FINAL PROJECT REPORT
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DETERMINING THRESHOLD CONDITIONS FOR EXTREME FIRE BEHAVIOUR

Final project report

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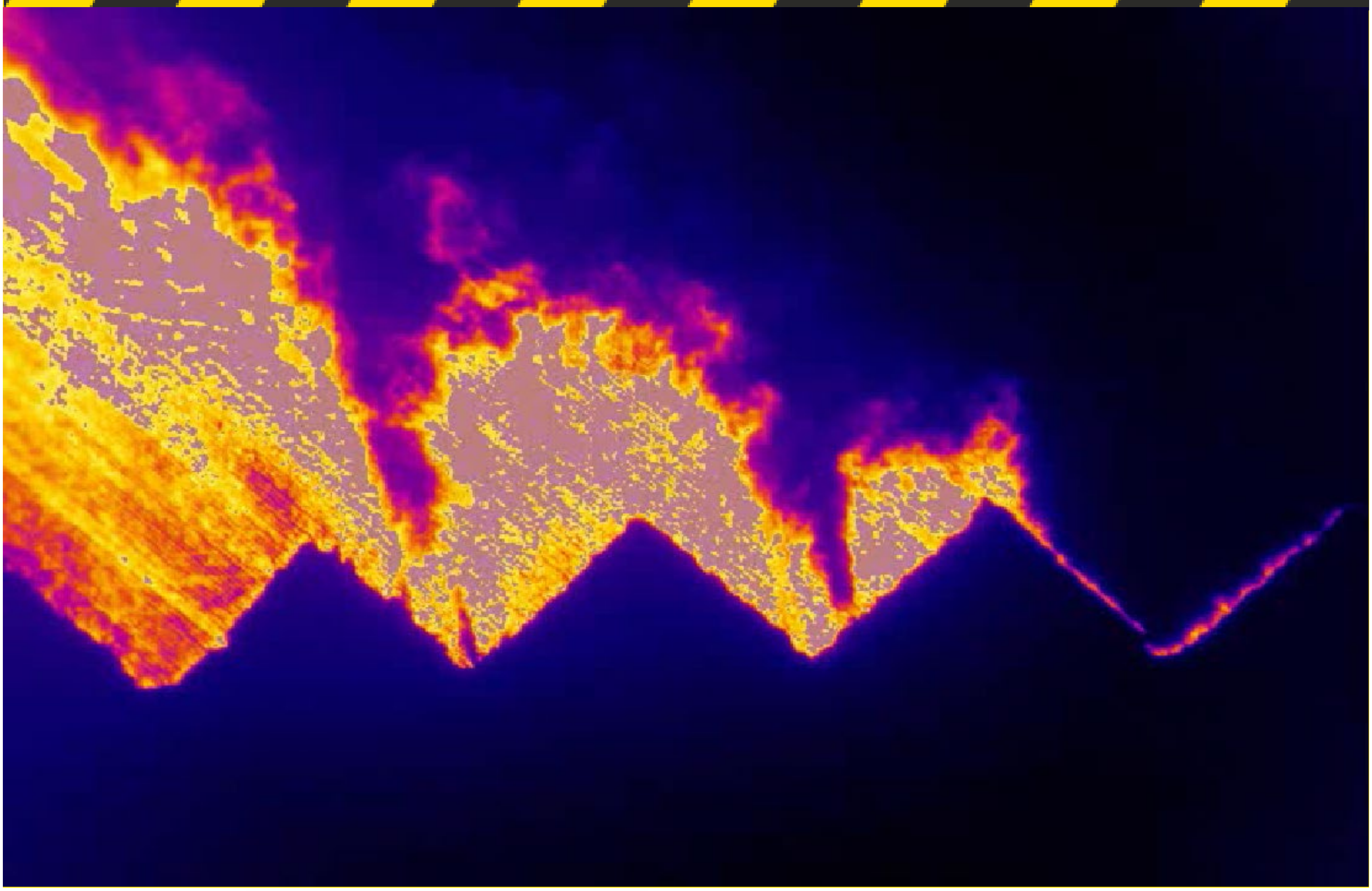

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EXECUTIVE SUMMARY

The first stage of the project *Determining threshold conditions for extreme fire behaviour* was focused on investigating the processes under which bushfires undergoes major transitions in behaviour, and the conditions under which these occur. Initial findings indicate that these 'dynamic' processes are associated with the most damaging fires Australia wide. Consequently, the failure of fire behaviour models to account for their effect, may result in them underestimating the potential fire spread and intensity. Currently, bushfire simulation systems are used to predict the spread of going fires, evaluate landscape risk and compare fire mitigation strategies. There is little or no modelling of common dynamic fire phenomena in these systems, and the degree to which this impacts on the accuracy of predictions is unknown.

To fill these gaps, the current project 'Determining threshold conditions for extreme fire behaviour' was focused on the following main tasks:

- Determinants of crown fire runs during extreme wildfires in eucalypt forests in Australia.
- Using technological advancements to uncover fire behaviour phenomena, to guide future operational support.
- Ignitibility of live plants.
- Current trends of Australian bushfires.

In general, extreme fire can involve one to several dynamic fire behaviours (previously, extreme fire behaviours) simultaneously. These include crown fires, spotting, fire generated tornado vortices, fire channelling, merging fires, eruptive fires and pyro-convective events. These phenomena can influence the intensity and rate of growth of wildfires, making them difficult to control. For example, fire suppression is not feasible when crown fires are occurring. Consequently, being able to anticipate when and where crown fires are likely to occur is critical, for planning safe and effective fire responses and for community safety. We developed a model to predict the likelihood and extent of crown fire events. To do this we used satellite derived fire severity mapping. Results from the empirical modelling showed that fuel and air moisture were most influential in determining crown fire runs; with fire weather and topography having intermediate influence; and fuel load and structure having the lowest influence. As weather variables can be forecast into the future, a developed model could be used to forecast the likelihood of crown fire runs, while fires are occurring. For example, potential fire runs could be forecast at an hourly temporal resolution for up to 7 days into the future. This could provide managers with a rapid means of assessing the likely fire impacts and risks to personnel. This research could be extended to include smoke generation and its potential transport. Such information would be invaluable for fire managers in terms of allocating fire suppression resources and issuing public warnings.

Merging fire fronts have been known for rapid fire spread and developing into extremely destructive fires, resulting in increased injuries, property losses, and deaths. To date, there have been few studies characterising merging fire behaviours outside of the laboratory. In our study, we conducted small and medium scale field experiments, to test both emerging technologies for measuring merging fire fronts and guidance for operational support; and to test if existing models developed from small-scale laboratory experiments are appropriate at the landscape scale. The rate of spread (ROS) of junction fire fronts was found to be at least 60% higher than head fire fronts. Comparison between several studies and empirical models showed considerable variation in ROS for similar conditions. The post-processing approach to the captured videos allows for a minimum amount of time (hours) to quantify the fire behaviour in the experiments, with the resulting data being highly accurate across space and time. With further development and testing, this approach shows promise to be a valuable tool in fire behaviour research, operational and management applications. Comparison between the few available studies showed considerable variation in ROS for similar conditions. Further investigation is required to explain the results as the relationship between fuel load, wind speed and scale is not known.

There is an increasing recognition of the role of species flammability in predicting fire behaviour. Determining the flammability of individual plant species, particularly understory species, can provide us with a much better understanding of expected fire behaviour in the broader landscape. We proposed an effective, replicable and accurate method of testing flammability in live vegetation. Two heating regimes were tested – a static heat flux to reflect current methods and a dynamic (increasing) heat flux to replicate real conditions of an approaching fire front more accurately. Significant differences were observed between heating regimes suggesting that it is important to test flammability of live plants under a dynamic heating regime. Adoption of this methodology is recommended to ensure more realistic and standardised data of flammability of individual plant species and plant communities, which will lead to better informed and more accurate wildfire behaviour modelling. Using data on flammability of species in dynamic conditions (ignition time, consumption time, energy released) and in their natural fuel structure (physical structure and composition) for validation and calibration of fire behaviour models will increase model ability to predict the flammability metrics. Application of the method presented here to a large number of species could allow for more dynamic modelling of fire behaviour. Species would not be represented based on fuel load and structure, as is the case in existing and emerging operational fire behaviour models. Rather, species would be represented based on a flammability profile that responds to fire behaviour.

Our methodology could be extended to include exposure of samples to a variety of dynamic heating regimes based on typical fire intensities. This, in combination with the development of a species flammability database, could lead to the development of dynamic wildfire behaviour models that can adjust flammability inputs (e.g., time to pyrolysis and ignition, consumption time) based on weather conditions, and fuel properties, to produce more accurate outputs of intensity, and rate of spread.

Wildfire seasons are extending as the number of dry and hot days increase. A longer fire season is expected to result in more frequent and severe fires. Australia's bushfire season in 2019/20 (Black Summer hereafter) appears to have supported these conclusions in terms of the ecological consequences and impacts on human populations. To understand its impact, we conducted a preliminary analysis of the 2019/20 bushfire season and compared it with the fire seasons between March 2000 and March 2020 in the states of New South Wales (NSW), Victoria, and South Australia (SA). By March of 2020, the Black Summer fires burnt almost 19 million hectares, destroyed over 3,000 houses, and killed 33 people. The data showed that they were unprecedented in terms of impact on all areas. Several mega-fires occurred in NSW resulting in more burned area than in any fire season during the last 20 years. One of them, the Gospers Mountain fire, was the largest recorded forest fire in Australian history. Victoria had a season with the highest number of fires, area burned, and second highest numbers of houses lost for the same period. SA had the highest number of houses lost in the last 20 years. The Black Summer fires confirmed existing trends in life and house losses, during the last two decades for both NSW and Victoria. It showed that the smoke from the bushfires may be a significant concern in the future for the global community, as it travels to other countries and continents.

While much has been learnt about dynamic fire behaviour and extreme bushfire development, there remain several significant gaps in our knowledge, e.g., the multi-scale processes governing dynamic fire propagation and extreme bushfire development; generation, transport and ignition potential of firebrands and spotting; bushfire transition into and within the Wildland-Urban Interface, etc. Addressing these gaps is a highly challenging task, ands will require coordinated collaboration between research organisations across Australia to effectively develop the requisite knowledge.

END-USER STATEMENT

Simeon Telfer, *Fire Management Branch, Department of Environment and Water, SA*

Extreme fire behaviour accounts for a disproportionality high amount of economic, environmental and social losses in Australia and around the world. The level of effort expended by governments at all levels is enormous, as is the level of anxiety caused to society by these extreme events. Understanding the causes and actions that can be taken by agencies and the public is critical to improving our response to these events. This project has highlighted the utility and future need for data to be collected and analysed during extreme fire events. Our understanding of conditions and process that influence extreme fire behaviour have been advanced and importantly this project has shown how technology can be utilised to gain further insight. The onus is now on researchers and fire agencies to build on the foundation laid by this research by continuing to study, collect and analyse data from extreme fire behaviour events, when normal operations are known to be ineffective.

INTRODUCTION

In the last decade, there have been extreme wildfire events around the world resulting in substantial social, economic and environmental impacts. They threaten many lives and cost billions of dollars in damage. Climate change is making the fire seasons around the world even worse by extending the number of dry and hot days [1-4]. A longer fire season is expected to result in more frequent and severe fires [5, 6]. Australia's bushfire season 2019/20 (Black Summer fires hereafter) appears to have supported these conclusions in terms of the ecological consequences and impacts on human populations [7].

In most cases, these consequences are the result of dynamic fire behaviours (DFBs) [8-11]. The DFBs are localised dynamic events that occur within fires, whereby physical feedbacks greatly enhance fire intensities and rates of spread. Understanding and having the ability to predict DFBs in wildfire events is essential to ensure the safety of communities living in or near the Wildland-Urban Interface.

In this regard, the project 'Determining threshold conditions for extreme fire behaviour' was focused on the understanding and analysis of dynamic fire effects; their influence on fire behaviour and structures; and the potential of including these effects in fire behaviour models and new building standards.

THE DETERMINANTS OF CROWN FIRE RUNS DURING EXTREME WILDFIRES IN EUCALYPT FORESTS IN AUSTRALIA

BACKGROUND

Crown fires are recognised as DFB in forest ecosystems. They occur in vegetation that has multiple strata, transitioning from surface and understory fuels to canopy fuels under certain environmental conditions. Crown fires in forests can have impacts on environmental assets (e.g. biodiversity, soils, water quality) [12-14] and present an extreme hazard to health and the built environment, due to the large amounts of radiant heat being released [15] and embers produced [16]. Fire suppression is not feasible when crown fires are occurring [17-19] and the chances of firefighter entrapment are enhanced [20]. Consequently, being able to anticipate where and when crown fires are likely to occur, is critical for planning safe and effective fire responses and community safety.

Fire severity mapping has been used to study crown fire behaviour in Eucalypt forests [17, 21], and it has provided valuable insight into the influence of climate, topography and fuels on crown fire occurrence [21-23]. The utility of models derived from severity mapping is limited from an operational viewpoint for several reasons. Firstly, these models have used coarse fire weather indices, which combine information on fire weather (i.e. temperature, humidity, wind) and fuel moisture into one value (e.g., FFDI) [21, 23], and as such do not allow the contribution of weather parameters and fuel moisture to be disentangled. The amalgamation of weather and moisture into a single index may reduce the predictive accuracy of models and limit their spatial application. Second, past studies have considered the likelihood of crown fire at a single point [21, 23], whereas from a management perspective the prediction of large patches of crown fire, or crown fire runs, is perhaps more desirable as they have larger impacts and are a greater threat to fire suppression activities.

In this study, we use satellite derived fire severity mapping from 15 large wildfires that occurred in eucalypt forests in Australia, to develop an empirical model to predict the likelihood and extent of crown fire events using, spatially derived environmental predictors and a range of weather measurements [24].

RESEARCH APPROACH

The study was conducted in forested areas of south-eastern Australia (Figure 1). The study area consisted of the states of South Australia (SA), Victoria (VIC) and New South Wales (NSW). All the fires in the case study are within the Temperate climate classification with warm or hot summers and no dry season[1]. Vegetation across each of the fires in the study region are predominately forest and woodland, with the dominant canopy species from the genera *Eucalyptus, Corymbia* and *Angophora,* which we collectively referred to as Eucalypts.

[1] http://www.bom.gov.au/climate/how/newproducts/images/zones.shtml

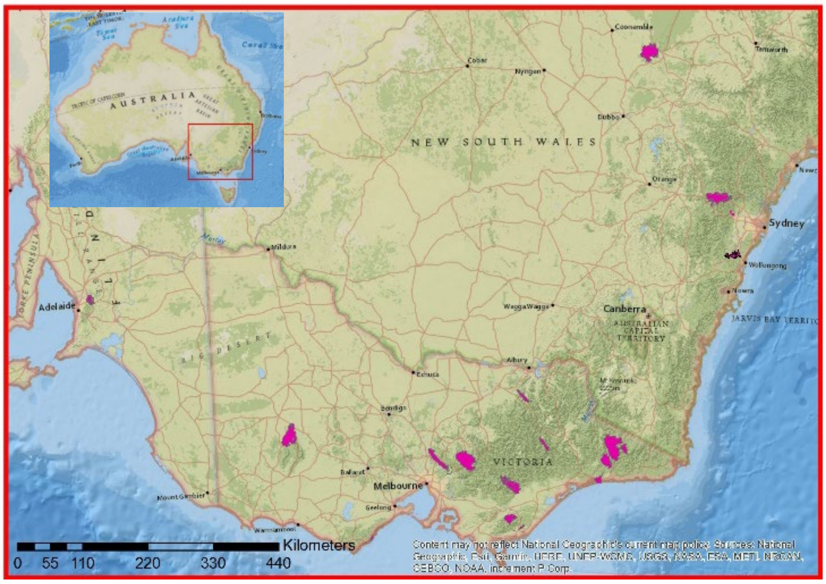


FIG. 1. CASE STUDY AREA AND LOCATION OF THE FIRES (MARKED BY PURPLE COLOUR). MOST FIRES ARE LOCATED IN VIC, WITH ONLY ONE IN SA AND FOUR IN NSW.

A key objective of this study was to model crown fire occurrence in eucalypt forests using fine temporal scale (i.e. sub daily) fire weather data. Therefore, in this study we only considered fires that had reconstructed perimeter isochrones of progression and linescans (images from high altitude aircraft mounted Infrared linescan systems) at a sub-daily resolution and burnt predominantly within eucalypt forests. Fifteen case study fires met the criteria to be suitable for analysis (Table 1). These fires all have several progression isochrones each day with an average interval of 4 hours.

Fire Name	State	Date (month/year)	Burned area (ha)	№ of progression isochrones	Maximum time between isochrones* (hours)
Sampson Flat	South Australia	01/2015	12569	14	5
North Grampians	Victoria	01/2015	54174	36	6
Wye River	Victoria	12/2015	2287	29	3
Kilmore	Victoria	02/2009	28421	9	1
Murrindindi	Victoria	07/2009	65504	15	1
Aberfeldy	Victoria	01/2013	25436	5	5
Churchill	Victoria	07/2009	21831	18	1
White Timber	Victoria	02/2009	9682	12	2
Beechworth	Victoria	02/2009	10938	21	2
Tostaree	Victoria	02/2011	10622	18	1
Deddick	Victoria	02/2014	112418	5	3
Hall	New South Wales	10/2013	15663	3	6
Linksview	New South Wales	10/2013	3295	18	6
State Mine	New South Wales	10/2013	51933	5	9
Wambelong	New South Wales	01/2013	54540	14	8

TABLE 1. WILDFIRES EXAMINED IN THE STUDY. * EXCEPT OVERNIGHT HOURS

Fire severity maps were created for all study fires using Landsat imagery (30 m resolution) and a Random Forest (RF) classifier, following the approach outlined in Collins *et al.* [25]. Five fire severity classes were classified during mapping, as unburnt, crown unburnt, partial crown scorch, crown scorch and crown consumption (Table 2). We reclassified each pixel as either experiencing crown fire (i.e. crown consumption) or not.

Severity class	Description
Crown consumption	>10% of canopy foliage has been completely consumed
Crown scorch	The majority (>90%) of the canopy foliage is scorched.
Partial crown scorch	Combination of both unburnt and scorched canopy foliage (10 – 90%).
Crown unburnt	Understorey has been burnt, but canopy foliage is largely unburnt (>90%).
Unburnt	Canopy and understorey foliage is unburnt.

TABLE 2. DESCRIPTION OF THE MAPPED FIRE SEVERITY CLASSES

Crown fire runs were the main focus of the study as they have larger impacts and present a greater challenge to fire suppression activities, than a single point crown fire. We quantified crown fire runs by calculating the proportion of pixels experiencing crown fire within a 5 x 5 pixel moving window (150 m x 150 m). This measure does not identify crown fire runs as discrete events, but rather provides a scale of the extremity of a run, whereby larger values represent more extreme crown fire runs.

Predictor variables were selected to represent the four key drivers of fire severity included in existing crown fire models and fire severity studies: fuel moisture, fuel load, fire weather and topography. Eleven predictor variables were used in the analysis, each representing different aspects of the four drivers: Live and dead fuel moisture content (fuel moisture); Surface, elevated and bark fuels and tree height (fuel load); Vapour-pressure deficit (the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated), wind speed and relative wind direction (fire weather); and Slope and topographic ruggedness (topography). Random Forest model was used to model the effect of environmental drivers on crown runs.

FINDINGS

Model performance and predictor importance

Assessment of the importance of predictor variables, based on the Gini scores (measures the inequality among values of a frequency distribution), indicates that variables reflecting fuel and air moisture were most influential in predicting crown fire runs, with fire weather and topography having intermediate influence, and fuel load and structure having the lowest influence (Figure 2).

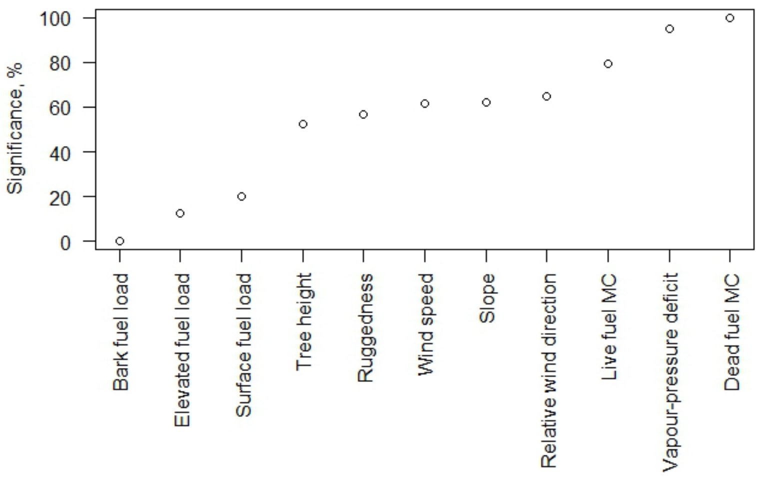
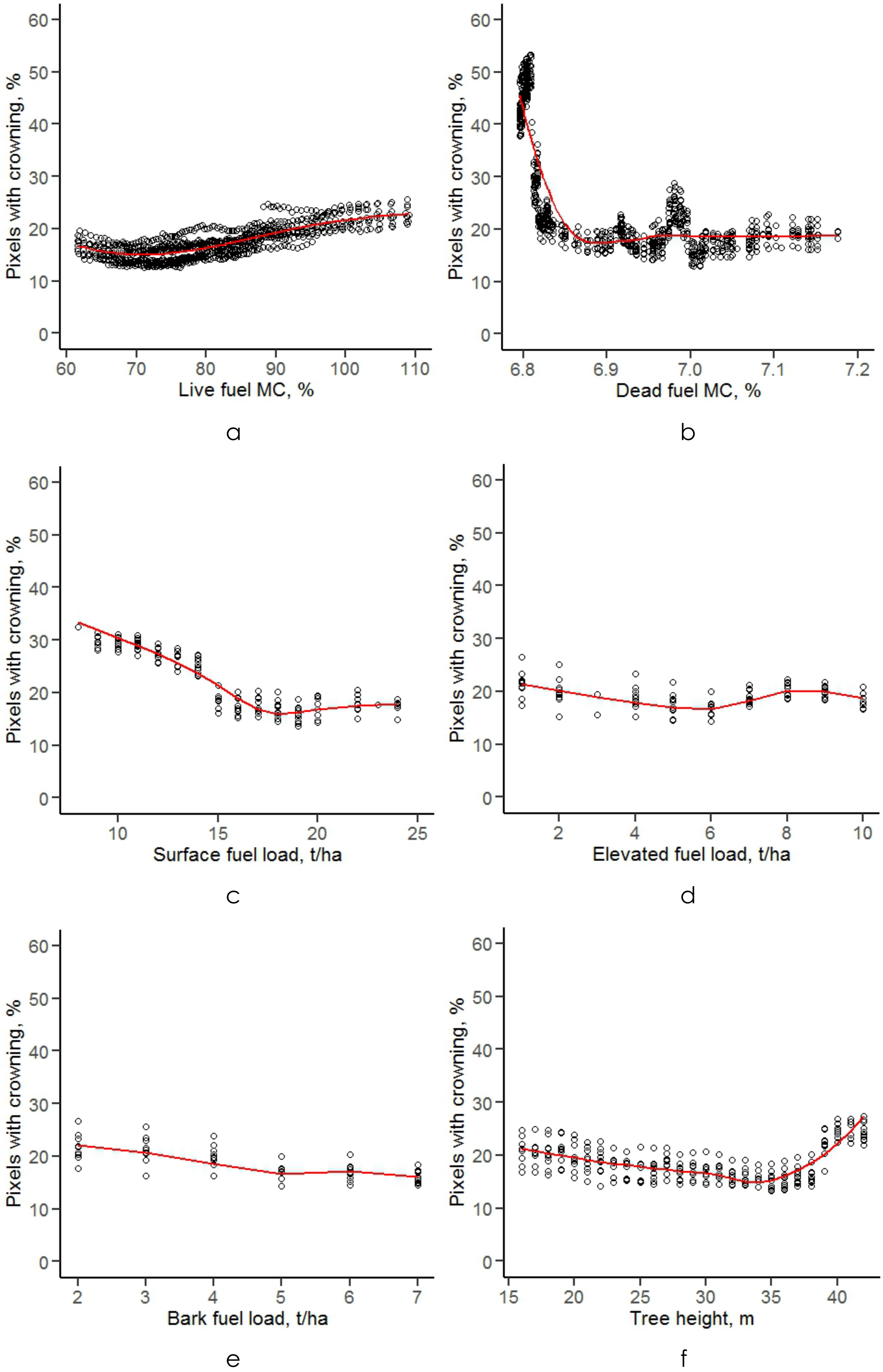


FIG. 2. IMPORTANCE OF PREDICTOR VARIABLES FOR THE PREDICTION OF CROWN FIRE EXTENT. RELATIVE SIGNIFICANCE OF VARIABLE IS DIMENSIONLESS VALUE CHANGING FROM 0 TO 100 %.

Model predictions were generated and plotted to understand the relationship between predictor variables and crown fire extent (Figure 3).



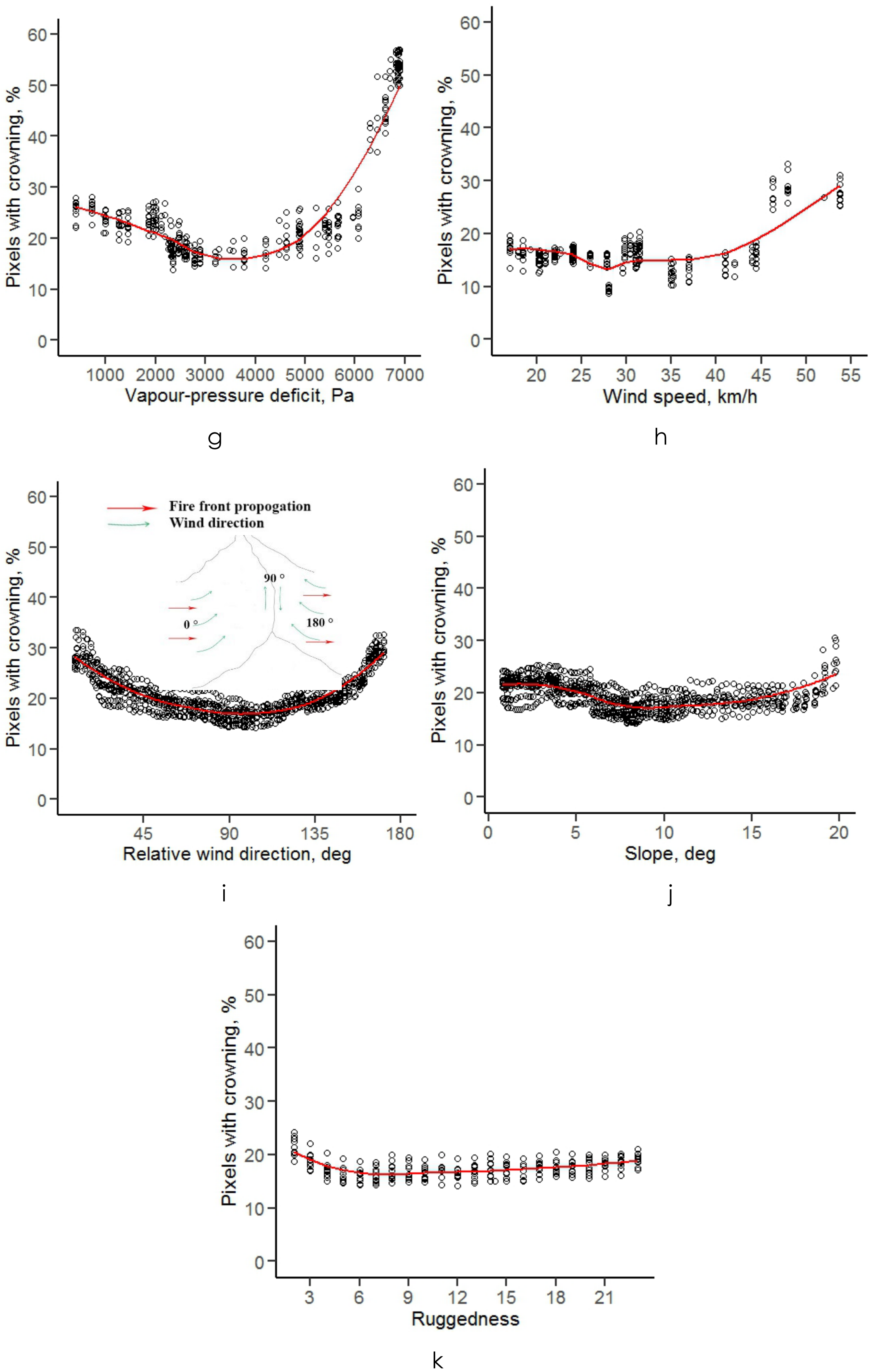


FIG. 3. INFLUENCE OF PREDICTOR VARIABLES ON CROWN FIRE EXTENT: a,b ARE FUEL MOISTURE VARIABLES, c-f ARE FUEL LOAD VARIABLES, g-i ARE FIRE WEATHER VARIABLES AND j,k ARE TOPOGRAPHY VARIABLES. PERCENTAGE IS CHANGING FROM 0 TO 100 %, WHICH CORRESPONDS TO THE TOTAL AMOUNT OF PIXELS.

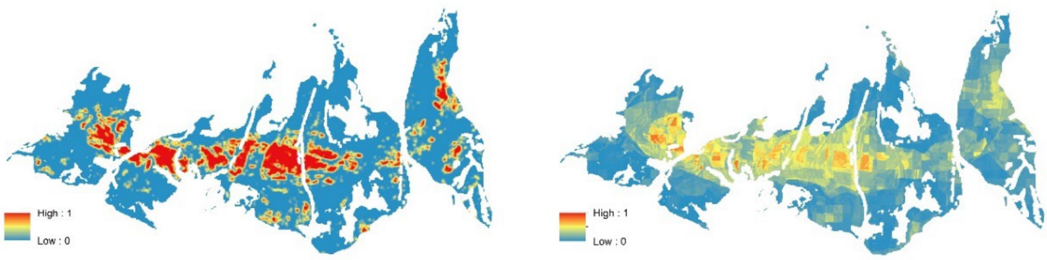
Several predictor variables were found to have a large effect on the crown fire extent. It was observed that live and dead fuel moisture content and vapour-pressure deficit were the most significant variables, influencing crown fire occurrence to 80% and above (Figure 3). Tree height, ruggedness, wind speed, slope, relative wind direction all had an intermediate significance on the likelihood of crown fire, increasing from 52 % to 64 %.

Analysis of individual predictor variables showed greater crown fire activity under warmer and drier conditions, which agrees with the observations. The highest influence on crown fire occurrence was observed for dead fuel moisture content (Figure 3b), and vapour-pressure deficit (Figure 3g), showing that these variables are the key drivers. A decrease of dead fuel moisture content below 6.9% and an increase of vapour-pressure deficit from 4 kPa to 7 kPa led to increase the proportion of pixels where crown fires occurred by 3fold. These findings highlight the fact, that moisture plays an important role in the ignition and combustion process [26, 27]. Even small changes in moisture can increase crown fire likelihood.

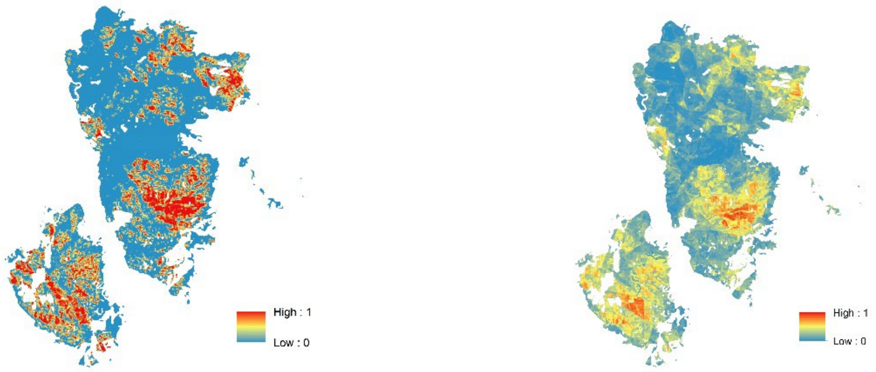
A smaller influence on crown fire likelihood was observed for tree height (Figure 3f), surface fuel load (Figure 3c), wind speed (Figure 3h) and relative wind direction (Figure 3i). The number of pixels experiencing crown fire doubled, if the following thresholds were crossed: >35 m tree height, <18 t/ha load, >40 km/h speed, 45°-90° and 135°-180° wind direction. The rest of the predictor variables changed the likelihood of crown fire in approximately 10 % of pixels without showing any consistent patterns.

Forecast results

To test the empirical model, we compared our predictions with the mapped fire severity observations (Table 1). Mapped predictions from the Random Forest model show a good degree of agreement with the raw fire severity maps (Figure 4). Analysis of the cells showed that the model over predicts crowning for pixels with low proportion of crowning in clusters (less than 50% of pixels), and under predicts for higher values.



Hall, NSW

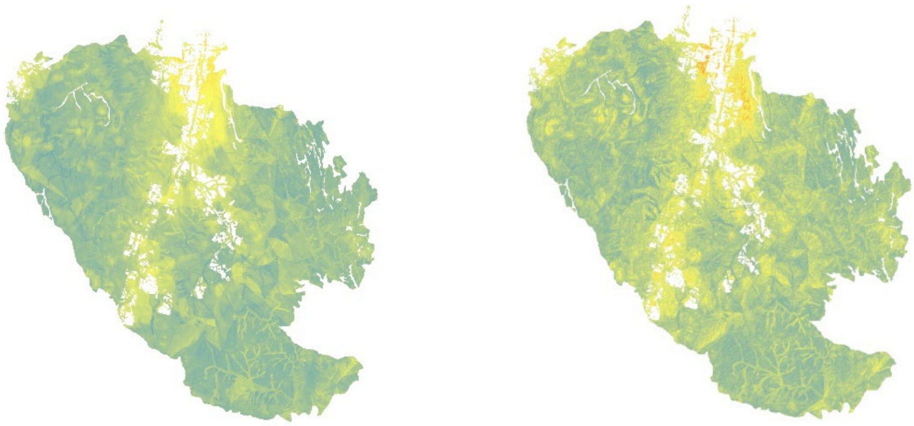


Deddick, Vic

Observation Prediction

FIG. 4. COMPARISON OF OBSERVED PROPORTION OF PIXELS WITH CROWNING VS PREDICTED. PROPORTION OF PIXELS WITH CROWNING IS CHANGING FROM 0 (NO CROWNING) TO 1 (ALL PIXELS WITH CROWNING).

Overall, the Random Forest model shows a good degree of agreement with the observations. Suggesting it could be a useful tool for decision support. To analyse its effectiveness for fire management, we compared predictions using our model for four consecutive days at 3 pm for the Murrindindi fire (Figure 5). The maximum likelihood of crown fire runs was observed on February 7th and equalled 0.71. The likelihood of crowning increased from the 5th of February to 7th (Figure 5). However, during intense bushfires, fire behaviour is changing very rapidly, and a daily forecast is not sufficient. For operational purposes it is desirable to have a more frequent forecast. To do so we ran simulations using the developed model with the hourly weather forecast for the same fire. Figure 6 shows the likelihood of crown fire runs for Murrindindi fire on Black Saturday (February 7th).



February 5th February 6th

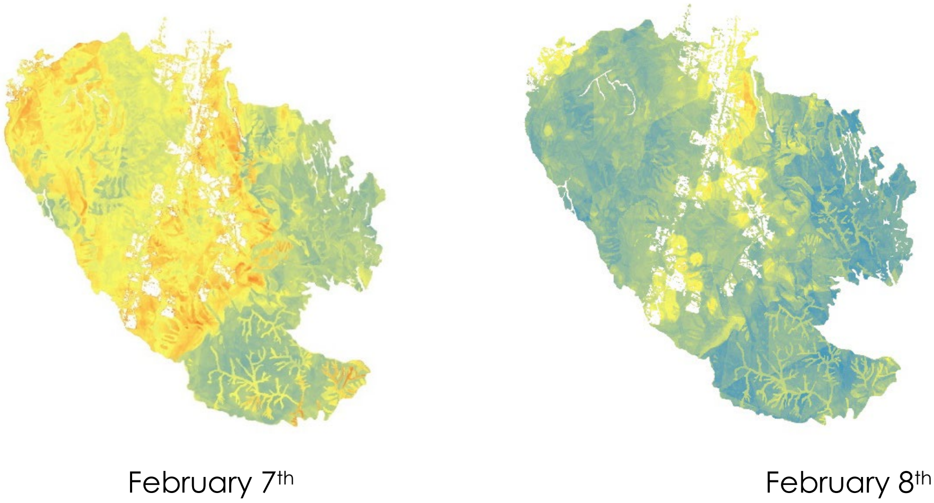
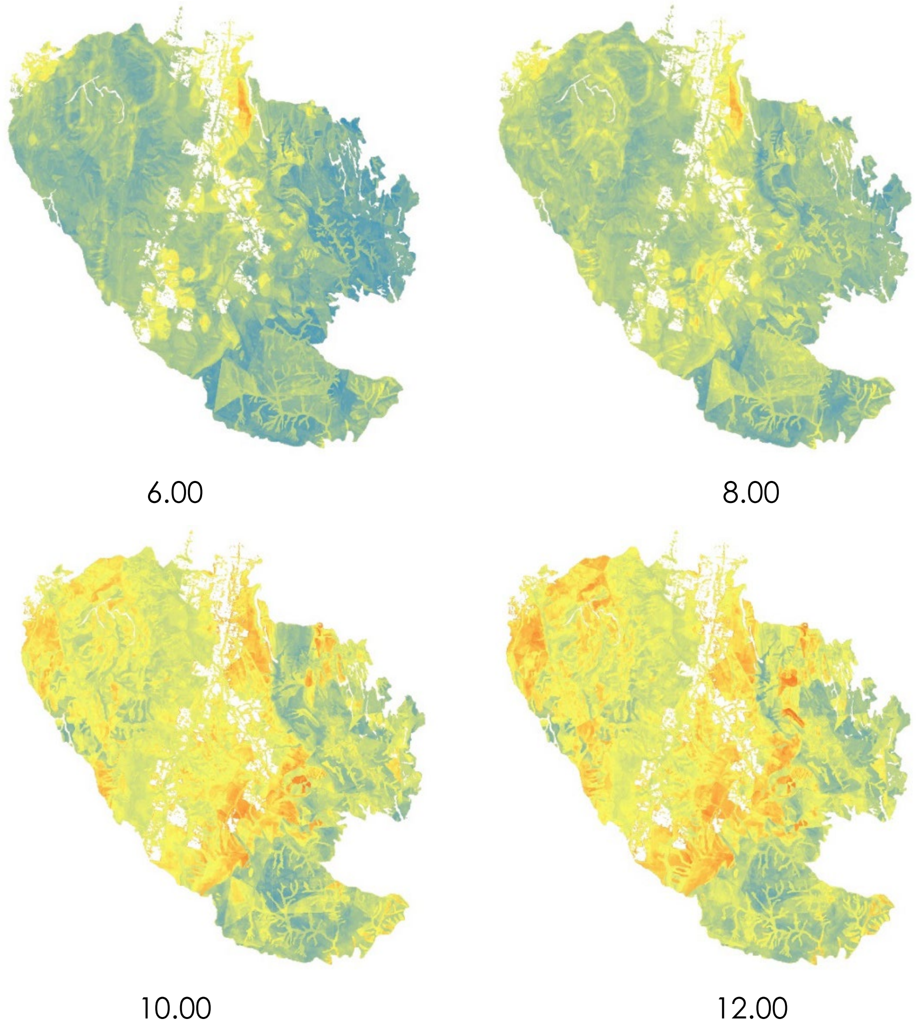


FIG. 5. DAILY FORECAST OF CROWN FIRE RUNS USING THE PROPOSED MODEL. THE SIMULATION RESULTS PRESENTED FOR 5^{TH}, 6^{TH}, 7^{TH} (BLACK SATURDAY) AND 8^{TH} OF FEBRUARY 2009 AT 3 PM FOR MURRINDINDI FIRE. FOR BETTER REPRESENTATION OF CROWN FIRE RUNS A LIKELIHOOD INCREASES ON FIGURE FROM 0 (GREEN, NO CROWNING) TO 0.8 (RED, 80% OF PIXELS WITH CROWNING).



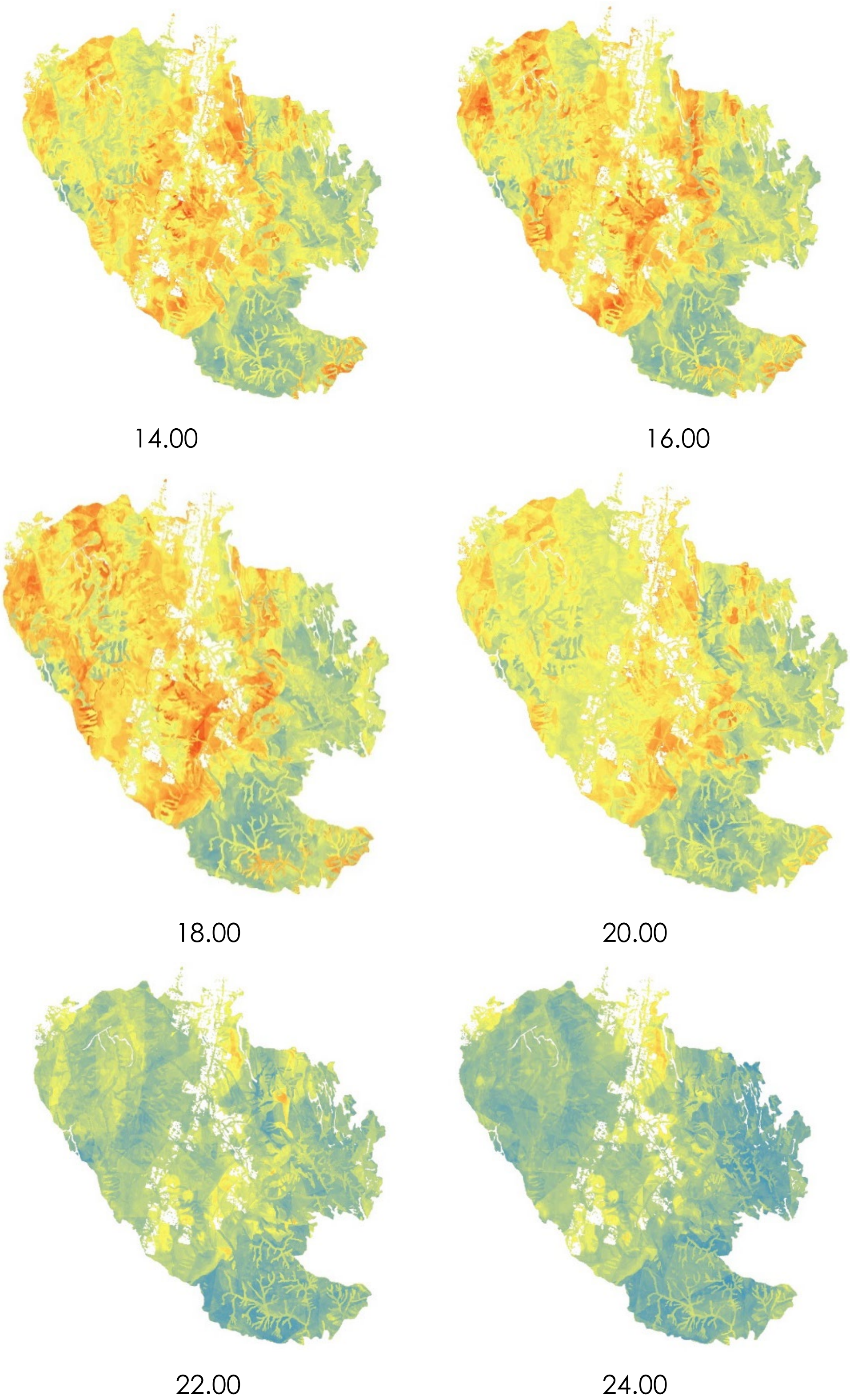


FIG. 6. ONE HOUR FORECAST FOR MURRINDINDI FIRE ON FEBRUARY 7TH (IMAGES ARE PRESENTED WITH 2H STEP). FOR BETTER REPRESENTATION OF CROWN FIRE RUNS A LIKELIHOOD INCREASES ON FIGURE FROM 0 (GREEN, NO CROWNING) TO 0.8 (RED, 80% OF PIXELS WITH CROWNING).

The maximum likelihood of 0.78 was observed at 14.00. However, the biggest areas with high likelihood of crown fire runs were observed between 14.00 and 18.00. These results suggest that high temporal prediction of crown fire runs can improve decision making and resource allocation.

SUMMARY

The study indicated that fuel and air moisture were most influential in determining crown fire runs, with fire weather and topography having intermediate influence, and fuel load and structure having the lowest influence. Several predictor variables were found to have a large effect on the proportion of pixels effected by crown fire. They were vapour-pressure deficit and dead fuel moisture content. These all had clearly identified thresholds, below which crown fires rarely occurred. These threshold values for vapour-pressure deficit and dead fuel moisture content were 4 kPa and 6.9 %, respectively. Unsurprisingly, these results highlight greater crown fire activity under warmer and drier conditions.

Predictions of crown fire runs using the proposed empirical model showed a good accuracy. Despite the model under predicting crowning under some circumstances, it is still a useful tool for decision support. Hourly predictions revealed the importance of high temporal forecasting. Combined with a good spatial resolution (150 x 150 m) this model can take into account local terrain and weather effects.

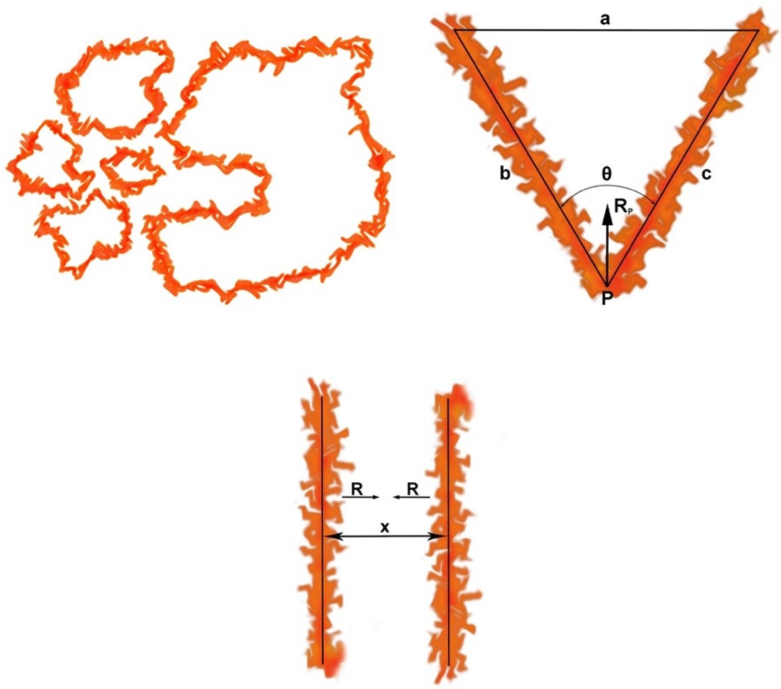
Guidelines developed from this model can be used to spatialize the risk of crown fires over landscapes at an hourly scale. These values would provide managers with a rapid means of assessing the risk of crown fire and subsequent damage at the resolution of local forecast values. In south-eastern Australia, these values would be at a 3km spatial resolution for up to seven days. Such information would be invaluable for fire managers in terms of allocating resources and communicating risk to the public.

USING TECHNOLOGICAL ADVANCEMENTS TO UNCOVER FIRE BEHAVIOUR PHENOMENA AND FOR OPERATIONAL SUPPORT

BACKGROUND

Catastrophic wildfires are often a result of dynamic fire behaviours. They can cause rapid escalation of fire behaviour increasing the danger to ground-based emergency personnel. Merging fires [28-32], are a dynamic fire behaviour that can lead to rapid increases in fire intensity and rate of spread [33]. The convergence of separate individual fires into larger fires is known as coalescence, and the merging of two lines of fire intersecting at an oblique angle is termed junction fire or junction fire fronts [28]. Fire coalescence, inward parallel fire fronts, and junction fire fronts are all examples of merging fire fronts (Figure 7). Merging fire fronts have been recorded in several significant bushfires. For example, in the 2003 Canberra fires, the McIntyre's Hut and Bendora fires merged in the early afternoon [34]. The merging fire apex spread rapidly and developed into an extremely destructive junction fire which resulted in four deaths, many injuries and property losses valued at $600 million to $1 billion [34].

To date, there have been few studies characterizing merging fire behaviours outside the laboratory. In this study, we conducted small and medium scale field experiments to test emerging technologies for measuring merging fire fronts; and to test if existing models developed from small-scale laboratory experiments are appropriate at the landscape scale [35, 36].



a b c

FIG. 7. Merging fire fronts: a) Fire coalescence, b) Junction fire, c) Parallel fire fronts. Where *a*, *b* and *c* are the dimensions of the junction fire; *θ* is the angle between oblique fire fronts; x is the distance between parallel fire fronts.

RESEARCH APPROACH

Study area and equipment

FIG. 8. Location of experimental plots. Green lines represent ignition lines.

Harvested wheat fields were used as experimental plots, as they form homogeneous fuel beds. Fuel height varied from 18 to 40 cm. Fuel load and moisture content was 0.1 kg/m^2 and 11.9 % respectively. An automatic weather station (AWS, 30-min temporal resolution) and two 2-dimensional DS-2 sonic sensors (Decagon Devices, Inc.) were used for air temperature, relative humidity, wind direction and speed measurements. A DJI Mavic Pro (UAV) was used to capture high-definition video imagery of fire propagation in synchronisation with sensor data from the on-board Global Positioning System (GPS) and Inertial Measurement Unit (IMU). These sensors enabled the platform/camera orientation and position in space to be aligned with the video footage and the fire propagation georeferenced in GIS software. Different configurations of ignition lines were tested during the experiments. Ignition of fuel was done downwind by a drip torch along the edge of the experimental plots (Figure 8). Six ignition lines were ignited during the experiment.

Data capture and processing

Video data was captured using the onboard camera on the DJI Mavic Pro. Video was recorded at a 1080p resolution at 60 fps. The CIRRUAS application was used with an android phone to record the necessary flight metadata for post processing [37]. The post processing phase was completed for each separate video and metadata file using the Full Motion Video (FMV) toolbox within the ArcGIS Pro software [38]. The metadata log file containing sensor information is combined with the video file in a process called Multiplexing. The result is a video file with each frame georeferenced. The multiplexed video file was then used to identify and spatially define fire fronts at set time intervals.

To compare ROS between different phenomena and with other studies we used the approach proposed by Sullivan *et al.* [39]. They introduced so-called null hypothesis:

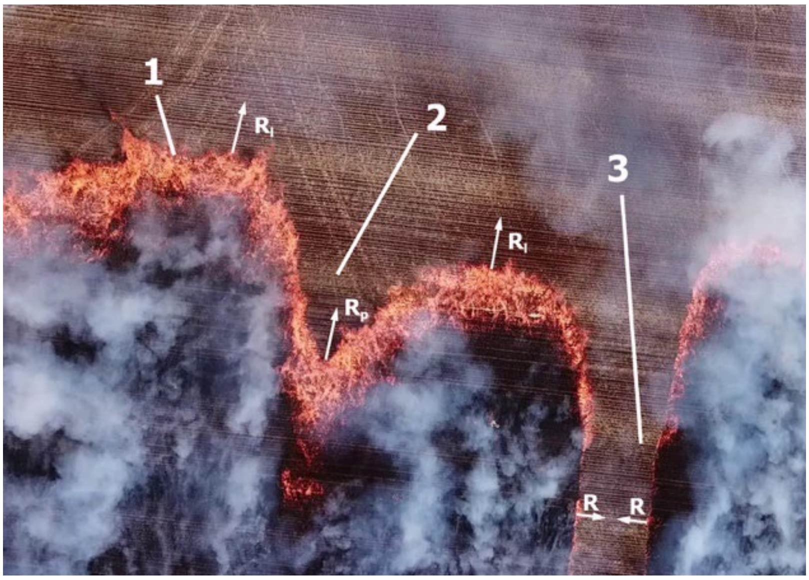
$$R' = \frac{R_P}{R_0} = \frac{1}{\sin(\theta/2)} = \operatorname{cosec}\left(\frac{\theta}{2}\right), R_0 = R_l\left(no\,wind\right), R_0 = R_l \sin\left(\frac{\theta}{2}\right)\left(wind\right) \qquad (1)$$

where R' is the non-dimensional form of the rate of spread of intersection point of two oblique fire fronts; R_P is the rate of spread of intersection point of two oblique fire fronts; R_0 is the basic rate of spread of a linear fire front; θ is the angle between oblique fire fronts and R_l is the rate of spread of the linear fire front. For windy conditions R_0 was calculated as the rate of spread of the linear fire front R_l perpendicular to the wind and corrected to compensate for the effect of the different junction angles on each R_0 (eq. 1).

FINDINGS

Eleven videos were filmed during the experiments and multiplexed. The georeferenced frames of each filmed area are shown on the map (Figure 9a). Twenty-six merging fire fronts in total were identified: 21 junction fire fronts and 5 parallel fire fronts. Examples of junction fire front, linear fire front and inward parallel fire fronts are presented on Figure 9b.

a



b

FIG. 9. a) Bird view of video footages. Each rectangular represents separate video footage. b) Observed fires: 1) linear fire front; 2) junction fire fronts; 3) parallel fire fronts. R_p is the rate of spread of intersect point of two junction fire fronts, R_l is the rate of spread of the linear fire front, R is the rate of spread of parallel fire fronts.

The junction fire fronts identified were separated into 4 groups depending on the recorded initial angle between oblique fire fronts θ_{in}: 4°-14°, 28°-34°, 40°-59° and above 76°. The highest number of fires (43%) were observed in 28°-34° group.

The ROS of junction, linear and parallel fire fronts was calculated as an average of all 2- and 5-s time intervals. The ROS of junction fire fronts is significantly different and higher than linear fire front ROS, which is consistent with other studies [29, 39, 40]. More than 60% increase in ROS was observed for junction fire fronts (Figure 10). However, ROS of junction fire fronts did not change notably during the merging process [35], which is in contrast to Viegas *et al.* [40], Raposo *et al.* [32], Thomas *et al.* [30], and Sullivan *et al.* [39]. Previous studies [29, 32] identified an initial acceleration phase followed by a deceleration phase for each junction fire development [29, 32], however, our results did not show these pronounced phases for each junction fire [35]. All fires behaved differently having either deceleration-only, acceleration-only or both phases for all initial angle groups. For instance, 38% of junction fire fronts showed an increase in ROS at the final stage of the merging process in contrast to [29, 32]. These observations demonstrate a high degree of variability even within a single set of weather conditions. It is problematic to make any conclusion as the number of junction fires and measurement points for individual fires are limited.

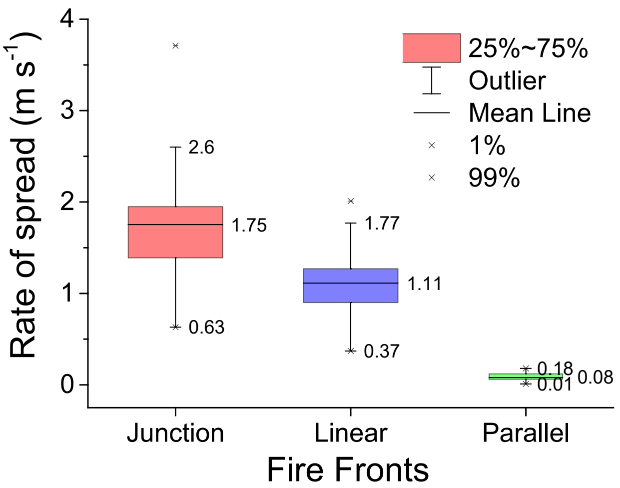


FIG. 10. Comparison of different types of fire front propagation

Comparison of junction fire fronts with different junction fire front lengths (3.6-22 m) and angles showed no notable influence in contrast to Sullivan *et al.* [39]. In the experiments of Sullivan *et al.* [39] fuel was both inwards and outwards of the junction lines, providing fire spread both inward and outward. Such fuel layout was not observed during field experiments and may be one of the reasons for the difference.

Analysis of video footages with merging fire fronts revealed that in all cases, junction fire fronts have a different shape to previous studies (Figure 11). Different configuration of ignition lines can result in different ROS of intersect point R_P. It is hypothesized that the left and right shoulder of junction fires (Figure 11b) create complex convective structures and cause changes in the ROS. In our experiments, we observed increase of the ROS in almost 40% of junction fire fronts at the final stage of merging in contrast to a decrease or no change in the ROS in previous research [29, 32, 39, 40].

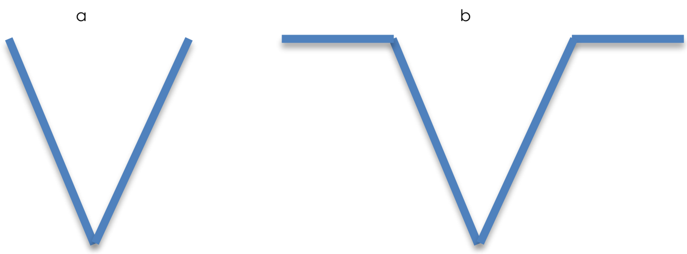


FIG. 11. Contour of a junction fire fronts: a) considered in all previous studies, b) observed in our field experiments.

Figure 12 shows comparison of our results with experimental and modelling studies of Sullivan *et al.* [39], Viegas *et al.* [40], and Thomas *et al.* [30]. Although Sullivan *et al.* [39] found that for the wind-driven experiments there is an increase of the rate of propagation of the vertex above what would be expected from trigonometry alone (1), we did not observe such increase for all junction fire fronts (Figure 12a). Our ROSs were above and below the null hypothesis (1) even with the wind speed 1.8-7.0 m s^{-1}. It can be assumed that in field conditions and for wind speed higher than 1 m s^{-1}, the *R'* of junction fire fronts is more complex.

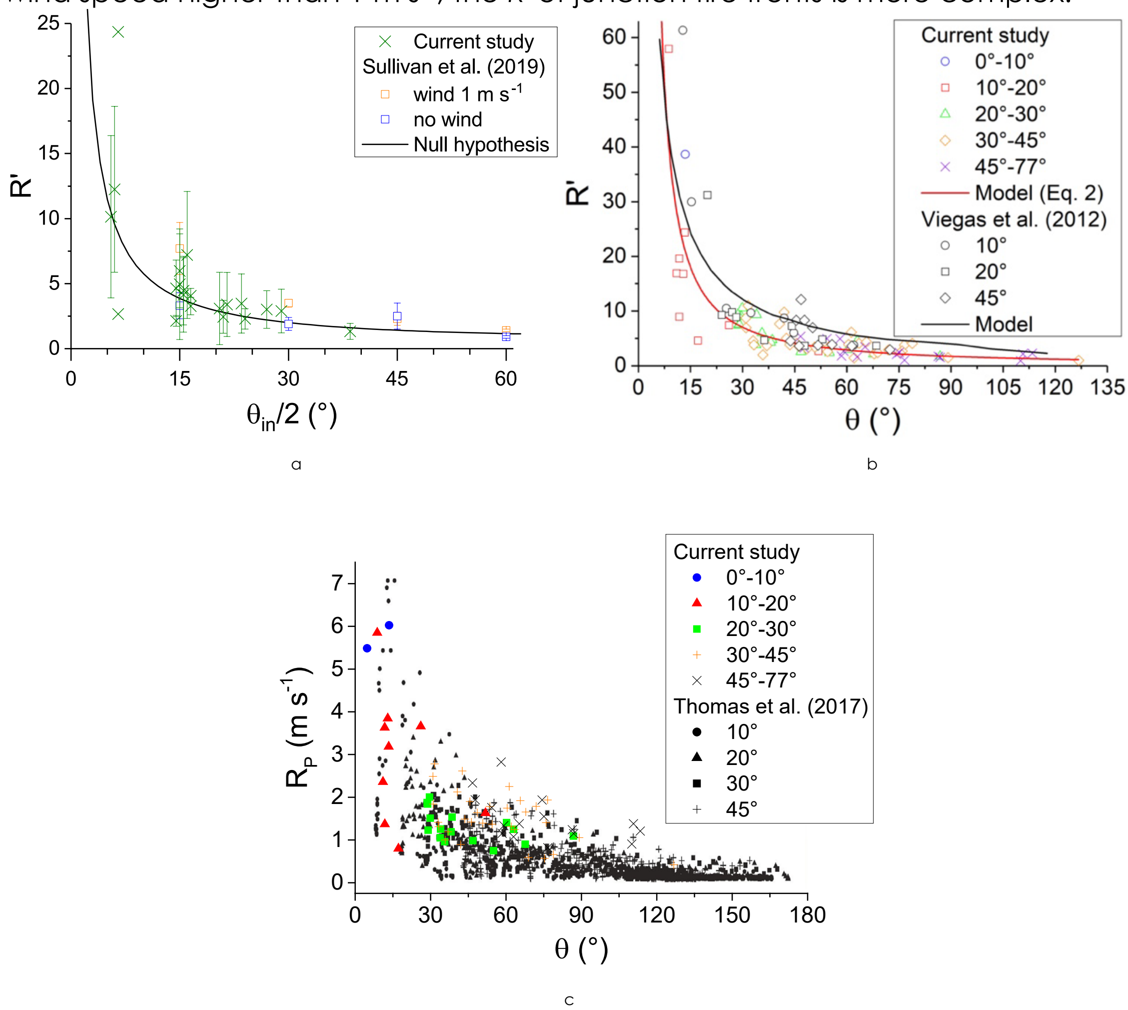


FIG. 12. Comparison with other studies:
a) Comparison of dimensionless rate of spread *R'* with study of Sullivan *et al.* [39]. Markers indicate *R'* for different initial angles θ_{in}. Current study represents results for wind conditions 1.8-7.0 m s^{-1}. Black line is the null hypothesis (1).
b) Comparison of dimensionless rate of spread *R'* with Viegas *et al.* [40]. Markers indicate angle between junction fire fronts at different moments of time. Legend shows the ranges of initial angles θ_{in}. Black line is the simplified analytical model of Viegas *et al.* [40]; red line is a regression line from current study (2), adjusted R^2=0.92.
c) Comparison of the rate of spread of intersect point of two junction fire fronts R_p with numerical results of Thomas *et al.* [30]. Markers indicate angle between junction fire fronts at different moments of time. Legend shows the ranges of initial angles θ_{in}.

To compare with the simplified analytical model of Viegas *et al.* [40] we modelled our data with the Belehradek model [41] (Figure 12b):

$$\mathrm{R}' = 421.92 * (\theta - 1.98)^{-1.23} \qquad (2)$$

Dimensionless ROS R' in our study is lower than that of Viegas *et al.* [40]. The difference was up to 373% with an average 66% (relative to our data). Comparison of dimension ROS (R_p) with numerical simulation of Thomas *et al.* [30] shows a good agreement (Figure 12c), despite different fuel type and load. Thomas *et al.* [30] also conducted a comparison of numerical simulation (length of fire lines ~1 km) with experimental results of Viegas *et al.* [40] (length ~ 8 m). Their results showed no quantitative agreement as well. They assumed that the reason is the different scale of experiments and numerical modelling.

SUMMARY

Small and medium scale field experiments were conducted on harvested wheat fields to characterise fire behaviour using emerging technologies. A UAV was used to capture high-definition video imagery of fire propagation. Twenty-one junction fire fronts and five inward parallel fire fronts were identified during the experiments.

The rate of spread (ROS) of junction fire fronts was found to be at least 60% higher than head fire fronts. Thirty-eight percent of junction fire fronts had increased ROS at the final stage of the merging process. These results contrast with previous published work.

Our results suggest that experimental design of existing studies on merging fires are not consistent as comparison between them showed considerable variation in ROS for similar conditions. Future research needs to conduct experiments with comparable initial conditions and measurements of convective and radiative energy. Without such data, it is not possible to understand merging fires and improve operational models. UAVs provide a means of improving data collection for this purpose.

IGNITIBILITY OF LIVE PLANTS

BACKGROUND

There is an increasing recognition of the role of species flammability in predicting fire behaviour [42-44]. Historically, flammability has been predicted based on fuel loads and ecological vegetation communities. Determining the flammability of individual plant species, particularly understory species, can provide us with a much better understanding of expected fire behaviour in the broader landscape [45, 46].

Elements of flammability were originally defined as ignitability (delay time between exposure to heat energy and ignition occurring), sustainability (how well a fire will continue to burn), and combustibility (how rapidly a fire burns) by Anderson [47]. Martin *et al.* [48] extended this definition of flammability to include consumability, which they defined as a measure of how much of a sample is consumed by the fire. Despite agreement on the definitions of flammability, there are several methodological limitations with previous studies on live plants. Firstly, many studies only use individual elements of a plant, usually leaves, which are then used to infer whole-plant or fuel bed flammability [49-52]. This method does not account for factors such as the physical arrangement of leaves on the plants or litter in fuel beds, the effect of which tends to dominate the effect of any leaf-specific characteristics [49, 53].

Secondly, simplistic apparatuses have been used to test larger samples in their natural physical arrangement [45, 54, 55]. Such experimental design does not allow the measurement and replication of realistic heat flux from wildfires. This is vital as heat flux quantifies the direct energy impact on the samples. Furthermore, most existing studies do not distinguish ignition mechanisms – autoignition (unpiloted) and piloted ignition. Perhaps one of the greatest limitations is that current plant flammability experiments have only exposed samples to static levels of radiant heat. In reality, vegetation is exposed to variable radiant heat flux as the fire front approaches due to its dynamic nature [56].

Here we propose a replicable and accurate experimental method to determine the impact of dynamic radiant heat flux on live plant species. So that more realistic measurement of species flammability can be gathered [57]. These measures can then be used to further improve the accuracy of fire behaviour models for different fuel types.

RESEARCH APPROACH

Samples and their properties

Several species were selected to determine whether an influence on flammability was solely due to the difference in heating regime, or if species characteristics (fuel, density and arrangement) were also drivers. The species selected for this study were *Acacia floribunda*, *Cassinia arcuata*, *Pinus radiata* (juvenile) and Bark from *Eucalyptus obliqua* (referred to as Acacia, Cassinia, Pine and Bark henceforth).

The samples of Acacia, Cassinia and Pine collected were approximately 300mm in length, and were intended to be representative of the standard shape and arrangement of fuel demonstrated by the live plant (Figure 13).

Bark samples were collected from the outer layer of trees the day prior to experimentation and cut to size (length 200mm, width 40mm, depth 10mm) and placed in an oven at 30°C overnight to allow for moisture content stabilisation.

FIG. 13. IMAGES OF REPRESENTATIVE SAMPLES: a) *ACACIA FLORIBUNDA* (FRONT AND SIDE VIEW), b) *CASSINIA ARCUATA* (FRONT AND SIDE VIEW), c) *PINUS RADIATA* (JUVENILE), AND d) BARK FROM *EUCALYPTUS OBLIQUA*.

Dimension measurements (length, width and depth) were collected from each sample, and the mean calculated to determine representative sample dimensions for each species.

Volume of solid fuel in each sample V_{fuel} was measured by submerging each sample in a measuring cylinder filled with water. The difference in water level before and after submersion of the sample provided the volume of the solid fuel in each sample. The mean of the volume measurements was then calculated to determine a representative solid fuel volume for each species.

Bulk volume of each sample V_{bulk} was obtained by calculating a sector of volume of a solid of revolution. A solid of revolution is a solid 3D figure obtained by rotating a plane curve around the axis of revolution. Volume of Bark samples was calculated as the volume of parallelepiped.

Packing ratio ξ was calculated as ratio of V_{fuel} to V_{bulk}. Porosity was calculated by subtracting the packing ratio from 1. As porosity and packing ratio similarly represent the fuel structure, only packing ratio was used hereafter. Bulk density was calculated by dividing the dry mass by the bulk volume for each species.

Exposed area and surface area to volume ratio (*SA:V*) were also used as a measure to characterise each of the sample species. Exposed area was calculated by scanning three samples of each species and analysing the scanned image in R statistical package version 3.6.0 [58] to produce the exposed area. Exposed area was not calculated for Bark samples because they were considered to be solid samples.

The following approach was used to calculate *SA:V* for leaves. Mean surface area of a single leaf was calculated by scanning 41 (Acacia), 55 (Pinus), and 91 (Cassinia) leaves and analysing the scanned image in the R statistical package version 3.6.0 [58]. Mean volume was calculated using measured perimeter, thickness and area of leaves. *SA:V* was not calculated for Bark samples.

Equipment

The Variable Heat Flux (VHFlux) Apparatus was used for this study (Figure 14). Two heating regimes were tested – a static heat flux to reflect current methods and a dynamic (increasing) heat flux to more accurately replicate real conditions (an approaching fire front). Piloted-ignition and unpiloted-ignition were also tested for both heating regimes.

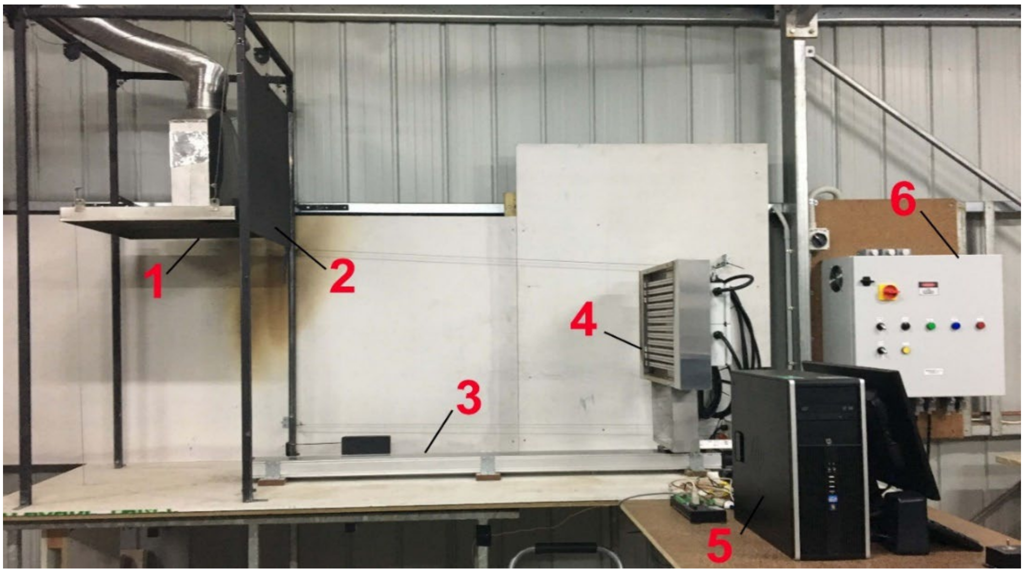


FIG. 14. VARIABLE HEAT FLUX (VHFLUX) APPARATUS 1) AN EXHAUST SYSTEM, 2) A SHUTTER, 3) A LINEAR STAGE, 4) A RADIATIVE PANEL, 5) A PC CONTROL SYSTEM AND 6) A POWER CONTROL BOX.

The VHFlux apparatus is a radiative panel containing 12 infrared short-wave lamps producing radiative heat flux. The panel is mounted on a 1.5m linear stage that allows it to move forward and backwards, creating a variable heat flux. The apparatus was configured as per Figure 15 below.

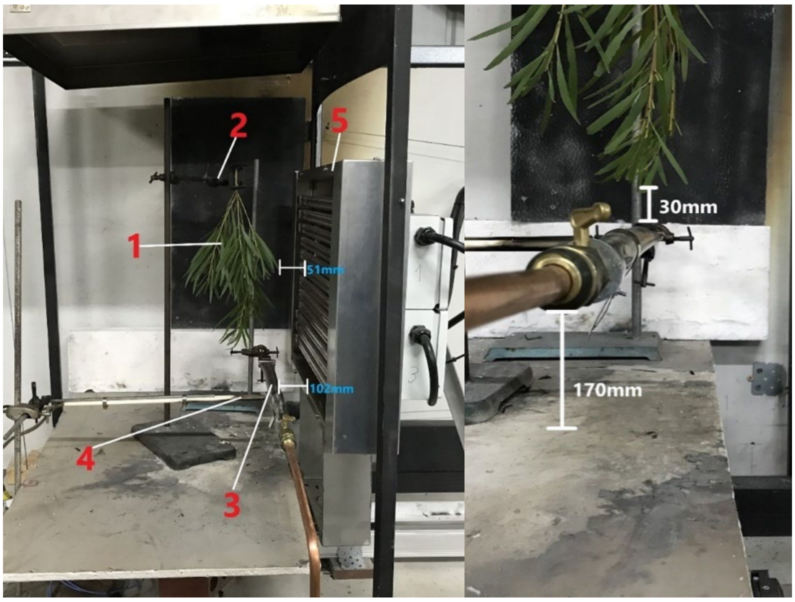


FIG. 15. EXPERIMENTAL DESIGN: a) HORIZONTAL ARRANGEMENT: 1) SAMPLE, 2) CLAMP, 3) PILOT IGNITER, 4) SPARK IGNITER, 5) RADIATIVE PANEL; b) VERTICAL ARRANGEMENT.

The pilot igniter consisted of a modified barbeque gas burner. We recorded each experiment with a DSLR camera (Canon EOS 600D) which was remotely operated from the computer desk.

Heating regimes

To determine the static radiative heat flux exposure to samples during the experiments, a water-cooled heat flux sensor SBG01-100 (Hukseflux Thermal Sensors B.V.) was placed 51mm from the radiative heat panel, and radiative heat flux measurements (kW/ m^2) were recorded for a ten-minute period at the centre of the panel. The mean of these measurements was calculated at 63kW/ m^2, which was henceforth assumed to be the radiative heat flux exposed for static experiments.

The radiative heat panel was programmed to travel 500mm over a ten-minute (600s) period for the dynamic increasing heat flux regime. The machine ran from 551 to 51mm from the sample to simulate a fire front moving towards the sample. The heat flux meter was placed at the same position as for calibration of static experiments, to determine the sample's exposure to radiative heat flux over this period. A dynamic heat flux curve was created from these measurements to determine the radiant exposure – the radiant energy received by a sample over a time of heating:

$$H_e = \int_{t1}^{t2} q_r(t)\,dt, \tag{3}$$

where H_e is the radiant exposure of a surface ("e" for "energetic"), J/m^2; *t* is time, sec; q_r is radiative heat flux, J/s·m^2 (W/m^2).

For static experiments, the radiant exposure H_e was calculated using the function *f(t)=63t*, where *t* is equal to time in seconds. For dynamic experiments, it was calculated using the fitted curve equation:

$$\mathrm{f(t)} = \text{2E-10}t^4 + \text{8E-08}t^3 - \text{2E-05}t^2 + 0.0325\mathrm{t} + 8.533, \tag{4}$$

where t is equal to time in seconds.

The definite integral for this function is the radiant exposure H_e for dynamic conditions. Over the ten-minute (600s) period it was ~15,700 J/m^2. The experimental time for the static heat flux was calculated to ensure that samples were exposed to the same total H_e as for the dynamic regime. The experimental time for the static experiments was determined to be 250s.

Data analysis

Video footage collected during the experiments was viewed in VLC media player to determine the time (s) to pyrolysis (production of volatile products), smouldering, leaf/foliage drop, flaming ignition, and complete consumption for each experiment. An explanation of how each flammability measure was defined is in Table 3.

Ignitibility Measure	Definition
Pyrolysis	First visible smoke is emanating from sample
Smouldering	Heavy smoke emanating from sample as a result of flameless thermal degradation– defined as point when smoke is thick enough to show as different colour in video playback
Foliage Drop	First leaf/needle falls from sample
Flaming Ignition	Flames produced from sample
Complete Consumption	All leaves/needles consumed from sample
Flaming Ignition to Complete Consumption	Interval between first flame produced and consumption of all leaves/needles from sample
False Ignition	Ignition of sample prior pyrolysis due to influence of the pilot ignitor

TABLE 3. EXPLANATION OF EACH IGNITIBILITY MEASURE

The Data was then used to calculate the total radiant exposure (kJ/m^2) of the sample at each of the above measures. The time between first flaming ignition and complete consumption (consumption time hereafter) was also calculated as an additional measure for discussion. The results of this calculation were also converted into radiant exposure using the process outlined above.

FINDINGS

Using the calculations and methods outlined above, Table 4 was produced to show the Mean moisture content (MC), bulk volume of material (V_{bulk}), volume of solid fuel (V_{fuel}), packing ratio (ξ), bulk density (ρ_f), exposed area, and surface area to volume ratio ($SA{:}V$) measures for each species used for this study.

Species	Mean MC (SD), %	Mean V_{bulk} (SD), m^3	Mean V_{fuel} (SD), m^3	Mean ξ (SD)	Mean ρ_f (SD), kg/m^3	Mean $SA{:}V$ (SD), 1/m	Mean exposed area (SD), m^2
Acacia	52 (2.8)	6.49E-03 (3.45E-03)	1.6E-05 (7.42E-06)	0.004 (0.004)	1.58 (0.92)	5,458 (139)	0.1 (0.001)
Cassinia	54 (1.6)	3.12E-03 (1.37E-03)	1.1E-05 (2.24E-06)	0.005 (0.005)	1.46 (1.26)	14,009 (660)	0.11 (0.0034)
Pinus	65.5 (2.5)	2.31E-03 (1.17E-04)	9E-06 (4.18E-06)	0.004 (0.002)	1.65 (0.15)	8,726 (353)	0.07 (0.0177)

Bark	23.1 (16.9)	9.81E-05 (1.75E-05)	7.7E-05 (9.75E-06)	0.793 (0.061)	158 (7.4)	N/A	N/A

TABLE 4. SUMMARY OF MEASURES USED TO CHARACTERISE A REPRESENTATIVE SAMPLE FOR EACH SPECIES. WHERE MC IS THE MOISTURE CONTENT; V_{BULK} IS THE TOTAL OR BULK VOLUME OF MATERIAL, INCLUDING THE SOLID AND VOID COMPONENTS; V_{FUEL} IS THE VOLUME OF SOLID FUEL; ξ IS THE PACKING RATIO; P_F IS THE BULK DENSITY; *SA:V* IS THE SURFACE AREA TO VOLUME RATIO; SD IS THE STANDARD DEVIATION.

It was found that the presence of the pilot ignitor greatly increased the likelihood of a sample reaching flaming ignition (Table 5). For Acacia, Cassinia and Pinus 1-4 of 10 samples reached flaming ignition in unpiloted experiments, while in piloted experiments 7-10 samples reached flaming ignition. However, all Bark samples reached flaming ignition under all test conditions. There was no notable difference for any species in the number of samples that reached flaming ignition when comparing static and dynamic heating regimes. A lower number of samples were reported for Bark in piloted experiments due to false ignition causing destruction of samples.

Species	Samples Reaching Flaming Ignition			
	Unpiloted		Piloted	
	Static	Dynamic	Static	Dynamic
Acacia	1	1	8	9
Cassinia	4	3	10*	10*
Pine	4	2	10*	7
Bark	10*	10*	8*	5*

TABLE 5. NUMBER OF SAMPLES FOR EACH EXPERIMENT TYPE THAT REACHED FLAMING IGNITION. SAMPLES MARKED WITH * INDICATE THAT ALL SAMPLES REACHED FLAMING IGNITION. IN MOST SPECIES MAXIMUM SAMPLE SIZE WAS 10, BUT FOR BARK THE MAXIMUM SAMPLE SIZES WERE LOWER DUE TO THE INFLUENCE OF THE PILOT IGNITOR.

Large differences were observed in the results based on both heating regime and ignition type. These results are consistent with past studies conducted on flammability of building materials [59-66].

Samples under a dynamic heating regime required more time and radiant heat exposure to reach ignition (and other flammability measures) (Figure 16). This difference is due to the period of low heat flux exposure at the beginning of the dynamic heating regime, which allows time for convective cooling of the samples and dilution of the pyrolysis gases to occur.

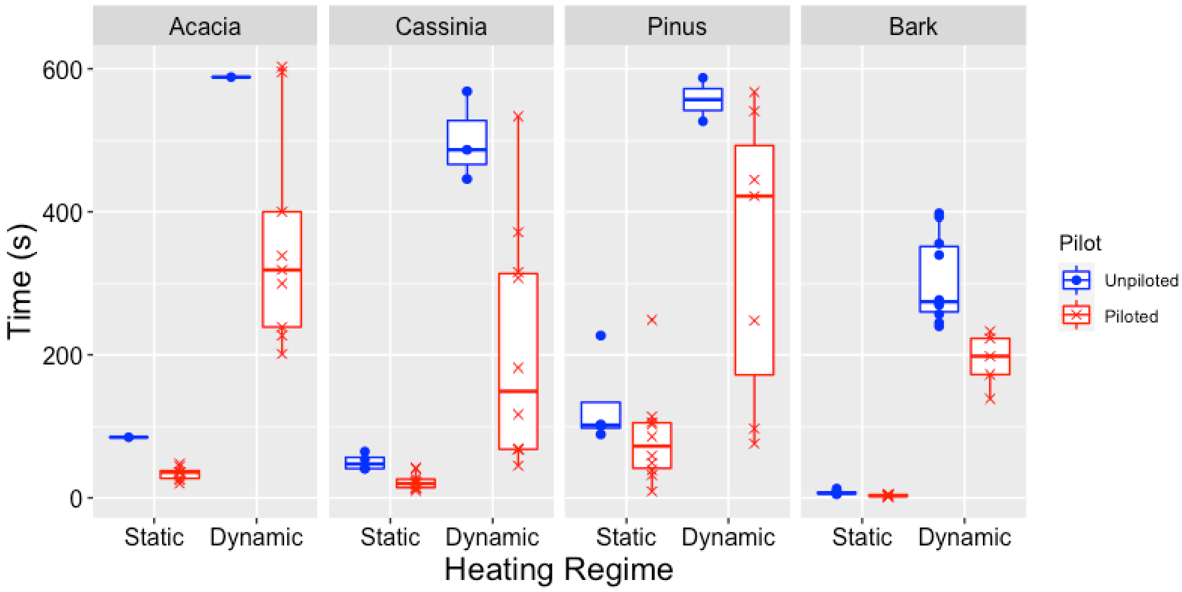


FIG. 16. TIME (S) TO FLAMING IGNITION COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (BLUE) AND PILOTED (RED) EXPERIMENTS.

We also observed that time and radiant exposure required to reach ignition and other flammability measures was generally higher in unpiloted experiments. This is consistent with a study by Bilbao *et al.* [65] into degradation and ignition of wood under constant and variable heat flux. They found that the presence of a pilot igniter results in ignition of the pyrolysis gases before the critical temperature for unpiloted ignition is reached, which lowers the time to ignition [65, 67].

The exposed area of a plant receives the radiant heat and is therefore exposed surface area is expected to be directly related to the time to flaming ignition. However, the differences in this measure between the species (Table 4) were not consistent with the differences observed in the results for the heating regimes (Figure 16). The results were consistent only for the static regime where increase in the exposed area resulted in faster ignition irrespective of piloted or unpiloted ignition. These results make sense, as the bigger the exposed area to radiative heat flux within a short period of time, produces more pyrolysis products and subsequently results in lower ignition time. One possible explanation of variability for dynamic regime is influence of convection, which could modify heat and mass transfer of the sample by cooling it down. In the static regime convective heat losses are much lower than exposed radiative heat flux.

Furthermore, Acacia, Cassinia and Pinus samples had a higher consumption time and consumption H_e under a static heating regime, except Cassinia in piloted experiments (Figure 17). It was observed that during the static heating regime ignition would occur in multiple stages, resulting in consumption of the dry fuel layer closest to the heating source and subsequent extinguishment. This would reduce the density and continuity of fuels, as well as the level of radiative heat flux on the remaining exposed surface of the sample. Once the next layer of the sample would dry out and produce enough pyrolysis gases, it would ignite again. This mechanism resulted in greater time and H_e required to reach complete consumption in static experiments. However, this pattern was not observed in piloted experiments for Cassinia, which is likely due to the influence of its unique physical and chemical traits.

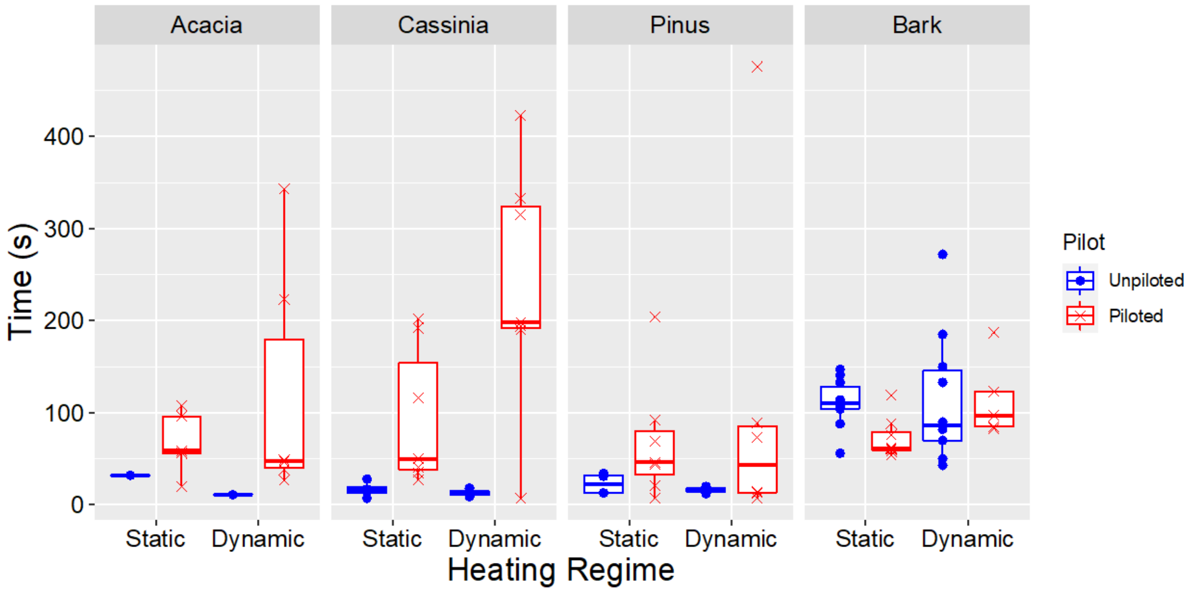


FIG. 17. TIME (S) BETWEEN FLAMING IGNITION AND COMPLETE CONSUMPTION (CONSUMPTION TIME) COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (BLUE) AND PILOTED (RED) EXPERIMENTS.

From the four species, there were two distinct fuel types used in this study. Live fuels (Acacia, Cassinia and Pinus) all demonstrated low packing ratio and low bulk density, whereas Bark had much higher packing ratio and high bulk density (Table 4). It was also evident that the live samples were more variable in size, shape and fuel arrangement than Bark samples due to the natural variability of fuel arrangement in live plants. These variations resulted in much higher variability of results in live samples and deviation in flammability between them. In particular, Acacia samples were found to have a much lower likelihood of flaming ignition in unpiloted experiments than Cassinia and Pinus samples (Table 5). Low *SA:V* of Acacia might be one of the reasons. Interestingly, although *SA:V* of Pinus was between Acacia and Cassinia's values, Pinus had the highest ignition time for piloted and unpiloted experiments (except of dynamic conditions). Acacia samples were also less susceptible to false ignitions in piloted experiments, evident by the much higher time (4-32 times higher) to false ignition compared to other samples. Given the similar packing ratio, bulk density and MC for Acacia, Pinus and Cassinia samples (Table 4), other species specific chemical traits were likely to be influencing these results [68-70].

Addressing limitations of previous studies

The methodology used in this study was designed to overcome the limitations of methods used in previous studies. Laboratory experiments testing flammability of individual plant elements have been limited in their ability to extrapolate results to infer whole-plant or fuel-bed flammability [71]. The VHFlux overcomes this limitation, as it has the ability to test whole-plant or shoot-level samples. This ensures that physical structure and arrangement of samples is considered, providing a more realistic representation of flammability of the species in its natural environment [53, 71].

This study has also addressed the limitations of boundary condition of previous studies [45, 54, 55]. This has been achieved by measuring and calibrating the radiative heat flux output from the VHFlux, as well as conducting experiments in a controlled environment free from any confounding effects on the samples. This ensured that consistent and replicable experiments were conducted throughout the study.

Introducing the use of dynamic heat flux to test flammability of live plants has allowed this study to overcome another significant limitation of previous studies. The result from this study show that the type of heating regime has a significant influence on the flammability of live plants. This suggests that it is important to test flammability of live plants under a dynamic heating regime, that more accurately replicates that of an approaching fire front. Using a dynamic heat flux in place of the previously used static heat flux will increase the accuracy of flammability data for live plant species.

Limitations of this study

The most significant limitation to this study was the influence of false ignitions. The pilot igniter had a large impact on some of the piloted experiment results. The presence of the pilot flame under the sample often resulted in false ignitions, which altered the fuel properties of the sample before flaming ignition occurred. This most noticeably impacted on measurements of consumption time and H_e under the dynamic heating regime. This also resulted in greater variability within the results under a dynamic heating regime, which has implications for using these results for modelling. These false ignitions also impacted the results for other flammability measures in piloted experiments. Pyrolysis was often difficult to identify when false ignitions occurred, as the smoke produced after the false ignition masked any evidence of pyrolysis gases. Alterations to the type and positioning of the pilot igniter in the apparatus will need to occur to ensure that impacts of false ignitions on results are mitigated in the future.

While a major step forward, the VHFlux apparatus only considers radiative heat flux which limits the application of this current methodology. Convection is known to be an important trigger of fuel flammability and fire front propagation [72-74]. In the future we will seek to incorporate a convective component into flammability testing as it will replicate the whole spectrum of fire conditions.

Overcoming these limitations will be important in ensuring the success of this methodology for future research.

SUMMARY

Our study has proposed a new standardised methodology for testing ignitability of live plant species, with potential for extending further to flammability metrics. The validity of using dynamic heating regimes as a standardised method has been demonstrated, with clear differences observed between heating regimes for time and H_e required for ignition and other flammability measures. The influences observed on flammability due to the pilot ignitor and species characteristics, were heavily outweighed by the influence of the heating regime. Adoption of this methodology is recommended to ensure more realistic data of flammability of individual plant species and plant communities. This will ultimately lead to better informed, and more accurate predictions of dynamic fire behaviour and decision making.

The VHFlux allows for flammability testing of live plant samples using dynamic heating regimes where parameters can be controlled to create repeatable and accurate testing in a controlled environment. With this improvement comes the ability to provide data that can expand current wildfire behaviour models to include species-specific traits (physical and chemical), rather than relying solely on surface fuel loads. This was shown in a study by Zylstra *et al.* [42], which demonstrated that accuracy of wildfire behaviour models could be significantly improved by incorporating the effects of vegetation structure and species-specific traits as inputs. The validity of their approach is supported by this current study, with the effect of some species-specific traits on flammability evident in the results (as discussed earlier). The presence of these influences on flammability, suggests that having an extensive dataset of flammability of individual species has the potential to greatly improve wildfire behaviour models. Testing different ranges of densities, packing ratios/porosities, surface area to volume ratios, moisture contents, and chemical compositions of species (wax, oils, resins, etc.) could also provide valuable knowledge to further inform fire behaviour models.

NUMBERS BEHIND AUSTRALIA'S CATASTROPHIC 2019/20 BUSHFIRE SEASON

BACKGROUND

Wildfire seasons are extending as the number of dry and hot days increases [1-4]. A longer fire season is expected to result in more frequent and severe fires [5, 6]. Australia's bushfire season 2019/20 (Black Summer hereafter) appears to have supported these conclusions, in terms of the ecological consequences and impacts on human populations. However, behind the mass media "noise" and subjective information, the real magnitude of Black Summer's events has not been compiled.

The aim of this study was to conduct a preliminary analysis of the 2019/20 bushfire season in Australia and to compare it with the last two decades of fires for the states of New South Wales, Victoria, and South Australia [7]. Specifically, we asked:

- Was there a trend or precondition for the 2019/20 catastrophic bushfire season?
- How abnormal or unusual was the 2019/20 bushfire season?
- Did the 2019/20 bushfire season change current trends.

RESEARCH APPROACH

We collected all available weather and bushfires impact information to understand the novelty of the Black Summer fires, in comparison with Australian bushfires during last 20 years. Forest and fire management in Australia is predominantly undertaken at a state level, and each state has its own fire service that defines the beginning of a fire season. Agencies were asked to provide data on the number of fires, burned area, life and house loss, as well as weather conditions between March 2000 and March 2020. Responses were received from New South Wales Rural Fire Service (NSW), Department of Environment, Land, Water and Planning, and Country Fire Authority of Victoria (Vic), and Department of Environment and Water, and Country Fire Service of South Australia (SA). Data for the 2019/20 bushfire season for other states were taken from a combination of news reports and media releases by the fire service agencies, as annual reports are not yet available. Additional weather data has been obtained from the Australian Government Bureau of Meteorology [75, 76]; data regarding the impact of bushfires was obtained from the annual reports of the fire service agencies responsible for firefighting in each the state.

The intention of this study was not to develop a best predictive model but to understand high-level trends in NSW, Vic, and SA. Therefore, data was analysed using linear regression analysis. Specifically, we calculated the slope of the regression line *m*, standard error of the regression *SE*, significance level *p*, Pearson's correlation coefficient *r*, coefficient of determination R^2. Response variables were burned area, number of fires, houses and lives lost, and the predictor variable was fire season. Negative and positive relationships were indicated as decreasing and increasing trends (slopes) respectively. To analyse the effect of the 2019/20 season on trends, we undertook regression analysis with and without the last years data (2019/20). Burned area includes all types of vegetation. House loss data refers to completely lost primary dwellings only. Fatalities included are directly resulting from fires.

FINDINGS

The Bureau of Meteorology has determined 2019 was Australia's warmest year on record [75]. An extended period of heatwaves over much of Australia began in early December, 2018 and continued into January, 2019. Heat continued to affect Australia until the end of 2019 bringing repeated periods of severe fire weather to the south-eastern States.

2019 was also the driest year on record for Australia at 277.6 mm (annual mean) [75], although parts of Queensland's northwest and northern tropics were wetter than average. Rainfall was 40 % below the 1961–1990 average. Low rainfall also led to very low soil moisture across large areas of Australia during 2019. Additionally, a very strong positive Indian Ocean Dipole (IOD, sustained changes in the difference between sea surface temperatures of the tropical western and eastern Indian Ocean [77]) was one of the main influences on Australia's climate during 2019, and contributed to very low rainfall and low humidity across Australia.

High temperatures, rainfall deficit and prolonged drought resulted in increased fuel availability and very high fire danger indexes [78, 79]. New South Wales, Queensland, Northern Territory, Western Australia and Tasmania all experienced record-high spring Forest Fire Danger Indexes (FFDI). As a consequence of these conditions, the fires, once they started, burnt almost 19 million hectares, destroyed over 3,000 houses, killed 33 people and an estimated 1 billion animals by 20th of March, 2020 [80] (Table 6).

State	Burned area, ha	Number of fires	Houses lost	Lives lost
VIC	1,505,004	3,500	396	5
NSW	5,595,739	10,520[1]	2,475	25
QLD	2,500,000	NA	48	0
TAS	36,000	NA	2	0
WA	2,200,000	NA	1	0
SA	286,845[2]	1,324	186	3
NT	6,800,000	NA	5	0
ACT	60,000	NA	0	0
Total	**18,983,588**	**15,344**	**3113**	**33**

TABLE 6. FIRE STATISTICS FOR 2019/20. THESE FIGURES ARE PRELIMINARY AND MAY BE REVISED WHEN OFFICIAL STATISTICS ARE RELEASED AT THE END OF THE 2019/20 FINANCIAL YEAR. NA – data is not available.
[1] NUMBER OF FIRES IN NSW INCLUDES ONLY THOSE ATTENDED BY THE NSW RFS. THIS DOES NOT INCLUDE ALL VEGETATION FIRES BUT PROVIDES A RELATIVE MEASURE OF FIRE ACTIVITY.
[2] THIS NUMBER IS EXPECTED TO INCREASE SIGNIFICANTLY WHEN FIRES IN REMOTE ARID AREAS OF THE STATE ARE MAPPED.

New South Wales

rainfall for most of 2019, with some areas experiencing the driest on record conditions [76]. Long-term rainfall deficiencies combined with record low rainfall for some areas in the north of the state, had severely impacted on water resources and firefighting tactics [81]. At the beginning of August 2019 (end of Australian winter) most of NSW was experiencing at least 1 of the following categories: drought affected (55 %), experiencing drought (23 %), and experiencing intense drought (17 %). The first 'Section 44' emergency declaration of the fire season was made on 10th of August, 2019, one of the earliest on record [82]. Significant soil moisture deficit and windy conditions resulted in a large number of bushfires [78].

A total of 5,595,739 hectares were burned, 2439 houses and 25 lives lost in 10,520 bushfires in NSW (Figure 18). Two mega-blazes were recorded in NSW. The Gospers Mountain fire started on 26th of October, 2019 and burned approximately 512,626 hectares, becoming one of the biggest forest fires in Australian history. By the 11th of January, three fires on the border of NSW and Victoria, the Dunns Road fire, the East Ournie Creek, and the Riverina's Green Valley merged and created a second mega-fire which burned through 895,744 hectares. Fires in NSW burned more area than any single fire season during the last 20 years (Figure 18a).

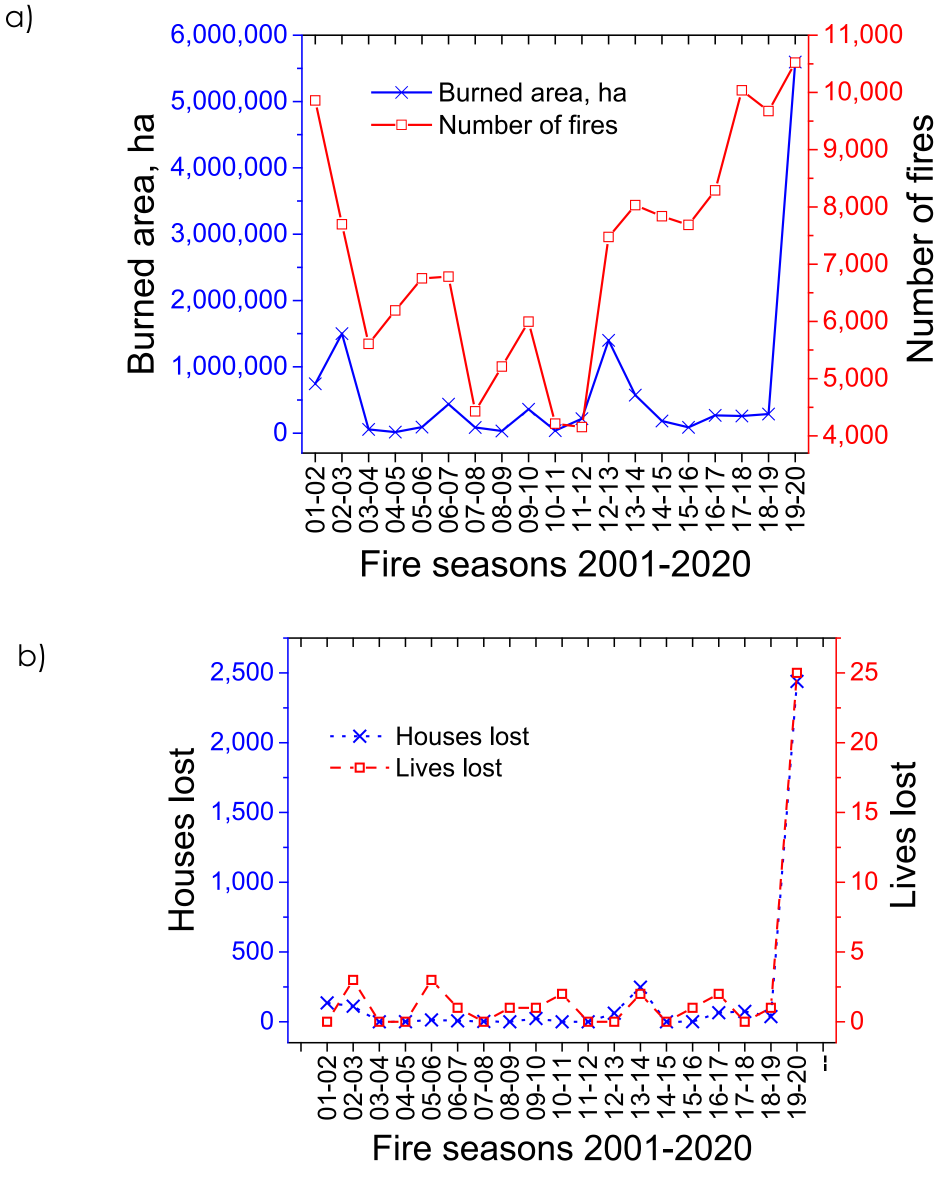


FIG. 18. BUSHFIRE AFTERMATH FOR 2001-2020 FIRE SEASONS IN NSW: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON, b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

The 2019/2020 fire season in NSW was exceptional regarding burned area and lives lost, at more than one order of magnitude higher, and houses lost almost two orders of magnitude higher, compared to the previous average of 370,000 hectares, 1 life and 43 houses respectively (Figure 18). The burned area before 2019 was below half a million hectares and relatively consistent, with two spikes in 2002/2003 and 2012/2013.

	2001-2019 dataset					2001-2020 dataset				
Impact category	**m**	**SE**	**p**	**r**	**R^2**	**m**	**SE**	**p**	**r**	**R^2**
Burned area (y) vs Fire season (x)	-14695	446590	0.479	-0.178	0.032	70032	1245657	0.197	0.310	0.096
Number of fires (y) vs Fire season (x)	116	1804	0.177	0.333	0.111	154	1828	0.061	0.438	0.192
Burned area (y) vs Number of fires(x)	85	423491	0.143	0.360	0.129	319	1137799	0.031	0.496	0.246
Houses lost (y) vs Fire season (x)	0.470	68	0.881	0.038	0.001	38	525	0.100	0.389	0.151
Lives lost (y) vs Fire season (x)	-0.013	1.09	0.789	-0.068	0.005	0.368	5.37	0.120	0.369	0.136
Lives lost (y) vs Houses lost (x)	0.005	1.04	0.259	0.281	0.079	0.01	1.08	7.7×10^{-14}	0.982	0.965

TABLE 7. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN NSW. WHERE *m IS THE SLOPE OF THE REGRESSION LINE, SE* IS THE STANDARD ERROR OF THE REGRESSION, *p IS THE SIGNIFICANCE, r* IS THE PEARSON'S CORRELATION COEFFICIENT, R^2 IS THE *COEFFICIENT OF DETERMINATION, x IS THE PREDICTOR VARIABLE, y IS THE RESPONSE VARIABLE.*

Before the 2019/20 fire season, the regression line of the burned area over time had a negative slope, switching to a positive slope with the 2019/20 dataset, a nearly significant correlation at P=0.197 (Table 7). The number of fires was decreasing till 2012 and constantly increasing after (Figure 18a). Resulting in a positive slope for both datasets with higher slope for the 2001-2020 dataset. Analysis of the data showed a notable positive linear relationship between the number of fires and burned area. It was close to the limit of significance (p=0.14) for 2001-2020 dataset and statistically significant (p=0.03) for 2001-2020 dataset.

A regression line of the houses lost over time had a positive slope for both datasets (Figure 18b). However, for 2001-20 dataset, it was almost 2 orders of magnitude higher and statistically significant (p=0.1). Before 2019, the slope for the lives lost was negative and not statistically significant. With additional data from 2019/20, it became positive and marginally significant (p=0.12). A positive linear relationship between the houses and lives lost existed for the 2001-2019 dataset, and it was not statistically significant (p=0.26). However, with additional data from 2019/20 it became 2 times higher, and it was statistically significant ($p=7.7 \times 10^{-14}$). Lives lost were approximately 1% of houses lost. With an absolute error of 0.85 lives lost for 2001-2020.

Victoria

In 2019/2020, Victoria was experiencing its third consecutive year of significant rainfall deficit, especially across the coastal and foothill forests of Gippsland [81]. These areas had soils with severe moisture deficit. Combined with above average temperatures, it resulted in an increase in surface fine fuel loads and higher flammability in live vegetation [78]. During the spring in 2019, cold fronts generated rainfall in southern Victoria leading to normal fire conditions [76].

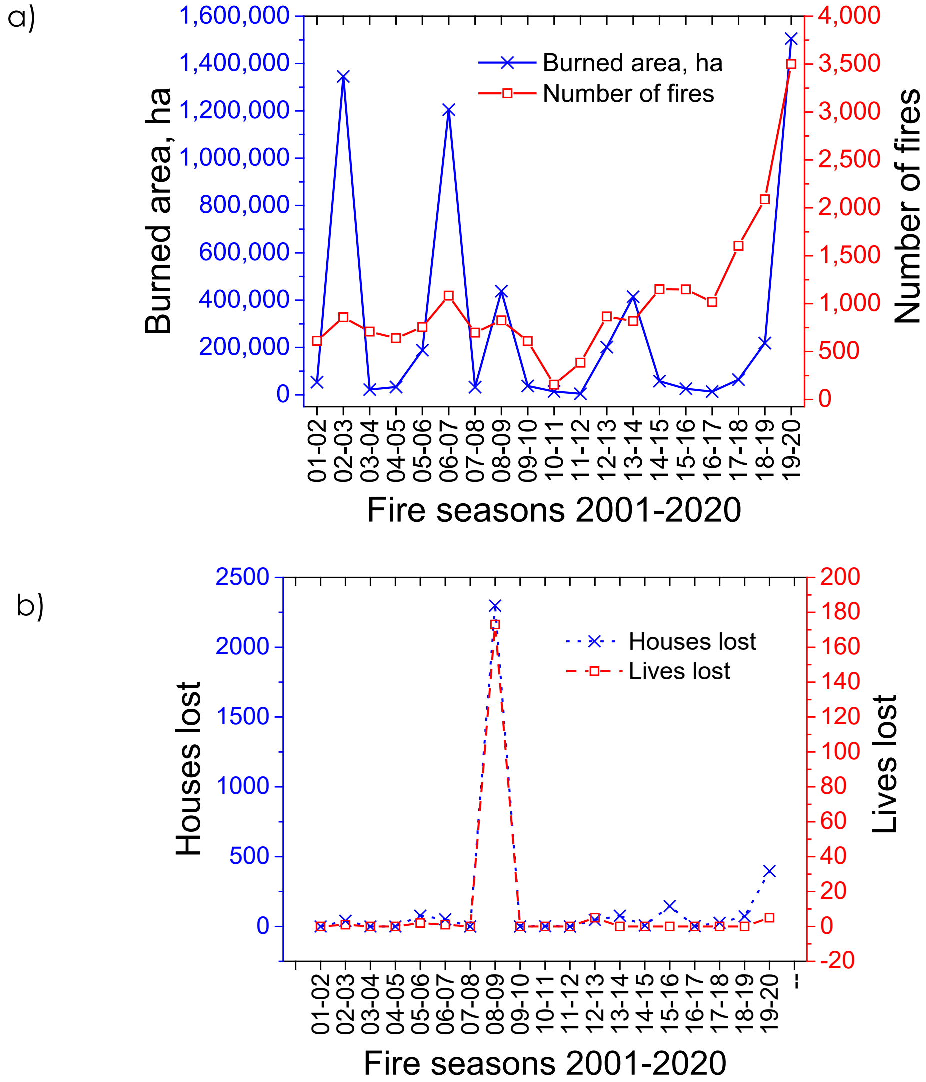


FIG. 19. BUSHFIRE AFTERMATH FOR 2001-2020 FIRE SEASONS IN VICTORIA: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON; b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

A total of 3500 fires were recorded during the 2019/2020 fire season in Victoria. These fires resulted in 1,505,004 hectares burned, 396 houses and 5 lives lost (as of 20th of March, 2020) (Figure 19). The number of fires and the burned area was one of the biggest in Victorian history. One of the most destructive fires was the Mallacoota fire in the far east of the state. A small fire started on 29th of December, 2019, 30 kilometres west of Mallacoota [83]. Mallacoota is a small town and an iconic tourist destination in the East Gippsland region of Victoria, with a population of approximately 1,000 people, increasing by about 8,000 at Christmas [84]. By 5 pm on the 30th of December, Emergency Management Victoria issued a warning that it was too late to evacuate, and people should take shelter immediately [83]. On the 31st of December, approximately 4,000 people, including 3,000 tourists remained in Mallacoota. By 11 am, fire began to burn the outskirts of Mallacoota. People gathered at the boat ramp on the coastline, with Country Fire Authority members working to protect them. By 1.30 pm, the fire had reached the water's edge. Roads to Mallacoota were blocked for 37 days due to bushfires and fallen trees. On the 2nd of January, for the first time in Victoria's history, a state of disaster was declared. On the 3rd of January, approximately 1,160 people from Mallacoota were evacuated on two naval vessels. The last group of people was evacuated on the 8th of January. With at least 300 homes lost.

The number of fires in Victoria has been increasing over the past 20 years, except for the 2010/11 and 2011/12 fire seasons (Figure 19a), irrespective to datasets (Table 8). Relationships were relatively strong (r>0.59) and statistically significant (p<0.01). Burned area in Victoria was variable over the last 20 years with considerable spikes in 2002/03, 2006/07, 2008/09, 2013/14 and 2019/20. However, the regression line of the burned area had a negative trend for all datasets. with a 25 times higher slope for 2001-2019 dataset (r=-0.33, p=0.18). A positive linear relationship between the number of fires and burned area was observed. The slope became 3 times higher with 2019/20 fire season data. The relationship was moderate (r=0.55) and was essentially significant (p=0.015).

	2001-2019 dataset					2001-2020 dataset				
Impact category	**m**	**SE**	**p**	**r**	**R²**	**m**	**SE**	**p**	**r**	**R²**
Burned area (y) vs Fire season (x)	-24568	388326	0.183	-0.329	0.108	-952	497886	0.964	-0.011	0.0001
Number of fires (y) vs Fire season (x)	48	365	0.01	0.588	0.346	82	587	0.004	0.630	0.396
Burned area (y) vs Number of fires(x)	116	407865	0.616	0.127	0.016	360	416873	0.015	0.547	0.299
Houses lost (y) vs Fire season (x)	2.7	40.7	0.2	0.327	0.107	8.7	85.4	0.04	0.487	0.237
Lives lost (y) vs Fire season (x)	-0.02	1.32	0.77	0.077	0.006	0.06	1.64	0.42	0.203	0.041
Lives lost (y) vs Houses lost (x)	0.007	1.29	0.399	0.219	0.048	0.011	1.27	0.003	0.656	0.431

TABLE 8. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN VICTORIA. WHERE *m IS THE SLOPE OF THE REGRESSION LINE, SE* IS THE STANDARD ERROR OF THE REGRESSION, *p IS THE SIGNIFICANCE, r* IS THE PEARSON'S CORRELATION COEFFICIENT, *R²* IS THE *COEFFICIENT OF DETERMINATION, x IS THE PREDICTOR VARIABLE, y IS THE RESPONSE VARIABLE*

The 2008/09 fire season was extraordinary in terms of the houses and lives lost (Figure 19b). A series of bushfires, sadly remembered as the Black Saturday bushfires, mostly contributed to this [85]. A total of 173 people died in these fires, and 2,029 houses were lost. As a result, both the houses and lives lost values in the 2008/09 fire season were higher than 3 standard deviations for all data (2001-2020). In order, to understand trends during the last 20 years, we excluded the 2008/09 fire season from the houses and lives lost analysis. The number of houses and lives lost in the 2019/20 fire season were also well above average, 32 and 0.5 respectively (excluding 2008/09). The houses lost data had a positive trend for both datasets (r>0.32). For the 2001-20 dataset, the slope was 3 times higher, and the relationship was significant (p=0.04). When including the 2019/20 data, the lives lost trend changed from negative to positive. However, both datasets showed a weak correlation and significance. A linear relationship between the number of houses and lives lost was positive for both datasets and significant for 2001-20 dataset (p=0.003).

South Australia

Average to below average rainfall had occurred across South Australia, with some areas experiencing persistent dry conditions since the start of 2018 [75]. Annual rainfall totals were in the lowest 10% of historical observations for most of South Australia. The maximum temperatures for the year were also well above average, and the highest on record for most of South Australia. December brought an exceptionally warm end to the year, with this month the warmest December on record. South Australia had the second highest average FFDI value for the 2019 spring. Within the Agricultural districts of South Australia, the highest peak area-averaged FFDI value for the season was recorded on the 20th of November 2019, which was over 100, easily the highest on record for the region, during spring and the highest for any one day of the year, for at last 50 years [76].

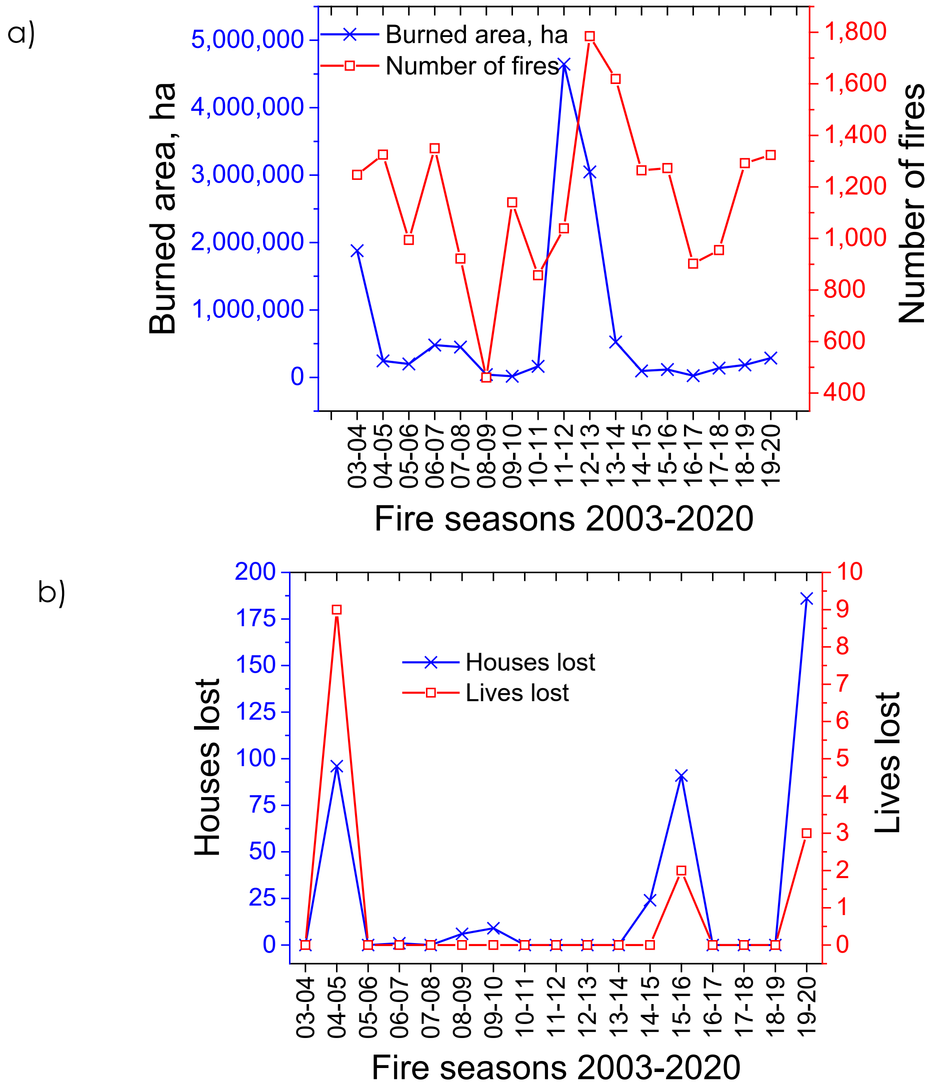


FIG. 20. BUSHFIRE AFTERMATH FOR 2003-2020 FIRE SEASONS IN SOUTH AUSTRALIA: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON; b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

In South Australia, 286,845 hectares burned, 186 houses and 3 lives lost in 1,324 bushfires in the 2019/20 fire season (Figure 20). On the 20th of December, 2019 some of the worst bushfires in South Australia started from a series of lightning strikes. These fires were declared contained one week later, however three days after that, on the 30th of December, 2019 another band of lightning started more fires in the remote Ravine de Casoars Wilderness area. These fires combined with the existing fires and became known as The Kangaroo Island Fire [86]. The fires were officially contained on the 21st of January, 2020 after burning for more than three weeks and blackening more than 210,000 hectares [87]. The fires burned most of the Ravine de Casoars Wilderness area, Flinders Chase National Park, Cape Bouguer Wilderness area, Cape Torrens Wilderness area, Western River Wilderness area, and Kelly Hill Caves Conservation Park. The fire caused significant stock losses for local farmers [87] and burnt between $100 million and $900 million of plantation timber [88]. The island blaze destroyed 89 homes and hundreds of other buildings along with high visitation tourism assets including the Flinders Chase Visitor Centre, Kelly Hill Cave Visitor Centre and the world-renown Southern Ocean Lodge. The fire also claimed two lives.

Another destructive fire began in the rural residential Adelaide Hills on the 20th of December, 2019, known as the Cuddlee Creek fire [89]. This fire burned 23,295 hectares, destroy 84 homes and hundreds of other buildings and thousands of stock losses. This fire also burnt through world famous viticulture and winery areas, large parts of the water catchment for Adelaide (the state's capital city), and led to the death of one person.

The total burned area and number of fires in 2019/20 were not abnormal for South Australia. The burned area and number of fires were below or close to average values, 765,719 hectares and 1,152, respectively. The number of fires and area burnt are usually dominated by remote fire in arid parts of South Australia, which have minimal impact on human lives and are not normally actively suppressed by fire agencies. However, due to the proximity to higher density populations and associated economically valuable land uses, houses and lives lost were above average for SA - more than 10 times higher for the houses lost and 4 times higher for lives lost.

	2001-2019 dataset					2001-2020 dataset				
Impact category	**m**	**SE**	**p**	**r**	**R^2**	**m**	**SE**	**p**	**r**	**R^2**
Burned area (y) vs Fire season (x)	-27142	1309693	0.717	-0.098	0.010	-32008	1354388	0.629	-0.126	0.016
Number of fires (y) vs Fire season (x)	6.6	326	0.716	0.099	0.010	8.9	316	0.580	0.145	0.021
Burned area (y) vs Number of fires(x)	1183	1304682	0.285	0.285	0.081	1110	1271787	0.297	0.269	0.072
Houses lost (y) vs Fire season (x)	-0.481	32.6	0.790	0.072	0.005	3	51.1	0.259	0.290	0.084
Lives lost (y) vs Fire season (x)	-0.146	2.24	0.251	-0.305	0.093	-0.076	2.31	0.517	-0.169	0.029
Lives lost (y) vs Houses lost (x)	0.059	1.32	7.9×10^{-5}	0.827	0.683	0.03	1.73	0.003	0.673	0.453

TABLE 9. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN SA. WHERE *m IS THE SLOPE OF THE REGRESSION LINE, SE* IS THE STANDARD ERROR OF THE REGRESSION, *p IS THE SIGNIFICANCE, r* IS THE PEARSON'S CORRELATION COEFFICIENT, R^2 IS THE *COEFFICIENT OF DETERMINATION, x IS THE PREDICTOR VARIABLE, y IS THE RESPONSE VARIABLE.*

The data showed that for South Australia there was no notable difference between 2003-2019 and 2003-2020 datasets for the burned area and the number of fires (Figure 20a). In both cases, the burned area had a negative trend, and the number of fires had a positive trend. For all datasets, the Pearson's correlation coefficient was between 0.016 and 0.099 and relationships were not statistically significant, above p=0.58. A weak positive linear relationship between the number of fires and burned area was found for both datasets. For 2003-2020 dataset, the Pearson's correlation coefficient was r=0.27 (R^2=0.07) and it was approaching a significance level (p=0.3). For 2003-2019 both dataset coefficients were similar (r=0.29, R^2 =0.08, p=0.29).

Slightly different patterns were observed for the houses and lives lost depending on the dataset (Figure 20b). Before 2019/2020, the regression line of the houses lost had a negative slope (m=-0.5) converting to a pronounced positive with 2019/20 data (m=3). The lives lost data had a negative trend for both datasets. However, for 2003-2020 dataset, the slope decreased (m=-0.076) compared to 2003-2019 dataset (m=-0.146). A very strong positive linear relationship between the houses and lives lost was present for 2003-2019 dataset (r=0.83, R^2=0.68) and it was statistically significant ($p=7.9\times10^{-5}$). With additional data from 2020, it became less pronounced but still considerable (r=0.67, R^2=0.45) and statistically significant (p=0.003).

SUMMARY

There is no doubt that the fire season of 2019/20 was extraordinary. NSW had the highest number of fires, area burned, houses and lives lost for the last 20 years. Two mega-blazes occurred in NSW and burned more than in any fire season during the last 20 years. Likewise, Victoria had the highest number of fires, area burned, and houses lost (except for the Black Saturday fires). With SA having the highest number of houses lost in the last 20 years.

Multiple studies [1, 90-93] show that fire weather will become more severe and unstable in many regions around the world. Based on this and observed positive trends for life and house loss for NSW and Victoria, it is likely that the values will continue to increase in these states in the future. South Australia before 2019/20 was in a relatively good position showing negative trends for almost all categories. However, the 2019/20 fire season changed that. We can see changes in the slopes and trends for the worse (Table 9). These results should be taken with caution because the 2019/20 fire season was extraordinary, which may have affected the projections. The magnitude of effect from increased fire weather, may also depend on how these conditions alter vegetation across Australia, however the indications support this analysis and are concerning for fire managers.

Smoke from bushfires may also be a significant problem in the future. As smoke impacts on people with cardiovascular and respiratory problems and increases mortality. It also has indirect impact on the economy. For instance, smoke produced by bushfires in December 2019 and January 2020 caused up to A$50 million worth of daily disruption of Sydney's economy [94].

The total impact of the 2019/20 bushfire season to the Australian economy is estimated to be as much as A$40 billion according to Wilkie [95]. It will take many years to restore the economy and infrastructure in impacted areas, and for animal and vegetation biodiversity to recover.

KEY MILESTONES

- The determinants of crown fire runs during extreme wildfires in eucalypt forests in Australia.
- Using technological advancements to uncover fire behaviour phenomena and for operational support.
- Ignitibility of live plants.
- Numbers behind Australia's catastrophic 2019/20 bushfire season.

UTILISATION AND IMPACT

SUMMARY

The following utilisation outcomes were produced during the project:

- An empirical model for the forecasting of crown fire potential at hourly to daily scales that is independent of fire simulation.
- A new method to test flammability of live vegetation in dynamic conditions that should improve fire simulation capacity.
- A new method to test fire performance of structural materials that could be adopted for standards such as AS3959.
- Educational material on different aspects of dynamic fire behaviours.

MODEL FOR FORECASTING OF CROWN FIRE POTENTIAL AT HOURLY TO DAILY SCALES

Output description

The model can be a useful tool for decision support. Hourly predictions revealed the importance of high temporal forecasting, combined with a good spatial resolution (150 x 150 m). This model can take into account local terrain and weather effects. As weather variables can be forecast into the future, model predictions could be used to forecast the likelihood of crown fire runs at an hourly temporal resolution for up to 7 days into the future.

Extent of use

- National and international level. Additional calibration would be required for international use.

Utilisation potential

- Modelling could provide managers with a rapid means of assessing the likelihood of fire impacts and risks to personnel.

Utilisation impact

- Modelling results would be invaluable for fire managers in terms of allocating fire suppression resources and issuing public warnings.

Utilisation and impact evidence

- Filkov A., Collins L., Rawlins A., Duff T., Cirulis B., Penman T. (2018) The determinants of crown fire runs during extreme wildfires in broadleaf forests in Australia // Advances in Forest Fire Research. Book chapter. Coimbra: Imprensa da Universidade de Coimbra, Pp. 1401-1405. http://dx.doi.org/10.14195/978-989-26-16-506_190.

NEW METHOD TO TEST FLAMMABILITY OF VEGETATION

Output description

A new standardised methodology for testing flammability of live plant species in dynamic conditions was proposed. The validity of using dynamic heating regimes as a standardised method has been demonstrated, with clear differences observed between heating regimes. The VHFlux apparatus allows for flammability testing of live plant samples using dynamic heating regimes where parameters can be controlled to create repeatable and accurate testing in a controlled environment. Accuracy of wildfire behaviour models could be significantly improved by incorporating the effects of vegetation structure and species-specific traits as inputs and developing an extensive dataset of flammability of individual species.

Extent of use

- International level. There is a high demand in such method around the world.

Utilisation potential

- Adoption of this methodology is recommended to ensure more realistic data on flammability of individual plant species and plant communities.

Utilisation impact

- This will ultimately lead to better informed, more accurate, and dynamic wildfire behaviour modelling.

Utilisation and impact evidence

- A few organisations and individuals have shown great interest in using the Variable Heat Flux Apparatus as a new method to test flammability of vegetation. A project "Up in flames: measuring how plants burn" led by Dr Jane Cawson from the University of Melbourne has utilised this method.
- Miller, T.; Filkov A.; Penman, T., (2020) Improved method to test flammability of live plants under dynamic conditions and future implications // International Journal *of Wildland Fire*, Submitted.

NEW METHOD TO TEST FIRE PERFORMANCE OF STRUCTURAL MATERIALS

Output description

A new method was proposed to test fire performance of structural materials at small scales. The research provides a preliminary foundation for the development of an intermediate fire test method.

Extent of use

- National and international level.

Utilisation potential

- The ultimate development of an improved intermediate fire test will significantly reduce the cost to manufacturers in the design and compliance phase of engineered timber products.

Utilisation impact

- A direct outcome of the optimisation of these processes is the reduction of the overall cost of the material.

Utilisation and impact evidence

- Shyanaka Rathnayaka, Alex Filkov, Pasindu Weerasinghe, Shanaka Kristombu Baduge, Kate Nguyen, (2020) Assessing Fire Resistance of Prefabricated Hybrid Timber Wall System: A Comparative Study of Infrared Radiant Panel and Gas Furnace, Journal of Building Engineering, Submitted.
- Filkov A, Penman T (2018) Spontaneous ignition of vertically positioned wood samples under time-dependent heat flux // Advances in Forest Fire Research. Book chapter. Coimbra: Imprensa da Universidade de Coimbra, Pp. 1308-1310. http://dx.doi.org/10.14195/978-989-26-16-506_165
- Trent Penman, Shyanaka Dananjaya, Alex Filkov, Kate Nguyen, Pasindu Weerasinghe, and Priyan Mendis (2019) An innovative Engineering approach on addressing Fire behaviour of Building facades. 6th Fire Behaviour and Fuels Conference, Sydney.

FIREPEDIA

Output description

A series of educational curated documents (a "FirePedia") on different aspects of fire behaviour was produced in cooperation with BNHCRC. This document provides the reader with an introduction to dynamic fire behaviours that may be observed during bushfires, and which may result in significant dangers to people, communities, infrastructure and the environment.

Extent of use

- National and international level.

Utilisation potential

- Developed documents will provide useful insights into extreme fires and dynamic fire behaviours and can be used to inform practitioners such as fire behaviour analysts, of types of fire phenomena they should be on the lookout for. After reading the documents, the reader should be able to describe several dynamic fire behaviours, and understand in general terms, why dynamic fire behaviours poses a potentially severe danger to fire-fighters, community, infrastructure and the environment, and understand situations in which dynamic fire behaviours may lead to elevated fire danger.

Utilisation impact

- Improved understanding of extreme fires and dynamic fire behaviours – the conditions in which they are likely to occur, the impact on the predictability of fire propagation and intensity, strategies for fire suppression, and the subsequent impact on community and firefighter safety.

Utilisation and impact evidence

- Cooperation with BNHCRC to develop a "FirePedia".

CONCLUSION

The project 'Determining threshold conditions for extreme fire behaviour' was focused on four main tasks: crown fires, merging fires, flammability of natural fuels and current trends of Australian bushfires. The following main outcomes were obtained:

- An empirical model that can forecast the likelihood of crown fire runs while fires are occurring. It has the ability to predict crown fire runs at an hourly temporal resolution for up to 7 days into the future.
- An empirical model for predicting the rate of spread of junction fires in harvested crops.
- A new approach to quantify fire behaviour on captured video and photo imagery.
- A new method to test flammabfilty of natural fuels under dynamic conditions.

FUTURE RESEARCH

Research undertaken has led to better understanding of dynamic fire behaviours and extreme bushfire development, and our ability to predict them. However, there remain significant gaps in our knowledge which require further investigation, specifically:

- *Crown fires*

Smoke generation and its potential transport. Such information would be invaluable for fire managers in terms of allocating fire suppression resources and issuing public warnings.

Firebrands and spotting. There is a need to predict and quantify the generation of firebrands, during the burning of vegetation and structures, their subsequent transport in the atmosphere followed by landing, and the final ignitability of wildland and structural materials exposed to firebrands. This will lead to more accurate predictions of fire behaviour and an improved ability to manage the risk of bushfire in WUI areas.

- *Merging fires*

Relationships between fuel load, wind speed and scale. Existing studies on merging fires are disconnected as comparison between them showed considerable variation in ROS for similar conditions. Without such relationships, it is not possible to understand merging fires and improve operational models.

- *Flammability of natural fuels*

Species flammability and heating regimes. Different heating rates result in differences in flammability. Exposure of samples to a variety of dynamic heating regimes based on typical fire intensities in combination with the development of a species flammability database, could lead to dynamic wildfire behaviour models that have the ability to adjust flammability inputs, based on weather conditions and fuel properties to produce more accurate outputs of intensity and rate of spread.

- *Dynamic fire development.*

Scale. All previous experimental studies have been done for meter and ten-meter scales which cannot replicate fire-weather interactions. These could include a series of large field-scale experiments, fine-scale physics-based modelling complemented with meso-scale fire-atmosphere modelling, as well as research into, and development of operational sub-models that can account for the dynamic fire behaviours. By addressing these gaps, we will substantially increase the ability of decision-makers to adequately evaluate risks during severe bushfire seasons.

PUBLICATIONS LIST

PEER-REVIEWED JOURNAL ARTICLES

1 Miller, T.; Filkov A.; Penman, T., (2020) Improved method to test flammability of live plants under dynamic conditions and future implications // International Journal *of Wildland Fire*, Submitted.

2 Shyanaka Rathnayaka, Alex Filkov, Pasindu Weerasinghe, Shanaka Kristombu Baduge, Kate Nguyen, (2020) Assessing Fire Resistance of Prefabricated Hybrid Timber Wall System: A Comparative Study of Infrared Radiant Panel and Gas Furnace, Journal of Building Engineering, Submitted.

3 Prohanov, Sergey, Alexander Filkov, Denis Kasymov, Mikhail Agafontsev, and Vladimir Reyno. "Determination of Firebrand Characteristics Using Thermal Videos." *Fire* 3, no. 4 (2020): 68. https://www.mdpi.com/2571-6255/3/4/68.

4 Burton, Jamie E., Jane G. Cawson, Alex I. Filkov, and Trent D. Penman. "Leaf Traits Predict Global Patterns in the Structure and Flammability of Forest Litter Beds." *Journal of Ecology* n/a, no. n/a (2020). https://doi.org/https://doi.org/10.1111/1365-2745.13561. https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1111/1365-2745.13561.

5 Filkov, A.I.; Duff, T.J.; Penman, T.D. (2020) Frequency of Dynamic Fire Behaviours in Australian Forest Environments // *Fire*, 2020, *3*, 1, pp. 1-17. https://doi.org/10.3390/fire3010001.

6 Tegan Brown, Jamie Burton, Geoffrey J. Cary, Thomas J. Duff, Alexander Filkov, James M. Furlaud, Tim Gazzard, Musa Kilinc, Petter Nyman, Ross Peacock, Mike Ryan, Jason Sharples, Gary Sheridan, Kevin Tolhurst, Tim Wells, Phil Zylstra, Trent D. Penman (2020) Exploring the key drivers of flammability in wet eucalypt forests using expert elicitation // Landscape Ecology, Accepted. Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models. Landscape Ecol. https://doi.org/10.1007/s10980-020-01055-z.

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8 Filkov, A.I.; Cirulis, B.; Penman, T.D. (2020) Quantifying merging fire behaviour phenomena using Unmanned Aerial Vehicle technology // International Journal *of Wildland Fire*, https://doi.org/https://doi.org/10.1071/WF20088. https://www.publish.csiro.au/paper/WF20088.

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10 Filkov A., Prohanov S. (2019) Particle Tracking and Detection Software for Firebrands Characterization in Wildland Fires // *Fire Technology*, V 55, I 3, pp. 817-836. http://dx.doi.org/10.1007/s10694-018-0805-0.

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6 Filkov A., Collins L., Rawlins A., Duff T., Cirulis B., Penman T. (2018) The determinants of crown fire runs during extreme wildfires in broadleaf forests in Australia // Advances in Forest Fire Research. Book chapter. Coimbra: Imprensa da Universidade de Coimbra, Pp. 1401-1405. http://dx.doi.org/10.14195/978-989-26-16-506_190.

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3 Trent Penman, Shyanaka Dananjaya, Alex Filkov, Kate Nguyen, Pasindu Weerasinghe, and Priyan Mendis (2019) An innovative Engineering approach on addressing Fire behaviour of Building facades. 6th Fire Behaviour and Fuels Conference, Sydney.

TEAM MEMBERS

RESEARCH TEAM

Dr Alexander Filkov, University of Melbourne

Dr Thomas Duff, University of Melbourne

Dr Trent Penman, University of Melbourne

END-USERS

End-user organisation	End-user representative	Extent of engagement
RFS, NSW	Simon Heemstra (lead end-user)	Annual reports, discussion of new projects
	Stuart Matthews (lead end-user)	Collaboration on a paper, data provider, quarterly and annual reports
	Brad Davies	Quarterly reports
CFA, VIC	Tim Well	Merging fires workshop
	Musa Kilinc	Flammability projects, merging fires workshop
DELWP, VIC	Evan Lewis	Data provider
	Andrew Ackland	Merging fires workshop
	Elizabeth Ashman	Merging fires workshop
	Glenn Rudolph	Prescribed burn experiments
	Timothy Miller	Flammability experiments
ACT Parks, ACT	Adam Leavesey	Data provider
DEWNR, SA	Mike Wouters	FirePedia
	Simeon Telfer	Collaboration on a paper, data provider

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