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Experimental investigation of fire propagation in single live shrubs

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Abstract. This work focuses broadly on individual, live shrubs and, more specifically, it examines bulk density in chaparral and its combined effects with wind and ignition location on the resulting fire behaviour. Empirical functions to predict bulk density as a function of height for 4-year-old chaparral were developed for two typical species of shrub fuels in southern California, USA, namely chamise *(Adenostoma fasciculatum* Hook & Arn.) and manzanita (*Arctostaphylos* spp. Adans.). Fuel beds of chamise foliage and small-diameter branches were burned in an open-topped wind tunnel. Three levels of bulk density, two ignition locations and two wind speeds were examined, focusing on overall fire behaviour. Mean maximum mass loss rate, elapsed time at which maximum mass loss rate occurred, flame height, flame angle, peak gas temperature and its peak change rate were measured. The mean maximum mass loss rate was not significantly affected by wind speed, ignition location, bulk density or moisture content. Both wind speed and ignition location significantly affected the time that maximum mass loss rate occurred. Only wind speed affected flame height and flame angle. The peak gas temperature within the shrub burning area was found to be mostly affected by the bulk density.

Additional keywords: bulk density, chamise, fire behaviour, live fuel, manzanita, southern California, wildland fire.

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Introduction

Wildland fires occur in mediterranean-climate regions of the world every year (Syphard *et al.* 2009) and cause significant damage and disruption. The spread of a wildland fire is influenced by many parameters including topography, vegetative fuel type, season of the year, and ambient local and regional weather conditions. Both its direction and rate of spread are influenced by these parameters. Prescribed burning is utilised as one of many strategies to control the build-up of hazardous fuels in regions that are proximal to urban lands. However, our ability to predict fire behaviour under prescribed burning conditions is complicated by the fact that fuel beds may be composed of both dead and live vegetation, and transitions in fire behaviour, such as marginal burning transition from surface to crown fires, can be abrupt in live fuels (Bruner and Klebenow 1979; Burrows *et al.* 1991; McCaw 1997; Weise *et al.* 2005). Several studies have demonstrated the high sensitivity of fire spread success to wind (Bruner and Klebenow 1979; Cohen and Bradshaw 1986; McCaw 1997) and Zhou *et al.* (2005) found a wind velocity of only 2.0 m s^{-1} was sufficient to tilt the flame, thereby increasing the convective heat flux to the unburnt fuel by flame contact. A better quantitative and physical understanding of the influence of wind-aided ignition and spread of fire in live fuels is needed, particularly when prescribed burning is to be used. The review by Sullivan (2009) reiterated the limitations of current operational fire spread models. Several experimental and modelling works have demonstrated the importance of wind and convective heating on both ignition and flame spread mechanisms (Zhou *et al.* 2004; Weise *et al.* 2005; Cole *et al.* 2011; Finney *et al.* 2013).

Chaparral is the primary fire-prone vegetation type that grows between sea level and 1700 m in the mediterranean-climate region of the west coast of North America (California, Baja California) and is composed of a mixture of evergreen sclerophyllous shrubs that occur in various combinations (Keeley 2000). In California, the dominant shrub species include chamise (*Adenostoma fasciculatum* Hook & Arn.), ceanothus (*Ceanothus* spp. L.), manzanita (*Arctostaphylos* spp. Adans.) and scrub oak (*Quercus berberidifolia* Liebm.).[1] Although operational fire spread models do not explicitly model

[1]Plant nomenclature follows USDA National Resources Conservation Service (2016).

the fire spread processes in living vegetation, general trends are captured reasonably well – especially for wildfire conditions (Albini and Anderson 1982; Anderson *et al.* 2015). As several authors have noted, numerous fuel factors influence fire spread (Weise and Wright 2013; Anderson *et al.* 2015). One such fuel characteristic is the crown bulk density, which is the focus of investigation in the present paper. Crown bulk density has been identified as an important variable for fire spread through coniferous forest canopies (Van Wagner 1977; Alexander and Cruz 2012); however, recent modelling in mallee-heath shrublands found that crown bulk density (0.28–1.53 kg m^{-3}) was not selected in models to predict crown fire success or spread (Cruz *et al.* 2013). In a laboratory study, Tachajapong *et al.* (2008) reported that bulk density (0.75–1.75 kg m^{-3}) affected the impingement of the flame from a surface fire on an elevated shrub canopy and the flow of hot gases through the canopy, which affected the heat accumulation and subsequent ignition of the crown fuel. Reported bulk density of various shrubs complexes ranged from 0.16 to 25 kg m^{-3} (Countryman and Philpot 1970; Brown 1981; Frandsen 1983; Van Wilgen *et al.* 1990; Papió and Trabaud 1991; Pereira *et al.* 1995; Hierro *et al.* 2000; Martins Fernandes 2001; Marino *et al.* 2012). The definition of volume over which the bulk density was calculated varied slightly between these studies. Some studies have examined the vertical distribution of canopy bulk density in conifers (Sando and Wick 1972; Alexander *et al.* 2004); however, no such studies were found for chaparral and only the study by Papió and Trabaud (1991) was identified for other mediterranean shrub types. Vertical distribution of leaf area has been examined in some forests (Sala *et al.* 1994; Vose *et al.* 1995); again, no such studies were found for chaparral.

Although canopy bulk density is known to affect wind and hot gas flow through a forest canopy (Martin *et al.* 1969; Van Wagner 1973), shrub fuels are generally less studied, especially their effects on fire dynamics. Cohen and Bradshaw (1986) qualitatively studied the impact on fire dynamics caused by changing bulk density, which was achieved by varying the depth of the fuel without changing the fuel loading. Tachajapong (2008) experimentally and numerically investigated the effect of crown fuel bulk density (ranging from 0.28 to 2.96 kg m^{-3}) on live crown fuel initiation and concluded that higher crown bulk density enhanced fire initiation by increasing thermal energy owing to increased drag inside the crown fuel matrix and reduced convective energy loss. However, higher bulk densities and other physical parameters were not comprehensively studied. Marino *et al.* (2012) compared the effects of bulk density and moisture content on observed and simulated fire spread and concluded that fuel bulk density was an important variable to accurately predict fire spread in future fire propagation models. Shrubs can be ignited by a flame originating from an ember that falls into the centre of a shrub, igniting dead fuel at its base, or at its edge by a propagating fire through dead surface fuels or via flame contact from an adjoining shrub. The path of a flame propagating through a shrub is a function of ignition location and leaf location (Prince 2014). As prior experimental and modelling work in chaparral fuels has used high-bulk-density fuel beds oriented horizontally (Weise *et al.* 2005; Zhou *et al.* 2005), the present work and other experiments have used vertically oriented shrubs (Prince 2014). To further extend our previous work using horizontal fuel beds, we conducted a study examining fire spread in shrub fuel beds oriented vertically to replicate their natural arrangement (Weise *et al.* 2005). The specific objective was to characterise fire progression through a chamise shrub in terms of fire spread rate, gas temperature, heat flux and solid-fuel mass evolution for several different combinations of bulk density, wind velocity and ignition location, which has not been frequently studied previously.

Methods

Bulk density measurement and modelling

Bulk density was defined as $\rho_B \equiv m_{DRY}/V_{BULK}$, where m_{DRY} is the dry mass of fuel elements less than 0.63 cm (0.25 inches) in diameter, and V_{BULK} is the bulk volume occupied by the canopy of a shrub. This definition sometimes is called effective bulk density (Van Wilgen *et al.* 1990; Marino *et al.* 2012) and is utilised because it has been observed that typically, live fuels less than 0.63 cm in diameter are consumed in the flame front. Larger fuels up to 1.27 cm in diameter tend to be consumed after the flame has passed. In order to describe fire behaviour as it spreads through a shrub, we need to better understand the variation in bulk density within shrubs, particularly vertically. To this end, we harvested chamise and manzanita shrubs from the North Mountain Experimental Area (NMEA) near Riverside, CA, to determine the changes in bulk density with vertical height for chamise and manzanita with the goal of developing a simple, empirical model. Chamise is the predominant species at NMEA, with much lower occurrence of Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.). The leaf shape differs markedly between these two shrubs (Fig. 1). Chamise leaves are needle-like and clustered on lateral shoots whereas manzanita leaves are bright shiny green, wedge-shaped and pointed.

In order to obtain bulk density, we measured the bulk volume and the dry fine mass separately. Three photographs of each individual shrub were taken before cutting it into pieces orthogonal to an *xyz* coordinate system with the origin located in the centre of the shrub. The area of each orthogonal polygon enclosing the perimeter of the shrub's canopy was determined using Matlab's image processing tools (Li 2011). Then, the shrub bulk volume was estimated from $V \approx k\sqrt{A_x A_y A_z}$ where A_i is the area of the orthogonal polygon ($i = x, y, z$) and k is an empirical shape factor that depends on the assumed geometric shape. The calculated values of k for sphere, cylinder, cube and cone are 0.75, 0.89, 1.00 and 0.60 respectively. The live shrub was then partitioned into vertical slices of 10 or 20 cm depending on species and the oven-dry mass of branches and foliage less than 0.63 cm was determined by drying the material in a convection oven at 95°C for 48 h. Bulk density for each vertical slice was estimated. The height of each shrub vertical slice was normalised to range from 0 to 1 by dividing by its height. Bulk density profiles of each shrub were plotted to identify potential trends (Sando and Wick 1972; Alexander *et al.* 2004). To develop a model relating bulk density to height for modelling purposes, a linear mixed-effects model (Pinheiro and Bates 2000; Pearce *et al.* 2010) was fitted to account for within-shrub correlation of the bulk density measurements; however, none of the coefficients for linear, quadratic, cubic, exponential, logarithmic and square-root functions of normalised height were

Fig. 1. Chamise (*a*), and manzanita (*b*) growth originating from sprouting lignotubers burned in October 2006 on the North Mountain Experimental Area near Riverside, California, July 2010. The square size is 1 × 1 m.

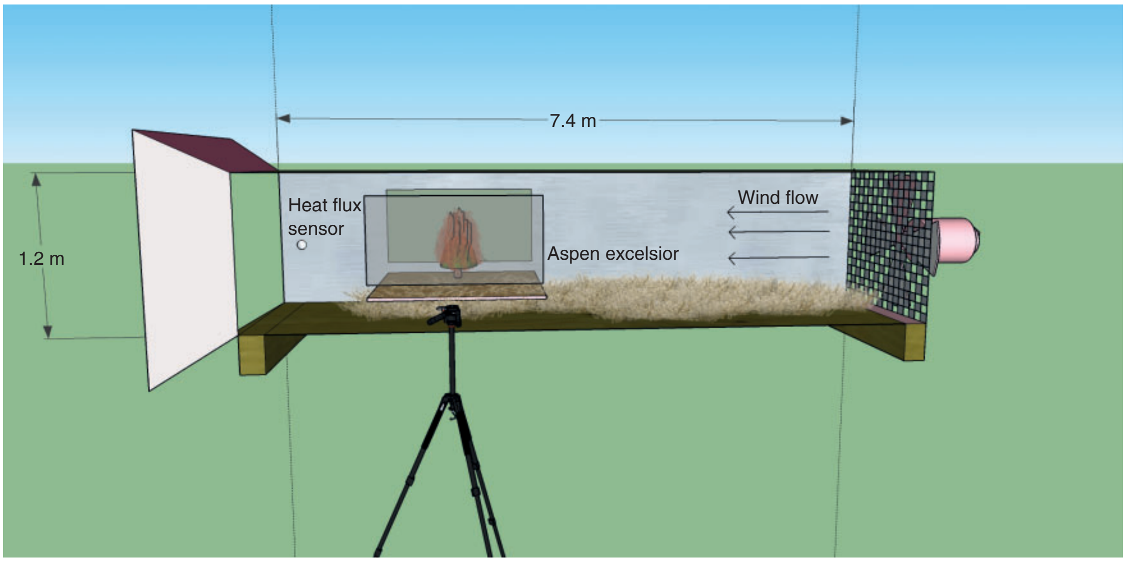

Fig. 2. Schematic of experimental setup in a wind tunnel.

significant. Within-shrub correlation estimates (ϕ) for bulk density were −0.04 and −0.08 for chamise and manzanita respectively; 95% confidence intervals included 0 indicating no within correlation. We then fitted splines to the individual shrubs using the smooth spline function in *R* and splines for each species assuming no effect due to shrub. This function used cubic splines, which are a form of generalised additive models (Hastie and Tibshirani 1990; Wood 2006). For comparison purposes, we plotted a cubic polynomial that had been fitted previously to the data (Li 2011).

Experimental setup

The effects of bulk density, wind velocity and ignition location on flame propagation through a single shrub were examined in a wind tunnel at the USDA Forest Service Pacific Southwest Research Station fire laboratory in Riverside, California. Hosseini *et al.* (2014) provide a detailed description of the fire laboratory. Environmental conditions inside the fire laboratory were not controlled and tended to be more extreme than ambient conditions (hotter in summer, cooler in winter, and with slightly higher relative humidity). Experiments were performed in an open-topped wind tunnel with a side panel open to permit video camera monitoring as shown in Fig. 2 (Tachajapong *et al.* 2014). The wind tunnel characteristics are described in detail elsewhere (Tachajapong *et al.* 2014). The wind tunnel includes a honeycomb and screens to condition the flow and minimise any swirl associated with the fan, before wind entry into the test section. The wind tunnel was modified to increase the length of the fuel bed by 1 m.

Individual shrubs were collected from a 4-year-old chamise (Fig. 1) resprout stand from the 2007 Esperanza Fire in the NMEA. Most of the shrubs were ≤1 m in height with a maximum stem diameter less than 2.54 cm. Visually identified dead branches were removed from the sample during collection so the samples were composed of only living branches. Fuel samples were collected in the morning and transported immediately to the laboratory to minimise fuel moisture loss. Shrubs were harvested from July 2010 to October 2010. Typical lack of

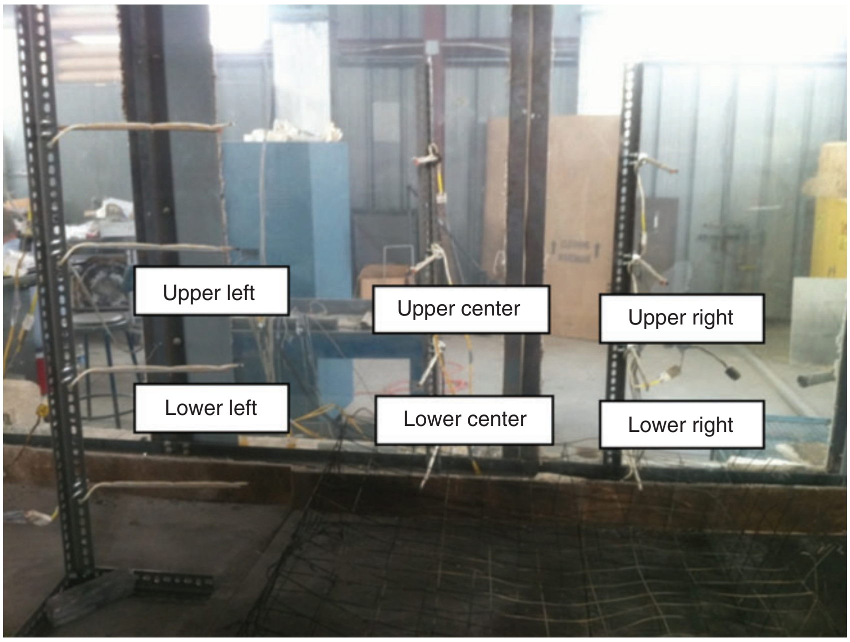

Fig. 3. Photograph illustrating location of thermocouples in experiment. Labels are underneath corresponding thermocouples.

precipitation and plant growth during this period meant that fuel moisture content decreased over the course of time to near the average yearly minimum value (Countryman and Dean 1979). The shrub was placed in an iron frame (length L $\times$ width W $\times$ height H $=$ 110 $\times$ 90 $\times$ 10 cm) to keep the fuel vertical to match field conditions. Wind flow was established in the wind tunnel before ignition.

The effects of bulk density (low, medium, high), wind velocity (0, 1.5 m s^{-1}) and ignition location (spot, line) on fire behaviour in a single vertical shrub were examined in the wind tunnel. A completely randomised design consisting of two replications of each experimental combination resulted in 24 experimental fires. Three levels of bulk density were studied: low, medium and high. The path of a flame propagating through a shrub is a function of ignition location and leaf location (Prince 2014). The spot ignition location represented an ignition in a dead surface fuel centred under a shrub; the line location represented a surface fire spreading horizontally and igniting the shrub on the upwind side. A sample of 250 g of aspen excelsior (*Populus tremuloides* Michx.) was evenly distributed under the shrub; for line ignition, an additional 150 g was added upwind.

Fire behaviour measurements

Moisture content of live fuel samples was estimated using an Arizona Instruments MAX® 1000 Moisture Analyser.[2] Excelsior mass loss was measured with four load cells (response time of 5 ms) at 10 Hz. Shrub mass was measured by an electronic balance. A set of 0.51-mm-diameter (24-gauge, response time of 1.1 s) type K thermocouples measured shrub canopy gas temperature at 10 Hz. As response time was greater than the capture rate period, a running mean using 10 adjacent values was calculated. These thermocouples were placed in the positions shown in Fig. 3. Note that although 12 thermocouples are shown in Fig. 3, only 10 were used to record data and 6 (marked in the figure) of the 10 available data sets are reported in the present study. All thermocouples were placed in the centreline of the fuel bed. Each thermocouple was vertically separated by 20 cm from the others. Lower left, lower centre and lower right thermocouples were located 40, 52 and 32 cm vertically above the fuel bed base respectively. A consumer-grade video camera was positioned to observe the fire spread rate from the front window of the wind tunnel (see Fig. 2). This video camera captured images at a frequency of 30 Hz.

A water-cooled RC01 total and radiant heat flux sensor (Hukseflux Thermal Sensors 2010) was used to measure the components of the heat flux downwind of the fuel bed, at a distance of 0.5 m from the fuel bed front edge and at a height of 0.3 m to characterise the heat flux that an adjacent shrub might experience (Finney *et al.* 2010; Lozano 2011). The minimum flux level that can be detected is 5 W m^{-2}. The sampling rate was 10 Hz and the instrument response time was 0.5 s so these data were also averaged. All the instruments were carefully calibrated before conducting any measurements.

Data reduction and statistical analysis

For those instruments that sampled data at rates greater than the response time, running means were calculated. Ten adjacent values comprised the running mean for temperature (thermocouples). Because of fluctuations in the mass loss rate data, the mean maximum mass loss rate (MMLR) was calculated by

[2]The use of trade or firm names in this paper is for reader information and does not constitute endorsement by the USDA of any product or service.

averaging 10 adjacent data points centred around the maximum. The time to reach maximum mass loss rate (MMLRT) was defined as the time from ignition (note that in the case of line ignition, ignition was defined as the time when the actual flame reached the unburnt shrub) to the time mass loss rate reached its maximum value. Total burning time was defined as the time period from ignition to when the visible flames subsided completely. Maximum flame length (FL) and flame angle (FA, measured from vertical) were obtained from analysis of at least three video camera images per experiment using *AutoCAD*. Flame height (FH) was defined as the vertical distance from the flame tip to the top of surface fuel bed, FH = FL × cos(FA). Positive FA indicated that flame was tilted downstream. Flame spread rate was obtained by tracking visual images from the appropriate video camera at 0.033-s intervals. Flame spread rates in both horizontal (HROS) and vertical (VROS) directions were determined. Peak gas temperature (T_{max}) and its peak change rate $(dT/dt)_{max}$ were also calculated.

In this experiment, bulk density, wind velocity and ignition location were ordered fixed factors and moisture content was a covariate. Analysis of variance was used to test for the significance of the factor effects on the fire behaviour variables. To determine whether a factor had a positive or negative effect on a fire behaviour variable, orthogonal polynomial contrasts were used; wind velocity and ignition location each had a linear contrast, bulk density had a linear and a quadratic contrast (Mason *et al.* 1989). For ignition location, the spot ignition was defined as the lower level of the factor and line ignition was the higher level. As FA was a circular variable, the effects of bulk density, wind speed and ignition location (coded as 0, 1) were tested by fitting a circular–linear regression and using analysis of variance (Fisher and Lee 1992; Agostinelli and Lund 2013). The fitting algorithm failed to converge when moisture content was included so it was dropped from the regression equation. An effect was considered significant if the probability value associated with the *F* statistical test was less than 0.05.

Results

Bulk density

Mean crown bulk density of the foliage and branches less than 0.63 cm in diameter for the nine individual shrubs (four manzanita, five chamise) ranged from 2.43 to 7.63 kg m^{-3} (Table 1). Assuming foliage and branch density of 513 and 737 kg m^{-3} and foliage/branch proportions of 0.1/0.9 and 0.27/0.73 for chamise and manzanita respectively (Weise *et al.* 2016), packing ratio of the shrubs ranged from 0.0034 to 0.011, which was generally greater than older and taller chaparral stands (Weise *et al.* 2011) but less than in previous experiments using horizontal fuel beds (Weise *et al.* 2005; Weise *et al.* 2016). Within the shrub crowns, the bulk density was somewhat variable (Fig. 4). In four of five chamise, maximum bulk density occurred at 35–55% of total height whereas bulk density in manzanita appeared to increase with height. The relationship between dimensionless height and bulk density differed between species. In the lower part of Fig. 4, we observe that both the smooth spline (dashed line) and the fitted cubic polynomial (black circles) differ between species. The cubic polynomial accounted for 31 and 67% of the variation in bulk density for chamise and manzanita respectively.

Table 1. Characteristics of 4-year-old chamise and manzanita shrubs originating from sprouting

H_T, shrub height; m_1, mass of foliage and branches <0.63 cm; m_2, mass of branches 0.63 to 2.54 cm in diameter; V, volume; CBD, crown bulk density; PR, packing ratio (Rothermel 1972)

Species	H_T	Canopy				
	(m)	m_1 (g)	m_2 (g)	V (L)	CBD (kg m^{-3})	PR
Chamise	1.00	447.2	75.2	175.6	2.55	0.0035
	1.10	272.8	86.7	112.2	2.43	0.0034
	0.97	705.7	0.0	113.7	6.21	0.0087
	0.63	418.3	0.0	79.8	5.24	0.0073
	0.90	566.4	77.1	180.0	3.15	0.0044
Manzanita	0.83	424.2	174.3	110.5	3.84	0.0057
	0.77	574.1	96.4	75.2	7.63	0.0110
	0.71	411.0	84.2	95.0	4.33	0.0064
	0.65	417.7	83.8	132.6	3.15	0.0047

However, none of the estimated coefficients were significantly different from 0 at the 0.05 level and only one coefficient (of eight estimated) was significant at the 0.10 level. Coefficient estimates for both species were highly correlated – absolute values of the correlations ranged from 0.78 to 0.99. Even though the fitted polynomial model was not significant statistically, an earlier version of the model (Li 2011) was used to improve the modelling of single-shrub fire behaviour by Dahale *et al.* (2013). Comparison of the cubic spline and cubic polynomial indicated that they produced similar results. Residual standard errors for the spline and polynomial were 2.35 and 2.08 for chamise and 1.43 and 1.40 for manzanita respectively.

Fire spread experiment

A total of 24 experiments were performed between July and October 2011. The amount of fuel consumed per experiment ranged from 55 to 2180 g and the time that single shrubs burned ranged from 66 to 333 s (Table 2). Moisture content of the shrubs was estimated to be 36 to 46%, which is lower than field conditions. Low, medium and high bulk density ranged from 1.75 to 2.20, 3.17 to 4.42 and 6.92 to 8.91 kg m^{-3} respectively. Flame length ranged over an order of magnitude (0.69 to 4.82 m) and flame angle also ranged considerably. Uncertainty in the measurement of FL and FA from separate tests was estimated as 0.23 m and 5° respectively. Horizontal rate of spread increased up to two orders of magnitude in the presence of wind. Vertical rate of spread also changed by an order of magnitude between the centre-ignited and laterally ignited fires. MMLR ranged from 9 to 68 g s^{-1} with no discernible trends. MMLRT was markedly different for the no-wind fires that were centre-ignited in comparison with laterally ignited.

Analysis of variance indicated that bulk density only affected a fire's vertical rate of spread. The effect of moisture content on both rates of spread measures was also significant. Wind speed and ignition location affected both rates of spread and the time to achieve maximum loss rate (MMRLT). Wind speed also affected FL. MMLR was not affected by any of the variables except bulk density, which was marginally significant.

For those factors (bulk density, wind speed, ignition location) that significantly affected the fire characteristics, the

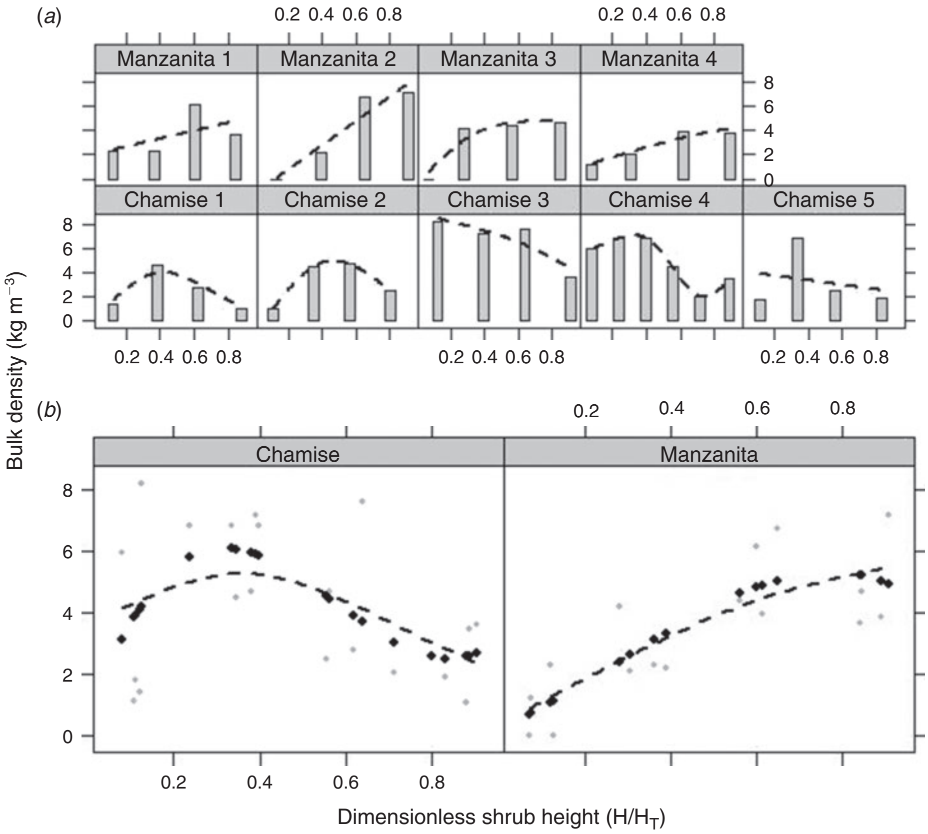

Fig. 4. Vertical distribution of bulk density within the canopy of 4-year-old individual (*a*), and grouped by species (*b*) shrubs. Dashed line is cubic spline (generalised additive model) fitted using smooth spline function, black dots are fitted values from cubic polynomial and grey dots are observed bulk density.

coefficients for the effect were estimated following standard estimation procedures for linear models (Chambers *et al.* 1992; Chambers and Hastie 1992). Given that this was an exploratory experiment examining fire spread through individual shrubs and most factors had only two levels, the coefficient estimates were used to determine whether the factor had a positive (+) or negative (−) effect on a fire behaviour variable (Table 3). The complete dataset can be found in the Forest Service Research Data Archive (Li *et al.* 2016).

For the variables with only two levels (wind velocity, ignition location), a positive coefficient indicates an increasing function. As a covariate, moisture content was significant for both HROS and VROS, but not significant for the maximum loss rate or the time that this occurred. The estimated coefficient associated with moisture content was negative for both measures of rate of spread, indicating that rate of spread decreased as moisture content increased – an expected result. Bulk density affected VROS, FL, T_{max} and $(dT/dt)_{max}$, but not HROS, MMLR or MMLRT, or FA. The coefficient estimates for bulk density were positive, indicating increasing vertical rate of spread as bulk density increased. Both wind velocity and ignition location affected HROS and VROS, the time at which maximum mass loss occurred and FA, but not the mass loss rate or FL. Wind velocity affected the spread rates differently. As wind velocity increased from 0 to 1.5 m s^{-1}, HROS increased and VROS decreased. The laterally ignited fires spread faster than the centre-ignited fires both horizontally and vertically. Increasing wind velocity decreased the MMLRT. The effect of bulk density on FL was positive; as bulk density increased, FL increased. This was particularly noticeable for the laterally ignited fires with an imposed wind velocity. MMLRT for the laterally ignited fires was greater than the time for the centre-ignited fires for the no-wind fires; this was not the case for the wind-driven fires, suggesting significant interaction between wind velocity and ignition location, whose combined effects can be clearly seen in Fig. 5. In Fig. 5, fire behaviour resulting from the two ignition locations illustrates the effects of wind speed and ignition location on the flame through the shrub canopy for medium bulk density. Note those images were captured from a lateral camera after 10 s when the flame reached the chamise shrub (in the case of spot ignition, it was 10 s after initial ignition). Note the dissimilarity in visual fire behaviour once the shrub canopy ignited. FLs for spot ignition, zero wind speed and line ignition, at 1.5 m s^{-1} wind speed are much longer than the other two cases (spot ignition at 1.5 m s^{-1} wind speed and line ignition, zero wind speed), which indicates the combined effects of the wind speed and ignition location on flame dynamics. T_{max}, but not $(dT/dt)_{max}$, was negatively affected by the moisture content. Both of these characteristics were influenced by the bulk density, wind speed and ignition locations.

Table 2. Observed fire characteristics in individual chamise shrubs for various levels of bulk density, wind velocity and ignition location

L, low bulk density class; M, medium bulk density class; H, high bulk density class; C, centre-ignited method; L, laterally-ignited method; H, horizontal flame spread rate; V, vertical flame spread rate; T_{max}, peak gas temperature; $(dT/dt)_{max}$, peak gas temperature change rate

Bulk density class	Wind velocity ($m\ s^{-1}$)	Ignition	Bulk density ($kg\ m^{-3}$)	Moisture content (%)	Mass consumed (g)	Burn time (s)	Rate of spread ($10^{-3}\ m\ s^{-1}$)		Maximum mass loss		Flame		Temperature	
							H	V	Rate ($g\ s^{-1}$)	Time (s)	Length (m)	Angle (°)	$(dT/dt)_{max}$ ($K\ s^{-1}$)	T_{max} (K)
L	0	C	1.78	45.4	333	66	6.2	16.3	45.0	12	1.69	−8	24.5	551
L	0	C	2.01	39.6	186	105	5.3	13.2	30.2	62	1.80	0	26.8	578
M	0	C	3.17	45.4	402	73	5.9	25.3	30.0	32	1.59	−7	65.4	693
M	0	C	4.42	39.6	553	112	6.2	23.2	31.0	45	1.71	0	69.4	708
H	0	C	7.51	45.4	2180	128	7.4	41.8	68.0	42	2.23	−14	69.5	851
H	0	C	8.91	39.6	1053	154	8.1	37.8	49.1	45	1.87	0	72.6	1049
L	1.5	C	1.90	45.4	182	135	4.2	6.2	26.5	58	2.77	35	14.2	553
L	1.5	C	1.75	36.4	55	114	5.5	7.1	11.0	63	4.82	40	16.2	503
M	1.5	C	3.35	45.4	312	146	15.2	4.5	39.0	5	3.39	35	24.2	541
M	1.5	C	3.80	36.4	194	108	18.1	6.4	21.0	50	2.43	33	8.3	449
H	1.5	C	6.92	45.4	393	157	21.5	10.5	28.0	65	1.87	21	37.6	650
H	1.5	C	8.90	36.4	519	173	23.4	12.8	14.5	87	2.31	28	29.4	698
L	0	L	1.92	42.4	272	260	6.8	104	9.1	194	0.70	−16	33.5	549
L	0	L	2.20	39.6	106	315	8.3	147	13.0	220	0.69	−9	26.5	603
M	0	L	3.77	42.4	469	256	3.7	167	19.5	163	1.42	0	23.2	573
M	0	L	4.00	36.4	833	275	5.4	184	34.0	191	1.84	−6	26.4	578
H	0	L	7.58	42.4	704	242	5.8	208	38.3	174	1.67	0	26.5	766
H	0	L	8.65	39.6	1045	333	6.3	278	25.2	260	2.57	−12	32.6	753
L	1.5	L	1.81	36.4	308	84	105	126	25.0	26	2.69	32	30.4	763
L	1.5	L	2.11	36.4	279	73	128	84	24.0	29	2.10	25	24.8	780
M	1.5	L	3.74	36.4	862	81	158	147	39.0	38	2.64	20	40.2	878
M	1.5	L	3.92	36.4	1368	75	147	165	48.0	28	4.09	28	39.8	987
H	1.5	L	8.60	36.4	1829	116	208	175	48.0	70	3.55	25	46.1	1078
H	1.5	L	8.17	36.4	1830	91	178	143	47.0	72	4.19	29	45.2	978

Table 3. Summary of linear model fitted coefficients used to estimate the effects of factors for wind speed, bulk density and ignition location on fire characteristics of burning chamise shrubs

L and Q refer to the linear and quadratic terms of the polynomial, + and – indicate sign of coefficient estimate, X indicates term not included in analysis; *, **, *** indicate *t*-statistic was significant at the 0.05, 0.01 and 0.001 levels. MMLR, mean maximum mass loss rate; MMLRT, time to reach mean maximum mass loss rate; FL, flame length; FA, flame angle; HROS, flame spread rate (horizontal); VROS, flame spread rate (vertical)

Fire characteristic	Moisture content	Bulk density		Wind speed	Ignition location
		L	Q		
HROS				+**	+**
VROS		+**		−*	+***
MMLR		+*			
MMLRT				−**	+**
FL				+**	
FA	X		X		
$(dT/dt)_{max}$		−*			
T_{max}		+*			

Thermocouples were placed directly above the ignition zone and responded rapidly (Fig. 6). A rapid rise in temperature commenced earlier for the high-bulk-density case, and the peak temperatures T_{max} were higher as well. However, bulk density (and other source variables) appears to have less of an influence on $(dT/dt)_{max}$. This result is consistent with observations by Tachajapong *et al.* (2008). The thermocouple measurements of gas temperature confirmed that temperatures close to the ignition zone were higher than those measured away from the ignition zone.

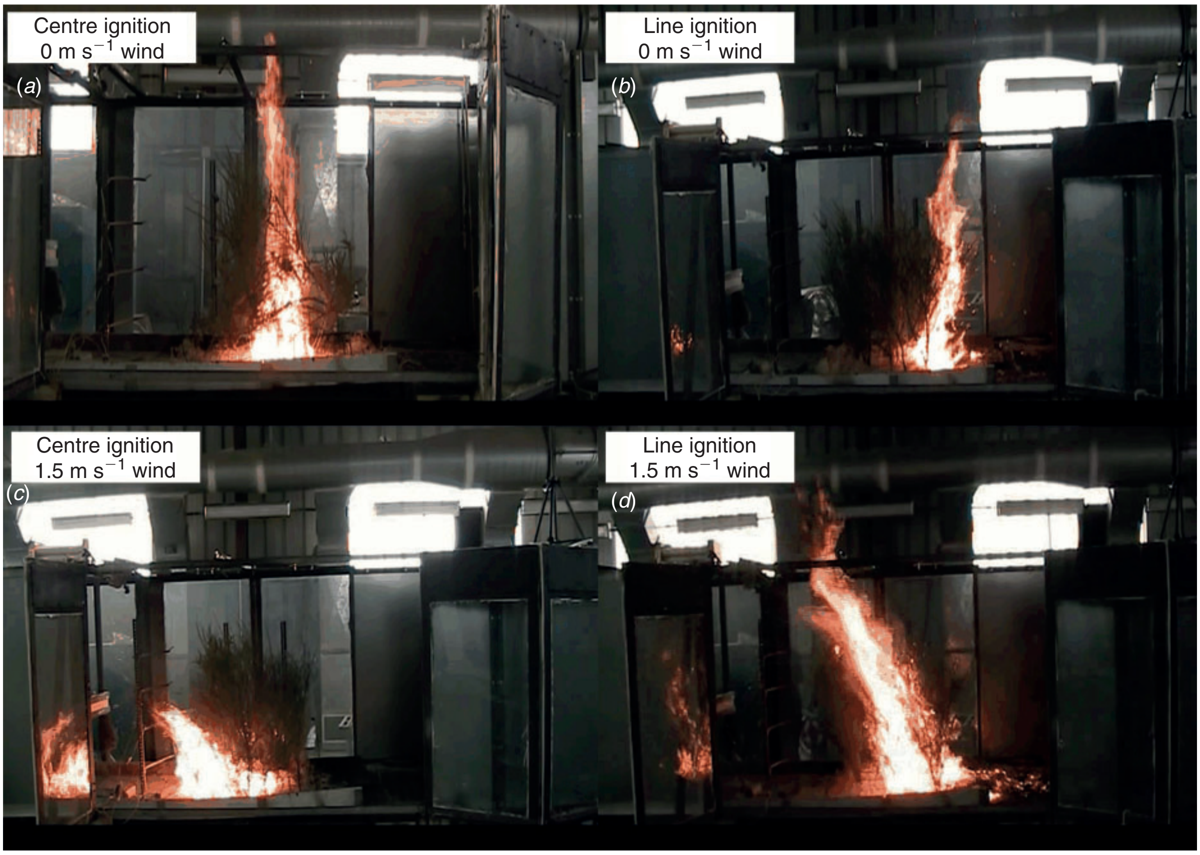

Fig. 5. Images of fire as viewed from the lateral camera in its flame spread direction. Those cases are for medium bulk density of (*a*) 3.17; (*b*) 4.00; (*c*) 3.80; and (*d*) 3.74 kg m^{-3} of the fuel bed. The imposed mean wind flow is from right to left.

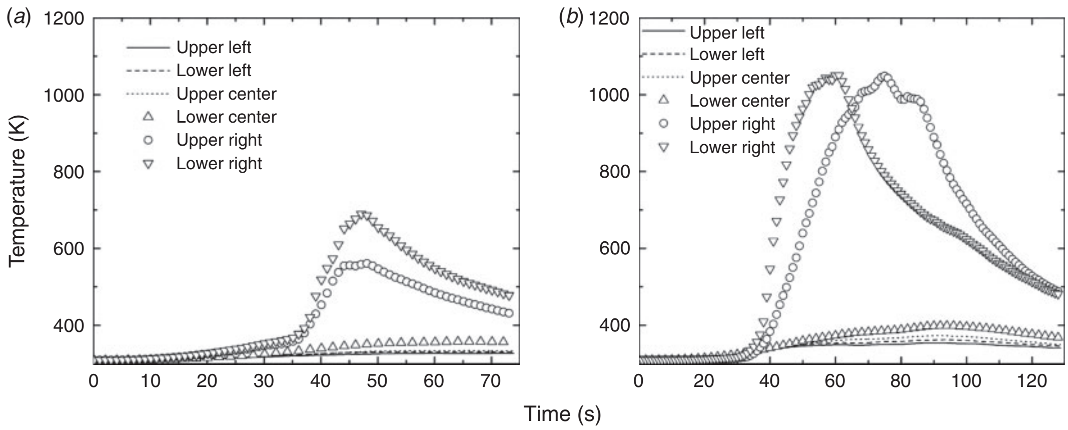

Fig. 6. Thermocouple temperature profiles for (*a*) medium bulk density (4.42 kg m^{-3}); and (*b*) high bulk density (8.91 kg m^{-3}). In both cases, there is no wind and ignition is initiated at the centre.

In the case of spot ignition with no wind, the FA was ~0°. The fire burned nearly vertically, thereby preheating and burning the shrub effectively, which can be clearly seen from the MMLR comparisons between Fig. 7 and Fig. 8. The large increase in burning time when lateral ignition was used is due to the fact that (i) the shrub was not in contact with the flame until the fire spread to a location under the shrub, and (ii) the relatively lower spread rate under no-wind conditions implies a significant amount of time elapsed before the surface fire was able to heat and burn the shrub fuel via convective heat transfer. The burning time was usually shorter for lateral ignition when wind was present (Table 2). In contrast, when ignition

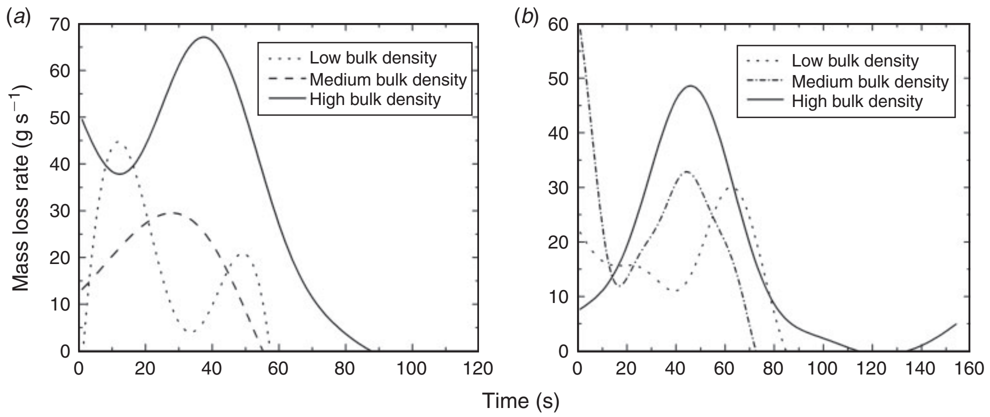

Fig. 7. Mass loss rate evolution with three different bulk densities for no wind and spot ignition: (*a*) test 1; (*b*) test 2.

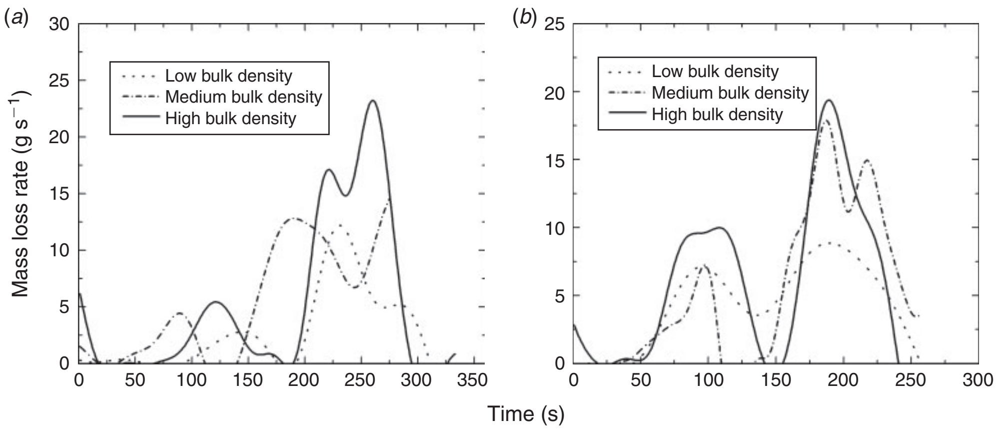

Fig. 8. Mass loss rate evolution with three different bulk densities for no wind and spot ignition: (*a*) test 1; (*b*) test 2.

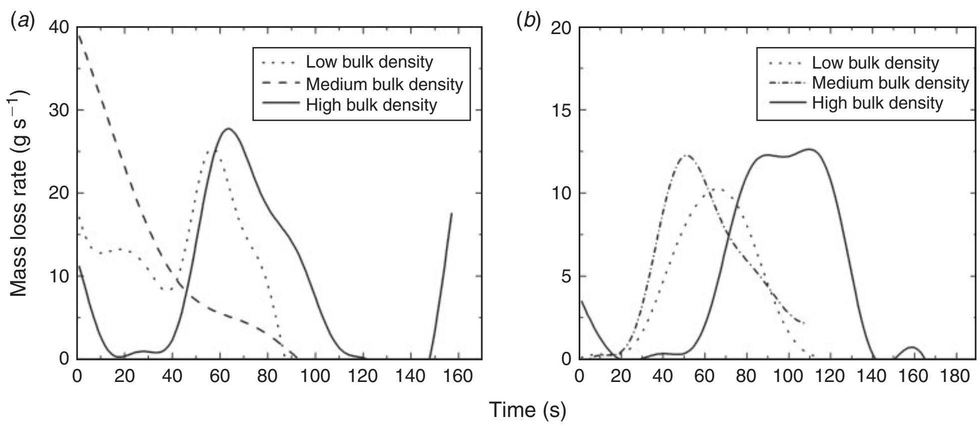

Fig. 9. Mass loss rate change with three different bulk densities with 1.5 m s^{-1} wind and spot ignition: (*a*) test 1; (*b*) test 2.

occurred under the centre of the shrub, the surface fire was unable to aid in preheating the shrub fuel because of the fairly large FA towards downstream induced by the imposed mean wind (see Fig. 9, spot ignition, 1.5 m s^{-1} wind). The flames were thus unable to contact the shrub to promote effective preheating. Heat generated from the combustion was therefore mainly transferred by radiation, which was insufficient to cause the ignition of the unburnt shrub fuel. The fire spread follows the wind direction initially, and then moves back in the opposite direction. The latter effect may be attributed to entrainment from

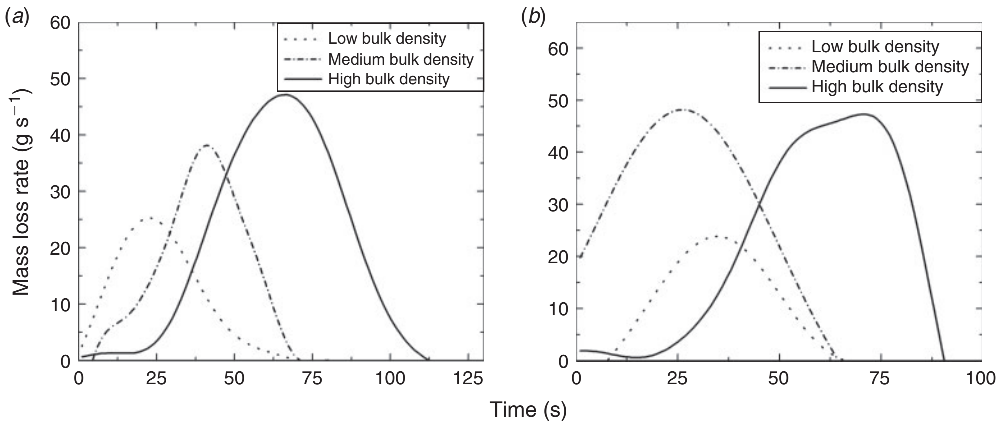

Fig. 10. Mass loss rate change with three different bulk densities with 1.5 m s^{-1} wind and line ignition: (*a*) test 1; (*b*) test 2.

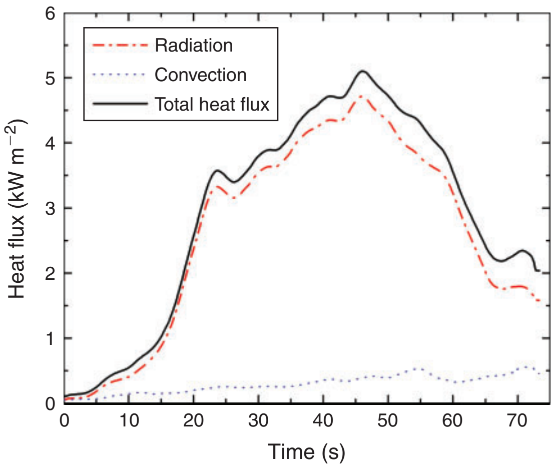

Fig. 11. Heat flux evolution for low bulk density of 2.11 kg m^{-3} in the case with wind speed of 1.5 m s^{-1} and line ignition.

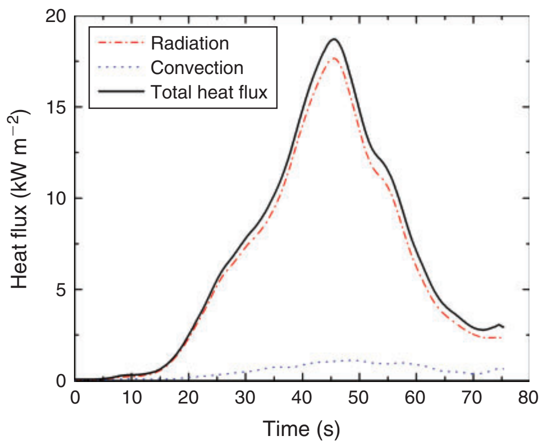

Fig. 12. Heat flux evolution for medium bulk density of 3.92 kg m^{-3} in the case with wind speed of 1.5 m s^{-1} and line ignition.

the lateral side that is open in the wind tunnel. In all situations, as expected, the mass consumed was largest for cases with the highest bulk density.

The effect of bulk density on mass loss rate for the two ignition types and two wind speeds is presented in Figs 7 to 10. Fast Fourier transform (FFT) filter smoothing was used to eliminate signal noise in all mass loss rate analysis. Test 1 and test 2 are two repetitions of same nominal experimental conditions. They are plotted separately to be better considered and compared. In Fig. 7, the bulk density values for low, medium and high cases were 1.78, 3.17 and 7.51 kg m^{-3} for Test 1, and 2.01, 4.42 and 8.91 kg m^{-3} for test 2. It is evident from these figures that for both methods of ignition, the MMLR is generally highest for the highest bulk density. Furthermore, the maximum value is attained at a later time than for the lowest bulk density. In the case of line ignition at the end of the surface fuel bed, at zero wind speed, it is evident from Fig. 8 that there exists a small peak before the mass loss rate reaches its peak value; however, at a wind speed of 1.5 m s^{-1}, the curve becomes smooth with a single, dominant peak, as seen in Fig. 9. The existence of the first peak is attributed to mass loss rate reaching a local maximum value as a result of the surface fire initiated by the line ignition attaining its maximum intensity. Subsequently, the shrub ignites and shortly thereafter, the mass loss rate reached a second maximum when the entire shrub burned intensely. In the wind-aided case, there was inadequate time for the first peak to manifest itself; consequently, only a single peak in mass loss rate was observed.

Measured heat fluxes were obtained for all the cases investigated. However, the focus is only on cases involving wind with line ignition (refer to Table 2) as shown in Figs 11–13. In all cases, heat flux measured at the sensor location was dominated by radiation heat transfer. Note the total time period over which significant heat flux was measured corresponds to the appropriate burning times in Table 2. Therefore, it is not surprising that convective heat transfer was likely dominant in regions within the intermittent flame region and in the plume region directly above the propagating fire. As the fire evolved, propagating towards the sensor, heat flux increased. In the low- and medium-bulk-density cases, although the peak

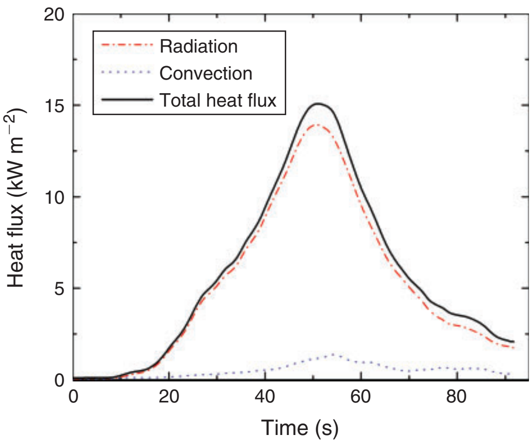

Fig. 13. Heat flux evolution for high bulk density of 8.17 kg m^{-3} in the case with wind speed of 1.5 m s^{-1} and line ignition.

mass loss rate occurred at 29 and 28 s respectively, the peak heat flux received by the sensor occurred later, between 40 and 50 s. In the high-bulk-density case, the peak mass loss rate occurred at 72 s, after which the measured heat flux reached a maximum. It can be seen that in the case of line ignition at 1.5 m s^{-1} wind speed, increasing the bulk density from medium to high did not change the heat flux significantly, consistent with the experimental observation of FH and measurements of MMLR data (Table 2).

Conclusions

Empirical functions to predict bulk density as a function of height for 4-year-old living chaparral harvested in southern California were developed for two typical species of shrub fuels, chamise and manzanita. Following these bulk density measurements, several fire behaviour characteristic variables including the rate of spread, FH, FA, full mass evolution, flame gas temperature and heat flux were measured during the burning of single live chamise shrubs.

A statistical analysis of the experimental data revealed that bulk density had a significant influence on the variance of VROS and peak flame gas temperature T_{max}. Furthermore, it had a marginal effect on the maximum flame gas temperature change rate $(dT/dt)_{max}$ and maximum mass loss rate MMLR. Bulk density had no significant influence on variance of HROS, time to reach MMLR (MMLRT) and FL. In addition, results showed that bulk density had less of an effect on FA than the other influence factors. The experimental results showed that MMLR was not significantly affected by wind speed, ignition location, bulk density, or moisture content. Both wind speed and ignition location significantly affected the time that maximum mass loss rate occurred. Only wind speed affected FH and FA. The T_{max} within the shrub area was found largely affected by the bulk density only. Heat flux measurements made downstream of the fire indicated that radiant heat transfer was predominant and in the case of line ignition at 1.5 m s^{-1} wind speed, increasing the bulk density from medium level to high level did not change the heat flux significantly.

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