to promote favorable heat release and rate of spread in the crown fuels.

To better understand the tilt in flame angle exhibited in the experiments here, we compared the flame tilt of experiments conducted at a crown base height of 0.6 m with and without wind. During the initial stage of the burn, the first 30 seconds after ignition, the surface flame tilt was nearly vertical at an average of 90 degrees in cases without wind whereas in cases with wind, the surface flame tilted to an average of 72 degrees from the horizontal. In the case of the crown flame, we examined the initial stage of crown fire spread, the first 30 seconds after surface-to-crown transition, and found that the crown flame tilted to an average of 96 degrees from the horizontal in cases without wind. In cases where the wind was added, the flames tilted to an average of 74 degrees from the horizontal. The analysis of flame tilt confirms that flame tilt was fostered by wind speed for both flames. The tilted flames in wind-driven fires provided conditions for favorable radiative heat transfer to the unburned fuel ahead of the fire thus contributing to a greater rate of spread and heat release rate.

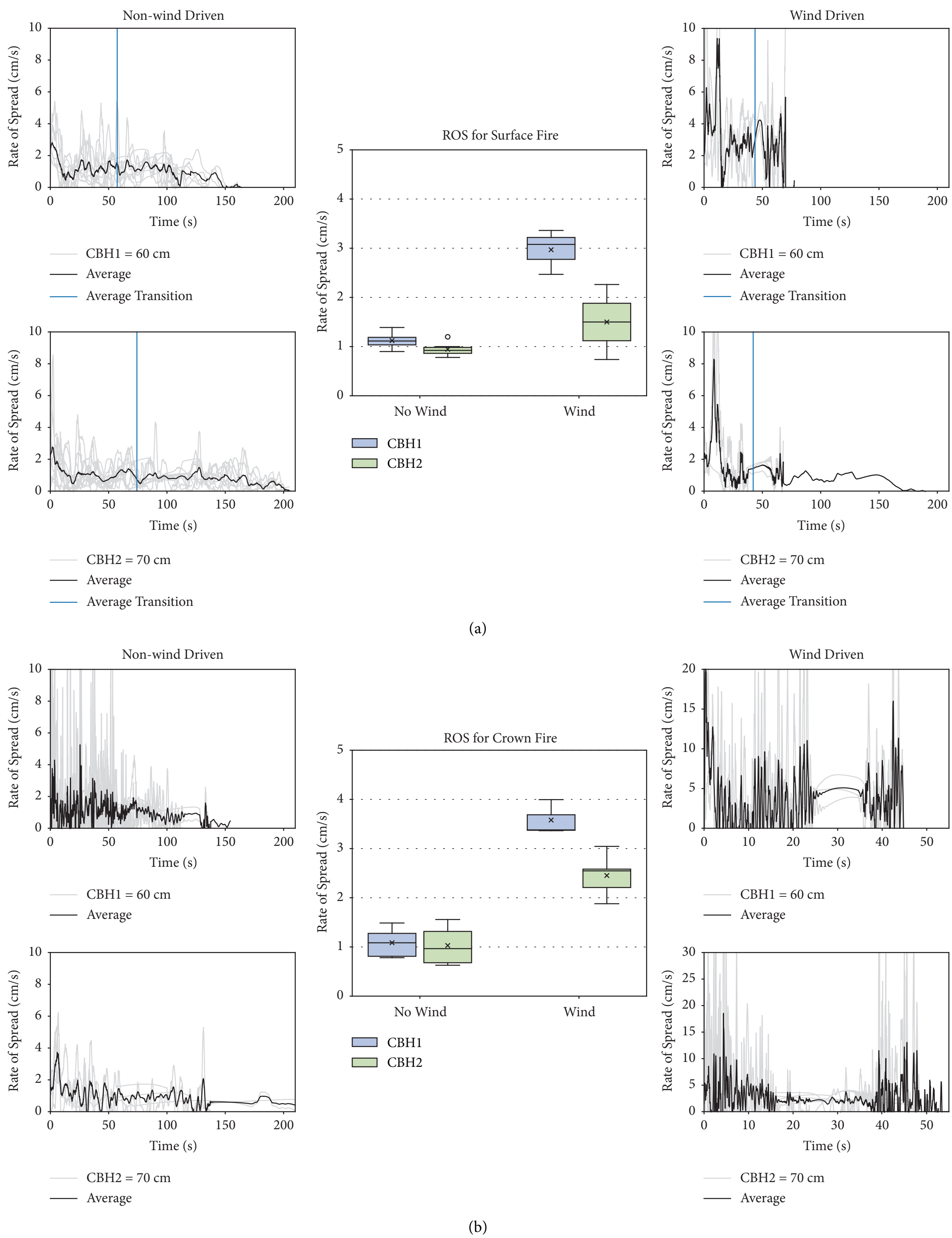



Figure 6: Rate of spread behavior in (a) surface fires and (b) crown fires. Rate of spread in nonwind-driven fires (left columns), wind-driven fires (right columns), and a box and whisker plot for the average rate of spread for all experiments (middle). On the box and whisker plot, the black line represents the median and the black “$x$” represents the mean.

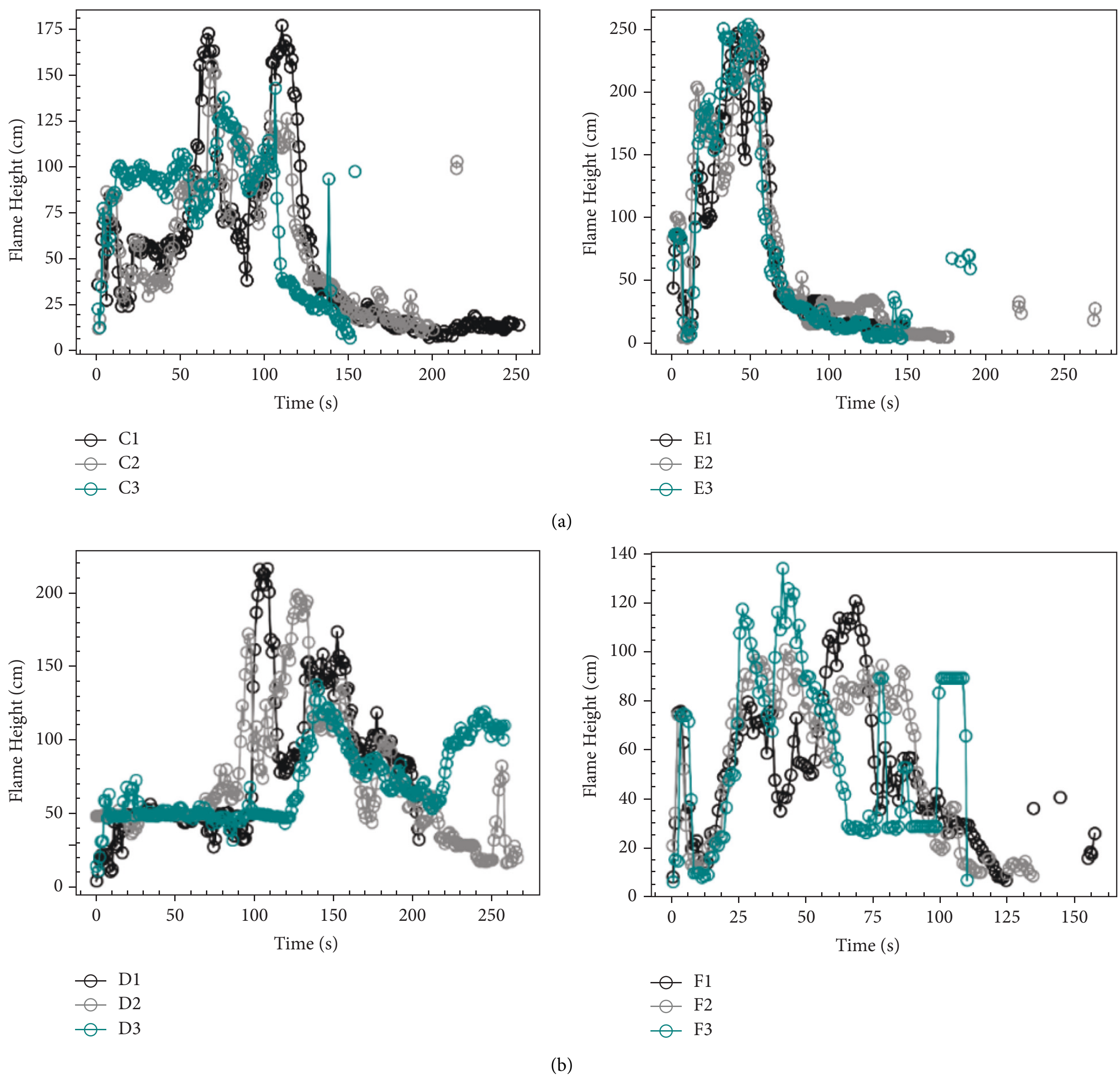



Figure 7: Time evolution of crown flame height in experiments with CBH = 0.7 m under wind conditions. (a) No wind. (b) $\overline{U} = 1$ m/s. Initial time, $t = 0$, is set as the time at the transition to the crown layer for each experiment. Experiments C1 and F3 are representative experiments for each experimental configuration.

*3.4. Flame Height.* The effects of crown base height and wind on flame height value for each experimental condition are shown in Figure 7.

Overall, in wind-driven fires, increasing crown base height decreased maximum flame height whereas the opposite was true for the no-wind cases. For the higher bound of the separation between fuel beds, CBH = 0.7 m, the maximum flame height was an average of 184 cm for cases without wind and 119 cm for cases with the wind. For the crown fuel bed at the lower bound of separation (CBH = 0.6 m), the maximum flame height was an average of 159 cm for cases without wind and 248 cm for cases with the wind. Thus, at CBH = 0.6 m, the analysis of flame heights showed a behavior similar to that of that observed for heat release rate and rate of spread where adding wind enhanced the fire spread behavior by producing larger flame heights. However, at CBH = 0.7 m, the crown flame height did not increase with the wind but decreased. In this case, surface heat release rate and rate of spread decreased with the wind which indicates a decrease in thermal energy production by the surface fuel layer. As a consequence, there was a reduction in the amount of thermal energy available for

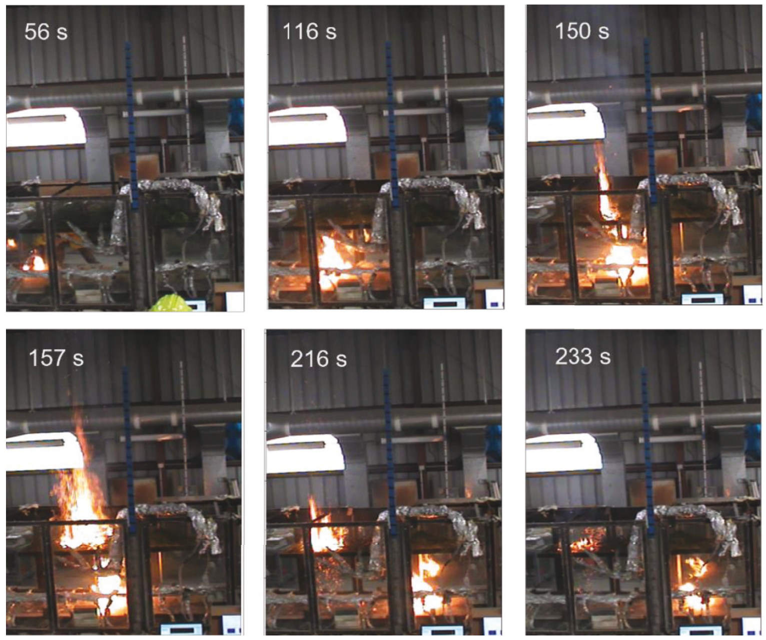



Figure 8: Special case of marginal spread at CBH = 0.7 m and no wind. The progression of images extracted from the experiment video shows the transition location, the development of the crown flame, and the eventual natural extinguishing of the flame which leaves a considerable portion of the fuel bed unburned.

delivery to the crown fuel layer which likely contributed to a reduction in overall spread behavior including flame height, rate of spread, and heat release.

*3.5. Special Cases of Crown Fire Spread: Marginal Spread and Spread in the Absence of a Surface Fuel Layer.* To better understand the mechanisms controlling crown fire spread, two special cases were analyzed, marginal spread and chaparral crown fires modeled without the presence of a surface fuel layer. Cases with marginal spread were those in which although successful surface-to-crown transition was achieved, limited or nearly negligible spread occurred in the crown. Two experiments conducted at a CBH = 0.7 m and without wind exhibited this behavior. The first experiment of this type is presented in Figure 8. In this case, the surface-to-crown transition was noticeably delayed. At transition, a full crown flame formed but did not travel forward considerably; instead, the flame grew in width and length to reach and consume some of the unburned fuel behind it. The flame diminished after a short period leaving a significant portion of the fuel bed unburned. In the second case with marginal crown spread, although the surface-to-crown transition was achieved at the leading edge of the fuel bed, the flame was short-lived, and the fire naturally extinguished without notable spread thus leaving most of the crown fuel unburned.

To better understand the mechanisms leading up to marginal spread through the crown fuel layer in the cases mentioned above, we compared the rate of spread of the surface fuel layer before and after the surface-to-crown transition. It was found that the two cases above exhibited a slower pretransition surface fire rate of spread, 0.89 cm/s and 1.9 cm/s, respectively, as compared to the average pre-transition spread rate of 3.3 cm/s for experiments exhibiting successful spread throughout the crown fuel layer. Given that rate intensity and rate of spread are correlated by the Byram fire intensity [41], these results seem to indicate that the marginal crown fire spread was likely a result of a weaker surface fire that was unable to supply sufficient thermal energy necessary for successful crown fire spread.

The examples above illustrate the role of the surface fire in controlling crown fire spread in chaparral crown fires. To better understand the role of the surface fire, we analyzed results from a series of experiments conducted without the presence of a surface fuel layer with and without the presence of wind. In the absence of a surface fuel layer, the crown fuel layer was ignited directly by following the same ignition protocols described in the Methods section for the surface fuel layer. In experiments conducted without a surface fuel layer and without wind, none of the experiments spread successfully thus showing the importance of a surface fuel layer in igniting the crown fuel layer in the absence of wind. On the other hand, successful crown spread was observed in cases without a surface fuel layer conducted under the presence of wind. Overall, both experiments conducted without the presence of a surface fuel layer but under the presence of wind exhibited a lower heat release rate (average = 101 kW) than the average heat release rate exhibited by wind-driven fires conducted with a surface frown fuel layer present, 526 kW for CBH = 0.6 m and 503 kW for CBH = 0.7 m. Moreover, in the two wind-driven experiments conducted without the presence of a surface fuel layer, the crown fire spread rate was 0.29 cm/sec and 0.19 cm/sec, respectively. The observed spread rates for these cases were substantially

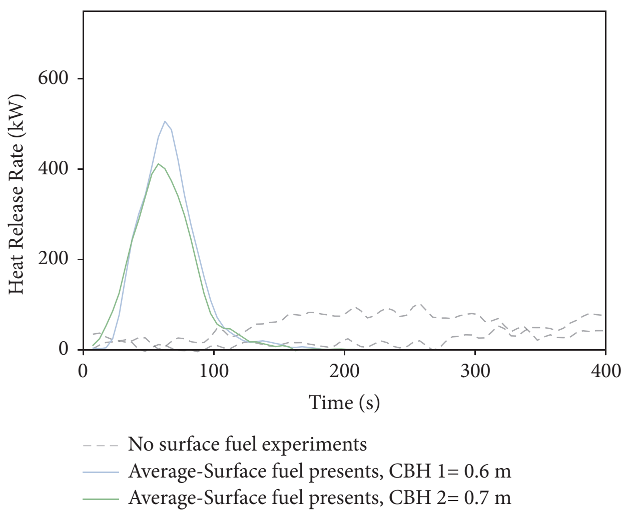



Figure 9: Crown fire behavior of wind-driven experiments conducted with a surface fuel bed (solid lines) and without a surface fuel bed (dashed lines).

lower than that of wind-driven experiments conducted with both a surface and crown fuel layer which exhibited average spread rates of 3.58 cm/sec (CBH = 0.60 m) and 1.52 cm/sec (CBH = 0.70 m).

Overall, wind-driven experiments conducted without the presence of a surface fuel layer exhibited a lower heat release rate (Figure 9) and slower flame spread rate than wind-driven fires conducted with a surface fuel layer. Thus, from the results presented here, it can be observed that the lack of a surface-crown fuel layer served to deteriorate crown fire behavior. As a consequence, these results highlight the role of the surface fire in propelling the crown fuel layer in chaparral fires. The role of the surface fire in contributing to crown fire spread is well known from early work by Van Wagner (1972) which describes the surface fire as providing supplemental fuel mass and heat flux for crown fire advancement. In this way, the experiments presented here show that the surface fire likely served to preheat unburned crown fuels ahead of the combustion zone thus facilitating crown fire spread. In the absence of a crown fuel layer, the fire behavior is diminished due to the lack of energy delivery from the surface fire.

## 4. Summary and Conclusions

A wind tunnel study of chaparral crown fire behavior was designed to investigate transition and fire spread behavior. Chamise chaparral was used as a crown fuel while excelsior was used to simulate dead fuels in the surface fuel layer. The influences of crown base height and wind on time to transition, heat release rate, rate of spread, and flame height were examined. A summary of the results is presented in Table 2.

In examining chaparral fire as crown fire, we followed similar wind tunnel studies (e.g., [19, 21]) in modeling a chaparral fire by using separate fuel beds for the crown and surface fuel layers. This is to capture energy and fuel mass exchange typical of crown fires. Our model setup was constructed by considering simplifying assumptions, namely, neglecting ladder fuels, representing dead fuels by excelsior, and considering a continuous canopy fuel layer. This enabled us to focus on a limited number of experimental variables and their effects on important features of crown fire behavior, that is, transition and crown fire evolution. The experiments were conducted during the southern California fire season under ambient conditions. Further, experiments were conducted during fire season, which takes place in the summer-fall time, fire conditions are characterized by high ambient temperatures and low relative humidity. Thus, the results presented can be considered applicable for such conditions. Future studies may focus on exploring other seasonal cycles with controlled environmental conditions as well as fuel moisture content.

Table 2: Summary of results for the maximum values for each experimental category.

| Average from the maximum values in each experiment: | | | | |
|---|---|---|---|---|
| Wind condition | Wind at 1 m/s | | No wind | |
| Surface-to-crown | 0.6 m | 0.7 m | 0.6 m | 0.7 m |
| Flame height (cm) | 245 | 119 | 159 | 184 |
| Surface heat release rate (kW) | 74 | 67 | 42 | 35 |
| Crown heat release rate (kW) | 526 | 503 | 328 | 243 |
| Surface rate of spread (cm/s) | 2.70 | 1.70 | 1.12 | 0.91 |
| Crown rate of spread (cm/s) | 3.58 | 2.45 | 1.08 | 1.03 |

Our results showed that wind enhanced fire spread behavior as was shown by the increase in heat release rate, rate of spread, and flame height in wind-driven fires as compared to nonwind-driven fires. Further, we found that increasing crown base height served to decrease heat release rate and rate of spread for wind-driven fires. Increasing the crown base height decreased flame height only for wind-driven fires. We argue that decreases in heat release rate and rate of spread with increasing crown base height were associated with enhanced fuel mass and thermal energy delivery to the crown which enhanced the crown fire behavior. The results here highlight the role of the fuel layer structure in chaparral fire spread as can be explained by the variations in behavior with crown base height. Wind acted to promote fire behavior thus emphasizing the role of wind in chaparral fires such as those in southern California where strong Foehn-type winds often accompany wildland fire.

## Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Acknowledgments

This work was supported in part by agreement 13JV11272167-062 between USDA Forest Service PSW

Research Station and the University of California-Riverside. Jeanette Cobian-Iñiguez is supported by the UC Merced Department of Mechanical Engineering through Startup funding. The authors would like to thank Gloria Burke and Joey Chong for their assistance during the experiments. The authors would also like to acknowledge and thank Albertina Zuniga, Alejandro Gonzalez, Matthew Choi, Ivan Herrera, and Jake Eagan for their help in experiments and in developing the diagrams presented here.

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