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Improving Fire Behaviour Data Obtained from Wildfires †

Alexander I. Filkov [1,2,*], Thomas J. Duff [1] and Trent D. Penman [1]

1 School of Ecosystem and Forest Sciences, University of Melbourne, Creswick 3363, Australia; tjduff@unimelb.edu.au (T.J.D.); trent.penman@unimelb.edu.au (T.D.P.)
2 Bushfire and Natural Hazards Cooperative Research Centre, Melbourne 3002, Australia
* Correspondence: alexander.filkov@unimelb.edu.au; Tel.: +61-353-214-198

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Abstract: Organisations that manage wildfires are expected to deliver scientifically defensible decisions. However, the limited availability of high quality data restricts the rate at which research can advance. The nature of wildfires contributes to this: they are infrequent, complex events, occur with limited notice and are of relatively short duration. Some information is typically collected during wildfires, however, it is often of limited quantity and may not be of an appropriate standard for research. Here we argue for a minimum standard of data collection from every wildfire event to enhance the advancement of fire behaviour research and make research findings more internationally relevant. First, we analyse the information routinely collected during fire events across Australia. Secondly, we review research methodologies that may be able to supplement existing data collection. Based on the results of these surveys, we develop a recommended list of variables for routine collection during wildfires. In a research field typified by scarce data, improved data collection standards and methodologies will enhance information quality and allow the advancement in the development of quality science.

Keywords: data collection and management; standard; fire behaviour; research utilization

1. Introduction

Wildfires can result in substantial social, economic and environmental impacts, and recovery activities may take many years. For example, an illegal campfire in California's Garrapata State Park, in July 2016, ignited the most expensive fire in US history, costing more than 250 million US dollars [1] Fires in Australia have resulted in mass house losses in the states of Victoria in 2009 [2] and 2015 [3], Western Australia in 2011, and New South Wales in 2013 [4]. The total annual economic cost of bushfires in Victoria is estimated to be approximately 180 million Australian dollars [5]. These costs have been forecast to double over the next 40 years to $378 million [6]. It is important to develop strategies that are able to reduce the risk of loss and thereby decrease the economic, environmental and social impacts of wildfire.

The occurrence and behavior of fires are driven by complex processes. Wildfires, and their associated management activities, have complex financial, social and environmental impacts. Here, we focus on fire behaviour alone, however recent research indicates [7–9] that there is a need for improved quantitative information and tools in a wide range of management areas. There are a few national or multinational systems [10,11] providing basic fire behaviour information during wildfires, such as fire size, hotspots or burned area. There are individual attempts to improve this situation, predominantly in the collection of data post-fire. For example, the US National Institute of Standards and Technology (NIST) [7] is developing wildland-urban interface (WUI) data collection methodology and first generation tools for improved risk assessment and risk mitigation in WUI communities at risk from wildfires.

Fire simulation systems [8,9,12,13] have been developed as part of management decision support systems and are vital to assessing fire risk to people and property. Most of these simulation tools are based on empirical fire forward rate of spread (FROS) models and do not necessarily emulate physical processes. 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 wildfires 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 [14], Canadian FBP system [15], Cheney et al. [16], CSIRO Grassland fire behaviour model [17]). 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, vortex structures and mass spotting events [18,19]. Consequently, simulation tools that utilise these FROS models are not able to emulate these dynamic wildfire 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 [20]. 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 wildfires as they occur. Case-study fires are commonly used in research [2,21,22]. However, 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 data collected during and post-fire is appropriate for meeting research requirements (consistent, accurate, correct and complete data). Without new data regarding wildfire behaviour, fire research, the future development of fire simulation tools and the associated decision support systems will be unable to improve significantly.

Fire information collected by management agencies varies by jurisdiction and fire size. In small fires, agencies may record simple details such as ignition location [23–26], final fire perimeter and fire area [27]. For large fires that have substantial impacts, data may be extended to include fire severity [28–31], fire progression [32,33] and impact [34–36]. However, much of this information is collected and collated post event. During fires there are many transient fire behaviour phenomena that cannot be easily reconstructed post event. These include spotting/fire storms, fire tornado/whirls, lateral vortices, junction zones (jump fires), eruptive fires, independent crown fires [37], conflagrations, downbursts, and pyro-convective events [18,19], among others.

Information about fire behaviour is best collected as fires occur, however, there is currently no agreed set of standards or methodologies that define (a) what information needs to be collected during fires and (b) when collected, what data standards are appropriate [27]. Data collected during a fire may be discarded if it is not required by an organisation. As a result, data that are saved will only be a subset of the information available during an incident.

In this paper we argue for a minimum standard of data collection during all wildfires. Doing this would enable fire behaviour phenomena to be documented and analysed. Furthermore, if such data collection were to be undertaken in a standardised manner across Australia or worldwide, it would enhance interagency collaboration, increase the research potential of datasets and make research findings more broadly relevant. To do this we first analyse the current information routinely collected during fire events for most states in Australia. Secondly, we provide an overview of some existing research methodologies that have the potential to be routinely used for observations during fires. Finally, we provide some initial recommendations of variables that would ideally be considered for routine collection during wildfires. While we focus primarily on Australian agencies, the recommendations are relevant for agencies worldwide.

2. 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 [38]. Land and fire management is the responsibility of state-level governments (which include 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 wildfires, 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 (Appendix A). 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? (Table A1);
- How frequently are data collected? (Table A2); and
- Does this information collection vary between fires under different conditions? (Table A2)

Responses (Appendix B) were received from Australian Capital Territory (ACT, Table A3), New South Wales (NSW, Table A4), Queensland (QLD, Table A5), South Australia (SA, Table A6), Victoria (VIC, Table A7) and Western Australia (WA, Table A8). 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 variable was considered 'collected' by the state.

Table 1. List of fire management agencies in Australia that were approached in relation to the collection of data during fires.

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)

ACT: Australian Capital Territory; NSW: New South Wales; NT: Northern Territory; QLD: Queensland; SA: South Australia; TAS: Tasmania; VIC: Victoria; WA: Western Australia.

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

The responses in relation to the fire data were broken into three categories relating to incident size as determined by the Australasian Inter-service Incident Management System (AIIMS)/Incident Control System (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.

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 forward looking infrared (FLIR) camera-based data) are collected in fewer states. This is due in part to the differing technical capabilities of the states (for example, some states do not have access to 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, the highest number of responses, irrespective to fire size, were received for 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 are curated. While we were unable to conduct quantitative analysis, it is evident that it is 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 are 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 are of high quality and correctly scoped, difficulty in access may hinder fire behaviour science.

Table 2. Categories and definitions used in fire data collection surveys.

Data Type	Definition
Incident type	The level of Incident Scale as determined by the AIIMS/ICS system [1]
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 (fire history)
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 [2]
Linescans	Images from high altitude aircraft mounted Infrared linescan systems [3]

[1] AIIMS is the Australasian Inter-service Incident Management System [39]. 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. [2] FLIR cameras are electro-optical thermal imaging devices that detect heat and provide a visual representation of small parts of a fire. [3] 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.

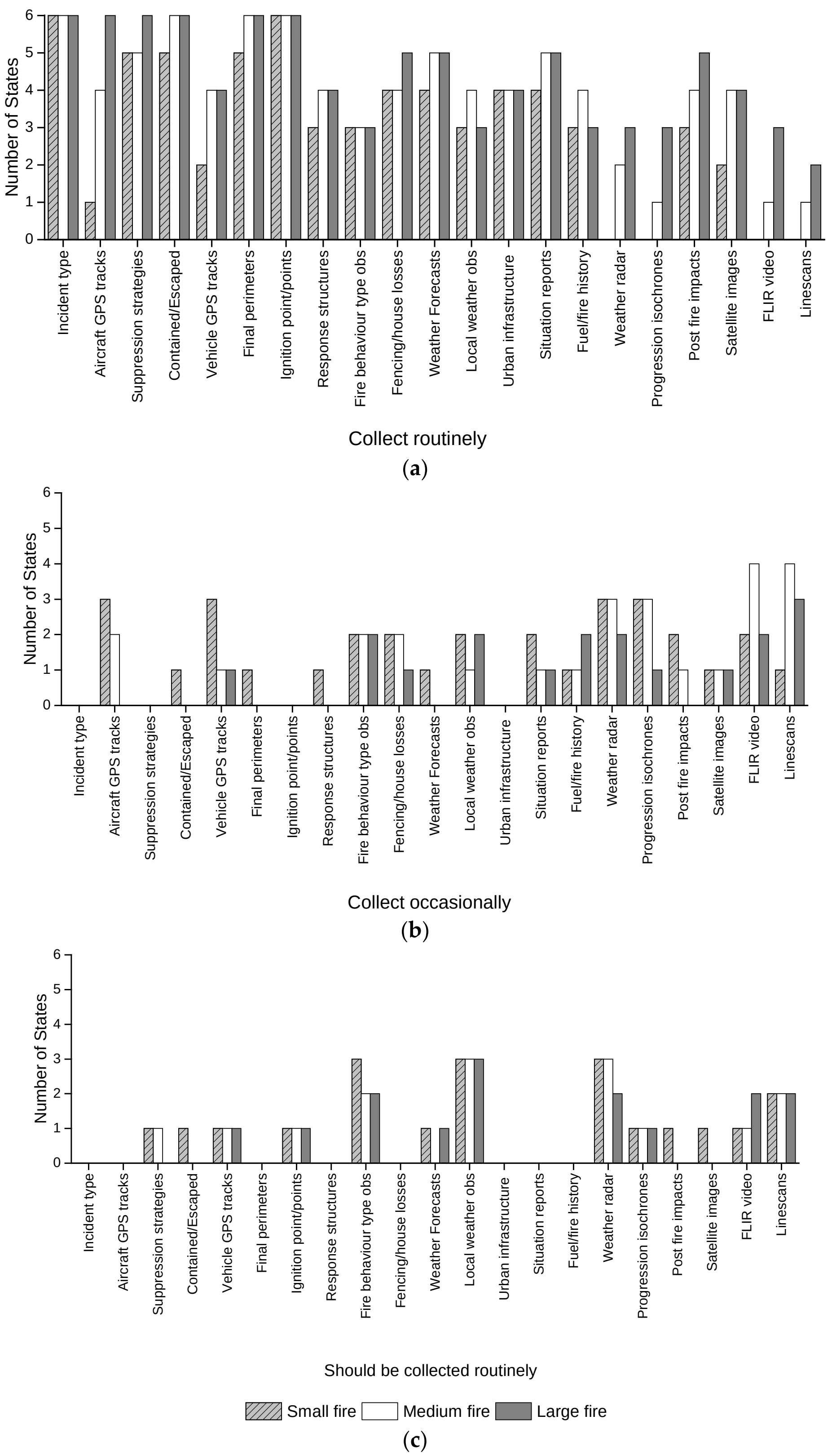

Figure 1. Responses from fire and land management agencies in Australia. Clustered columns show the number of states, which collect specific data type routinely (**a**), occasionally (**b**) or should collect routinely (**c**). The responses are given for small, medium and large fires.

3. Innovation in Data Collection

The management of information during active wildfires 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 it should offer (1) a tangible immediate benefit to the agency utilising it; (2) a long-term benefit to the agency through improved decision support as a result of research outputs; (3) feasible implementation within the operational context and (4) ease of use. 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 advance in fire behaviour research are data derived from remote sensing before, during and after the fire. Remotely sensed data provide 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 [40,41]. Remotely sensed data have been used to detect active fires [42,43]; map fire extents scales [44–47]; estimate surface and crown fuel loading [48,49]; assess active fire behaviour [50–52] and examine post-fire vegetation response [53,54].

Fire behaviour and measures of the fuel consumed have been quantified through the analysis of thermal infrared imagery [55–57]. Infrared (IR) sensors and Infrared Line Scanning Systems on aircrafts 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 [58]. 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) (TIR band includes spectrum from both MWIR and LWIR (mainly LWIR) spectral regions [59]) sensors [60]. 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 pixel may correspond to the fire. Using multi-spectral methods can solve this problem. For example, in the USA, the airborne fire data gathering is 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 [60]. Also, by using a multispectral approach the fire radiative power, fire fractional area and temperature can be estimated [61]. 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 wildfire smoke plumes and the atmosphere using LIDAR (LIght Detection And Ranging) [62–64], SODAR (SOnic Detection And Ranging) [65,66] and RADAR (RAdio Detection and Ranging) [63,67–70]. These methods extract vertical profiles of the smoke plumes, as well as 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. The intensity and evolution of convective plumes is critical in the understanding of lofting and spotting of firebrands, where plume structure begins to play an important role in how the firebrands are spatially distributed. A number of studies have also characterised smoke plume behaviour using information derived from satellite data [71–73]. Information on smoke-plume heights and their dynamics and these related data will allow for improvements in smoke dispersion and air quality models.

Weather RADAR [67–70] and LIDAR [62–64] 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 as part of 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 thunderstorms 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 considered an important auxiliary tool for detecting unauthorised burning and forest fires, adding significant value to the information for decision-making in monitoring, detecting and suppressing wildfires. 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) [74]. 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 [43]. Secondly, unmanned aerial vehicles (UAVs, commonly known as drones) as remote sensing platforms have the great potential to increase the efficiency of data acquisition, but their applications are still at an experimental stage [75–77]. 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 UAVs and sensors increases, so will our ability to capture high resolution spatial data at wildfires. 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.

Table 3 shows innovations for which adoption can bring immediate benefit to fire science and management.

Table 3. List of innovations in wildfire data collection with immediate benefits.

Innovation	Data Source	Platform	Features	Advantages	Disadvantages	Usage
Advanced Himawari Imager	Satellite images, dNBR [1], NDVI [2], fire severity maps	Himawari-8 satellite	Pre-, real-time and post fire events	Large area of detection, ten minute frequency	Not enough spatial resolution	Partially in use
Infrared Line Scanning Systems	Progression isochrones	Aircrafts, helicopters	Real time data collection	High temporal and spatial resolution	Small area of detection	Partially in use
Multiple Infrared (IR) Sensors	IR video and images	Aircrafts, helicopters	Real time data collection	High temporal and spatial resolution	High cost	Prototypes
LIDAR, SODAR and RADAR	2D/3D images	Ground-based and mobile systems	Real time weather measurements, fire detection	2D/3D visualisation and measurement of wildfire smoke plumes and the atmosphere, High temporal resolution	Influence of terrain, reduction of spatial resolution with distance, high cost	Occasionally in use
Weather RADAR	2D images	Ground-based system	Fire detection, plume development	Broad coverage, high frequency	Influence of terrain, reduction of spatial resolution with distance	Occasionally in use
UAVs	IR/visual video and images	Drones, remote control aircrafts and helicopters	Usage at high risk areas	Low material and operational costs, flexible control of spatial and temporal resolution, high-intensity data collection	Low operational time, undeveloped policy	Prototypes

[1] dNBR is the Normalized Burn Ratio. [2] NDVI is the Normalized Difference Vegetation Index.

4. Challenges of Data Collection and an Ideal Dataset

Experience of fire behaviour data collection from different fire agencies in Australia showed that there are a substantial amount of data across events. However, these data are often inconsistent and limit quantitative analysis of fire behaviour. For example, line scanning frequency varies significantly during a fire, from several times to only a single scan per day. Aircraft infrared video consists of fragments of fire front depending on the preferences of the pilot and does not show the fire front or spotting development. A further complication is the source of data. For example, weather records are often derived from weather stations, which are sparsely located across the landscape. Data from these stations can differ significantly from weather at the fire location, which may only be 10 km away. Also, mismatches in temporal and spatial resolution of data between multiple sources create challenges in aligning data for meaningful analysis.

Our paper is focused on measuring data for analysis of various fire behaviour phenomena—how to understand them and take them into account in operational and physical based models. The ideal dataset for these analyses would be recorded every 5–15 min and include information about fire progression (linescans and ground observations), infrared video in SWIR, MWIR and LWIR spectral regions of fire front and spot fires, RADAR and LIDAR measurements, high resolution satellite images (<100 m), photo and video of fire and plume development and ground weather observations. Such data would allow researchers to catch even short lifetime phenomena and dynamic effects, such as extreme fire behaviours which can have devastating consequences. Unfortunately, while this dataset is desirable it is unrealistic as it requires huge human and equipment resources, which are very limited during wildfires.

As a starting point we recommend a focus on particular categories (Table 4). These categories are those that will provide the greatest information gains, with minimum additional resources. Our focus list is 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.

Any system or set of measures must be accompanied by the development of a robust data storage and sharing system. The development of such system could greatly reduce data discoverability issues for research and governmental inquires. The information needs for fire behavior research are not necessarily the same of those needed for managing the control of wildfires. Control requires information at high temporal frequencies, but does not necessarily require the degree of accuracy or precision required for research. However, intelligence gathering infrastructures are in place for fire control, and, at the very least, the information currently being collected could be archived in a way to make it suitable for future analysis. 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. From a research perspective this should allow for more comprehensive datasets to be developed, thereby increasing the application of research results. As a starting point, data could be collected in each state fire agency with the perspective to create a national data collection system. Also, all data formats should comply with the International System of Units (SI). Such a system would provide a number of challenges in terms of collation and management of the data, but it is beyond the scope of this paper to discuss these issues. Of the data sources in Table 4, much of the information is already being collected (e.g., fire observations, line scans), so there is the potential for rapidly improving data available for research. While the information currently collected may not be of a suitable standard for research, integrating scientific data collection into existing systems is much more likely to be supported by managers, in contrast to demanding new data collection activities that compete for the resources being used for fire control.

Table 4. List of recommended wildfire-related data and protocols for routine collection using current technologies. It proposes which data should be collected routinely, how and what the research output would be.

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/mobile application 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 min minimum (moderate and extreme conditions) • 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

Table 4. *Cont.*

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 • Understanding fire behaviour under suppression

5. Conclusions

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 wildfire 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.

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Appendix A. Data Collection Survey Example

Table A1. Data types.

Data Types		
1. Incident type	2. Aircraft GPS tracks	3. Suppression strategies
4. Contained/escaped	5. Vehicle GPS tracks	6. Final perimeters
7. Ignition point/points	8. Response structures	9. Post fire impacts
10. Fencing/house losses	11. Weather Forecasts	12. Local weather observations
13. Urban infrastructure	14. Situation reports	15. Fuel/fire history
16. Weather radar	17. Progression isochrones	18. Fire behaviour type observations
19. Satellite images	20. FLIR video	21. Line scans

FLIR: forward looking infrared.

Table A2. What kind of data are you collecting during an accident?

Name	Collect Routinely	Collect Occasionally	Should Be Collected Routinely	Data Storage (Logbook/PC/Web)
Small fire				
Medium fire				
Large fire				

Appendix B. Data Collection Surveys

Table A3. Australian Capital Territory.

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS
1	Incident type	1	1					1	1					1	1				
2	Aircraft GPS tracks			1	1				1	1					1	1			
3	Suppression strategies	1	1					1	1					1	1				
4	Contained/Escaped	1	1					1	1					1	1				
5	Vehicle GPS tracks		1			1			1			1			1			1	
6	Final perimeters	1			1			1	1					1	1				
7	Ignition point/points	1			1			1	1					1	1				
8	Response structures	1						1	1					1	1				
9	Fire behaviour type observations	1						1	1					1	1				
10	Fencing/house losses	1	1					1	1					1	1				
11	Weather Forecasts	1						1	1					1	1				
12	Local weather observations	1						1	1					1	1				
13	Urban infrastructure	1	1					1	1					1	1				
14	Situation reports	1	1					1	1					1	1				
15	Fuel/fire history	1	1					1	1					1	1				
16	Weather radar					1					1	1					1	1	
17	Progression isochrones										1						1		
18	Post fire impacts	1						1	1					1	1				
19	Satellite images							1			1			1			1		
20	FLIR video								1	1					1	1			
21	Linescans								1	1					1	1			

R—routinely; O—occasionally; S—should be collected routinely; Parks—Parks and Conservation Service; RFS—Rural Fire Service.

Table A4. New South Wales.

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS
1	Incident type		1						1						1				
2	Aircraft GPS tracks	1	1					1	1					1	1				
3	Suppression strategies	1	1					1	1					1	1				
4	Contained/Escaped		1						1						1				
5	Vehicle GPS tracks																		
6	Final perimeters	1			1			1	1					1	1				
7	Ignition point/points	1	1					1	1					1	1				
8	Response structures	1			1			1	1					1	1				
9	Fire behaviour type observations				1	1				1	1						1		
10	Fencing/house losses		1						1						1				

Table A4. *Cont.*

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS	Parks	RFS
11	Weather Forecasts	1	1					1	1					1	1				
12	Local weather observations	1				1		1	1					1	1				
13	Urban infrastructure																		
14	Situation reports	1	1					1	1					1	1				
15	Fuel/fire history	1			1			1	1					1	1				
16	Weather radar				1	1			1			1			1				
17	Progression isochrones				1						1				1	1			
18	Post fire impacts		1						1						1	1			
19	Satellite images		1			1			1						1	1			
20	FLIR video				1					1	1			1	1				
21	Linescans				1						1			1	1				

R—routinely; O—occasionally; S—should be collected routinely; Parks—National Parks and Wildlife Service; RFS—Rural Fire Service.

Table A5. Queensland.

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		Parks	FES	Parks	FES	Parks	FES	Parks	FES	Parks	FES	Parks	FES	Parks	FES	Parks	FES	Parks	FES
1	Incident type	1	1					1	1					1	1				
2	Aircraft GPS tracks				1					1	1				1				
3	Suppression strategies	1						1						1					
4	Contained/Escaped	1						1						1					
5	Vehicle GPS tracks				1				1						1				
6	Final perimeters	1						1						1					
7	Ignition point/points	1					1	1					1	1					1
8	Response structures																		
9	Fire behaviour type observations			1			1			1			1			1			1
10	Fencing/house losses			1						1						1			
11	Weather Forecasts		1	1		1			1	1		1			1	1		1	
12	Local weather observations		1	1		1				1		1	1			1		1	1
13	Urban infrastructure		1						1						1				
14	Situation reports	1						1						1			1		
15	Fuel/fire history										1						1		
16	Weather radar				1				1						1				
17	Progression isochrones																		
18	Post fire impacts	1						1						1					
19	Satellite images		1						1						1				
20	FLIR video																		
21	Linescans						1						1						1

R—routinely; O—occasionally; S—should be collected routinely; Parks—Queensland Parks and Wildlife Service; FES—Queensland Fire and Emergency Services.

Table A6. South Australia.

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS	DEWNR	CFS
1	Incident type	1	1					1	1					1	1				
2	Aircraft GPS tracks			1	1			1			1			1	1				
3	Suppression strategies		1	1					1	1				1	1				
4	Contained/Escaped				1	1			1	1				1	1				
5	Vehicle GPS tracks			1						1						1			
6	Final perimeters			1	1			1			1			1	1				
7	Ignition point/points	1	1					1	1					1	1				
8	Response structures			1	1			1			1			1	1				
9	Fire behaviour type observations		1	1					1	1					1	1			
10	Fencing/house losses		1	1				1	1					1	1				
11	Weather Forecasts			1				1	1					1	1				
12	Local weather observations			1	1			1			1						1		
13	Urban infrastructure		1	1					1	1				1	1				
14	Situation reports			1	1			1	1					1	1				
15	Fuel/fire history			1	1			1		1	1					1	1		
16	Weather radar			1						1				1					
17	Progression isochrones			1						1	1			1	1				
18	Post fire impacts			1						1	1			1	1				
19	Satellite images									1						1	1		
20	FLIR video										1	1					1	1	
21	Linescans									1						1	1		

R—routinely; O—occasionally; S—should be collected routinely; DEWNR—Department of Environment, Water and Natural Resources; CFS—Country Fire Service.

Table A7. Victoria.

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA
1	Incident type		1						1						1				
2	Aircraft GPS tracks								1						1				
3	Suppression strategies						1						1		1				
4	Contained/Escaped		1						1						1				
5	Vehicle GPS tracks		1						1						1				
6	Final perimeters		1						1						1				
7	Ignition point/points		1						1						1				
8	Response structures																		
9	Fire behaviour type observations						1						1						1
10	Fencing/house losses				1						1				1				

Table A7. *Cont.*

No.	Data Type	Small Fire						Medium Fire						Large Fire					
		R		O		S		R		O		S		R		O		S	
		DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA	DEWLP	CFA
11	Weather Forecasts																		
12	Local weather observations						1						1						1
13	Urban infrastructure																		
14	Situation reports				1						1						1		
15	Fuel/fire history																		
16	Weather radar						1						1						1
17	Progression isochrones						1						1						1
18	Post fire impacts						1												
19	Satellite images																		
20	FLIR video						1				1						1		
21	Linescans						1				1						1		

R—routinely; O—occasionally; S—should be collected routinely; DEWLP—Department of Environment, Land, Water and Planning; CFA—Country Fire Authority.

Table A8. Western Australia.

No.	Data Type	Small Fire			Medium Fire			Large Fire		
		R	O	S	R	O	S	R	O	S
		DPAW	DPAW	DPAW	DPAW	DPAW	DPAW	DPAW	DPAW	DPAW
1	Incident type	1			1			1		
2	Aircraft GPS tracks					1		1		
3	Suppression strategies	1	1		1			1		
4	Contained/Escaped	1			1			1		
5	Vehicle GPS tracks		1		1	1		1	1	
6	Final perimeters	1			1			1		
7	Ignition point/points	1			1			1		
8	Response structures	1	1		1			1		
9	Fire behaviour type observations	1	1		1			1		
10	Fencing/house losses	1			1			1		
11	Weather Forecasts	1			1			1		
12	Local weather observations		1		1	1	1	1	1	1
13	Urban infrastructure	1	1		1			1		
14	Situation reports	1	1		1			1		
15	Fuel/fire history	1			1			1		
16	Weather radar					1			1	
17	Progression isochrones		1		1	1		1		
18	Post fire impacts		1		1	1		1		
19	Satellite images		1		1	1		1		
20	FLIR video		1			1		1	1	1
21	Linescans					1	1		1	1

R—routinely; O—occasionally; S—should be collected routinely; DPAW—Department of Parks and Wildlife.

References

1. Burned Area Emergency Response (BAER) Team. Soberanes 2 Burned Area. USDA Forest Service Report FSH 2509.13. Available online: http://www.co.monterey.ca.us/home/showdocument?id=14136 (accessed on 8 February 2018).
2. Cruz, M.G.; Sullivan, A.L.; Gould, J.S.; Sims, N.C.; Bannister, A.J.; Hollis, J.J.; Hurley, R.J. Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *For. Ecol. Manag.* **2012**, *284*, 269–285. [CrossRef]
3. Leonard, J.E.; Opie, K.; Blanchi, R.; Newnham, G.; Holland, M. Wye River/Separation Creek Post-Bushfire Building Survey Findings. CSIRO Client Report EP16924. Available online: https://publications.csiro.au/rpr/download?pid=csiro:EP16924&dsid=DS2 (accessed on 8 February 2018).
4. Wilkinson, C.; Eriksen, C.; Penman, T. Into the firing line: Civilian ingress during the 2013 "Red October" bushfires, Australia. *Nat. Hazards* **2016**, *80*, 521–538. [CrossRef]
5. Hughes, L.; Alexander, D. Climate Change and the Victoria Bushfire Threat: Update 2017. Climate Council Report. Available online: http://www.climatecouncil.org.au/uploads/98c26db6af45080a32377f3ef4800102.pdf (accessed on 8 February 2018).
6. Deloitte Access Economics Scoping Study on a Cost Benefit Analysis of Bushfire Mitigation Australian Forest Products. Available online: http://ausfpa.com.au/wp-content/uploads/2016/01/AFPA-DAE-report-Amended-Final-2014-05-27.pdf (accessed on 8 February 2018).
7. Maranghides, A.; Mell, W.; Ridenour, K.; McNamara, D. Initial Reconnaissance of the 2011 Wildland-Urban Interface Fires in Amarillo, Texas. *Fire Technol.* **2014**, *50*, 93–104. [CrossRef]
8. Finney, M. *FARSITE: Fire Area Simulator-Model Development and Evaluation*; RMRS-RP-4; Rocky Mountain Research Station: Ogden, UT, USA, 2004.
9. Garcia, T.; Braun, J.; Bryce, R.; Tymstra, C. Smoothing and bootstrapping the PROMETHEUS fire growth model. *Environmetrics* **2008**, *19*, 836–848. [CrossRef]
10. Fraser, R.H.; Li, Z.; Cihlar, J. Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest. *Remote Sens. Environ* **2000**, *74*, 362–376. [CrossRef]
11. McInerney, D.; San-Miguel-Ayanz, J.; Corti, P.; Whitmore, C.; Giovando, C.; Camia, A. Design and Function of the European Forest Fire Information System. *Photogramm. Eng. Remote Sens.* **2013**, *79*, 965–973. [CrossRef]
12. Miller, C.; Hilton, J.; Sullivan, A.; Prakash, M. SPARK—A Bushfire Spread Prediction Tool. In *Environmental Software Systems: Infrastructures, Services and Applications*; Springer: Cham, Switzerland, 2015; Volume 448, pp. 262–271.
13. Duff, T.J.; Chong, D.M.; Tolhurst, K.G. Indices for the evaluation of wildfire spread simulations using contemporaneous predictions and observations of burnt area. *Environ. Model. Softw.* **2016**, *83*, 276–285. [CrossRef]
14. Rothermel, R.C. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*; USDA Forest Service Research Paper INT-115; Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1972; 40p. Available online: https://www.fs.fed.us/rm/pubs_int/int_rp115.pdf (accessed on 8 February 2018).
15. Van Nest, T.A.; Alexander, M.E. Systems for rating fire danger and predicting fire behavior used in Canada. In Proceedings of the National Interagency Behavior Workshop, Phoenix, AZ, USA, 1–5 March 1999; Volume 13, pp. 1–8.
16. Cheney, N.P.; Gould, J.S.; McCaw, W.L.; Anderson, W.R. Predicting fire behaviour in dry eucalypt forest in southern Australia. *For. Ecol. Manag.* **2012**, *280*, 120–131. [CrossRef]
17. Cheney, N.P.; Gould, J.S.; Catchpole, W.R. Prediction of fire spread in grasslands. *Int. J. Wildland Fire* **1998**, *8*. [CrossRef]
18. Viegas, D.X.; Ribeiro, L.M.; Viegas, M.T.; Pita, L.P.; Rossa, C. Impacts of fire on society: Extreme fire propagation issues. In *Earth Observation of Wildland Fires in Mediterranean Ecosystems*; Springer: Berlin, Germany, 2009; pp. 97–109, ISBN 9783642017537.
19. Werth, P.A.; Potter, B.E.; Alexander, M.E.; Clements, C.B.; Cruz, M.G.; Finney, M.A.; Forthofer, J.M.; Goodrick, S.L.; Hoffman, C.; Jolly, W.M.; et al. *Synthesis of Knowledge of Extreme Fire Behavior: Volume 2 for Fire Behavior Specialists, Researchers, and Meteorologists*; General Technical Report PNW-GTR-891; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2016; p. 258.

20. Benali, A.; Sá, A.C.L.; Ervilha, A.R.; Trigo, R.M.; Fernandes, P.M.; Pereira, J.M.C. Fire spread predictions: Sweeping uncertainty under the rug. *Sci. Total Environ.* **2017**, *592*, 187–196. [CrossRef] [PubMed]
21. Martin, W.E.; Martin, I.M.; Kent, B. The role of risk perceptions in the risk mitigation process: The case of wildfire in high risk communities. *J. Environ. Manag.* **2009**, *91*, 489–498. [CrossRef] [PubMed]
22. Tutsch, M.; Haider, W.; Beardmore, B.; Lertzman, K.; Cooper, A.B.; Walker, R.C. Estimating the consequences of wildfire for wildfire risk assessment, a case study in the southern Gulf Islands, British Columbia, Canada. *Can. J. For. Res.* **2010**, *40*, 2104–2114. [CrossRef]
23. State Government of NSW and Office of Environment and Heritage (OEH). *Fire History—Ignition Points*; OEH: Sydney, Australia, 2011.
24. Penman, T.D.; Bradstock, R.A.; Price, O. Modelling the determinants of ignition in the Sydney Basin, Australia: Implications for future management. *Int. J. Wildland Fire* **2013**, *22*, 469–478. [CrossRef]
25. Collins, K.; Price, O.; Penman, T. Spatial patterns of wildfire ignitions in south-eastern Australia. *Int. J. Wildland Fire* **2015**, *24*, 1098–1108. [CrossRef]
26. Country Fire Authority. *CFA Call Summary Reports*; Country Fire Authority: Melbourne, Australia, 2017.
27. Chong, D.M.; Cirulis, B.A.; Duff, T.J.; Walsh, S.F.; Penmanb, T.D.; Tolhust, K.G. Gaining benefits from adversity: The need for systems and frameworks to maximise the data obtained from wildfires. In *Advances in Forest Fire Research*; Universidade de Coimbra: Coimbra, Portugal, 2014; ISBN 9789892608846.
28. Keeley, J.E. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *Int. J. Wildland Fire* **2009**, *18*, 116–126. [CrossRef]
29. Harris, S.; Anderson, W.; Kilinc, M.; Fogarty, L. The relationship between fire behaviour measures and community loss: An exploratory analysis for developing a bushfire severity scale. *Nat. Hazards* **2012**, *63*, 391–415. [CrossRef]
30. The State of Victoria. *Boundary of Fire Severity Classes (FIRE_SEV03) for Alpine Fires January/February 2003*; Department of Environment, Land, Water & Planning: Melbourne, Australia, 2014.
31. Collins, L.; Bradstock, R.A.; Penman, T.D. Can precipitation influence landscape controls on wildfire severity? A case study within temperate eucalypt forests of south-eastern Australia. *Int. J. Wildland Fire* **2014**, *23*, 9–20. [CrossRef]
32. Peterson, D.A.; Hyer, E.J.; Campbell, J.R.; Michael, D.F.; Hair, J.W.; Butler, C.F.; Fenn, M.A. The 2013 Rim Fire: Implications for Predicting Extreme Fire Spread, Pyroconvection, and Smoke Emissions. *Bull. Am. Meteorol. Soc.* **2015**, *96*, 229–247. [CrossRef]
33. Peace, M.; Mattner, T.; Mills, G.; Kepert, J.; Mccaw, L. Fire-modified meteorology in a coupled fire-atmosphere model. *J. Appl. Meteorol. Climatol.* **2015**, *54*, 704–720. [CrossRef]
34. Ramsay, G.; McArthur, N.; Dowling, V. Preliminary results from an examination of house survival in the 16 February 1983 Bushfires in Australia. *Fire Mater.* **1987**, *11*, 49–51. [CrossRef]
35. Donovan, G.H.; Noordijk, P. Assessing the Accuracy of Wildland Fire Situation Analysis (WFSA) Fire Size and Suppression Cost Estimates. *J. For.* **2005**, *103*, 10–13.
36. Gill, M.; Cary, G. Socially disasterous landscape fires in southeastern Australia: Impact, responses, implications. In *Wildfire and Community: Facilitating Preparedness and Resilience*; Paton, B., Tedim, F., Eds.; Charles C Thomas Publisher Ltd.: Springfield, IL, USA, 2012; pp. 14–32.
37. Van Wagner, C.E. Conditions for the start and spread of crown fire. *Can. J. For. Res.* **1977**, *7*, 23–34. [CrossRef]
38. Murphy, B.P.; Bradstock, R.A.; Boer, M.M.; Carter, J.; Cary, G.J.; Cochrane, M.A.; Fensham, R.J.; Russell-Smith, J.; Williamson, G.J.; Bowman, D.M.J.S. Fire regimes of Australia: A pyrogeographic model system. *J. Biogeogr.* **2013**, *40*, 1048–1058. [CrossRef]
39. Australasian Fire and Emergency Services Authorities Council. *The Australasian Inter-service Incident Management System: A Management System for Any Emergency: 2017*, 5th ed.; Australasian Fire and Emergency Services Authorities Council Limited: East Melbourne, Australia, 2017.
40. Lentile, L.B.; Holden, Z.A.; Smith, A.M.S.; Falkowski, M.J.; Hudak, A.T.; Morgan, P.; Lewis, S.A.; Gessler, P.E.; Benson, N.C. Remote sensing techniques to assess active fire characteristics and post-fire effects. *Int. J. Wildland Fire* **2006**, *15*, 319–345. [CrossRef]
41. Lu, B.; He, Y.; Tong, A. Evaluation of spectral indices for estimating burn severity in semiarid grasslands. *Int. J. Wildland Fire* **2015**, *25*, 147–157. [CrossRef]
42. Matvienko, G.G.; Afonin, S.V.; Belov, V.V. *Early Detection of Forest Fires from Space*; Nova Science Publishers Inc.: New York, NY, USA, 2011; ISBN 978-1-61324-509-5.

43. Hally, B.; Wallace, L.; Reinke, K.; Jones, S. Assessment of the utility of the Advanced Himawari Imager to detect active fire over Australia. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2016**, *41*, 65–71. [CrossRef]
44. Scholes, R.; Kendall, J.; Justice, C. The quantity of biomass burned in southern Africa. *J. Geophys. Res.* **1996**, *101*, 23667–23676. [CrossRef]
45. Holden, Z.A.; Smith, A.M.S.; Morgan, P.; Rollins, M.G.; Gessler, P.E. Evaluation of novel thermally enhanced spectral indices for mapping fire perimeters and comparisons with fire atlas data. *Int. J. Remote Sens.* **2005**, *26*, 4801–4808. [CrossRef]
46. Sertel, E.; Alganci, U. Comparison of pixel and object-based classification for burned area mapping using SPOT-6 images. *Geomat. Nat. Hazards Risk* **2015**, *5705*, 1–9. [CrossRef]
47. Linke, J.; Fortin, M.J.; Courtenay, S.; Cormier, R. High-resolution global maps of 21st-Century annual forest loss: Independent accuracy assessment and application in a temperate forest region of Atlantic Canada. *Remote Sens. Environ.* **2017**, *188*, 164–176. [CrossRef]
48. Schmidt, I.T.; O'Leary, J.F.; Stow, D.A.; Uyeda, K.A.; Riggan, P.J. Use of ultra-high spatial resolution aerial imagery in the estimation of chaparral wildfire fuel loads. *Environ. Monit. Assess.* **2016**, *188*. [CrossRef] [PubMed]
49. Zhou, Q.; Hill, M.J.; Sun, Q.; Schaaf, C.B. Retrieving understorey dynamics in the Australian tropical savannah from time series decomposition and linear unmixing of MODIS data. *Int. J. Remote Sens.* **2016**, *37*, 1445–1475. [CrossRef]
50. Smith, A.M.S.; Wooster, M.J. Remote classification of head and backfire types from MODIS fire radiative power and smoke plume observations. *Int. J. Wildland Fire* **2005**, *14*, 249–254. [CrossRef]
51. Dennison, P.E.; Charoensiri, K.; Roberts, D.A.; Peterson, S.H.; Green, R.O. Wildfire temperature and land cover modeling using hyperspectral data. *Remote Sens. Environ.* **2006**, *100*, 212–222. [CrossRef]
52. Barrett, K.; Loboda, T.; McGuire, A.D.; Genet, H.; Hoy, E.; Kasischke, E. Static and dynamic controls on fire activity at moderate spatial and temporal scales in the Alaskan boreal forest. *Ecosphere* **2016**, *7*, e01572. [CrossRef]
53. Jones, M.O.; Kimball, J.S.; Jones, L.A. Satellite microwave detection of boreal forest recovery from the extreme 2004 wildfires in Alaska and Canada. *Glob. Chang. Biol.* **2013**, *19*, 3111–3122. [CrossRef] [PubMed]
54. Di-Mauro, B.; Fava, F.; Busetto, L.; Crosta, G.F.; Colombo, R. Post-fire resilience in the Alpine region estimated from MODIS satellite multispectral data. *Int. J. Appl. Earth Obs. Geoinf.* **2014**, *32*, 163–172. [CrossRef]
55. Briz, S.; De Castro, A.J.; Aranda, J.M.; Meléndez, J.; López, F. Reduction of false alarm rate in automatic forest fire infrared surveillance systems. *Remote Sens. Environ.* **2003**, *86*, 19–29. [CrossRef]
56. Veraverbeke, S.; Hook, S.; Hulley, G. An alternative spectral index for rapid fire severity assessments. *Remote Sens. Environ.* **2012**, *123*, 72–80. [CrossRef]
57. Polivka, T.N.; Wang, J.; Ellison, L.T.; Hyer, E.J.; Ichoku, C.M. Improving Nocturnal Fire Detection with the VIIRS Day-Night Band. *IEEE Trans. Geosci. Remote Sens.* **2016**, *54*, 5503–5519. [CrossRef]
58. Billing, P. *Operational Aspects of the Infra-Red Line Scanner*; Fire Protection Branch, Department of Conservation, Forests & Lands: East Melbourne, Australia, 1986.
59. Allison, R.S.; Johnston, J.M.; Craig, G.; Jennings, S. Airborne optical and thermal remote sensing for wildfire detection and monitoring. *Sensors (Switzerland)* **2016**, *16*, 1310. [CrossRef] [PubMed]
60. Johnston, J.M.; Wooster, M.J.; Lynham, T.J. Experimental confirmation of the MWIR and LWIR grey body assumption for vegetation fire flame emissivity. *Int. J. Wildland Fire* **2014**, *23*, 463–479. [CrossRef]
61. Schroeder, W.; Ellicott, E.; Ichoku, C.; Ellison, L.; Dickinson, M.B.; Ottmar, R.D.; Clements, C.; Hall, D.; Ambrosia, V.; Kremens, R. Integrated active fire retrievals and biomass burning emissions using complementary near-coincident ground, airborne and spaceborne sensor data. *Remote Sens. Environ.* **2014**, *140*, 719–730. [CrossRef]
62. Kovalev, V.A.; Petkov, A.; Wold, C.; Urbanski, S.; Min Hao, W. Determination of smoke plume and layer heights using scanning lidar data. *Appl. Opt.* **2009**, *48*, 5287–5294. [CrossRef] [PubMed]
63. Banta, R.M.; Olivier, L.D.; Holloway, E.T.; Kropfli, R.A.; Bartram, B.W.; Cupp, R.E.; Post, M.J. Smoke-Column Observations from Two Forest Fires Using Doppler Lidar and Doppler Radar. *J. Appl. Meteorol.* **1992**, *31*, 1328–1349. [CrossRef]
64. Lareau, N.P.; Clements, C.B. Environmental controls on pyrocumulus and pyrocumulonimbus initiation and development. *Atmos. Chem. Phys.* **2016**, *16*, 4005–4022. [CrossRef]

65. Thor, S.-E.; Risø, O. State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites. In Proceedings of the 51st IEA Wind Topical Expert Meeting, Roskilde, Denmark, 1 January 2007; p. 287.
66. Bradley, S.; Perrott, Y.; Behrens, P.; Oldroyd, A. Corrections for Wind-Speed Errors from Sodar and Lidar in Complex Terrain. *Bound. Layer Meteorol.* **2012**, *143*, 37–48. [CrossRef]
67. Hufford, G.L.; Kelley, H.L.; Sparkman, W.; Moore, R.K. Use of real-time multisatellite and radar data to support forest fire management. *Weather Forecast.* **1998**, *13*, 592–605. [CrossRef]
68. Chong, D.; Tolhurst, K.; Duff, T. *PHOENIX Rapidfire 4.0's Convection and Ember Dispersal Model*; Bushfire CRC: Melbourne, Australia, 2012.
69. Saraiva, E.; Soares, R.V.; Batista, A.C.; Tertuliano, H.; Gomes, M. Weather Radar: An Efficient Tool for Forest Fire Detection. In Proceedings of the 15th International Conference on Automatic Fire Detection (Aube'14), Duisburg, Germany, 14–16 October 2014.
70. McCarthy, N.; McGowan, H.; Guyot, A. The Bushfire Convective Plume Experiment: Mobile Radar Observations of Pyro-Convection from the Mt Bolton Fire, 2016. In Proceedings of the AFAC16 Bushfire and Natural Hazards CRC, Brisbane, Australia, 30 August–1 September 2016.
71. Dirksen, R.J.; Folkert Boersma, K.; De Laat, J.; Stammes, P.; Van Der Werf, G.R.; Martin, M.V.; Kelder, H.M. An aerosol boomerang: Rapid around-the-world transport of smoke from the December 2006 Australian forest fires observed from space. *J. Geophys. Res. Atmos.* **2009**, *114*. [CrossRef]
72. Amiridis, V.; Giannakaki, E.; Balis, D.S.; Gerasopoulos, E.; Pytharoulis, I.; Zanis, P.; Kazadzis, S.; Melas, D.; Zerefos, C. Smoke injection heights from agricultural burning in Eastern Europe as seen by CALIPSO. *Atmos. Chem. Phys.* **2010**, *10*, 11567–11576. [CrossRef]
73. Raffuse, S.M.; Craig, K.J.; Larkin, N.K.; Strand, T.T.; Sullivan, D.C.; Wheeler, N.J.M.; Solomon, R. An evaluation of modeled plume injection height with satellite-derived observed plume height. *Atmosphere* **2012**, *3*, 103–123. [CrossRef]
74. Zhang, Y.; Lim, S.; Sharples, J.J. Modelling spatial patterns of wildfire occurrence in South-Eastern Australia. *Geomat. Nat. Hazards Risk* **2016**, *7*, 1800–1815. [CrossRef]
75. Ambrosia, V.G.; Wegener, S.; Zajkowski, T.; Sullivan, D.V.; Buechel, S.; Enomoto, F.; Lobitz, B.; Johan, S.; Brass, J.; Hinkley, E. The Ikhana unmanned airborne system (UAS) western states fire imaging missions: From concept to reality (2006–2010). *Geocarto Int.* **2011**, *26*, 85–101. [CrossRef]
76. Wing, M.G.; Burnett, J.; Sessions, J.; Brungardt, J.; Cordell, V.; Dobler, D.; Wilson, D. Eyes in the Sky: Remote Sensing Technology Development Using Small Unmanned Aircraft Systems. *J. For.* **2013**, *111*, 341–347. [CrossRef]
77. Shahbazi, M.; Théau, J.; Ménard, P. Recent applications of unmanned aerial imagery in natural resource management. *GISci. Remote Sens.* **2014**, *51*, 339–365. [CrossRef]