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DETERMINING THRESHOLD CONDITIONS FOR EXTREME FIRE BEHAVIOUR

Annual report 2018-2019

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University of Melbourne & Bushfire and Natural Hazards CRC

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Cover: A bushfire experiment conducted as part of the *Threshold conditions for extreme fire behaviour* project. Credit: Brett Cirulis

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

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At this phase the project was focused on prediction of crown fires, modelling of dynamic heat flux and testing new technologies for fire characterisation and management.

Crown fires in forest ecosystems can pose a major threat to life and property due to their high intensities and rapid rates of spread. However, research into the prediction of crown fire dynamics in the Eucalyptus forests of Australia is limited. Previous studies have focused on coarse temporal scales, utilised low resolution weather based predictors, and often disregard the spatial nature of crown fires. Our study aimed to use observations from large wildfires in eucalypt forests to develop an empirical model to predict the likelihood of crown fire events using environmental predictors at an hourly scale. Our study was conducted in south-eastern Australia using data from fifteen large wildfires that occurred between 2009 and 2015. Fire severity maps were created for each fire at a 30 m resolution using Landsat imagery from which we calculated the proportion of 30 m pixels experiencing crown fire within a 150 x 150 m window (2.25 ha). Predictor variables were chosen to represent the four key environmental drivers of fire behaviour, namely fuel moisture (i.e. live and dead fuel), fuel load and structure (i.e. surface, elevated, and bark fuels, and tree height), fire weather (i.e. vapour-pressure deficit, wind speed, relative wind direction) and topography (i.e. slope and ruggedness). Random Forests were used to model the effect of environmental drivers on the proportion of crown fire. Fuel moisture content variables were the best predictors of probability of crown consumption. Topographic variables and fire weather had only an intermediate influence and fuel load and structure had the lowest influence. Crown fire runs largely occurred when thresholds in vapour-pressure deficit (<4 kPa) and dead fuel moisture content (<7%) were exceeded. Predictions from the model showed a high degree of agreement with the raw fire severity maps. The proposed models have the potential to provide guidance on the likelihood of crown fire during fire events.

Dynamic heating regimes are observed during wildland-urban interface (WUI) and wildland fires. Most experiments to date use static/constant heating regimes, whereas ignition characteristics under time-dependent heat flux has been poorly studied. Existing apparatuses have limitations to study this effect, such as heating conditions and sample size/position. In this study, we conduct experiments on a custom-made apparatus to investigate the spontaneous ignition and convection cooling effect on the ignition of different vertically positioned wood species subjected to both static and dynamic heat fluxes. All experiments were conducted on cypress wood. Temperature, mass and ignition time were recorded during the experiment. Samples were exposed to 30 kW/m2 static heat flux and increasing heat flux. It was found that convective cooling increased the time to the initiation of the observed phenomena and decreased the surface temperature. These effects become more significant with the increasing of exposure time. Convective cooling also influences the exposed surface temperature before initiation of glowing combustion. Blocked convection increases instability of the combustion process. The increasing heat flux required

higher radiant exposure energy to initiate similar processes and significantly increased internal temperature of the sample. The next step of the proposed research will be to investigate the effects of convective cooling and wood type on spontaneous ignition. Different static and dynamic heating regimes will be used and their influence on the ignition will be evaluated. Further investigation is also required to determine why some samples were not ignited in flaming mode under considered heat flux. The results obtained to date will help with the improvement of fire impact models by recognising the effects of dynamic heat flux regimes.

An emerged approach to better understand one of the extreme fire behaviours, namely junction fires, has been tested. Several preliminary small and medium scale field experiments were conducted in April 2019 on harvested wheat fields in Australia. An Unmanned Aerial Vehicle was used to capture high definition video imagery of fire propagation. Twenty-one junction fires and five parallel fire fronts were identified during the experiments. Rate of spread (ROS) of merging fire fronts was found to be at least two times higher than for the basic fire fronts and for acute angles (< 14°) it increased by 6 times or more. Parallel fire fronts spread much slower, varying between 0.05 and 0.25 m/s. It was found that the more acute the angle, the higher the ROS, which is in agreement with other studies. Forty-six percent of junction fires had an increase in the ROS at the final stage of the merging process, in constrast to Thomas et al. (1) and Viegas et al. (2). It was also observed that the angle between two oblique fire fronts did not change significantly over time if the initial angle was smaller than 34°. It can be assumed that the main fire front influences on the shape and ROS respectively of junction fires and laboratory experiments cannot fully replicate these conditions. Although the initial conditions were very different in relation to scale, fuel and wind, similar ROS to that shown in numerical simulations by Thomas et al. (1) were observed in our field experiments. Further investigation is required to explain the similarities as the relationship between fuel load, wind speed and scale is not known. The comparison of corrected values of dimensionless ROS for different angles between fire fronts with laboratory experiments of Viegas et al. (2) showed good quantitative agreement. These results have shown that the method of using UAV's to capture georeferenced video footage can be used reliably to quantify fire behaviour phenomena for research, operation and management purposes.

END-USER PROJECT IMPACT STATEMENT

Dr. Stuart Matthews, *Operational Services, Rural Fire Service, NSW*

Understanding and predicting Extreme Fire Behaviours such as crowning in Eucalypt forests is a challenging but important problem for scientists and fire managers. Meeting this challenge requires multiple approaches including field and laboratory experiments, detailed physical modellings, simplified empirically derived models, and development of operational tools.

In 2018-19 this project has made important steps towards developing science and tools to help predict EFBs. This includes a crown fire prediction model that will be suitable for operational predictions, testing of new techniques to measure the resistance of building materials to radiation, and very promising field experiments to better understand complex fire merging effects.

The work done so far in this project and paths for integration with other BNHCRC work, such as the fire spread modelling in the fire coalescence and mass spotfire dynamics will help to advance our understanding of complex fire behavior leading to better fire predictions and safer outcomes for the community and firefighters.

INTRODUCTION

Extreme fire events are becoming more regular around the world. Attempting to supress them requires extensive human resources, and they can result in many casualties. In most cases, these consequences are the result of dynamic fire behaviour (3-5). At the moment there are nine recognized extreme fire behaviours (6). Crown fires are recognised as an extreme fire behaviour phenomena (EFBs) in forest ecosystems (5). They are localised dynamic events that occur within fires, whereby physical feedbacks greatly enhance fire intensities and rates of spread. They occur in vegetation that have multiple strata, transitioning from surface and understory fuels to canopy fuels under certain environmental conditions. The flames ignite the canopy when fire intensities (and corresponding flame heights) increase above a threshold, adding to overall fuel being consumed and energy being released (7). Crown fires in forests can have impacts on environmental assets (e.g. biodiversity, soils, water quality) (8-10) and present an extreme hazard to health and the built environment due to the large amounts of radiant heat being released (11) and the large number of embers produced (12). Fire suppression is not feasible when crown fires are occurring (13-15) and the chances of firefighter entrapment are increased (16). Consequently, being able to anticipate where and when crown fires are likely to occur is critical for planning safe and effective fire responses and for ensuring community safety.

There has been substantial research into the drivers behind crown fire occurrence in forest ecosystems dominated by conifers. In these systems, crown fire potential is a function of weather, topography, canopy properties, ladder fuels and surface fuels (17-20). Despite the fact that crown fires occur frequently in Eucalypt forests (21), there has been comparatively little research into the factors driving crown fire occurrence. Crown fire behaviour in Eucalypt forests may have different drivers than conifer forests. There is greater stratification in the vegetation structure and each strata will often contain different species and therefore different fuel properties (22). The drivers and thresholds behind crown fire occurrence in broadleaved forests are unlikely to be well represented using conifer models.

Fire severity mapping has been used to study crown fire behaviour in Eucalypt forests (23, 24). These maps provide a retrospective measure of the loss of above-ground organic matter resulting from fire (25) across large areas in a consistent manner (26-28). Satellite derived maps of fire severity have been used to study environmental drivers of fire behaviour across many ecosystems globally (24, 29, 30). Previous studies have provided valuable insight into the influence of climate, topography and fuels on crown fire occurrence in eucalypt forest (24, 29, 31). However, the utility of the models derived from this work 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 (24, 31), 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 (24, 31), 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.

Flame spread is an important process in the propagation of bushfires. The likelihood of ignition and combustion rates of fuels are dependent on the type and nature of the heat flux. Most previous research has used static heat flux, whereby a consistent heating source is used to ignite samples in a laboratory setting. However, the heat flux typically observed during structural and wildland fires is highly dynamic. regimes. Dynamic fluxes have been tested previously (32-34) but these studies have generally been limited. Many use only one regime that is simulated to be either increasing, decreasing or parabolic. Most studies use a cone calorimeter or flame propagation apparatus, which each have limitations such as the heating conditions and sample size/position (32, 35). Furthermore, the majority of past experiments have been conducted on horizontally oriented samples heated from above - in contrast to “classical” fire where the flame propagates horizontally, heating the fuel from the side. Chen et al. (36) have shown that ignition time is strongly dependent on sample orientation. Although some of the extereme fire behaviours were described and investigated, others require further study, such as fire coalescence and junction fires (previously known as jump fires) (1, 2, 37-39). The convergence of individual fires into larger fires is called coalescence and can lead to rapid increases in fire intensity and spread rate (40). Junction fires are the result of the merging of two lines of fire intersecting at an oblique angle (2). Fire coalescence and junction fires are particular cases of the merging of fire fronts.

Despite the intensive investigation of merging fires (1, 2, 37-39), there is no clear understanding of the mechanisms that drive them. Viegas with colleagues started to study this phenomenon in laboratory settings conducting a range of experiments. They varied the angle between two fire fronts (2), slope and fuel type (37). Recently they compared laboratory experiments with 3 field experiments and one real fire (39). In their studies, they measured rate of spread, flame height and air flow at 5 points along the central line of the fire front. They determined two stages of junction fire development; acceleration and deceleration. They showed that convection and radiation play a significant role in junction fires. Using the concept of propagation flux proposed by Rothermel, they assumed that only in the final stage of fire deceleration is flame radiation the main mechanism of fire spread.

The WRF-Fire coupled atmosphere-fire model was used by Thomas et al. (1) to simulate the dynamic propagation of junction fires. They found that in addition to the bulk fire-induced surface flow, the formation of counter-rotating pairs of vertical vortices lying on or ahead of the fireline results in acceleration of fire front propagation. They concluded that the vortical structures are not well resolved at 20-m resolution and are too small to be properly represented in their simulations. Moreover, the WRF-Fire model uses the Rothermel model as its basis for fire propagation, which assumes quasi-steady conditions and a straight fireline. It is conceptually problematic to use this model with dynamic inputs from convection and radiation. Therefore, they did not get agreement with the Viegas et al. (2) study.

Recently Hilton et al. (38) developed a two-dimensional propagation model coupled to a ‘pyrogenic’ potential flow formulation to simulate merging fires. They calculated the pyrogenic potential from which the velocity field for the air inflow due to the fire could be derived. One of the assumptions of the model is that the plume is not affected by the wind. This assumption is problematic as other research has shown that the wind tilts the flame, resulting in increased radiative heat flux on the fuel under the flame at higher wind speeds. The authors concluded that despite the good match to experimental results, the model should take flame attachment into account and it is likely that the model only applies under certain conditions which have not been fully explored in the experimental parameter space.

Analysis of literature showed that there is no clear answer as to what mechanisms prevail in merging fires. The recent study of Raposo et al. (39) showed that laboratory experiments for low angles of V-fires cannot capture all effects due to small scales. To effectively capture the effect of convection and radiation at different stages of a merging fires development, high temporal and spatial measurements of wind and radiative heat flux in the field are required. This would allow a better understanding of the effects of convection and radiation on merging fires and support the development of functions to include in operational fire behaviour models.

Unmanned Aerial Vehicles (UAV or drones) have the potential to be used for these types of measurements. In the last decade UAVs have been used for fire detection and monitoring (41), fire management (42), and post fire monitoring (43). They can be equipped with various sensing instruments, ranging from optical sensors (including visible and infrared) to microwave sensors (Radar and Lidar). Owing to their flexibility, low cost, and high-resolution data collection, rotary-wing drone remote sensing can fill data gaps around different fire behaviour phenomena.

The currect phase of the project was devoted to the development of

- a model to predict the likelihood and extent of crown fire events using spatially derived environmental predictors and a range of weather measurements,
- development of a novel system to better represent the dynamic heat fluxes of real fires in a laboratory setting and
- testing of emerging technologies for measuring fire behavior in the field and potential application for fire management.

RESEARCH APPROACH

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

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

Methods

Study area

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) in south-eastern Australia. All of the fires in the case study region are within the Temperate climate classification with warm or hot summers and no dry season[1]. Mean annual rainfall for each of the fires varies from 400 mm in the Lofty Ranges (SA) and Northern NSW to 1500 mm in the Victorian Alps.

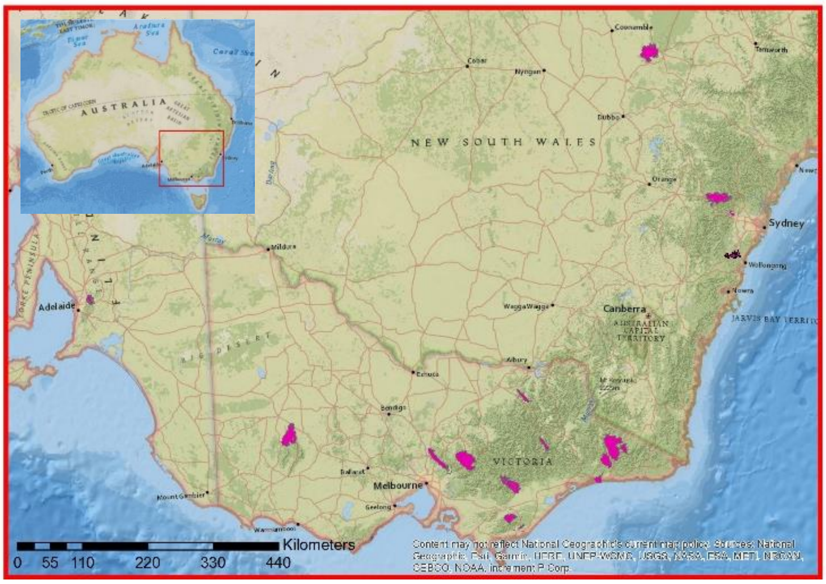


FIG. 1. CASE STUDY AREA AND LOCATION OF THE FIRES (MARKED BY RED COLOUR). MOST FIRES ARE LOCATED IN VIC, WITH ONLY ONE IN SA AND FOUR IN NSW.

The south-eastern area of the study area is mountainous with elevations ranging from sea level to the peak of the Great Dividing Range at 2228 m above sea level. The rest of the study area is between 0 and 300 m above sea level except for the Southern Mount Lofty Ranges (SA) in the far west of the study region which has a peak of 727 m.Vegetation across each of the fires in the study region is predominately forest and woodland, with dominant canopy species from the genera *Eucalyptus, Corymbia* and *Angophora,* which we collectively referred to as Eucalypts.

The fire regime for the lower productivity areas in this region is characterised by infrequent low intensity surface fires in spring with medium to high intensity fires in spring and summer. For the higher productivity tall eucalypt forest areas, the fire regime is characterised as very infrequent high-intensity crown fires in the summer

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

(44). Large wildfires (e.g. >10 000 ha) tend to occur during dry periods when fuel moisture drops below critical thresholds (45), which are conditions typically associated with El Nino events (13).

Data compilation

A key objective of our study was to model crown fire occurrence in eucalypt forests using fine temporal scale (i.e. sub daily) fire weather data. Therefore, in our study we only considered fires that had reconstructed perimeter isochrones of progression and linescans at a sub-daily resolution[2] 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*
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

Wildfire isochrones and progression lines data were obtained for areas managed by the Country Fire Authority (CFA) and the Department of Environment, Land, Water and Planning (DELWP) in VIC, Department of Environment, Water and Natural Resources (DEWNR) and Country Fire Service (CFS) in SA and the NSW Rural Fire Service (RFS). The CFA and CFS are responsible for the management of fires on private land in the outer metropolitan, regional and rural areas of VIC and SA. The DELWP and DEWNR are responsible for the management of fires on public land. The RFS is responsible for the management of fires in 95% of NSW.

Fire severity

Fire severity maps were created for the study fires using Landsat imagery (30 m resolution) and a Random Forest (RF) classifier, following the approach outlined in Collins et al. (46). The mapping approach used numerous spectral indices derived from pre- and post-fire Landsat imagery as predictor variables for a RF

[2] Linescans are images from high altitude aircraft mounted Infrared linescan systems

classifier. The RF classifier was trained using a dataset consisting of fire severity observations (n = ~10 000) derived from high resolution post-fire aerial photographs for sixteen large wildfires occurring across south-eastern Australia, including eight of the fires examined in our study. The RF classification approach has been shown to outperform commonly applied fire severity mapping approaches using only a single satellite derived index (e.g. differenced Normalised Burn Ratio), and has been found to have ~95% classification accuracy of crown fires in the study area (46). Five fire severity classes were classified in the mapping, including unburnt, crown unburnt, partial crown scorch, crown scorch and crown consumption (Table 2). Fire severity maps were generated using the Google Earth Engine platform (47). 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

Data input parameters

Crown fire runs were the focus of our 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: i) Live and dead fuel moisture content (fuel moisture); ii) Surface, elevated and bark fuels and tree height (fuel load); iii) Vapour-pressure deficit, wind speed and relative wind direction (fire weather); and iv) Slope and topographic ruggedness (topography).

Gridded values for dead fuel moisture content (DFMC) were derived from Australian Water Availability Project[3] (AWAP) using a model described in Nolan et al. (48). It is a semi-mechanistic model of fine dead fuel moisture content based on the experimental decline of fuel moisture content with atmospheric vapour pressure deficit that predicts the daily minimum fuel moisture content. The DFMC dataset was calculated and saved as NetCDF files, from which, cells bounded spatially and temporally by each fire were extracted. The live fuel moisture content (LFMC) was derived from MODIS[4] 8-day composite surface reflectance data at 500-m resolution (MOD09A1, collection6) as described by Caccamo et al. (49).

[3] http://www.bom.gov.au/jsp/awap/
[4] https://modis.gsfc.nasa.gov/

Fuel loads in tonnes per hectare for surface, elevated and bark fuels were derived from PHOENIX RapidFire using fuel datasets obtained by state government agencies in South Australia, Victoria and New South Wales. Fuel load was calculated retrospectively for each case-study fire by using fire history (time since fire), fuel type and fuel accumulation curves. Fuel types in PHOENIX are derived by aggregating major vegetation types (50) based on similar fuel composition. Fuel accumulation is modelled for each component (surface/elevated/bark) of each fuel type using a negative exponential equation (51) where the rate of fuel accumulation decreases with time since fire. The spatial resolution of the surface, elevated and bark layers was 30 m.

Vapour-pressure deficit, wind speed and wind direction were derived from Automatic Weather Stations[5] (AWS) with a temporal resolution of 1 hour.

A Digital Elevation Model[6] (DEM) was used to derive elevation, aspect, slope and ruggedness at a 30 m resolution across all the case study regions. To minimise irregularities and improve processing time, the 30 m DEM was converted into a triangle irregular network (TIN). Surface aspect and slope were calculated from this TIN and then converted back to a raster at a 30 m resolution. Ruggedness was calculated using a neighbourhood analysis of the DEM raster layer. In this process the standard deviation of elevation was calculated within a 3 x 3 and a 5 x 5 moving window to give two different ruggedness index raster layers at 30m resolution.

Results and Discussion

Model performance and predictor importance

The Random Forest model used in this study contains the full set of predictor variables. Assessment of the importance of predictor variables, based the Gini scores, indicates that variables reflecting 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 (Figure 2).

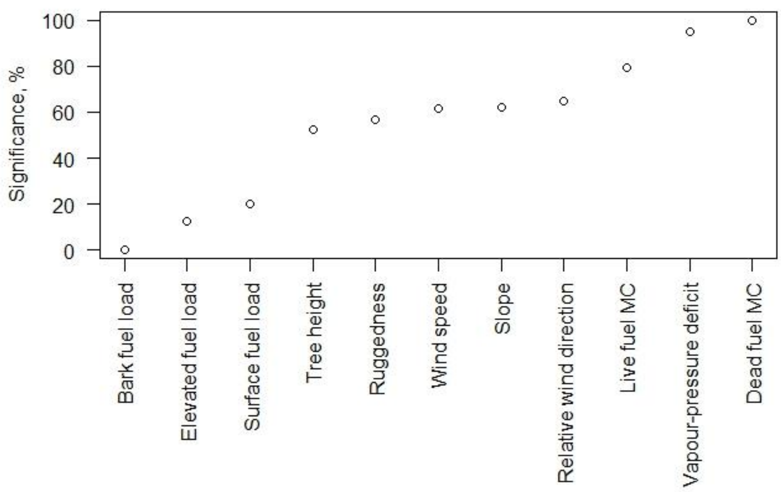
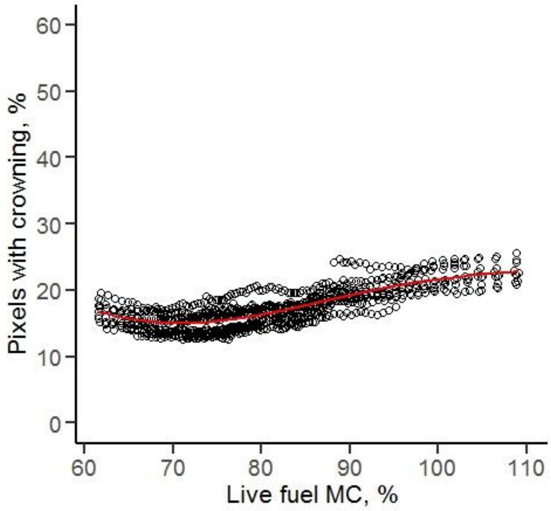


FIG. 2. IMPORTANCE OF PREDICTOR VARIABLES FOR THE PREDICTION OF CROWN FIRE EXTENT. RELATIVE SIGNIFICANCE OF VARIABLE IS DIMENSIONLESS VALUE CHANGING FROM 0 TO 100 %.

[5] http://www.bom.gov.au/inside/services_policy/pub_ag/aws/aws.shtml
[6] http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data

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



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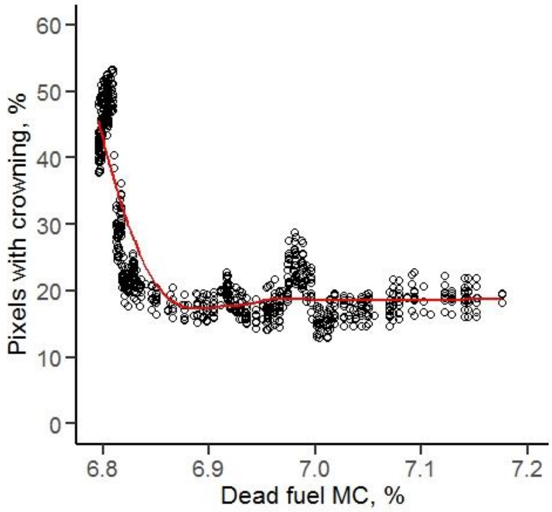

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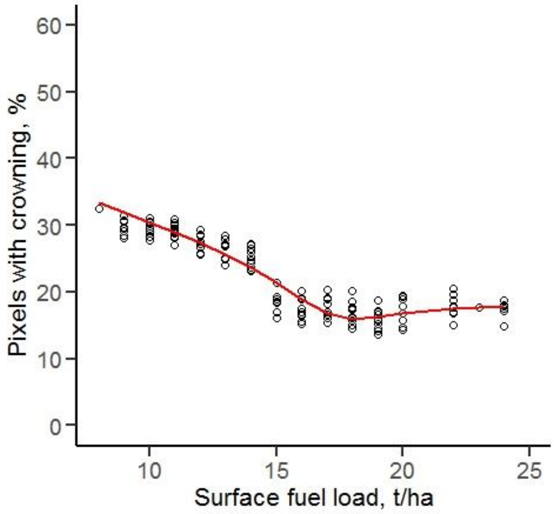

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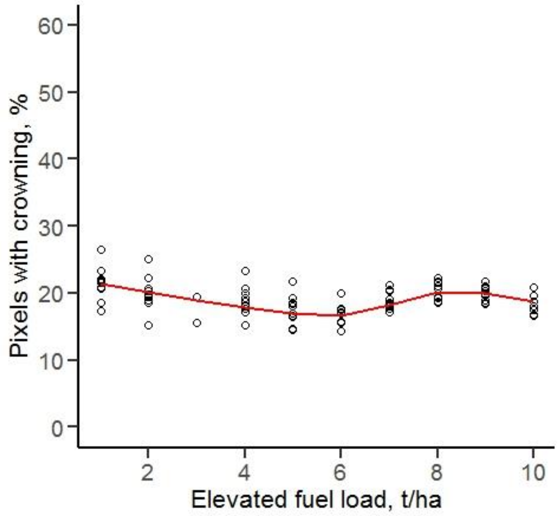

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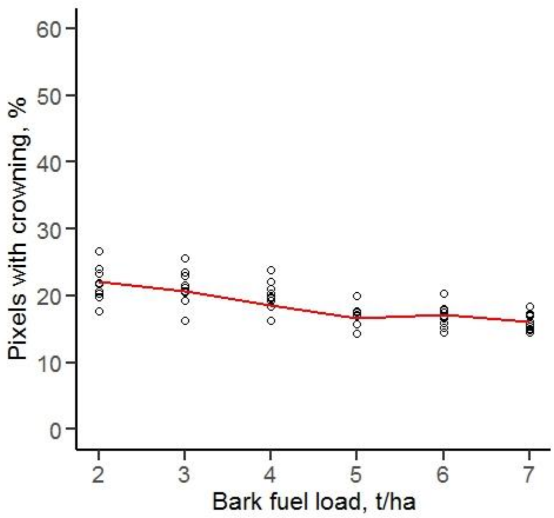

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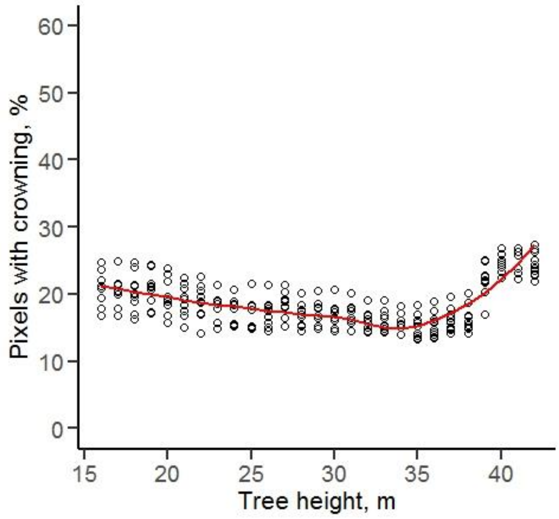

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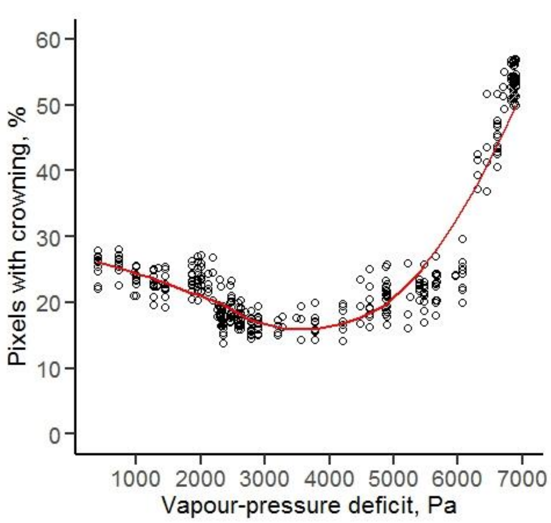

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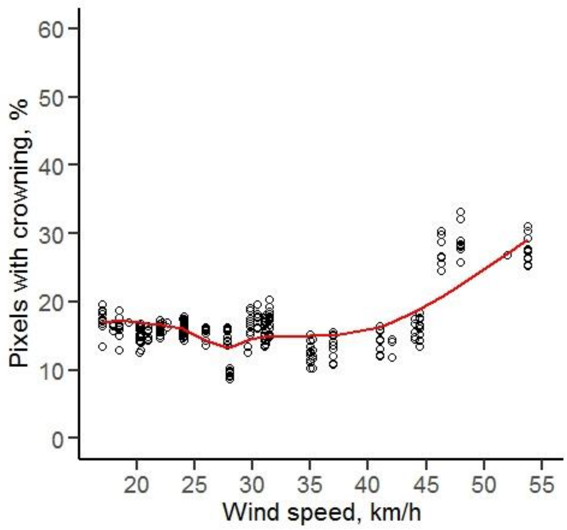

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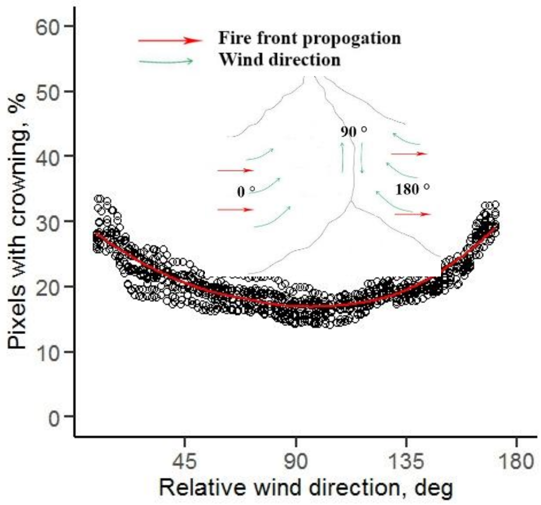

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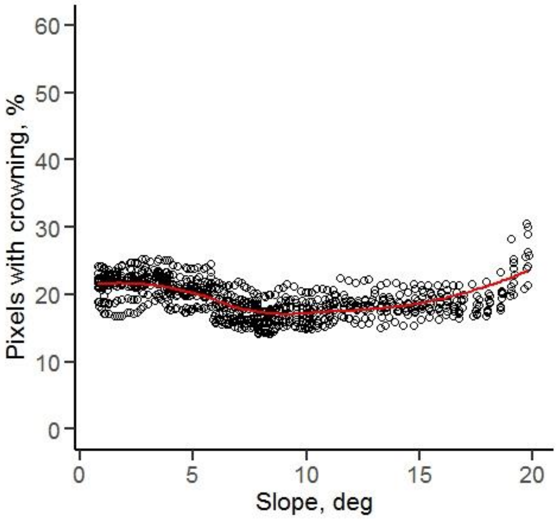

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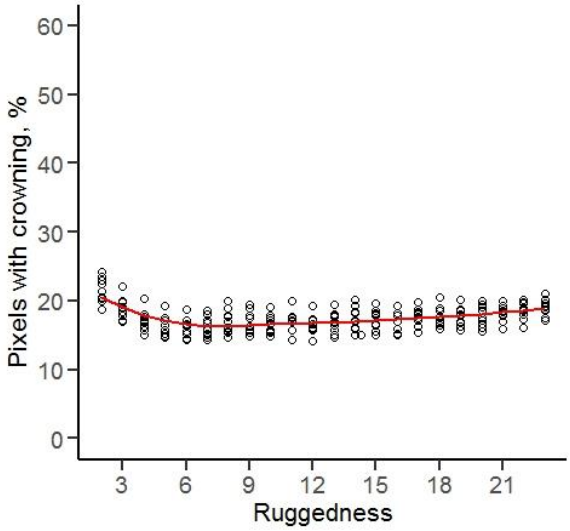

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FIG. 3. INFLUENCE OF PREDICTOR VARIABLES ON CROWN FIRE EXTENT: A,B ARE FUEL MOISTURE VARIABLES, C-F ARE FUEL LOAD VARIABLES, G-I ARE FIRE WEATHER VARIABLES AND J,K ARE TOPOGRAPHY VARIABLES. PERCENTAGE CHANGESs FROM 0 TO 100 %, WHICH CORRESPONDS TO THE TOTAL AMOUNT OF PIXELS.

Several predictor variables were found to have a large effect on the crown fire extent. They were dead fuel moisture content (Figure 3b) and vapour-pressure deficit (Figure 3g). 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.

Forecast results

Mapped predictions from the Random Forest model show a good degree of agreement with the mapped fire severity observations suggesting it could be useful tool for decision support (Figure 4). Analysis of the cells showed that the Random Forest model over predicts crowning for a low proportion of pixels with crowning in cluster (less than 50% of pixels) and under predicts for higher values.

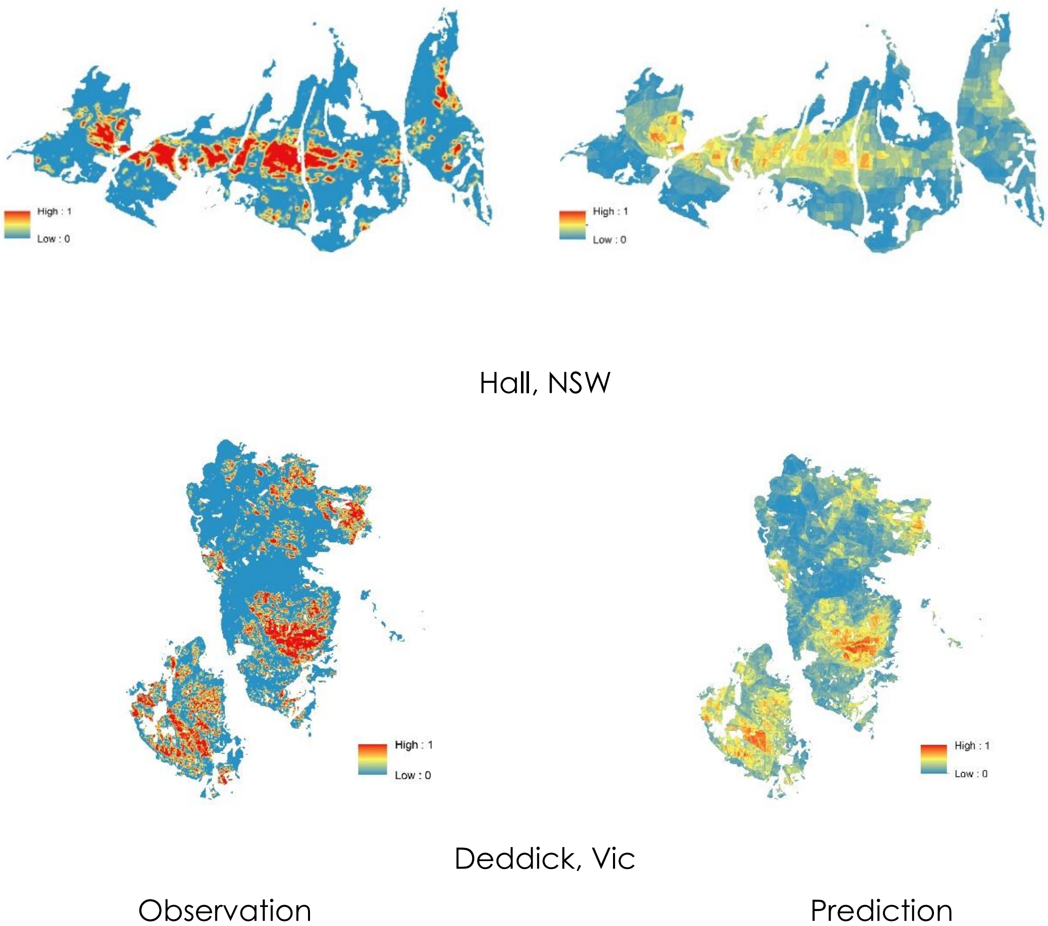


FIG. 4. COMPARISON OF OBSERVED PROPORTION OF PIXELS WITH CROWNING VS PREDICTED. PROPORTION OF PIXELS WITH CROWNING IS CHANGING FROM 0 (NO CROWNING) TO 1 (ALL PIXELS WITH CROWNING).

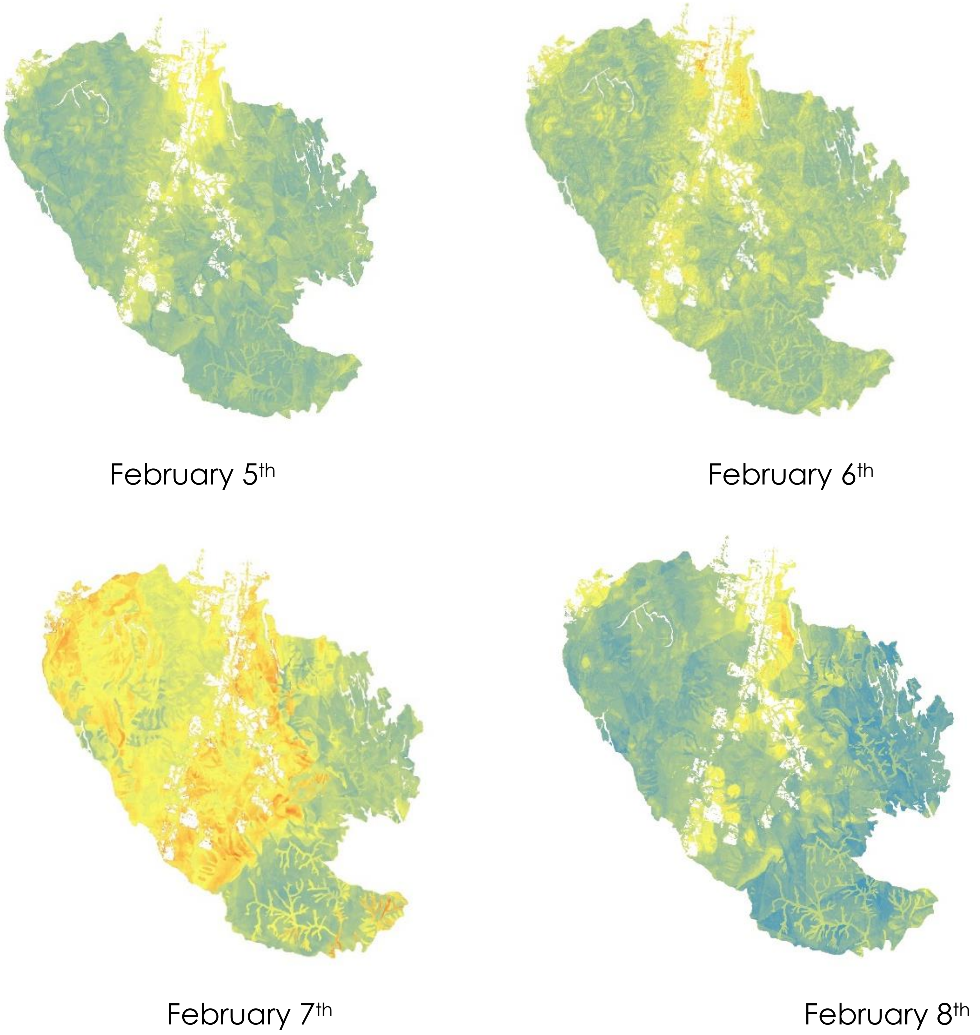
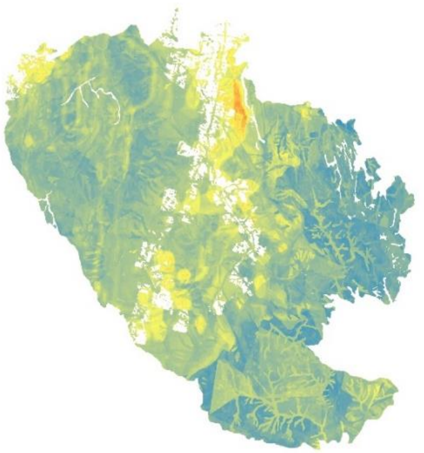


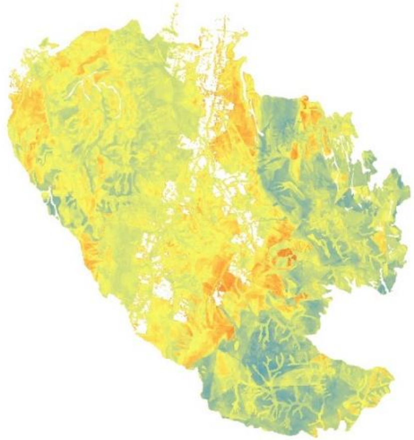
FIG. 5. DAILY FORECAST OF CROWN FIRE RUNS USING THE PROPOSED MODEL. THE SIMULATION RESULTS PRESENTED FOR 5^{TH}, 6^{TH}, 7^{TH} (BLACK SATURDAY) AND 8^{TH} OF FEBRUARY 2009 AT 3 PM FOR MURRINDINDI FIRE. FOR BETTER REPRESENTATION OF CROWN FIRE RUNS A LIKELIHOOD INCREASES ON FIGURE FROM 0 (GREEN) TO 0.8 (RED).

Figure 5 shows predictions for four consequent days at 3 pm for Murrindindi fire. The maximum likelihood of crown fire runs was observed on February 7^{th} and was equal 0.71. The likelihood of crowning increased from the 5^{th} of February to 7^{th} (Figure 5), which is in agreement with observations. 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 run simulations with the hourly weather forecast for the same fire. Figure 6 shows the likelihood of crown fire runs for Murrindindi fire with 2 hour time step (due to limited space) on Black Saturday.

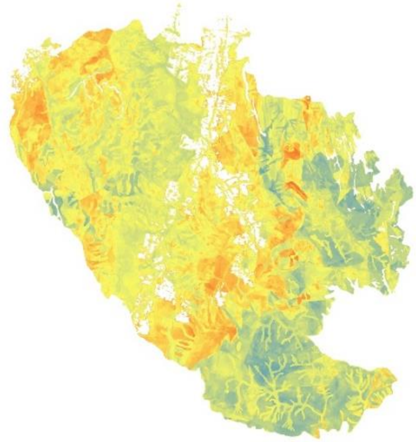


6.00

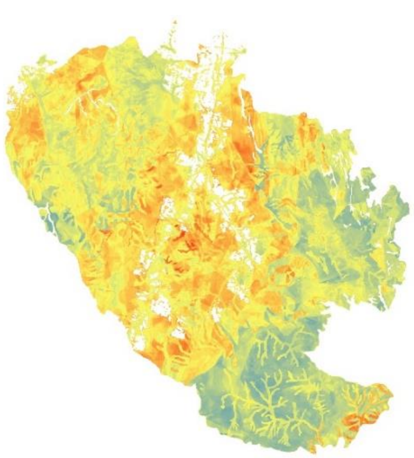
8.00



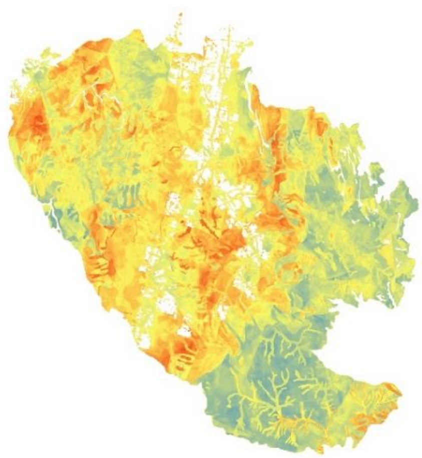
10.00



12.00



14.00



16.00

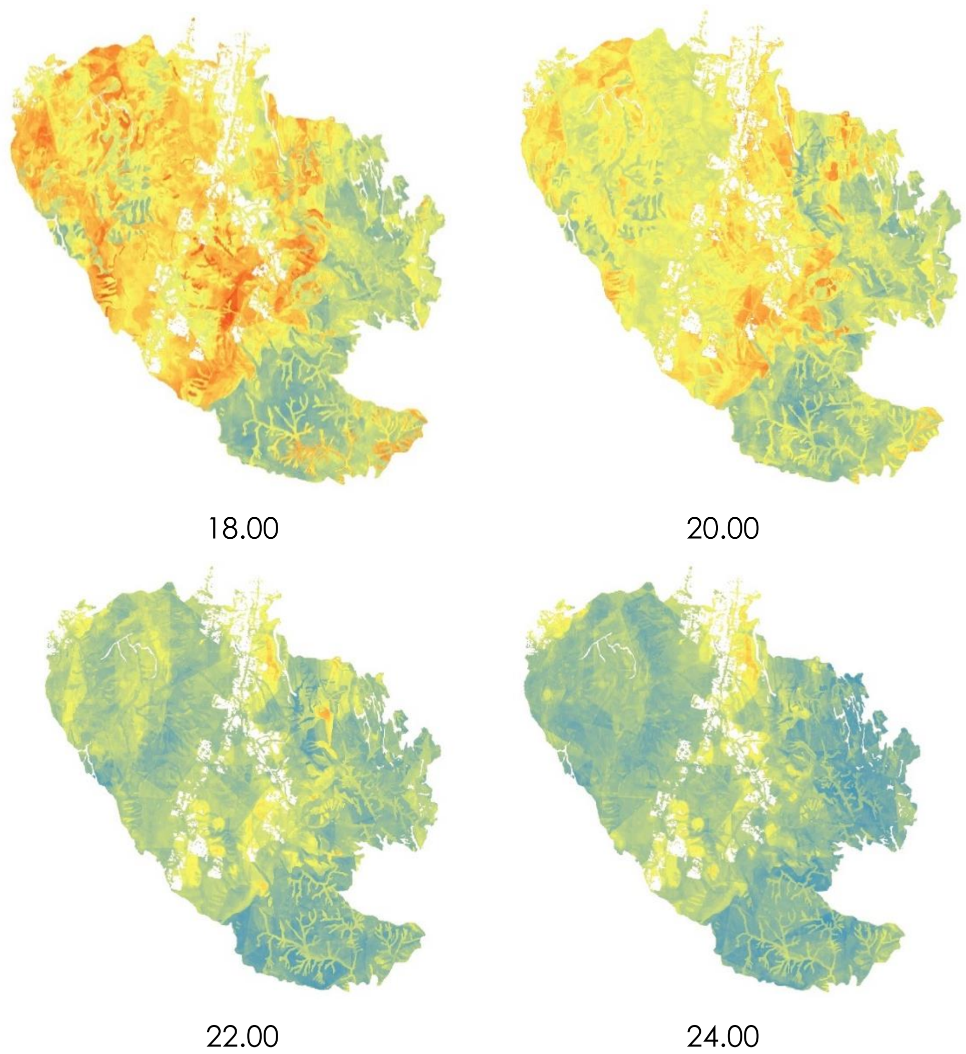


FIG. 6. 2 HOUR FORECAST FOR MURRINDINDI FIRE ON FEBRUARY 7TH. FOR BETTER REPRESENTATION OF CROWN FIRE RUNS A LIKELIHOOD INCREASES ON FIGURE FROM 0 (GREEN) TO 0.8 (RED).

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.

Based on this method we tested the significance of all predictors and their effect on crown fire occurrence. It was observed that live and dead fuel moisture content and vapour-pressure deficit were the most significant variables influencing crown fire occurrence, 80% and above (Figure 2). Tree height, ruggedness, wind speed, slope, relative wind direction 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 is in agreement 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 one of 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 growth of the proportion of pixels where crown fires occurred by 3 times. These findings highlight the fact, that moisture plays an important role in the ignition and combustion process (52, 53). Even small changes in mositure 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 croseed: >35 m tree height, <18 t/ha load, >40 km/h speed, 45°-90° and 135°-180° wind direction.

It is known that high density fuel beds decrease fire spread rate (54). This effect is coupled with fuel bed porosity. We may be seeing the effects of this phenomena in our results. For as surface fuel load decreased, there was an increasing likelihood of crown fire (figure 3c). Low spread rates of fire do not create sufficient conditions for the transition of fire to the elevated fuel. This is reflected in the wind speed threshold. There was a larger number of pixels predicted to experience crowning with tall trees (>35m). It can be assumed that for those areas there is a well-developed sub-canopy layer which provided surface-to-crown transition.

Zhou et al. (55) found that upslope fire spread depends not only on the increased radiant heat transfer, but also on the aerodynamic effect created by the interaction of the flame with the inclined surface. We see this effect as there was an increased likelihood of crown fire with a relative wind direction range of between 45°-90° (figure 3i). The increasing likelihood of crown fire between the wind direction range of 135°-180° could be explained by the turbulence of an air flow (56). On the lee side of the ridge, a turbulent reversal (wind eddies) of general wind flow is possible (Figure 3i). It brings a lot of firebrands and embers to the unburned fuel and could be the reason for crowning.

The rest of the predictor variables changed the likelihood of crown fire in approximately 10 % of pixels without showing any consistent patterns.

Predictions of crown fire runs using the proposed model showed a good accuracy. In spite of the model under predicting crowning under some circumstances, it 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.

Conclusion

By creating severity maps and using a Random Forest model, we have modelled the effects of environmental drivers on crown fires. Predictor variables were chosen to represent the four key environmental drivers of fire behaviour. For the first time the influence of each selected predictor variable on crown fire runs was tested. A new approach to predict the likelihood of crown fire runs within a 150 x 150 m window was used.

Results of the 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.

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.

As the weather variables can be forecast into the future, Random Forest predictions could be used to forecast the likelihood of crown fire runs while fires are occurring. In the study area, 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. Such information would be invaluable for fire managers in terms of allocating fire suppression resources and issuing public warnings

SPONTANEOUS IGNITION OF VERTICALLY POSITIONED WOOD SAMPLES UNDER TIME-DEPENDENT HEAT FLUX

In this study we have developed a novel system to better represent the dynamic heat fluxes of real fires in a laboratory setting. In this study, we are able to experimentally test the spontaneous ignition and convection cooling effect of different vertically positioned wood species subjected to both static and dynamic heat fluxes.

Methods

A custom-made Radiative Heat Flux Apparatus (Fig. 7) was developed as part of this project. It has been used for heat flux experiments.

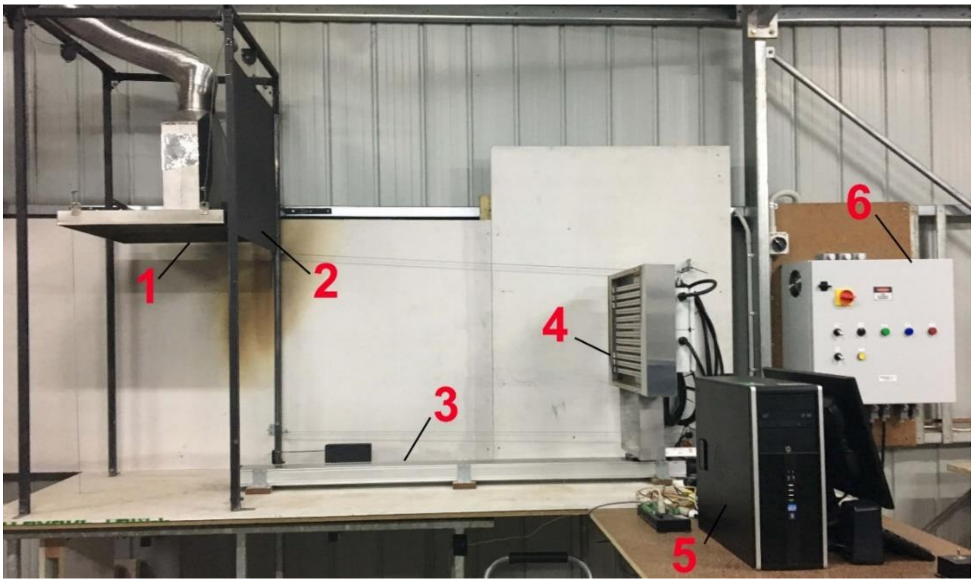


FIG. 7. Radiative Heat Flux Apparatus 1) an exhaust system, 2) a shutter, 3) a linear stage, 4) a radiative panel, 5) a control system and 6) a power control box.

The apparatus consists of: 1) an exhaust system, 2) a shutter, 3) a linear stage, 4) a radiative panel, 5) a control system and 6) a power control box. The shutter protects the sample from radiation prior to the experiment. The shutter has two positions, open and closed. A remote control operates the shutter and opens it within 1 s. The radiative panel is installed on the 1.5 m linear stage to allow the panel to be moved forward or backward, simulating variable heat flux. A programmable step motor controller PCL601USB (Anaheim Automation, Inc.) is used to change movement speed within the range of 0.001-0.3 m/s. The radiative panel produces radiative heat flux q_r using 12 shortwave infrared quartz lamps. Each lamp has the following characteristics: draws 2400 W power, has peak wavelengths of 1.2-1.4 µm, has a maximum surface power 150 kW/m^2 and filament temperature of 1800-2200°C. The control system allows the operator to control the conditions of the experiment. The power control box controls the radiant heat flux produced by the lamps.

Two CR1000 dataloggers (Campbell Scientific, Inc.) with frequency of 1 Hz are used to measure thermal characteristics of materials in the study. To measure heat flux, a water-cooled heat flux sensor SBG01-100 (Hukseflux Thermal Sensors B.V.) is used. It was factory calibrated for a heat flux of 100 kW/m2 (± 6.4 %) and has a response time of less than 0.25 s. The system is designed for samples being tested with Type K glass braided insulated thermocouples (OMEGA Engineering Inc.) with stripped leads and diameter of 0.25 mm in accordance to Australian

Standard (AS) 1530.4:2014. (57). These are used to measure temperatures inside samples and on their surfaces. An infrared camera (FLIR T1050sc) is used to measure temperatures on the exposed surface at a resolution of 1024 x 768 and a frequency of 30 Hz. A DSLR camera (Canon EOS 600D) is used to film the experiments.

The samples being tested are square cypress wood samples with height and width of 65 mm and a depth of 19 mm. To measure temperature distribution in the sample 4 thermocouples were used. Two thermocouples T1 and T2 were imbedded at a depth of 10 mm from the exposed surface to record temperature difference along the width, one thermocouple T3 at a depth of 3 mm from the exposed surface, and one T4 on the back side of the sample. (Figure 8).

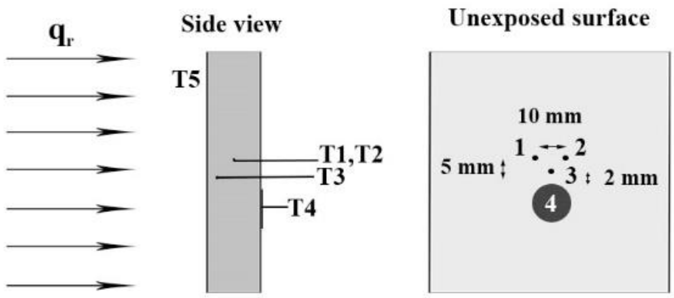
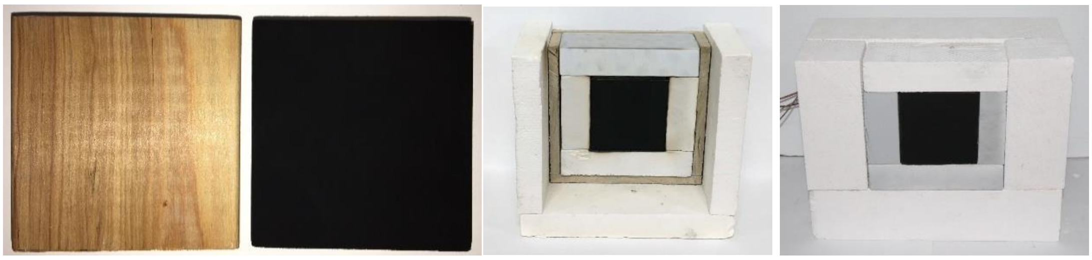


FIG. 8. Location of thermocouples.

Before testing samples are dried to a constant mass state using an oven at 104 °C for 48 hours (58). To avoid the influence of heterogenous wood surface properties (texture, colour etc.) on heat flux absorption, the exposed surface of the sample is coated with lampblack (58) (Figure 9a). To investigate the influence of convection cooling effect on the ignition time, two sample holders have been designed, one with blocked sides and bottom (Figure 9b) and a second without (Figure 9c).



a b c

FIG. 9. a) Original (left) and blackened (right) sample; b) sample holder to block convective cooling (blocked convection); c) sample holder with open sides (free convection).

The sample holder is constructed of 7.5 mm thick cement board and of 25 mm silica board to prevent heat loss along the edges of the sample. The entire sample holder is positioned on a scale during experimentation to record mass loss (Figure 10).

FIG. 10. Design of the experiment.

Samples have been exposed to 30 kW/m^2 static heat flux for 5 min and an increasing heat flux for a duration of 12.5 min (Figure 11). For the dynamic regime, the heat flux was increased by moving the radiative panel closer to the sample with a constant speed of 0.4 mm/sec. Five repetitions were conducted for each experimental condition.

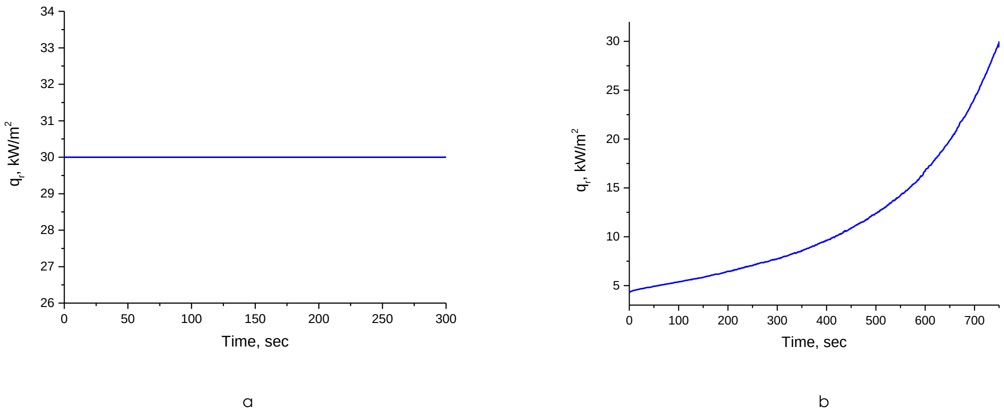


FIG. 11. Heating regimes: a) static; b) increasing.

The length of time for the increasing regime was chosen to have a similar value to a static regime value of radiant exposure of a surface H_e, defined as

$$He = \int_0^T qr(t)\,dt,$$

where H_e is 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.

In a second stage of experimentation the influence of convection cooling on the autoignition of samples has been tested.

Results and discussion

Twenty eight experiments were conducted for static heat flux (18 with blocked convection and 10 with free convection) and thirty one for increasing heat flux (21 with blocked convection and 10 with free convection).

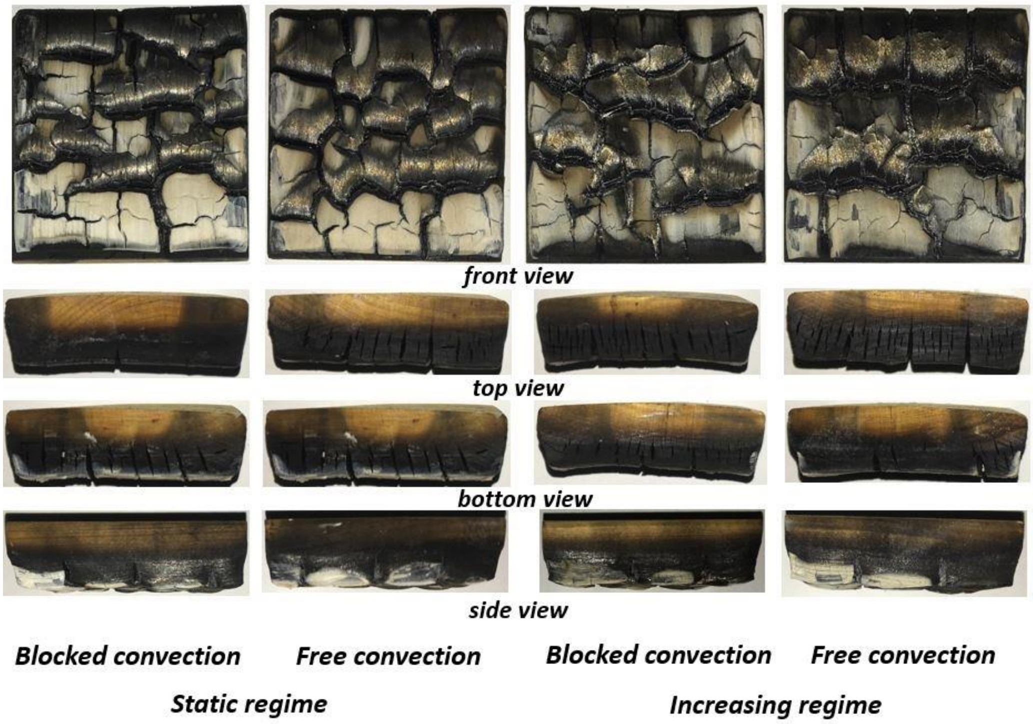


FIG. 12. Exposed samples.

All samples after the experiments had a typical "crocodiling" pattern irrespective to the heating regime (Figure 12).

Only six samples ignited in the flaming mode, the rest had glowing combustion. Therefore, to compare the heating regimes and the influence of convection we used specific indicators. Appearence of smoke, first crack on the exposed surface and start of glowing can be used as the indicators in our particular case (Figure 13). Due to the design of the experiment it was not possible to record smoke initiation with reasonable accuracy for the static regime. Therefore, a maximum observed time of 30 sec was used.

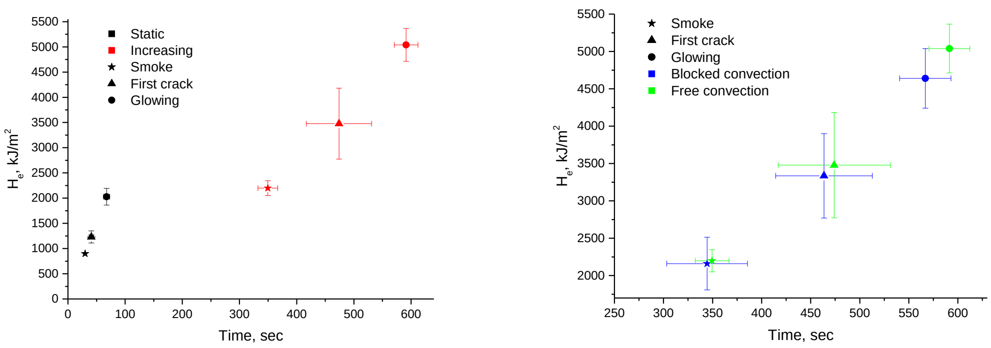


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FIG. 13. Appearance of selected indicators: a) two heating regimes with free convection; b) increasing regime with free and blocked convection.

Radiant exposure for the increasing regime is always much higher than for the static regime (Figure 13a).

Comparison of conditions with blocked and open convection (Figure 13b) showed that convective cooling increases the time to the initiation of the observed indicators. The mean times for all indicators with open convection were always higher than with blocked samples. As the length of time increases this effect becomes more pronounced.

Analysis of the mass loss showed that for the increasing regime, mass loss was slower than for static regime, which was expected. However, the final mass was similar for all conditions. Mean mass loss was slightly different for blocked and open convection, but in general, all values were inside confidence intervals.

It is interesting to analyse the influence of heating regime and convection on the mass loss. Figure 14 shows the change of sample mass for static and increasing regimes.

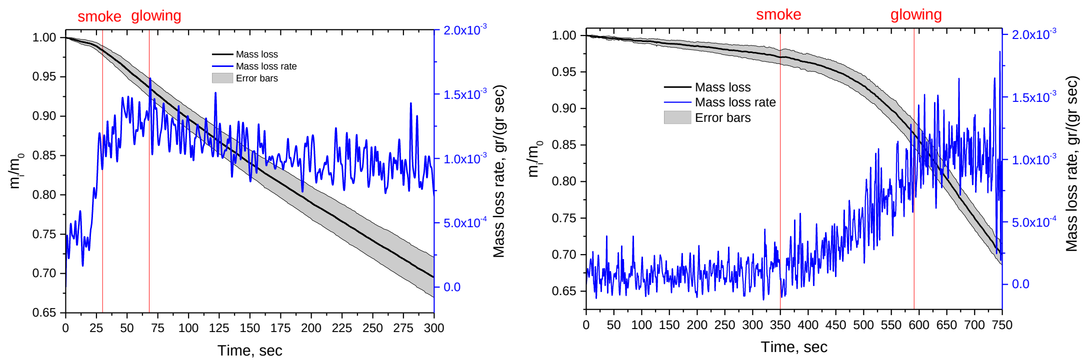

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FIG. 14. Variation of mass loss and mass loss rate with free convection: a) static regime; b) increasing regime.

Analysis of the mass loss rates (MLR) on Figure 14 shows that after the stage of active gasification and initiation of glowing the MLR for the static regime stabilizes and slightly decreases. While for the increasing regime, the stage of active gasification starts after 350th second and lasts until 600 seconds. During this stage, the MLR increases. It also can be seen that vaiation of MLR is larger for the increasing regime than for the static one.

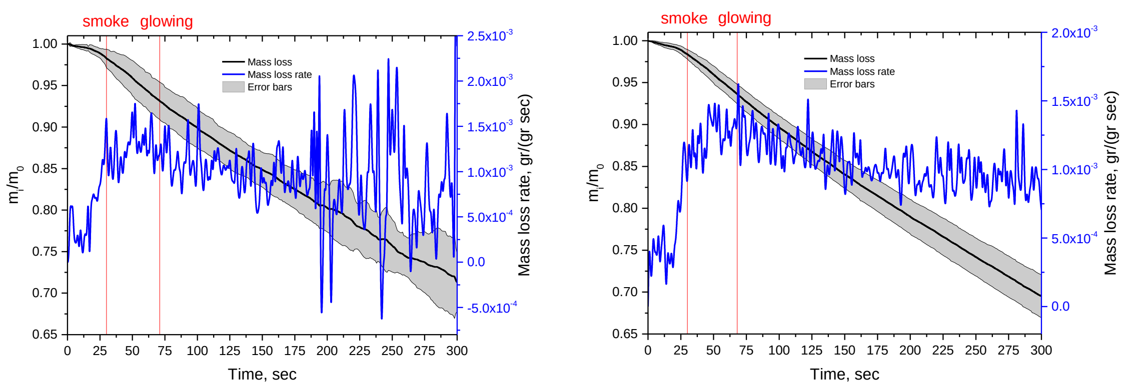

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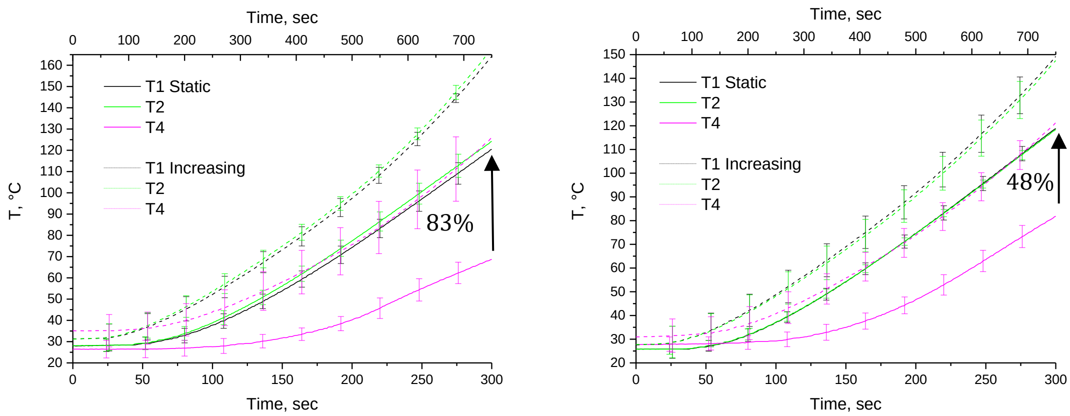
FIG. 15. Variation of mass loss and mass loss rate for the static regime: a) blocked convection; b) free convection.

Influence of convection on the mass loss rate is presented on Figure 15. MLR for the blocked convection has a range that is five times wider than for open convection. It can be assumed that for conditions with open convection, the air flow stabilizes the combustion process and slows it down at the same time.

Analysis of the temperature distribution in the samples for open and blocked convection for each heating regime did not show any significant difference between them. It is of interest to compare the temperatures T1-T3 between static and increasing regimes (Figure 16).



a b

FIG. 16. Variation of the temperature for static and increasing regimes: a) blocked convection; b) free convection.

It can be seen on Figure 16 that the internal temperatures T1, T2 and the temperature of the back surface for the increasing regime are always higher than for the static regime. The difference at the end of the experiment ranged from 25 to 83 %, with the maximum difference occurring for the back surface of 83 % for blocked convection, and 48 % for open convection.

Analysis of the IR temperatures showed that convection influences the exposed surface temperature before initiation of glowing combustion and the temperatures are always lower for the open convection. The maximum difference of mean temperatures for blocked and open convection is 80 degrees for the static regime and 137 degrees for the increasing regime.

Conclusion

Analysis of obtained results showed that dynamic heat flux and convection cooling influence ignition and thermal degradation of wood samples. Higher radiant exposure was required to initiate similar processes for the increasing regime than for the static one. Additionally, the increasing heating regime significantly increases internal temperature of the sample compare to the static regime.

It was found that convection cooling lead to an increase of time to the initiation of observed indicators and with increasing exposure time, the convection cooling effect becomes more significant. It decreases the mean surface temperature by 80 degrees for the static regime and by 137 degres for the increasing regime. However, it'sinfluence on the exposed surface temperature was only before initiation of the glowing combustion. It was observed that blocked convection increases instability of the combustion process.

Neither the type of heating regime, nor the convective cooling effectinfluenced the final mass of the sample for the considered experimental conditions.

Only six samples out of 59 were ignited in the flaming mode. Further investigation is required to determine why most samples were not ignited in the flaming mode under considered heat flux.

The results obtained to date will help with the improvement of fire impact models by allowing the recognition of the effects of dynamic heat flux regimes.

The next step of the proposed research will be to investigate the effects of convective cooling and wood type on flaming ignition. Different static and dynamic heating regimes will be used and their influence on the flaming ignition will be evaluated.

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

In this study, we conducted several preliminary small and medium scale field experiments to test emerging technologies for measuring merging fire fronts (Figure 17); and to test if existing models developed from small-scale laboratory experiments are appropriate at the landscape scale.

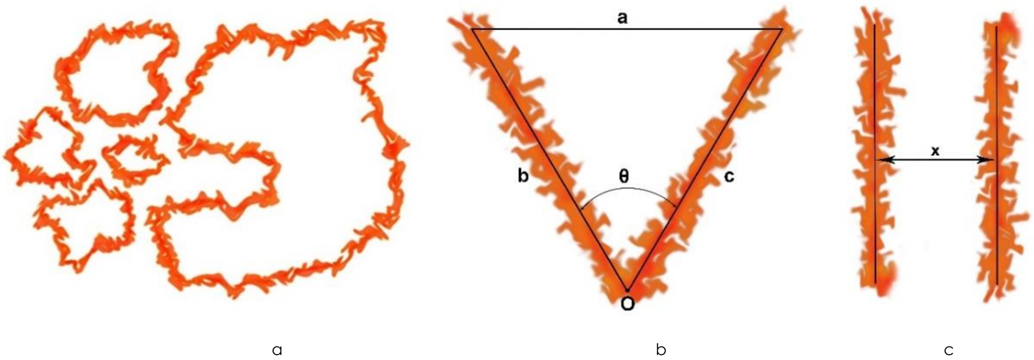


FIG. 17. Merging fire fronts: a) Fire coalescence, b) Junction fire, c) Parallel fire fronts. Where *a*, *b* and *c* are the dimensions of the junction fire; *θ* is the angle between oblique fire fronts; *x* is the distance between parallel fire fronts.

Methods

Study area and equipment

The study was conducted on farmlands in Victoria, Australia (Figure 18). Several preliminary small and medium scale field experiments were conducted on 12th of April 2019 near Kingston.

FIG. 18. 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 were 0.1 kg/m^2 and 11.9 % respectively. Wind speed and direction was mostly southern eastern and varied in the range of 1.5-6.5 m/s. The plots were relatively flat. 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 (50% diesel fuel to 50% petrol) along the edge of the experimental plots (Figure 2). 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. To minimise the georeferencing error of the final imagery, a flight altitude of 30 m and a 90° camera angle were maintained whilst video footage was being recorded. 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 (59).

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 (60). Prior to analysing the video footage, the video file must be converted into a FMV-compliant format. 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 calculate ROS of merging fire fronts we measured travelling distance of intersect point O (Figure 17b) every 2 seconds. For parallel fire fronts we randomly selected two points in the fire fronts in front of each other and measured the distance between them every 5 seconds. Basic ROS was measured in vicinity to junction fire every 5 seconds as well. Different time intervals of selected phenomena were chosen due to the significant distinction of time scales.

To compare ROS between different phenomena and with other studies we used approach proposed by Viegas et al. (2). He used non-dimensional form of the rate of spread of intersection point of two oblique fire fronts (merging fire fronts):

$$V' = \frac{V_O}{R_0} \qquad (1)$$

where V_O 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, i.e. the rate of spread of a linear fire front in the same fuel bed in no-wind and no-slope conditions. In our particular case we measured R_0 of a closest linear fire front in presence of wind to analysed merging fire fronts.

Results and discussion

Several preliminary small and medium scale field experiments were conducted during 2019 to test emerging technologies for measuring fire behaviour; and to test if existing models developed from small-scale laboratory experiments are appropriate at the landscape scale. As a result, eleven video footages were filmed during experiments (Figure 3a).

After analysis of video footages twenty-six merging fires were identified, namely 21 junction fires and 5 parallel fire fronts (Table 3).

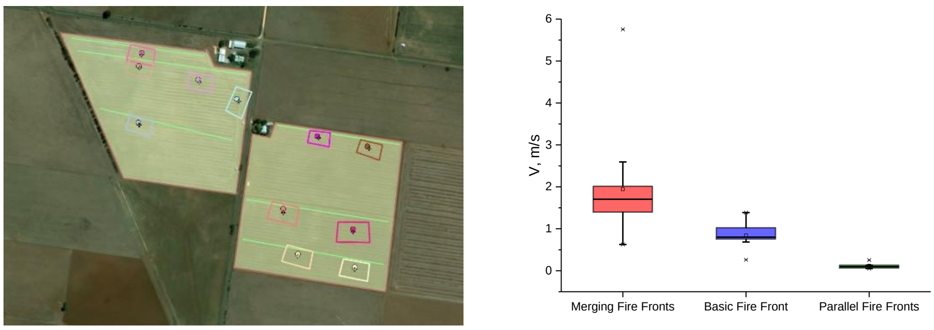
Type of merging fires	a, m	b, m	c, m	θ, deg	x, m
Junction fire	3.6	4.2	4.8	46.7	-
	3.2	5.5	3.6	33	-
	2.9	5.6	4.8	31	-
	2	7.9	6.9	13.3	-
	3.8	6.9	6.9	31.6	-
	9.2	13.4	8.8	42.6	-
	2.2	18.9	17.3	4.8	-
	6.3	11.7	11.8	31	-
	4.1	17.4	19.4	11.1	-
	9.4	12.1	10.8	47.8	-
	9.6	7.8	11.1	58.1	-

	11.4	15.3	21.7	29.9	-
	4.4	19.7	21.2	11.8	-
	6.3	5	7.7	54.3	-
	8.5	7.6	6	76.7	-
	3.6	5.5	7.1	29.6	-
	3	6.1	6.1	28.7	-
	4.7	8.2	8.1	33.3	-
	5.7	8.4	8.1	40.6	-
	4	4.3	5.9	42	-
	4.3	8.5	6.4	29	-
Parallel fire fronts	-	-	-	-	5.2
	-	-	-	-	5.5
	-	-	-	-	2.3
	-	-	-	-	2.6
	-	-	-	-	3

TABLE 3. Geometrical characteristics of merging fires. 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 (see Figure 17c).

It was found that all considered junction fires can be separated into 5 groups depending on the angle between oblique fire fronts θ: 4°-14°, 28°-34°, 40°-59° and above 76°. Highest number of fires (43%) were observed in 28°-34° group.

Figure 19b shows comparison of ROS of observed fire fronts.



a b

FIG. 19. a) Birds eye view of study site. Each rectangular represents separate video footage. b) Comparison of different types of fire front propagation.

ROS of merging and parallel fire fronts was calculated as an average of all 2 and 5 second time intervals. It was observed that propagation of merging fire fronts was faster compare to other fire fronts, which is consistent with other studies (2, 37). Median ROS of merging fire fronts was at least two times higher than for basic and parallel, 1.7 m/s compare to 0.8 and 0.096 m/s respectively. Moreover, for acute angles (< 14°) ROS of merging fires was greater than 6 times that of basic ROS. Parallel fire fronts spread much slower, varying between 0.05 and 0.25 m/s.

Comparison of θ and ROS for observed junction fires are presented on Figure 20.

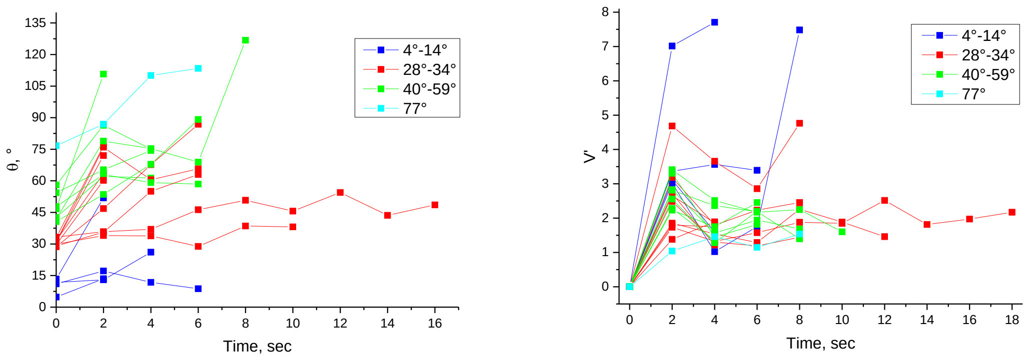


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FIG. 20. Evolution of fire fronts in time: a) variation of the angle θ between oblique fire fronts; b) variation of the dimensionless rate of spread V'. Angles in the legend indicate the value at the initial time.

It is clearly seen that the more acute the angle, the higher the ROS. In other studies (1, 2, 37) it was shown that ROS at the final stages of merging process decreases due to increase of θ. However, our observations showed opposite effect in almost of half cases (46%) and the rest had slight decreases (Figure 4b). Also, it was observed that the angle θ did not change much in time for initial angles up to 34° (Figure 4a). It can be assumed that the main fire front influences on the shape of junction fires and ROS respectively and laboratory experiments cannot fully replicate these conditions. This requires further investigation. This requires further investigation.

It is interesting to compare obtained results with studies of Viegas et al. (2) and Thomas et al. (1). In their study Viegas et al. (2) conducted a series of laboratory experiments on a horizontal fuel bed with area of 6 m x 8 m and angles θ=10°-45°between oblique fire lines. The fuel bed was composed of dead needles of *Pinus pinaster* with a fuel load of 0.6 kg/m^2 (dry basis). Thomas et al. (1) used a coupled atmosphere-fire model to simulate the dynamic propagation of junction fires. They tested similar θ, but at much bigger scale, each fire line was 1000 m long. 'Long grass', Category 3 of the Anderson fuel model system (61) was taken as a fuel. According to Anderson (61) 'long grass' has the following properties: total fuel load 0.67 kg/m^2; fuel bed depth 76.2 cm. Both studies were conducted without wind. Neither Viegas et al. (2) nor Thomas et al. (1) mentioned moisture content of fuel bed in their studies.

Figures 21 and 22 show comparison of ROS with experimental (2) and modelling (1) studies.

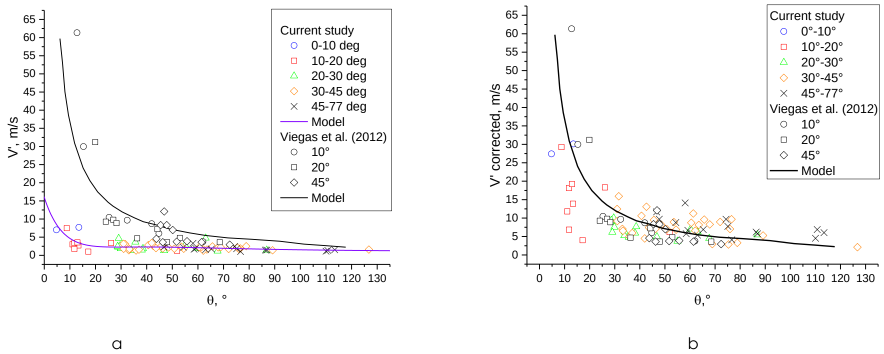

FIG. 21. Comparison of dimensionless rate of spread V' with Viegas et al. (2): a) original *V'*; b) corrected V'. Markers indicate angle between merging fire fronts at different moments of time. Legend shows the ranges of initial angles θ. Black line is the model of Viegas et al. (2); violet line is a regression line from current study, adjusted R^2=0.99.

It can be seen from Figure 5a that results differ. However, both datasets can be modelled with the exponential function. Nonlinear regression with Orthogonal Distance Regression algorithm was used to model our experimental data. The data were fitted using the following equation:

$$V' = 1.08 + 3.85 * \exp(-(\theta - 31.58)/9.81) - 5.04 * \exp(-(\theta - 31.58)/11.11) + 2.4 * \exp(-(\theta - 31.58)/41.2 \quad (2)$$

The difference can be related to different fuel load and structure, 6 times higher in Viegas et al. (2). Also, basic ROS was calculated in presence of wind unlike Viegas et al. (2). To exclude this factor we recalculated *V'* using an average basic ROS of Viegas, which was 0.2 m/s (≈1 m/s in our study). Comparison of corrected values of *V'* with Viegas' experimental results is presented on Figure 5b. Analysis shows a good quantitative agreement with Viegas et al. (2). This is evidence that the approach is applicable for determining fire behaviour parameters in field conditions.

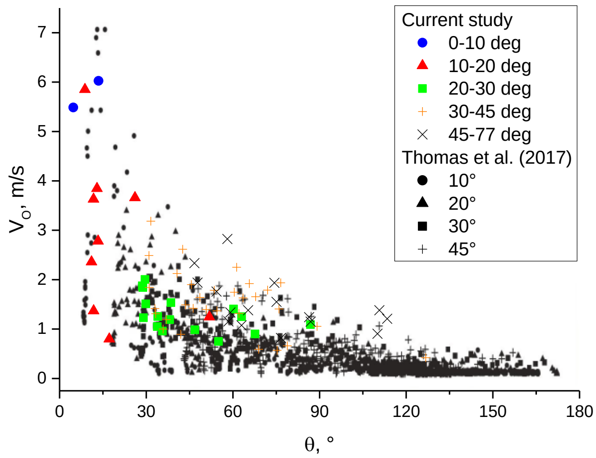

FIG. 22. Comparison of the rate of spread of intersection point of two oblique fire fronts with Thomas et al. (1). Markers indicate angle between merging fire fronts at different moments of time. Legend shows the ranges of initial angles θ.

Thomas et al. (1) conducted a comparison with experimental results of Viegas et al. (2) and they could not get quantitative agreement with them. They assumed that the reason is the different scale of experiments and numerical modelling.

Analysis of the data on Figure 22 shows a good agreement between the two datasets. However, it should be mentioned that fuel load in Thomas et al. (1) was 7 times higher and the experiments were conducted in no wind conditions. Without having the same initial conditions in both studies it is not possible to make any conclusion regarding influence of scale effect on the ROS of merging fire fronts.

The quantification of captured video and photo imagery has traditionally been challenging and requires significant pre-experiment set up time or a complex post processing workflow. The approach used in these experiments has the benefit of minimal set up time with the resulting data being highly accurate across space and time. With further development and testing it shows promise to be a valuable tool for fire behavior research, operation and management applications.

Conclusion

This study described an emerging approach to better understand one of the extreme fire behaviours, namely junction fires. Several preliminary small and medium scale field experiments were conducted in April 2019 on harvested wheat fields in Australia. A UAV was used to capture high definition video imagery of fire propagation. Twenty-one junction fires and five parallel fire fronts were identified during the experiments.

ROS of merging fire fronts V_O was found to be at least two times higher than for the basic fire fronts and for acute angles (< 14°) it increased by 6 times or more. Parallel fire fronts spread much slower, varying between 0.05 and 0.25 m/s. Forty-six percent of junction fires had increased in the ROS at the final stage of the merging process, a result in contrast to Thomas et al. (1) and Viegas et al. (2). It was also observed that the angle between two oblique fire fronts did not change significantly over time if the initial angle was smaller than 34°. It can be assumed that the main fire front influences on the shape and ROS respectively of junction fires and laboratory experiments cannot fully replicate these conditions. Although the initial conditions were very different in relation to scale, fuel and wind, similar ROS to that shown in numerical simulations by Thomas et al. (1) were observed in our field experiments. Further investigation is required to explain the similarities as the relationship between fuel load, wind speed and scale is not known. The comparison of corrected values of dimensionless ROS for different angles between fire fronts with laboratory experiments of Viegas et al. (2) showed good quantitative agreement.

Obtained results have shown that the method of using UAV's to capture georeferenced video footage can be used reliably to quantify fire behaviour phenomena for research, operation and management purposes.

KEY MILESTONES

2.1.1: Memo on experimental design
2.1.3: Quarterly Report
2.2.1: VIII International Conference on Forest Fire Research (presentation and paper)
2.2.2: Paper submitted for approval
2.2.3: Quarterly Report
2.3.1: Selection of case fires and selection of fire behaviour simulator
2.3.2: Quarterly Report
2.4.1: Poster for BNHCRC Conference
2.4.4: Quarterly Report, Annual Report, Self Assessment Matrix

UTILISATION AND IMPACT

SUMMARY

This project examined the prioritisation of extreme fire behviours, produced a model for the forecasting of crown fire potential at hourly to daily scales and a new method to test fire performance of structural materials.

PRIORITISATION OF EXTREME FIRE BEHAVIOURS

Output Description

We found that extreme fire behaviours (EFBs) occur frequently in fires greater than 1000ha and often with multiple EFBs per fire. Our survey indicated that Spotting, Crown fires, PyroEvs, Eruptive fires and Conflagrations are the most commonly observed EFBs, and so these should be the highest priority in determining which EFBs to research for inclusion in fire models. All the EFBs considered can take place in any landscape.

Extent of Use

- National and international level.

Utilisation Potential

- The EFBs that are common and have substantial impacts on fire behaviour should be prioritised for the development of models so that their physical processes can be understood and so they can be predicted for operational fire management purposes.

Utilisation Impact

- Improved prediction of fire front propagation and related risks.

Utilisation and Impact Evidence

- **Alex Filkov, Tom Duff, Trent Penman** (2018) Extreme fire behaviours: Surveying fire management staff to determine behaviour frequencies and importance, AFAC18, Sydney. https://www.bnhcrc.com.au/sites/default/files/managed/downloads/369id15._trent_penman.pdf

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

Output Description

As weather variables can be forecast into the future, Random Forest predictions could be used to forecast the likelihood of crown fire runs while fires are occurring. In the study area, potential fire runs could be forecast at an hourly temporal resolution for up to 7 days into the future.

Extent of Use

- National and international level.

Utilisation Potential

- Modelling could provide managers with a rapid means of assessing the likely 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 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. New structural materials provided by Industrial partners (TBS Australia and Fairview) have been tested.

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

- **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.

NEXT STEPS

- Development of guidelines for identifying environmental conditions causing the extreme fire behaviour phenomena during operational fire behaviour analysis.
- Development of quick-reference materials for operational guidance.

PUBLICATIONS LIST

Articles

- **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 (**IF=1.51**, 134 downloads)
- **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
- Kasymov DP, Agafontsev MV, Fateev VN, Reyno VV, **Filkov A** (2018) Critical conditions for the ignition of cedar needle fuel bed as a result of firebrands accumulation // Advances in Forest Fire Research. Book chapter. Coimbra: Imprensa da Universidade de Coimbra, Pp. 1340-1342. http://dx.doi.org/10.14195/978-989-26-16-506_173
- **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
- **Alex Filkov, Tom Duff, Trent Penman** (2018) Extreme fire behaviours: Surveying fire management staff to determine behaviour frequencies and importance, AFAC18, Sydney. https://www.bnhcrc.com.au/sites/default/files/managed/downloads/369id15._trent_penman.pdf

Abstracts

1. **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.

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