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DETERMINING THRESHOLD CONDITIONS FOR EXTREME FIRE BEHAVIOUR: INTERIM REPORT DESCRIBING OUTCOMES FROM PHASE 1 OF THE PROJECT

Annual Project Report 2017-2018

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EXECUTIVE SUMMARY

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Extreme fires cause disproportionate impacts on the environment and the community. There are significant incentives to being able to predict their occurrence and behaviour. Most existing fire behaviour models have been developed based on data and observations of fires that were small to moderate in size. Consequently, they are not able to emulate the dynamic bushfire behaviour that can occur under extreme conditions.

The main aim of this project is to investigate the conditions and processes under which bushfire behaviour undergoes major transitions, including fire convection and plume dynamics, evaluating the consequences of eruptive fire behaviour (spotting events, convection driven wind damage, rapid fire spread) and determining the combination of conditions for such behaviours to occur (e.g. unstable atmosphere, fuel properties and weather conditions). To do this the project was separated into two phases. The first phase of the project was focused on data collection about extreme fires, analysis the frequency of occurrence of extreme fire phenomena and determination the potential of including them in fire behaviour models.

Two major research projects have been conducted in the first phase. The first project lead to the development of a recommended list of data for routine collection during bushfires (Filkov *et al.* 2018). In this work, we have also proposed standards for data collection from bushfire events to enhance the advancement of fire behaviour research and make research findings more internationally relevant. The second project was a survey of fire management staff to examine the frequency of extreme fire behaviours. Analysis of the surveys showed that further research should be focused on the most common phenomena; Spotting, Crown fires, PyroCb, Eruptive fires and Conflagrations. Spotting, Crown Fires and PyroCb are responsible for 68 % of all extreme fire behaviours observed, and there is evidence that they interact with each other. These for fire simulation models to be robust, understanding how to incorporate these phenomena is likely to be important.

END USER STATEMENT

Dr. Simon Heemstra, *Manager Planning and Predictive Services, NSW Rural Fire Service*

The first phase of the project has delivered a number of achievements. It has compiled a national dataset of significant fires; quantified the inconsistency around data collection across the country; suggested a schema to be considered for future data collection (to address that inconsistency); undertaken an analysis of the frequency of fires with 'eruptive fire behaviours' (EFBs); and identified the frequency of individual types of EFBs. This phase of the project has also looked into the determinants of crown fire runs, with the results providing a potential basis for predictive modelling – potentially, a spatial 'crown fire risk forecast', which if developed would have a clear path to utilisation via incorporation into existing fire-weather explorer tools.

INTRODUCTION

Bushfires can result in substantial social, economic and environmental impacts and recovery activities may take many years. Fires in Australia have resulted in mass house loss in Victoria in 2009 (Cruz *et al.* 2012), Western Australia in 2011 and New South Wales and Tasmania in 2013 (Kepert *et al.* 2013). The total annual economic cost of bushfires in Victoria is estimated to be approximately 180 million Australian dollars (Hughes and Alexander 2017). These costs have been forecast to double over the next 40 years (Deloitte Access Economics 2014). Consequently, It is important to develop strategies that are able to reduce the risk of loss and thereby decrease the economic and social impacts of bushfire.

Fire simulation systems have been developed as part of management decision support systems and are vital tools for supporting decision makers to reduce risks to people and property (Finney 2004; Garcia *et al.* 2008; Tolhurst *et al.* 2008; Miller *et al.* 2015). However, most of these simulation tools are based on empirical fire forward rate of spread (FROS) models and do not emulate physical processes. Existing empirical FROS models were predominantly developed using observations of experimental fires burning in conditions that allow the fires to be safely managed. As a result, data representing the conditions under which damaging bushfires occur were rarely included. Indeed, current operational fire spread models assume that fires burn at an approximately constant (quasi-steady) rate of spread under a specific set of environmental conditions (e.g. Rothermel (Rothermel 1972), Canadian FBP system (Van Nest and Alexander 1999), VESTA (Gould *et al.* 2008), CSIRO Grassland fire behaviour model (Cruz and Gould 2009)). However; under extreme weather conditions, there are emergent forms of fire behaviour that can rapidly change fire progression and intensity, including phenomena such as plume dominated spread and mass spotting events (Viegas *et al.* 2009). Consequently, simulation tools that solely utilise FROS models for their spread calculations are not able to emulate these dynamic bushfire behaviours.

Fire behaviour and management research cannot develop fully without better quantification of the various fire behaviour phenomena that occur under moderate and extreme weather conditions. To do so requires comprehensive and accurate data. Experimental research into intense fire behaviour cannot be undertaken as these fires cannot be safely managed; as a result alternative sources of data are required and the only opportunity to collect information about fires under moderate and extreme conditions is to collect observations at bushfires as they occur. Case-study fires are commonly used in research (Martin *et al.* 2009; Tutsch *et al.* 2010; Cruz *et al.* 2012) however, the data is usually collated from various sources post event, hence data availability and quality is highly variable. There is currently no formal procedure for ensuring the data collected during and post-fire is appropriate for meeting research requirements.

Moreover, there is no quantitative research describing the frequency of Extreme Fire Behaviours (EFBs). 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 they can be predicted for operational fire management purposes. The factors that result in different EFBs and the consequences of these cannot be statistically analysed without replications of observations from wildfires, as they will are likely to be a complex functions of many parameters, such as weather, terrain and the fire itself. To understand the importance of EFBs in fire behaviour, we initially need to understand how frequently they occur in order to prioritise future research effort. Without new data regarding bushfire behaviour, fire research, the future development of fire simulation tools and the associated decision support systems will be unable to improve significantly.

To do so, the first phase of the project was devoted to the development of data collection methodology about extreme fires, analysis the frequency of occurrence of extreme fire phenomena and determination the potential of including them in fire behaviour models.

RESEARCH APPROACH

STANDARDISING DATA OBTAINED FROM BUSHFIRES

This section is based on the paper prepared and published during the first phase of the project: Alexander Filkov, Thomas J. Duff, Trent D. Penman Improving Fire Behaviour Data Obtained from Wildfires (2018) Forests, 9, 81; doi:10.3390/f9020081 (Q1, H22, Scimago Journal & Country Rank).

Data collection in Australia

Australia is a diverse continent with ecosystems ranging from tropical rainforests through to desert environments. Fires occur at varying intervals and intensities across the country (Murphy *et al*. 2013). Land and fire management is the responsibility of state-level governments (which include are six states and two territories). The industry body AFAC (The Australasian Fire and Emergency Service Authorities Council) endeavours to bring together fire and land management agencies across Australia and New Zealand to provide a co-ordinated response to fire and emergency management. To date, there has been no national policy developed focused on data collection and management during fires.

To understand what data are collected during bushfires, we approached representatives from all fire and land management agencies in Australia (Table 1). Representatives of state agencies were contacted via email and telephone and asked to complete a guided survey. There were multiple agencies from each state as fire management responsibilities are typically divided by land tenure. Specifically, we asked:

- What information is collected and stored during fires?;
- How frequently are the data is collected?; and
- Does this information collection vary between fires under different conditions?

Responses were received from Australian Capital Territory (ACT), New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA) and Western Australia (WA) (Table 1). No responses were received from Tasmania (TAS) and the Northern Territory (NT). Where multiple agencies responded from the same state, if at least one of the agencies in the state collects a certain type of data the attribute was considered ‘collected’ by the state.

State or Territory	Agency
ACT	Parks and Conservation Service
	Rural Fire Service (RFS)
NSW	National Parks and Wildlife Service
	Rural Fire Service (RFS)
NT	Darwin Centre for Bushfire Research
	Bushfires NT
QLD	Queensland Parks and Wildlife Service
	Queensland Fire and Emergency Services (FES)
SA	Department of Environment, Water and Natural Resources (DEWNR)
	Country Fire Service (CFS)
TAS	Forestry Tasmania
	Tasmania Fire Service
VIC	Country Fire Authority (CFA)
	Department of Environment, Land, Water and Planning (DEWLP)
WA	Department of Parks and Wildlife (DPAW)

TABLE 1. LIST OF FIRE MANAGEMENT AGENCIES IN AUSTRALIA THAT WERE APPROACHED IN RELATION TO THE COLLECTION OF DATA DURING FIRES

As fires are complex events and there are many sources of data, in the surveys we classified fire data into broad groups (Table 2).

Data type	Definition
Incident type	The level of Incident Scale as determined by the AIIMS/ICS system*
GPS tracks	Global Positioning System records recorded by transponders mounted on firefighting vehicles. This may include ground based vehicles or aircrafts
Suppression strategies	Details pertaining to the methods and strategies of firefighting used
Containment	Details relating to the effectiveness of fire containment lines at different times during the fire
Final perimeters	Maps or surveys of the final burned area
Ignition point/points	Details about where the fire started
Situation reports	During a fire, firefighting agencies routinely report on the status of the fire (including fire behaviour and area affected).
Fire behaviour observations	Information from firefighters and ground observers recorded
Private property losses	The losses of private property (e.g. houses, fences)
Local weather observations	Information recorded at or near the fire using portable weather stations
Urban infrastructure	Details relating to infrastructure impacted by the fire
Response structures	Details relating to the command and coordination of the fire suppression effort
Fuel condition	Observations relating to the condition of the fuel at the fire, including the nature and whether there is evidence of prior fires
Weather radar	Data collected by the Australian Bureau of Meteorology rain radar illustrating the nature of fire smoke plumes
Progression isochrones	Archives of maps created at different times during the fire as part of firefighting efforts
Post fire impacts	Details in relation to fire impacts to values at large
Satellite images	Satellite images from around the time of the fire (include before, during and after)
FLIR	Images and video from low altitude aircraft mounted FLIR (Forward looking infrared) cameras**
Linescans	Images from high altitude aircraft mounted Infrared linescan systems***

TABLE 2. CATEGORIES AND DEFINITIONS USED IN FIRE DATA COLLECTION SURVEYS

*AIIMS IS THE AUSTRALASIAN INTER-SERVICE INCIDENT MANAGEMENT SYSTEM (Australasian Fire and Emergency Services Authorities Council 2013). THE CORE OF THE AIIMS IS THE INCIDENT CONTROL SYSTEM (ICS) THAT AIMS TO PROVIDE AN INTEGRATED STRUCTURE TO MANAGE THE RESPONSE TO ANY EMERGENCY INCIDENT THAT CAN BE USED BY ANY ORGANISATION INVOLVED IN THE RESPONSE.

**FLIR CAMERAS ARE ELECTRO-OPTICAL THERMAL IMAGING DEVICES THAT DETECT HEAT AND PROVIDE A VISUAL REPRESENTATION OF SMALL PARTS OF A FIRE.

***INFRARED LINESCAN SYSTEM IS A PASSIVE AIRBORNE INFRARED RECORDING SYSTEM, WHICH SCANS ACROSS THE GROUND BENEATH THE FLIGHTPATH, ADDING SUCCESSIVE LINES TO THE RECORD AS THE AIRCRAFT ADVANCES ALONG THE FLIGHT PATH.

The responses in relation to the fire data were broken into three categories relating to incident size as determined by the AIIMS/ICS system:

- Small fire (Level 1) – characterised by being able to be controlled through local or initial response resources within a few hours of notification;
- Medium fire (Level 2) – are more complex either in size, resources, risk or community impact. May require interagency response;
- Large fire (Level 3) – are protracted, large and resource intensive. They may affect community assets and/or public infrastructure, and attract significant community, media and political interest.

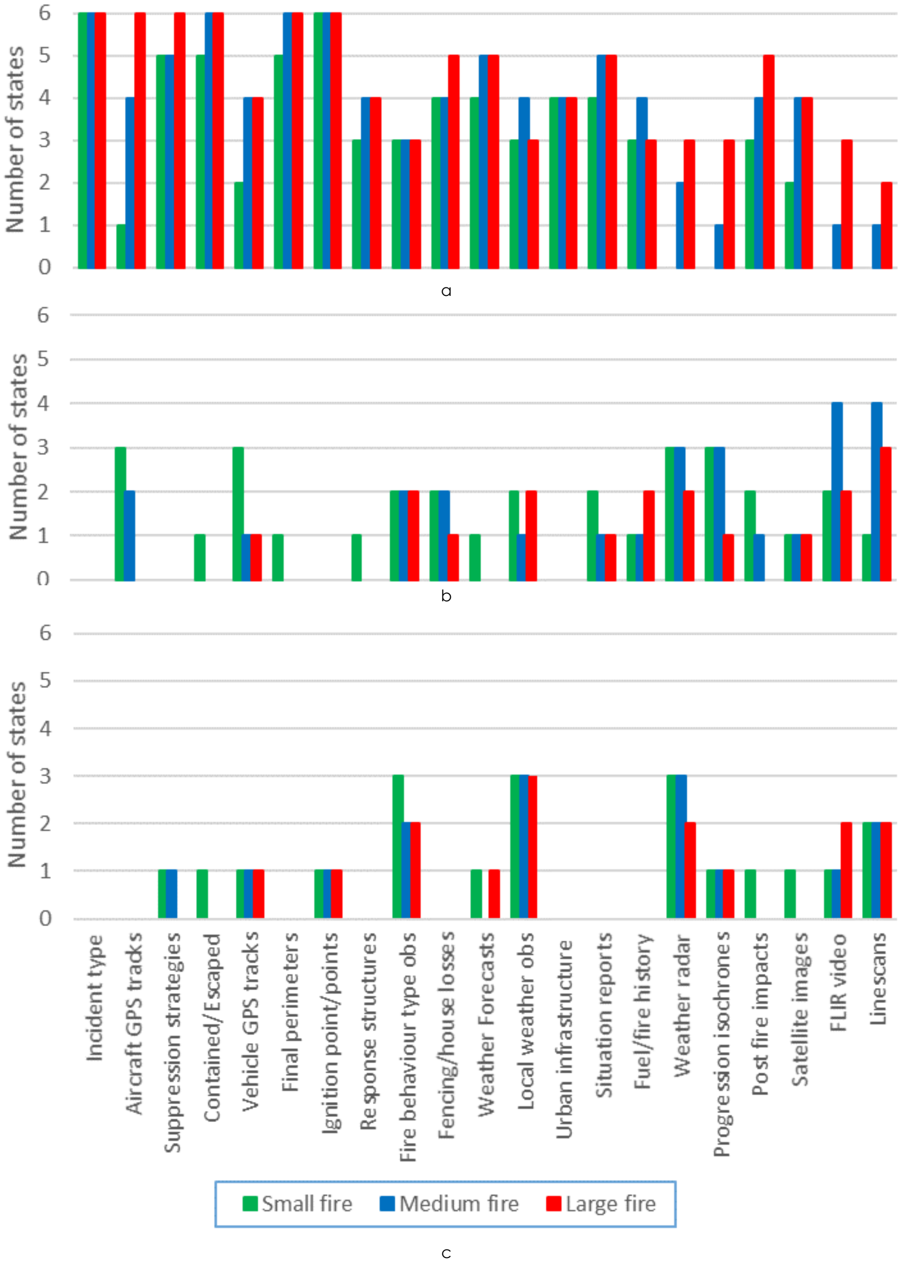

FIG. 1. RESPONSES FROM FIRE AND LAND MANAGEMENT AGENCIES IN AUSTRALIA. CLUSTERED COLUMNS SHOW THE NUMBER OF STATES, WHICH COLLECT SPECIFIC DATA TYPE ROUTINELY (A), OCCASIONALLY (B) OR SHOULD COLLECT ROUTINELY (C). THE RESPONSES ARE GIVEN FOR SMALL (GREEN), MEDIUM (BLUE) AND LARGE (RED) FIRES.

We found that the amount of information collected increases with increasing fire size (Figure 1). Basic information that is simple to collect such as ignition location, incident type and final perimeters are recorded by at least one agency in all states. Data types that are more complex to collect (such as fire perimeters) or have technological requirements (such as FLIR) are collected in fewer states. This is due in part to the differing technical capabilities of the states (for example, some states lack of aircraft with linescan and infrared equipment). There more detailed quantitative data (which is important for conduction analysis of fire behaviour) such as weather radar, progression isochrones, FLIR video, linescans, are generally only collected occasionally (Figure 1b). Apart from fire sizes, it is unclear what stimulates the collection of such data. If these data are only collected from fires of a specific nature, it may result in biases that affect analysis and interpretation of the frequency of extreme fire behaviour.

When asked what kind of data should be collected routinely in the future, almost all interviewees noted that for all groups of fires it would be ideal to start recording fire behaviour type, weather radar and local weather (Figure 1c). From our surveys, we also identified that there is a high degree of variation in the way data is curated. While we were unable to conduct quantitative analysis, it is evident that stored in a variety of ways (e.g. hard copies, local servers, online data repositories). Databases are not shared between states and rarely between agencies within the same state, and information storage is not centralised; i.e. different categories of fire data may be stored in different systems or at different physical locations. For example, in South Australia data is stored in an Incident database, logbooks, a fire behaviour analyst server, a Corporate GIS database, the Critical Resource Incident Information Management System Online Network (CRIIMSON), the SA Computer Aided Dispatch (SACAD) system, the Australasian Incident Reporting System (AIRS), and Incident Management Teams reports (IMTs). For access to each data source, separate permissions are typically required. Even if data is of high quality and correctly scoped, difficulty in access may hinder fire behaviour science.

Innovation in data collection

The management of information during active bushfires is an undoubtable challenge to managers. However, with recent technological developments, it is likely to become simpler to collect some information. There are a wide range of methods that have been developed in the research space that have not yet been adapted for operational use by fire management agencies. Research will always produce more methods than agencies will adopt, however methods that can be demonstrated to efficiently provide meaningful data are likely to be considered. For a new method to be adopted ideally there will need to be 1) a tangible immediate benefit to the agency utilising it and 2) a long term benefit to the agency through improved decision support as a result of research outputs. Researchers and agencies need to work more closely to identify such methodologies and develop strategies for data collection that ensure the quality of the data recorded while minimising cost and disruption to the agencies. In this section, we review a number of recent innovations that have the potential to assist with both management and science. Some of these are already in use in parts of Australia.

Perhaps the greatest recent advancement in fire behaviour research is data derived from remote sensing before, during and after the fire. Remotely sensed data give researchers a means to quantify patterns of variation in space and time. The utility of these data depends on the scale of application. Satellites and aircraft are the main sources of these data. Multi-temporal remote sensing techniques based on space and airborne sensors have been effectively employed to assess and monitor landscape change in a rapid and cost-effective manner (Matvienko *et al.* 2011; Hally *et al.* 2016). Remotely sensed data have been used to detect active fires (Scholes *et al.* 1996; Holden *et al.* 2005; Sertel and Alganci 2015; Linke *et al.* 2017); map fire extents (Schmidt *et al.* 2016; Zhou *et al.* 2016); estimate surface and crown fuel loading (Smith and Wooster 2005; Dennison *et al.* 2006; Barrett *et al.* 2016); assess active fire behaviour (Jones *et al.* 2013; Di-Mauro *et al.* 2014) and examine post-fire vegetation response (Keeley 2009).

One of the more developed remote sensing approaches is the mapping of metrics that can be used to derive fire severity. Fire severity is a retrospective measure of the environmental impact of a fire (Cocke *et al.* 2005; Picotte and Robertson 2011). Such approaches include assessing changes in indices such as Normalized Burn Ratio (dNBR) (Rouse *et al.* 1973; Coban and Ozdamar 2014; Chang *et al.* 2016), and the Normalized Difference Vegetation Index (NDVI) (Bradstock *et al.* 2010; Collins *et al.* 2014; Holsinger *et al.* 2016; Chu *et al.* 2017). Severity maps can be used to determine the relative importance of factors including fuels, weather, terrain and disturbance history to fire post event (Briz *et al.* 2003; Veraverbeke *et al.* 2012; Polivka *et al.* 2016). Recording the sequence of satellite derived metrics over time can provide valuable data to understand a range of issues such as fuel accumulation, ecological responses and vegetation change. A fire severity map can also be used as a detailed map of the burned area and an indirect measure of fire behaviour.

Fire behaviour and measures of the fuel consumed have been quantified through the analysis of thermal infrared imagery (Billing 1986). Infrared (IR) sensors and Infrared Line Scanning Systems on aircraft allow land managers to detect actively burning areas, spot fires, estimate the energy radiated from the fire as it burns and to analyse fire behaviour. These approaches allow for the determination of key parameters of the fire, such as intensity, size, rate of spread, hazards and other factors relevant to suppression activities and logistics. Line Scanning Systems have been used for many years for fire mapping for firefighting purposes (Johnston *et al.* 2014). However, to-date the systematic use of them to collect fire behaviour data has been limited. When routinely collected, progression isochrones will significantly simplify the process of fire reconstruction and improve fire simulation tool validation. Mapped data will also provide an understanding of how spatial processes like climate, topography, and vegetation dynamics influence fire behaviour and regimes. Combining these data with information on fire behaviour type and evidence of "unusual" behaviour, such as extreme fire behaviour, is vital. Routinely collecting information about fire intensity, fire front depth, spotting ignitions and "unusual" fire behaviour will help to better understand fire behaviour and improve operational and physical models.

Another system in operational use for firefighting that has had limited adoption for systematic data collection is the use of low altitude IR fire observation. Operationally in Australia, aircraft use a single IR sensor which can detect fire fronts or hot spots and firebrands but not both. Most imaging techniques intended to detect the heat signature of fire are based on MWIR (Medium Wavelength Infrared) and TIR (Thermal Infrared) sensors (Schroeder *et al.* 2014). Using a single IR sensor is problematic as the signal varies with emissivity, there is considerable incident energy and only a small fraction of the pixels may correspond to the fire. Using multi-spectral methods can solve of this problem. For example, in the USA the airborne fire data gathering derived from multi-spectral data acquired by autonomous modular line-scanner sensors (AMS) operating in shortwave (SWIR), MWIR and LWIR spectral regions and providing enhanced dynamic range in support of active fire imaging (Schroeder *et al.* 2014). Using also a multispectral approach the fire radiative power, fire fractional area and temperature estimates can be estimated (Dirksen *et al.* 2009; Amiridis *et al.* 2010; Raffuse *et al.* 2012). Furthermore such systems can view through smoke, allowing the nature of ember generation and transport to be observed.

A relatively recent set of methods used in research but not yet in operational fire management is the 3D visualisation and measurement of bushfire smoke plumes and the atmosphere using LIDAR (LIght Detection And Ranging), SODAR (SOnic

Detection And Ranging) and RADAR (RAdio Detection And Ranging). These methods extract vertical profiles of the smoke plumes and also record the movement of winds and hot gases from the fire. Such information is critical for scientists to understand fire behaviour – in particular, the rapid acceleration that occurs with some fires as they become large. Understanding the intensity and evolution of convective plumes is critical in the understanding of lofting and spotting of embers, where plume structure begins to play an important role in how the embers are spatially distributed. A number of studies have also characterised smoke plume behaviour using information derived from satellite data (Banta *et al.* 1992; Kovalev *et al.* 2009; Lareau and Clements 2016). Information on smoke-plume heights and their dynamics and these data will allow for improvements in smoke dispersion and air quality models (Hufford *et al.* 1998; Chong *et al.* 2012; Saraiva *et al.* 2014; McCarthy *et al.* 2016).

Weather RADAR (Banta *et al.* 1992; Kovalev *et al.* 2009; Lareau and Clements 2016) and LIDAR (Zhang *et al.* 2016) have also been used for visualizing active fires in context of dynamic broad scale weather events, understanding plume formation and estimation of it characteristics. As weather RADARs are maintained over large parts of Australia for rain monitoring, they have very broad coverage and scan at a high frequency. Extreme fire weather features like sudden wind changes, the escalation of a plume into a pyrocumulonimbus (PyroCb) (or Cumulonimbus Flammagenitus (CbFg) according to the new International Cloud Atlas, https://cloudatlas.wmo.int) or the advent of dry thunder storms and associated lightning are all important events to be considered during a major bushfire event but are rarely captured using existing methods. Ground-based scanning systems such as RADAR can be considerate an important auxiliary tool for detecting unauthorized burning and forest fires, adding significant value to the information for decision-making in monitoring, detecting and suppressing bushfires. An advantage of using weather RADAR to analyse fire is that the network is already in place and maintained for another purpose. Consequently, barriers to its adoption are low.

Remote sensing methods have provided a major step forward in data collection and understanding fire behaviour. Methods for collecting these data are also under constant development. Two major areas are worth highlighting. Firstly, as new satellites are launched the quality and quantity of data available will increase. In Australia, research and management have both used the Advanced Very High Resolution Radiometer (AVHRR) imagery and the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra (1999) and Aqua (2002) (Ambrosia *et al.* 2011; Wing *et al.* 2013; Shahbazi *et al.* 2014). The launch of the Japan Meteorological Agency (JMA) Himawari-8 satellite, with the 16-band Advanced Himawari Imager (AHI-8) onboard in October 2014 presents a significant opportunity to improve the timeliness of satellite fire detection across Australia. The near real-time availability of images, at a ten minute frequency, may also provide contextual information (background temperature) leading to improvements in the assessment of fire characteristics (Hally et al. 2016). Secondly, unmanned aerial vehicles (UAVs) as remote sensing platforms have the great potential to increase the efficiency of data acquisition, but their applications are still at an experimental stage (Werth *et al.* 2011, 2016; Viegas 2012). UAV remote sensing has low material and operational costs, flexible control of spatial and temporal resolution, high-intensity data collection, and a reduction of risk to crews. As the complexity of UAV and sensors increase, so will our ability to capture high resolution spatial data at bushfires. An additional advantage is that they can be used in conditions that would be hazardous to human health; particularly around fast moving fires or where there is unstable weather.

While there are a wide range of sources of information in relation to fires, as a starting point we recommend a focus on particular categories (Table 3). These categories are those that will provide the greatest information in relation to all types of fire behaviour, but particularly extreme fire behaviour – the phenomena that only occur at large scales and under severe conditions that cannot be safely replicated experimentally. As extreme fires are those that are most damaging to society, improved knowledge in relation to them are likely to have the greatest dividends to improved management.

Data category	Data types	Protocol	Research outputs
Ground observations and operational information	▪ Building column ▪ Extreme fire behaviour ▪ Plume colour ▪ Wind entrainment ▪ Blocking plume ▪ Channelling ▪ Asset impact/losses ▪ Ignition point/points ▪ Fuel/fire history ▪ Ground weather observations	▪ Having an online system for noting significant events ▪ Periodic on-ground observations of weather ▪ Standardised data collection procedures for every data type to reduce dependence on the observer. E.g. for convective column: colour, height, sudden size/colour changes, tilt, PyroCb, downdraft, wind direction change.	▪ Understanding fire behaviour and fire-atmosphere interactions under regular/extreme conditions
Linescans	▪ Linescan images	▪ Clear metadata on linescan flights ▪ Repeated linescans of fires every 30-60 minutes minimum ▪ A focus on active parts of fires and expected fire behaviour changes ▪ Using simultaneously multispectral sensors in both MWIR and TIR(LWIR) bands	▪ Fire intensity ▪ Flame depth ▪ Rate of spread ▪ Fire perimeter ▪ Flaming/smouldering combustion ▪ Hot spots
Forward Looking IR	▪ IR/visual video and images ▪ Progression isochrones	▪ An online/digital documented process ▪ Every video and footage must have time and location ▪ Using simultaneously three sensors in MWIR, TIR(LWIR) and visual ranges ▪ Post processing of these data using specific algorithms ▪ Flight plan ▪ Targeting of spot fires ahead of moving fire fronts ▪ Opportunistic IR measurements/Guidelines on what to look for ▪ Recording of operator observations	▪ Real time fire dynamics ▪ Ember transport and ignition ▪ Suppression methodologies ▪ Actively burning areas ▪ Spot fires ▪ Energy radiated from the fire ▪ Fire intensity ▪ Flame depth ▪ Rate of spread ▪ Surface temperature ▪ Models validation
Aerial observers	▪ Atmospheric profile ▪ Plume characteristics ▪ Changes in fireground conditions	▪ Standardised data collection procedures to reduce dependence on the observer ▪ Geolocation and time stamping imagery and digitally recording times and places of noteworthy fire behaviour ▪ Weather observation	▪ Understanding fire behaviour and fire-atmosphere interactions under regular/extreme conditions

Data category	Data types	Protocol	Research outputs
Satellites	▪ Satellite images ▪ Fire severity maps	▪ Procedure to adopt active sensors during fires ▪ System to identify and store data from satellites recording over fire areas as fires occur	▪ Fire intensity ▪ Flame depth ▪ Rate of spread ▪ Surface temperature ▪ Fire radiative power ▪ Char and ash cover ▪ Area burned ▪ Fire perimeter ▪ Flaming/smouldering combustion ▪ Smoke plume ▪ Plume injection heights ▪ Hot spots ▪ Atmospheric chemistry changes
Remote weather observations	▪ Meteorological parameters ▪ Radar data	▪ Having an online system to store data	▪ Visualization of active fires ▪ Detection of dynamic effects
Unmanned Aerial Vehicle	▪ Local weather characteristics ▪ IR/visual video and images ▪ Lidar data	▪ Development and implementation of regulations to use UAVs during fires.	▪ Mapping canopy gaps and height ▪ Tracking fires ▪ Supporting intensive forest management ▪ Fire intensity ▪ Flame depth ▪ Rate of spread ▪ Hot spots/Spotting ▪ Real time fire dynamics ▪ Ember transport and ignition ▪ Suppression methodologies
Vehicle/aircraft GPS tracks and suppression strategies	▪ Aerial and ground GPS tracks ▪ Time of the water drop/suppression ▪ Vehicle type and fire size class	▪ Having an online system for data recording	▪ Optimisation suppression activities and strategy

TABLE 3. LIST OF RECOMMENDED DATA AND PROTOCOLS FOR ROUTINELY COLLECTION USING CURRENT TECHNOLOGIES.

Any system or set of measures must be accompanied by the development of a robust data storage system. The development of systems to recognise, tag, store and share fire related information could greatly reduce data discoverability issues for research and governmental inquires. Much of the information currently gathered during a fire by a fire management agency is stored in some form, however only a small proportion is centralised and can be easily accessed. A centralised and/or standardised data storage approach would streamline this process and result in better management and research outcomes. Furthermore, consistency in data storage and management should result in improved data sharing between fire management agencies and from a research perspective this should allow for more comprehensive datasets to be developed increasing the application of research results.

Summary

Land and emergency response organisations are increasingly being expected to deliver scientifically defensible decisions and to demonstrate continuous improvement in management and resource use. The limited availability of high quality data on bushfire behaviour restricts the rate at which research can advance particularly on the most damaging fires that occur. It is imperative that the losses caused by severe fires are not in vain; losses should be offset by efforts to maximise the information obtained, helping to prevent a repeat of such events in the future. Improvement of data collection will facilitate providing leverage on data collected and allow robust conclusions to be reached sooner and with less expense. This would include improving systems and processes in use today, as well as considering new technologies than can help information to be collected more efficiently. To be successful, this must be in a form of partnership between researchers and fire agencies, and ideally with a coordinated approach that standardises methods, technologies and approaches Australia wide.

FREQUENCY OF EXTREME FIRE BEHAVIOURS IN FORESTED ENVIRONMENTS

This section is based on the paper prepared during the project and submitted for review to the International Journal of Wildland Fire: Alexander Filkov, Thomas J. Duff, Trent D. Penman Frequency of extreme fire behaviours in forested environments.

Data collection in Australia

Extreme fire behaviours (EFBs) are physical phenomena which occur within extreme fires (Werth *et al.* 2011, 2016; Viegas 2012). Definitional issues are present for both extreme fires and EFBs. Tedim *et al*. (2018) proposed the term *extreme fire event* instead of *extreme fire*. Based on comprehensive literature review the authors described extreme fire event as a combination of EFBs and the consequences of them. However, they considered only limited number of EFBs. At the moment, there are no standardised definitions for EFBs (Werth *et al.* 2011, 2016; Viegas 2012; Sharples *et al.* 2016; Bowman *et al.* 2017). EFBs are physical phenomena of fire behaviour that may occur when fires burn under specific conditions. These have the potential to be identified, described and modelled. In general, extreme fires can involve one to several EFBs simultaneously (Cruz *et al.* 2012; Tedim *et al.* 2018). Viegas (Viegas 2012) described EFB as "a set of situations that are more like manifestations or forms of extreme fire behaviour rather than one particular form of fire behaviour". It means that EFB is not a single process or event, but a combination of different phenomena. This definition is used in this work.

A number of recent studies have been devoted to describing the processes behind particular EFBs (Viegas and Simeoni 2011; Fox and Whitesides 2015; BNHCRC 2016). However, there is no quantitative research describing the frequency of EFBs. 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 they can be predicted for operational fire management purposes. The factors that result in different EFBs and the consequences of these cannot be statistically analysed without replications of observations from wildfires, as they are likely to be a complex functions of many parameters, such as weather, terrain and the fire itself. To understand the importance of EFBs in fire behaviour, we initially need to understand how frequently they occur in order to prioritise future research efforts.

We used an expert elicitation approach to determine the frequency of occurrence of nine recognised extreme fire behaviours: Spotting, Crown fires, Pyro-convective events (PyroEvs), Eruptive fires, Conflagrations, Jump fires, Fire tornados/whirls, Fire channelling and Downbursts.

Methods

EFBs have been reported to be a feature of extreme fires. To collect data on these, we considered all fires greater than 1,000 ha in Australia that occurred between 2006 and 2016. We approached representatives from management agencies responsible for fire response in each state) via email and telephone and asked them to complete a guided survey. For each fire, we asked which (if any) EFBs had been observed (see below) and what data there may be to support this. Data were categorised into three types: direct measurements (linescans, images, video, etc.), indirect data (weather records, etc.) and the data based on anecdotal evidence (observations recorded in situation reports, etc.).

The surveys divided EFBs into 9 different types:

1. Spotting. Spotting is a "behaviour of a fire producing firebrands or embers that are carried by the wind and which start new fires beyond the zone of direct ignition by the main fire" (NWCG 2017).
2. Fire tornados. A fire tornado/whirl is a "spinning vortex column of ascending hot air and gases rising from a fire and carrying aloft smoke, debris, and flame. Fire whirls range in size from less than one foot (0.3 m) to over 500 feet (152 m) in diameter. Large fire whirls have the intensity of a small tornado" (NWCG 2017).
3. Fire channelling. Fire channelling/Lateral vortices is a rapid lateral fire spread across a steep leeward slope in a direction approximately transverse to the background winds, in addition to the usual downwind direction (Sharples *et al.* 2012).
4. Jump fires. Jump fire/Junction zones are associated to the merging of the fire fronts making a small angle between them producing very high rates of spread and with the potential to generate fire whirls and tornadoes (Viegas 2012).
5. Eruptive fires. Eruptive fires are fires that occur usually in canyons or steep slopes and are characterised by a rapid acceleration of the head fire rate of spread (Viegas 2012).
6. Crown fires. "A fire that advances from top to top of trees or shrubs more or less independent of a surface fire." (NWCG 2017).
7. Conflagrations. "Conflagration are raging, destructive fires. Often used to connote such a fire with a moving front as distinguished from a fire storm" (NWCG 2017).
8. Downbursts. Downbursts are downdrafts associated with a Cumulus flammagenitus[1] clouds that induces an outburst of strong winds on or near

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[1] Cumulus flammagenitus is also known by the unofficial, common name, 'pyrocumulus') ('International Cloud Atlas' 2017).

Cumulus (Cu) are detached clouds, generally dense and with sharp outlines, developing vertically in the form of rising mounds, domes or towers, of which the bulging upper part often resembles a cauliflower. The sunlit parts of these clouds are mostly brilliant white; their bases are relatively dark and nearly horizontal ('International Cloud Atlas' 2017).

Flammagenitus (Fg) are clouds that are clearly observed to have originated as a consequence of localized natural heat sources, such as forest fires, wildfires or volcanic activity and which, at least in part, consist of water drops (for example, Cumulus flammagenitus (CuFg) or Cumulonimbus flammagenitus (CbFg)) ('International Cloud Atlas' 2017).

the ground (Haines 2004). These winds spread from the location of the downburns and may result in fire spread into the prevailing wind direction.

9. Pyro-convective events. Pyro-convective event is an extreme manifestation of a flammagenitus cloud, generated by the heat of a wildfire, that often rises to the upper troposphere or lower stratosphere ('International Cloud Atlas' 2017).

All participants in the survey were provided a presentation, which briefly defined the above EFBs. Participants were requested to view the presentation before completing the survey.

All responses were grouped for each fire. Where multiple agencies responded with information for the same fire, the data from the highest quality data type was retained. Obtained data were analysed regarding to frequency of EFBs, quantity of EFBs per fire and confidence level of data.

Results and discussion

Responses were received from New South Wales (NSW), Victoria (VIC), South Australia (SA) and Tasmania (TAS). No responses were received from Australian Capital Territory (ACT), Western Australia (WA), Queensland (QLD), and the Northern Territory (NT). Information on EFBs was received for a total of 96 fires among 934 fires surveyed (~10 %) (Table 4). It should be noted, that it was impossible to accurately calculate the percentage of fires with EFBs, interviewees could only answer for fires that they were familiar with. Therefore, 10 % is likely to be a conservative estimate.

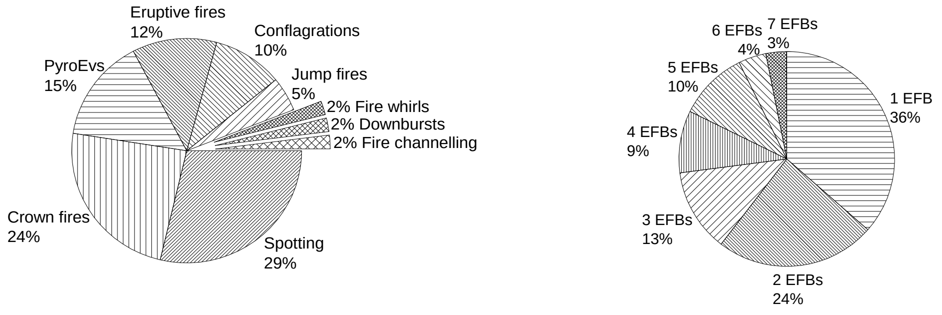
Data type	Spotting	Fire tornado/ whirls	Fire channelling	Jump fires	Eruptive fires	Crown fires	Conflagrations	Downbursts	PyroEvs	Total
Direct	32	3	2	4	13	22	14	2	27	*119*
Indirect	22	0	1	7	13	20	4	2	5	*74*
Anecdotal	18	2	1	1	4	18	6	1	4	*55*
Total	*72*	*5*	*4*	*12*	*30*	*60*	*24*	*5*	*36*	*248*

TABLE 4. EXTREME FIRE BEHAVIOURS. TALLY OF EXTREME FIRES IN DEPENDS ON THE DATA TYPE.

All EFBs were recorded at least four times. with spotting being observed most frequently (72 times). Table 4 shows that the Fire tornado/whirls (n=5), Fire channelling (n=4) and Downburst (n=5) were observed the fewest times.

The relative frequency of various EFBs are presented in Figure 2.

Cumulonimbus (Cb) are heavy and dense cloud, with a considerable vertical extent, in the form of a mountain or huge towers. At least part of its upper portion is usually smooth, or fibrous or striated, and nearly always flattened; this part often spreads out in the shape of an anvil or vast plume ('International Cloud Atlas' 2017).



a

b

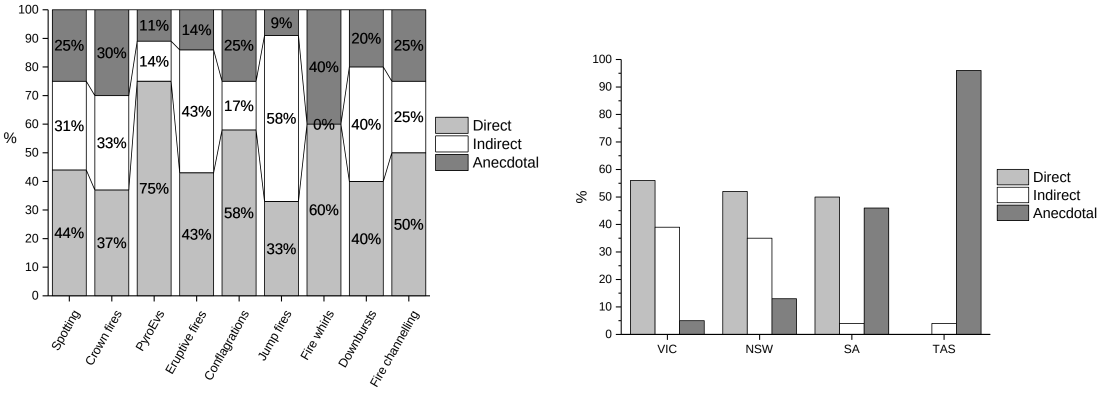
FIG. 2. RELATIVE FREQUENCY OF EFBS. FIGURE 1A SHOWS THE RELATIVE FREQUENCY OF EACH EFB FORM. THE SUM OF ALL EFBS IS 100 %. FIGURE 1B SHOWS PERCENTAGE OF FIRES WITH DIFFERENT QUANTITIES OF DIFFERENT EFBS.

Figure 2a shows the percentage of occurrence of each EFB form per fire. Spotting and Crown fires were the most frequent EFBs, making up a total of 53 % of all EFB observations. PyroEvs, Eruptive fires and Conflagrations were observed to have similar frequencies of occurrence, accounting for 37 % of the remaining observations. Jump fires, Fire tornado/whirls, Fire channelling and Downbursts combined accounted for 11 % of EFBs in total.

The low frequency of last four EFBs may be connected with limited knowledge about them and challenges of identification. For example, Fire channelling was only described in 2012 (Sharples *et al.* 2012). The detection of Downbursts requires local measurements of weather, which, given the sophistication of equipment requred, is rare. Scale effects and the transience of events also could be mean that the frequences of observation do not refelect the frequency of occurence. Some EFBs occur only at large scales, e.g. PyroEvs and Conflagrations. Jump fires and Fire whirls can manifest at smaller scales and may only occur for seconds or minutes. Simetimes, the same EFB can manifest at different scales. E.g. spotting can be classified into three categories, depending on the distance and the distribution density: short distance spot fires (up to 750 m), average distance spot fires (1000-1500 m) and large distance spot fires (> 5000 m) (Cruz *et al.* 2012). All of this makes the identification of EFBs very challenging task.

Spotting, Crown fires, PyroEvs, Eruptive fires and Conflagrations were the most frequent EFBs observed. They can be more easily identified and detected and fire managers are more likely to be familiar with them in contrast to less frequently occuring EFBs. Crown fires have been studed intensively, with several empirical models developed (Cruz *et al.* 2005). More recently, attention has been given to other EFBs; in particular PyroEvs (Peace *et al.* 2016; Peterson *et al.* 2017), Spotting (Martin and Hillen 2016; Thurston *et al.* 2017), Fire chanelling (Sharples *et al.* 2012) and Fire whirls (Forthofer and Goodrick 2011; Potter 2012). Most of these studies are based on CFD or conceptual modelling and results from these can not easily be translated into systems for prediction during fires for operational decision support. To date, Conflagrations and Downbursts have not been included at any physical or operational models.

One third of fires in this study had at least one EFB observed (Figure 2b). Two and more EFBs were recorded in 64 % of these fires. Therefore, their interactions could have complimentary effects on fire behaviour, e.g. PyroEvs can facilitate long distance Spotting and Fire tornados/whirls. Consequently, the potential interactions of these phenomena should be a focus of investigation.



a b

FIG. 3. COMPARISON OF EFBS DISTRIBUTIONS FOR DIFFERENT DATA TYPE (A) AND DATA TYPES AMONG THE STATES (B). THE SUM OF FIRES SUPPORTED BY DIRECT, INDIRECT AND ANECDOTAL DATA FOR EACH EFB IS EQUAL 100 %.

Roughly half of all observations were recorded as direct data; 48 % (average value of all EFBs) (Figure 3a). While indirect and anecdotal data were less common but similar proportions (30 % and 22 % respectively). The highest percentage of EFBs supported with direct data was for PyroEvs, Conflagrations, Fire tornado/whirls and Fire channelling, with direct data in over 50 % of cases. However, due to the limited number of observations for Fire tornado/whirls (5 cases) and Fire channelling (4 cases), these results could be overestimated. The percentage of direct data for all EFBs was always higher then anecdotal data. Despite this, there have been few studies devoted to analysis of EFBs. The number of events where EFBs are supported by direct data indicate that there is potential for future quantitative studies. While the indirect data varied between EFBs, the highest percentage of indirect data is observed for Eruptive fires, Jump fires and Downbursts, (>40 %). As noted above, the small spatial and temporal scales of these EFBs makes it difficult to collect as direct data.

Analysis of data types between the States (Figure 3b) shows that VIC and NSW have similar patterns in the way EFBs are observed, with a high number of total observations and a high proportion of these being in direct data. This is likely to be reflective of the higher frequency of damaging wildfires in these states, which has resulted in a greater investment into infrastructure for fire monitoring. The greater availability of information for these states means that they are potentially suited for the future collection of quantitative data for the robust analysis of EFBs. Such data is important, as while there has been work in emulating the physical processes of EFBs, there has been limited opportunity to confirm these processes with field measured data.

Summary

There is no consensus in the literature on what extreme fire behaviour is and no final list of their forms and agreed definitions. Rather than pursuing semantic arguments, more effort is required to understand, describe and utilize EFBs. We found that EFBs occur frequently in fires greater than 1000 ha and often with multiple EFBs per fire. Fire predictions will be less accurate until these phenomena are considered. 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. The relative commonness of direct evidence available for EFBs is indicative that there should be data available for the development of models.

THE DETERMINANTS OF CROWN FIRE RUNS DURING EXTREME WILDFIRES

This section is based on the paper accepted for presentation at VIII International Conference on Forest Fire Research in Portugal: Alexander I. Filkov, Luke Collins, Anthony Rawlins, Thomas J. Duff, Brett Cirulis, Trent D. Penman The determinants of crown fire runs during extreme wildfires in broadleaf forests in Australia.

Crown fires are a relatively common type of extreme fire behaviour in forest ecosystems, which are characterised by high fire intensities, rapid rates of spread and high release of radiant heat. Consequently, crown fires reduce the likelihood of successful suppression and can threaten human lives through burnovers and entrapments. Crown fires can have negative impacts on some ecosystems services such as biodiversity and water quality.

The occurrence and nature of crown fires has been extensively studied in conifer systems, with a large number of models having been developed (Cruz and Alexander 2013). Crown fires have been found to be a function of crown fuel properties (such as dead fuel moisture content, bulk density and the gap from the surface fuels to the canopy), surface fuel properties, topography and weather conditions (such as wind speed, temperature). Despite its importance, research into crown fire dynamics in the broadleaved Eucalyptus forests of Australia is limited.

Remotely sensed maps of fire severity have been used to study environmental drivers of crown fires occurrence. Fire severity is a retrospective measure of the environmental impact of a fire (Keeley 2009). Severity maps can be used to determine the influence of factors including fuels, weather, terrain and disturbance history on fire severity, as a surrogate of crown fire behaviour. Previous studies examining crown fire occurrence in eucalypt forest have used coarse scale measures of fire weather indices, which combine information on fire weather and moisture availability into one value (Price and Bradstock 2012; Storey et al. 2016). Furthermore, past studies have considered the likelihood of crown fire at a single point (Price and Bradstock 2012; Storey et al. 2016) whereas from a management perspective the prediction of large patches of crown fire, or crown fire runs is desirable as they have larger impacts and are a greater threat to fire suppression activities.

In this study, we use observations from 15 large wildfires that occurred in eucalypt forest in Australia to 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

The study was conducted in forested areas of south-eastern Australia. We focused on fifteen large wildfires that occurred in forest between 2009 and 2015. These fires all have several progression isochrones each day.

Fire severity maps were created for each fire at 30 m resolution using Landsat imagery. We reclassified each pixel as either experiencing crown fire or not. We measured crown fire runs as the proportion of 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, tree height), fire weather (i.e. vapour-pressure deficit, wind speed, relative wind direction) and topography (i.e. slope and ruggedness). We used Random Forests to model the effect of these environmental drivers on (i) crown fire occurrence and (ii) the proportion of pixels experiencing crown fire.

Results and discussion

Results of the modelling showed that fuel moisture and fire weather were most influential in determining crown fire runs, with 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, dead fuel moisture content and wind speed. These all had clearly identified thresholds, below which crown fires rarely occurred. These threshold values for vapour-pressure deficit, dead fuel moisture content and wind speed were 3 kPa, 7 % and 40 km/h respectively. Unsurprisingly, these results highlight greater crown fire activity under warmer and drier conditions. A decrease of dead moisture content of one percent and an increase of vapour-pressure deficit from 3 kPa to 7 kPa led to growth of the proportion of pixels where crown fires occurred by 40 %. An increase of wind speed from 40 km/h to 60 km/h led to 30 % growth in the proportion of area.

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 public engagement.

KEY MILESTONES

1. Annual Report on Project (2015)
2. Annual RAF presentation
3. Appoint postdoctoral fellow (UMelb)
4. Communications plan submitted for review by End User panel
5. Workshop with end users to develop science plan
6. Progress report (including science plan)
7. Data sources identified and described in a project note
8. Database protocols developed and agreed with end-users. Preliminary data sets
9. Project note (describing progress in data collation)
10. Annual Report on Project (2016)
11. Project note (describing preliminary analysis of fire phenomena)
12. Annual RAF presentation
13. Paper submitted for approval (Proceedings of the Combustion Institute)
14. Workshop with end uses on project direction and outcomes
15. Project note (describing progress in database development)
16. Conference presentation of research findings (12th International Symposium on Fire Safety Science)
17. Paper submitted for approval (Fire Safety Journal)
18. Annual Report on Project (2017)
19. Hazard Note (Issue 21)
20. Conference presentation of research findings (AFAC).
21. Showcase 2017 presentation
22. Project note (describing future directions for research)
23. Paper submitted for approval (Forests)
24. Summary document outlining the current status of the fire database being collated, including the number of fires and nature of the data

UTILISATION OUTPUTS

Commercialisation/Utilisation

An unexpected outcome from this part of the project was a set of suggested optimal data collection protocols. During this reporting period an opportunity for end users to investigate the use of the data collection protocols became apparent. It is envisaged that end user representatives will collaboratively explore opportunities to use the protocols for standardising elements of data collection, and that this exploration will commence in the coming quarter.

Education & Training

- Course in Basic Wildfire Awareness (Certificate)
- Course in 4 wheel drive operations (Certificate)
- HLTAID003 Provide first aid (Certificate)
- Bushfire and Climate (FRST90025) laboratory exercises

End User Engagement

A workshop was held on the 20th of May 2016 at the AFAC offices in Melbourne. At the workshop, there were representatives from fire agencies from WA, NSW, ACT, SA, Victoria and Queensland, as well as representatives from BOM and the University of New South Wales. The stakeholders:

- Provided feedback on the proposed research methodology for examining extreme fire behaviour.
- Contributed to the identification of a study set of fires.
- Assisted in the identification of available datasets for the study.
- Agreed to provide large spatial data sets for modelling and analyses.

The outcomes of this workshop were extended through face to face meetings in each of the relevant states. In addition to agency collaboration, Melbourne University has been actively working to develop links to the BOM fire research projects and other BNHCRC researchers.

A second an end-user workshop was held at BNHCRC RAF 2017 in Canberra. It was devoted to discussion of findings and future research plans. Stakeholders provided positive feedback on the proposed research methodology and agreed to provide large spatial data sets for modelling and analyses. Together with key agency stakeholders we identified potential linkages to other projects. List of recommended data and protocols for routinely collection during wildfires was forwarded to NSW RFS.

Opportunities

Thomas Duff undertook an external travel fellowship (funded by the Churchill Trust) to foster international collaboration on research on extreme fire behaviour and rare fire events. This included visiting the University of Athens, undertaking experimental work at the University of Coimbra in Portugal, and working on research methods with the University of Edinburgh and the Missoula Fire lab in the US. Trent Penman met with US Forest Service research staff in Portland Oregon May 2016 to develop future collaborations in fire behaviour and impact research.

Impacts

Alex Filkov presented at Research Advisory Forum, 2016 and 2017; AFAC16 and 17, Brisbane 2016, Sydney 2017; XXth Conference on Conjugate Problems of Mechanics of Reactive Media, Informatics and Ecology, Tomsk, Russia, 2016; 12th International Symposium on Fire Safety Science, Lund, Sweden, 2017; XXXIII Siberian Thermophysical Seminar, Novosibirsk, Russia, 2017; Research Driving Change Showcase 2017, Adelaide 2017.

Project presentation at:

- Forest, Fire and Regions, Horsham
- ACT Parks and Conservation Service, Canberra
- DEWLP, Melbourne
- BOM, DEWNR, Adelaide
- Department of Parks and Wildlife, Manjimup
- UNSW, CSIRO, Canberra

PUBLICATIONS LIST

Articles

1. **Filkov, A.,** Prohanov, S., Mueller, E., Kasymov, D., Martynov, P., Houssami, M.E., Thomas, J., Skowronski, N., Butler, B., Gallagher, M., Clark, K., Mell, W., Kremens, R., Hadden, R.M., Simeoni, A. Investigation of firebrand production during prescribed fires conducted in a pine forest (2017) Proceedings of the Combustion Institute, 36 (2), pp. 3263-3270. DOI: 10.1016/j.proci.2016.06.125 (Q1, H106, Scimago Journal & Country Rank)
2. Fateev, V., Agafontsev, M, Volkov, S, **Filkov, A.** Determination of smoldering time and thermal characteristics of firebrands under laboratory conditions (2017) Fire Safety Journal 91, DOI: 10.1016/j.firesaf.2017.03.080 (Q1, H58, Scimago Journal & Country Rank)
3. Mueller, E.V., N. Skowronski, K. Clark, M. Gallagher, R. Kremens, J.C. Thomas, M. El Houssami, **Alexander Filkov** et al. Utilization of remote sensing techniques for the quantification of fire behavior in two pine stands (2017) Fire Safety Journal 91, doi: 10.1016/j.firesaf.2017.03.076 (Q1, H58, Scimago Journal & Country Rank)
4. Thomas, Jan C., Eric V. Mueller, Simon Santamaria, Michael Gallagher, Mohamad El Houssami, **Alexander Filkov**, Kenneth Clark, et al. Investigation of firebrand generation from an experimental fire: Development of a reliable data collection methodology (2017) Fire Safety Journal 91, 864–871, doi: 10.1016/j.firesaf.2017.04.002 (Q1, H58, Scimago Journal & Country Rank)
5. **Alexander Filkov, Thomas J. Duff, Trent D. Penman** Improving Fire Behaviour Data Obtained from Wildfires (2018) Forests, 9, 81; doi:10.3390/f9020081 (Q1, H22, Scimago Journal & Country Rank)

Hazard Note

6. **Duff T, Penman T, Filkov A** (2016) Threshold conditions for extreme fire behaviour, Hazard Note, ISSUE 21, OCTOBER 2016

Poster

7. **Alex Filkov, Trent Penman, Tom Duff**, Kevin Tolhurst (2016) Determining Threshold Conditions for Extreme Fire Behaviour, AFAC16, Brisbane
8. **Alex Filkov, Trent Penman, Tom Duff** (2017) Gaining benefits from adversity: standardising data obtained from bushfires, AFAC17, Sydney

Submitted

9. An article **Alexander Filkov, Thomas J. Duff, Trent D. Penman** Frequency of extreme fire behaviours in forested environments, International Journal of Wildland Fire
10. A poster "Extreme fire behaviours: Surveying fire management staff to determine behaviour frequencies and importance", AFAC 2018.

CURRENT TEAM MEMBERS

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Project lead End users:
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End users:
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Andrew Sturgess, Qld
Lachie McCaw, WA
Adam Leavesey, ACT
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Jason J. Sharples, UNSW
Jeff Kepert, BOM

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