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A GUIDE TO RECONSTRUCTING CROPLAND FIRES

Data collection, collation and analysis for case study construction

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CSIRO & Bushfire and Natural Hazards CRC

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END-USER RECOMMENDATIONS ON FUTURE NEEDS FOR TRAINING USERS TO IMPLEMENT THE GUIDE

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Over the decade leading up to 2017 when this project was commissioned, rural communities in Australia experienced an unprecedented increase in destructive fires on agricultural lands across Australia (e.g. 2016 Esperance fire in WA; 2016 Pinery Fire in SA; 2005 Wangary fire in SA). These three fires alone have resulted in the loss of 15 lives and the loss of hundreds of properties, 500,000 hectares burnt and a cost of between 280 and 370 million AUD. Apart from these catastrophic fires, crop and stubble fires igniting during and after harvest operations cost the rural communities millions of dollars each year due to loss of crop yield and farm assets.

This guide provides an important stocktake of many of the practiced processes of reconstruction efforts for crop fires. It was leveraged in a number of reconstructions throughout the project period, though not all of them crop fires. The fire seasons of 2017/2018, 2018/2019 and 2019/2020 all had limited crop fires with which to test and implement the guide. Following this and the extension of the project, overall fire activity substantially subdued during the 2020/2021 La Nina season combined with the impact of the COVID-19 pandemic. This does not detract from the priority associated with reconstruction work. The strong stated needs for crop fire behaviour observations in this guide have been simultaneous complemented in the last 5 years by a program of crop fire experiments with CFA and CSIRO, studying fire behaviour in wheat, canola and barley in various harvest states.

The integration of fire reconstructions into business as usual has been successful through the last 5 years with now a large number being produced by agencies each year. During this same period, fireground safety practice continues to modernise and become more accountable, particularly with respect to tree safety, hazardous materials, working around machinery and fatigue management. Although the live fire threat may have eased while reconstructions are occurring as this guide suggest, sufficient training, experience and endorsement are fundamental requirements for safe and sustainable fire reconstruction work. With this in mind, the following recommendations are provided to implement the insights of the guide through training and doctrine reform:

- Expand the number and diversity of people conducting reconstructions through appropriate 'fire role' time allocation to existing incident roles/functions. For example, staffing analysts into incidents following the peak periods they are typically only needed for. Reconstructions will not occur if people capable of doing them (experienced fire professionals) have competing priorities and are not given the time conduct the reconstructions.
- Establish formal processes for fireground attendance when assignment to fires in not through usual channels, associated with research on

firegrounds that may not align with agency and fireground dispatch procedures.

- Review and establish national and interagency governance around best practice reconstruction compiling, aggregation and storage, especially with regards to data and meta-data storage and access. This should be similar or build on to the effort with the National Fire History Information system, managed by AFAC Predictive Services Group – Data Working Group.
- Encourage adaptable reconstruction approaches with regards to topic-many of the methods in this guide are true of reconstructions outside of croplands. Given the variability of fire seasons and the types of fires between them, it is better to allow data collection to be opportunistic around individual fires and fire season. While this does not lend itself to short term projects (except where data is already collected), it does allow far better data gathering opportunities for progression in key knowledge gaps.

While exhaustive, the guide is quite extensive for a practical reference book. Ultimately this guide will assist in the development of a field guide, which can be delivered with training, to expand this capability within the fire agencies more broadly.

EXECUTIVE SUMMARY

This guide is intended to provide the fire behaviour analyst tasked with preparing a case study of a cropland wildfire with the basic set of methods, tools and information necessary to create a meaningful summary of the behaviour and spread of that fire. While the information and examples provided are specific to the case of wildfires burning in cropland fuels, the methods and tools are such that they can be applied to wildfires burning in any vegetation type given due consideration of the differences in the applicable factors and conditions.

This guide provides background information on the importance of undertaking case studies of wildfires, particularly across the broad range of wildfire types and intensities, for developing a case study library from which a large range of lessons may be learned—those immediately related to the incident itself but also those that may be gained from a perspective of time and space later.

A detailed discussion of fire behaviour in cropland fuels and the factors that affect fire perimeter shape and growth are discussed. The effects of suppression efforts, their effectiveness and likely impact on fire shape and spread are also discussed. Understanding the fuels and landscape features across which a cropland wildfire burns, in particular those non-crop fuels such as roadside verges and grazing paddocks, and their condition and state, are critical to interpreting observed fire behaviour and fire propagation across the landscape. Similarly, detailed information on the weather driving the wildfire is critical to understanding how and why a fire spread the way it did. These data can be divided into two groups—those that should be collected during the fire, such as observations of fire behaviour and spotting, and those that can be collected after the fire, such as fire progression and burnt area and crop status and distribution. Assessment of the reliability of the data collected for the purpose of compiling a case study is essential to providing context and informing assessment of dependability of data used for later analysis.

Finally, the guide provides suggestions for documenting the fire event, building the chronology and development of the incident, and writing a case study that is pithy and to the point. Checklists of essential information to be collected during and immediately after the fire (including sample fire spread observation forms), suggested observations to be collected from first attack personnel and prompter questions for when doing firefighter debriefs and interviews of eyewitnesses are also provided.

1. THE IMPORTANCE OF THE WILDFIRE CASE STUDY APPROACH

A wildfire, also commonly called bushfire, is a dramatic phenomenon that can be characterised by its rapid spread over the landscape, tall flames burning above a tree canopy, chaotic winds, multiple secondary ignitions and often a towering convection plume. Many of the behaviours of a wildfire are scale dependent and impossible to replicate in a modelling or small-scale experimental setup. Field observations collected during wildfire events are therefore key to improving our general understanding of the factors that drive fire propagation and expected behaviour.

A wildfire case study can be defined simply as an account of the event. A case study will include qualitative and quantitative information from which one can understand the interrelationships driving the propagation and behaviour of the fire. Wildfire documentation can provide data to evaluate fire behaviour models, verify fire growth forecasts, improve our understanding of possible fire-fighting threats, brief personnel unfamiliar with a specific fire environment and general training of operational staff. Sharing learned experiences helps to improve preparedness and response at many levels. As such, lessons learned from bushfire events, from the benign to the catastrophic, are key to devise better ways to manage them.

Historically, the documentation of wildfire events as case studies have been relatively rare. Occasionally a wildfire event may have significant immediate impacts on lives and livelihoods and the potential for long-term effects on government policy or strategy. Some of these events may lead to criminal or civil litigation or formal inquiry such as that of a coroner or Royal Commission. In such cases, detailed and veracious records of the unfolding of the event are invaluable and ultimately can help build an understanding of what happened, why it happened and begin to identify what could be done differently to reduce potential impacts from similar events in the future.

While our knowledge of bushfire behaviour has grown over the last six decades of fire research in Australia, and with it the systems developed for operational prediction of fire spread, there remains the need for documenting wildfire events to continue the process of validating, testing, evaluating and improving our knowledge, our systems, our firefighter training, and our preparedness. And the only way to do this robustly and effectively is through the creation of accurate case studies of bushfire behaviour under the full range of conditions in which bushfires are possible built on reliable estimates, accurate measurements and well-documented observations. Not just the disastrous fires, the fires that make the news or reach court or a coroner, but as many fires as possible. Without a full and complete account of the behaviour of fire in the wild, we will never get a complete understanding of the potential behaviour of a bushfire.

It is important, therefore, that bushfire case studies are constructed as detailed and complete descriptions of a fire's behaviour and spread as possible. It is also important that these accounts of fire are objective and quantified to scientific standards of precision and accuracy. Similarly, the factors that influence the behaviour of the fire must be objectively and consistently observed and quantified so that the conditions under which a particular fire is burning can be taken into account.

We will never know the complete circumstances of every aspect of every fire and inferences and interpretations will need to be made to fill the gaps in information and data. However, it is essential that these inferences and interpretations are grounded in a fundamental understanding of fire behaviour. Poorly grounded subjective interpretations of even the most robust observations of fire behaviour can quickly unravel a case study to the point that it is of little use.

This guide endeavours to provide a practical framework for the construction of objective and well-quantified bushfire case studies that will be useful for a range of uses, not the least of which is the testing of existing fire spread prediction systems.

1.1 OBJECTIVE

Agricultural crops cover approximately 22 million hectares in Australia, representing about 2.9% of land area. Cropland fires in Australia represent a significant threat to human lives and farmers' livelihoods. The occurrence of multiple or large fires in croplands can have significant negative impact upon the local economy (McArthur et al. 1982). Nonetheless, our understanding of fire dynamics in croplands is still limited.

The purpose of this guide is to set out a standard set of definitions, descriptors, metrics, and data collection methodologies by which the conditions and behaviour of wildfires burning in cropland fuels can be quantified across a wide range of crop types, prevailing weather and locations. Such a standard set will enable the collection, collation and analysis of observations and measurements of prevailing fuel, weather, topography and fire behaviour to enable detailed reconstructions of wildfire events to be undertaken and case studies to be constructed.

Resultant cropland wildfire case studies can then be used to assess and quantify the performance of existing fire spread prediction systems in croplands to identify the need for modifications of these systems or for development of customised systems.

1.2 USE AND ORGANISATION OF THIS GUIDE

This guide is intended for the use of fire agency staff tasked with collecting data for the reconstruction of the spread and behaviour of cropland wildfires. Users of this guide will have the competencies and experience in fire behaviour to undertake fire behaviour and spread predictions and are expected to be working in the role of fire behaviour analyst. These agency staff will be assigned to an incident management team (IMT) during suitable wildfire events and utilise access to fireground intelligence and IMT members and knowledge during the fire event to apply the methodologies of this guide to facilitate the collection of requisite data and construction of a case study for that fire event.

This guide is divided into three main sections:

1) Description and discussion of the types and ranges of data that can be collected during a fire as events are unfolding;
2) Description and discussion of the types and ranges of data that can be collected once a fire event has concluded; and
3) Methodologies for analysing the data collecting and reconstructing the wildfire event.

Standard methodologies for the collection and reliability assessment of observational and measurement data are provided that ultimately set the limit of reliability of any fire reconstructions made from that data. Appendices are provided that detail appropriate measurement techniques for key variables such as weather and fuels, a discussion of the basis for the existing system used for predicting fire behaviour in croplands, as well as a checklist of items essential for comprehensive data collection.

It is understood that as a member of an IMT, it may not be practical for the person charged with constructing a wildfire case study to collect all pertinent data during and in the immediate aftermath of a wildfire event. The structure of this guide identifies those sources of critical data that should be collected on the day of the event if possible (section 2) and those sources of data that may be delayed until some short time after the event (section 3). However, the longer the delay between the event and data collection, the less data will be available and the lower the quality will be. It may be necessary to carryout data collection and IMT tasks as small teams, essentially tag-teaming activities to ensure all tasks are carried out as required.

2. DATA THAT CAN BE COLLECTED DURING THE FIRE

Wildfires are highly dynamic and their behaviour can change rapidly or slowly over time as a result of fire growth or possibly imperceptible changes in fuel, weather or topographic conditions. The larger the amount of information that can be gathered during the event, the more accurately the fire propagation can be reconstructed. During the heat and excitement of a going wildfire, many opportunities exist to collect data on fuels, weather and fire behaviour from direct, primary sources. These include observations you may make yourself of the variables critical to fire behaviour, observations that are supplied to you directly from the field and answers to specific questions you put to those in the field. This is likely to be some of the most reliable information collected for a fire case study, and some of this information can only be collected reliably during the fire. Some information may be collected shortly after the fire has been controlled but the level of reliability may be much reduced or uncertainty increased. During the fire event opportunities for collecting time-critical data must be taken where feasible.

It is advisable that the individual or group tasked with developing the case study contact key personnel involved or likely to be involved in fire suppression operations to make them aware of the need to collect data. If possible, these personnel should be aware of this need even before a fire starts, allowing them to take proactive steps to collect information, such as photos or videos, or observation notes, etc., that can be collated after the event. While formal training for operations personnel to support reconstructions is not required, building awareness and demonstrating value to these personnel over multiple fires will help establish the value, understanding and needs of reconstruction efforts.

2.1 FIRE PROPAGATION AND BEHAVIOUR

2.1.1 Fire perimeter shape and growth

A key component of any case study is the ability to determine the location of the active fire perimeter at various points in time. This information will enable the calculation of the forward and flank rates of fire spread, fireline intensity and overall energy release rates. Information for mapping fire perimeter evolution can arise from a multitude of sources, such as infra-red line scans from a dedicated aircraft, forward-looking infra-red (FLIR) imagery from an aircraft, and aerial photographs or sketches from an air observer.

Still photos or video taken by firefighters in prime locations and photos or video from the general public and land-owners will provide time-stamped and, at times geo-referenced, information as to the location of the fire perimeter at different times. It is important that such photos and video are geo-referenced (i.e. correctly located in space) either when the imagery is taken by the photographer, or during follow-up interviews as soon as possible after the fire event. Location of where the photographer stood when taking the imagery and the direction in which the imagery was taken are essential in order to allow accurate geo-referencing. Time-stamps (particularly for non-smart phone) imagery must be checked. In the absence of geo-referenced information, photos should include landscape features that can be later identified and located.

Table 1. Direct, high priority, fire data sources.

Data	**Source**	**Requirements**	**Purpose**
Infrared linescan imagery	Aviation Services Unit	Raw imagery is preferred over processed to ensure exact fire perimeter locations	Reconstruct fire location at specific times.
Oblique aerial photos and videos	Aircraft attack supervisors or aerial fire observers	Clear photos that allow precise identification of fire edge and absolute location along with time. Additionally, video feeds from air observer aircraft are streamed to online locations allowing for very high frequency fire location observations.	Reconstruct fire location at specific times.
Firefighter observations	Fire teams' & individuals' records and recollections	Fire logs, written and oral records, still and video photography	Reconstruct fire location at specific times. Understand suppression activity.
Field fire observations	Fire reconstructor (you!)	Measurement of fuel moisture, weather(PAWS), identification of key fuel types, direct observations of fire behaviour, location and spread (inc. spotting).	Reconstruct fire location at specific times, understand burning conditions, fire behaviour and spread mechanisms.
Climate and weather	Bureau of Meteorology AWS network, Agency PAWS network	Daily and hourly weather data, Doppler radar, atmospheric soundings, seasonal drought indices	Calculate fuel moisture; fuel availability, understand prevailing and local winds; dynamics of convection columns, potential for spotting, etc.
Satellite Imagery	Sentinel, LANDSAT series satellites available from servers such as EO Browser	Crop states such as irrigated paddocks in the area, occasionally fire location during certain passes. In some cases, low spatial/high temporal resolution satellites such as Himawari-8 can provide a first pass.	Evaluate paddock conditions and in some cases instantaneous fire location of coarse progression mapping.

Information derived from radio traffic will also enable the position of the fire to be determined at different times as well as other relevant information on fire behaviour (e.g., spotting activity) and suppression activity and its effectiveness.

Although one can consider that interviews with eyewitnesses and people involved in suppressing the fire can be considered a post-fire data collection task (see next section), if firefighters are aware of the need to capture opportunistic fire spread and behaviour information during the fire, then they will be able to conduct some of this work during the fire.

Sketch maps of fire progression and areas of active fire suppression are often made during a fire event for a variety of purposes (e.g. situation reports, etc). You should also make sketch maps of fire progression frequently during the fire, particularly when critical information becomes available, noting time and source of new information, time of map creation (and time for which the map is pertinent, if different).

Table 2. Ancillary, fire and environmental data sources

Data	Source	Requirements	Purpose
Field post-fire investigations	Fire reconstructor (you!)	Measurement of fuel state/condition, estimation of fire behaviour and direction of spread (leaf-freeze, fire severity	Reconstruct fire behaviour, understand fire spread and influences of conditions, determine fire impacts
Fire management	Incident Management Team members	Incident Action Plan (IAP) maps, aerial and ground situation reports, personal recollections	Reconstruct fire location at specific times, identify suppression strategies and suppression impacts
Airborne Imagery	Aviation Services Unit/ Agency	Pre- and post-fire digital aerial photography	Reconstruct fire extent, severity, impacts.
Vegetation maps, fuel states	Agency GIS databases, State and Fed. Govt depts. (RTA, Primary Industry, etc)	Vegetation type, structure and condition, fuel accumulation, disturbance history	Determine fuel location, structure, condition, hazard and loading of dead and live fuel components
Infrastructure	Agency GIS databases, State and Fed. Govt depts. (RTA, Primary Industry, etc)	Roads, utility infrastructure, buildings	Assist with geographical orientation of ground or aerial oblique photos on a GIS as well as people's location. Understand likely fuel breaks, impacts on fire spread
Terrain	Agency GIS databases, Google Earth	Digital Terrain Models (DTMs), rivers and streams, and 3D terrain models	Assess influence of terrain on fire spread and extent of fire
Satellite Imagery	NASA, 3rd party service providers	Pre- and post-fire panchromatic, infrared and thermal based Satellite imagery	Reconstruct fire extent, severity, impacts.
Public observations	Private residents, other members of public	Fire logs, written and oral records, ground still and video photography	Reconstruct fire location at specific times
Police investigations	Police, Coroner's Office	Fire investigation data, interviews with key witnesses, findings	Establish the cause and origin of the fire and in some cases deaths and injury resulting from a fire
Firefighter ground and aerial vehicle position tracking	Agencies, Aviation Services Unit	Radio logs and GPS tracking system data (e.g Icon, etc),	Determine suppression activity from which head or flank fire positions may be inferred, spotfire locations
Media	News and social media	Television videography (raw and broadcast), radio and television transcripts	Reconstruct fire location at specific times, point-based fire behaviour
Upper atmosphere	Air traffic control	Aircraft reports	Determine height and characteristics of smoke plumes
Emergency records	Telephone records	Triple-0 calls, mobile phone, GPS tracking, White Pages	Reconstruct fire location at specific times, point-based fire behaviour
Aviation Data	Drop data including 'doors open/doors close' data	ARENA database or agency digital mapping/common operating picture	Location of head or flank fires when aided by interpretation/guidance from air attack supervisors.

All sources of information should be carefully annotated (see forms) and a reliability/accuracy rating should be given (see Section 3.5).

2.1.2 Flame front characteristics

Descriptions of general fire behaviour[1], such as flame dimensions, tree torching and type of fire (e.g., surface vs crown), can be used to describe the state of a fire at different times, its difficulty of control and its impact on assets and the ecosystem. Such descriptions can be used to build an overall sense of fire behaviour for the reconstruction which can be used and to interpret observations from lower reliability sources.

Flame dimensions can be visually estimated by trained observers during a fire run or inferred from digital photos and video. Interview with fire-fighters and eye-witnesses can provide further detailed information in this regard.

Flame height is the average peak height of the flames measured vertically from the ground surface (litter surface), excluding occasional flame flashes or the torching of individual or small groups of shrubs or trees. Its estimation is subjective and may be influenced by vegetation type and observer experience. Therefore, an assessment of fuel type or complex is required in order to aid interpretation of observations.

Flame length is the length of the leading or fuel side edge of a flame estimated from the ground surface and is equal to flame height when the flame is vertical. Flame length is strongly related to fire intensity, although the relationship is dependent on and specific to fuel structure.

Flame depth is the width of continuously flaming fuel behind the fire perimeter (edge) measured perpendicular to the fire perimeter.

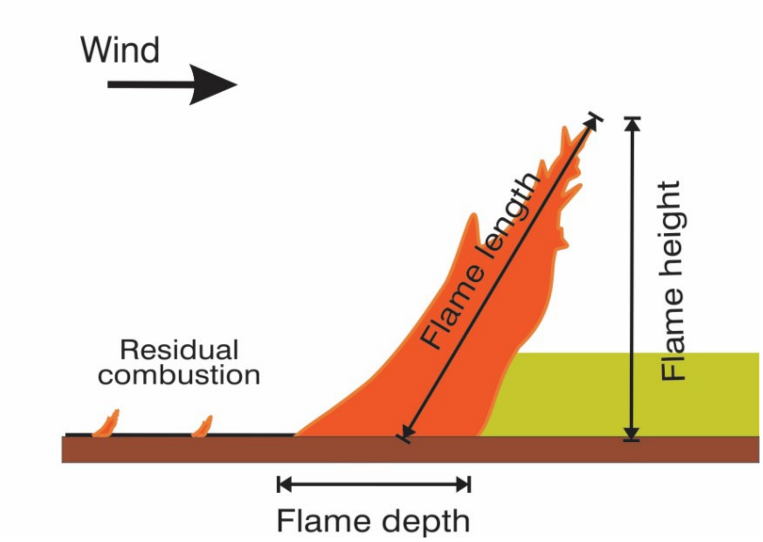

Figure 1. Cross-section of a stylised flame profile in a wind driven surface fire.

Flame angle is the angle between the flame and the surface of unburnt fuel. Thus, head fires typically have flame angles less than 90 degrees between the flame and unburnt fuels, while backing fires usually have flame angles greater than 90 degrees. Small flame angles of a headfire, which may occur due to wind or slope, increase radiative and conductive heating of the fuel bed and hence

[1] For definitions of fire-related terminology used in the report, please refer to the Australian Institute for Disaster Resilience Australian Disaster Resilience Glossary (Australian Institute for Disaster Resilience).

promote rapid advance of the fire. Backfires usually have large flame angles, resulting in less heat directed towards unburnt fuels and this retards the rate of spread. On flank fires, flame angles will be close to 90 degrees as their spread is usually perpendicular to the wind direction or slope.

Flame dimensions are related to the energy released by a fire, which is often quantified as fireline intensity. Fireline intensity, or Byram's intensity is the energy release rate by a linear meter of fireline width (kW/m) and is determined by the product of the energy stored in the fuel (the low heat content, H, kJ/kg), the fuel consumed in the active flaming front (w_a, kg/m^2) and the rate of fire spread (ROS, m/s):

$$I_B = H \times w_a \times ROS \qquad [3.1]$$

Fireline intensity combines three fundamental variables into a single number which may useful for understanding wildfire suppression difficulty, prescribed burning planning and fire effects. However, the value cannot be independently measured and thus can only be calculated.

2.1.3 Spotting

It is expected that different crop types will have different spotting potential and that this potential will change depending on the state of the crop (i.e. whether it has been harvested or not).

The occurrence of spot fires should be noted and mapped. Key information required are: their location and time of occurrence, estimated distance to the main flame front at the time of occurrence, number or density of spot fires (i.e. isolated vs multiple), interaction with other spot fires or the main flame front, and possible firebrand sources. Spotting information can be derived from infrared line scan imagery, aerial and ground based photos and video taken during the event, and interviews with fire suppression personnel and situation reports. Spotting information can also be collated after the fire from extinguished spot fires, but this will require information on fire suppression actions. Determination of whether the spotfire was subsequently overrun by the main fire (i.e. it played no part in overall fire behaviour) or whether it enabled the fire to cross an obstruction such as a road, break in topography or water feature) should be made from collected imagery and interviews.

2.1.4 Other fire behaviour characteristics

Other fire characteristics that are worth documenting are the occurrence of fire whirls and convection column characteristics.

Fire whirls are a common sight on fires, most of them being short lived and remaining within the burn area. Sizable fire whirls, as determined by large amount of fuels being burnt, atmospheric instability and local wind patterns, can increase spotting activity by transporting larger firebrands into the convection plume as well as carry burning material outside the fire perimeter to contribute to fire spread.

The characteristics of the plume above the fire can be an indicator of the combustion dynamics and the surrounding fire environment (e.g., atmospheric stability, shear layers, effect of wind on the overall fire propagation). The plume colour (white, grey, black) is an indicator of the fuels burning and intensity of the headfire. The more intense the fire, the darker the smoke as a result of incomplete combustion occurring in the flaming front. The angle of the plume can indicate the influence of the wind on the fire. The height of the plume and the height at which condensation occurs can be estimated from nearby aircraft of from knowledge of the structure of the atmospheric boundary layer.

2.2 SUPPRESSION ACTIVITIES AND EFFECTIVENESS

Knowledge of the extent of suppression activities and their effectiveness is required to (1) understand how fire growth and shape are constrained from their natural development; and (2) understand and evaluate the effectiveness of different suppression actions for containing fires. Suppression details should be sought from three main perspectives, fireground incident controllers, crew leaders and crews operating suppression units (such as tankers) and those coordinating aerial suppression operations. Some of this information may also be available in agency incident logs and databases such as turnout times. Increasing, fire agencies are using GPS-enabled radios and vehicle tracking systems collected in central databases, as well as centrally collated aviation suppression (drop) data. These are opening up new avenues for reconstruction methods, but require strict business and privacy rule compliance, and are usually on valuable to the extent that the suppression activities are contextualised by crews and managers performing or directing the tasks.. As a result, obtaining details directly from the personnel involved remains extremely valuable, even if done through conversation.

The fireground incident controller will be able to provide details on aspects such as the priorities for suppression and rationale behind the selection of tactics, including how these change over time. On large fires it would also be valuable to collect this information from divisional or sector commanders. A range of people may act in these roles over the course of larger and longer running fires and it is important to try and interview those who acted in this role particularly during initial attack, times of peak fire activity and when fires burn through fuels of interest. The first incident controller will often be the crew leader of the first arriving unit. Details from their initial size-up of the fire will provide valuable insights on growth and development of the fire. Often the first incident controller will hand the role over to a more experienced person (e.g. group officer) travelling in a dedicated vehicle. These incident controllers will also provide valuable perspectives on the suppression operation, particularly when they have coordinated suppression during peak fire danger conditions, when a fire has burned through multiple fuel types and when they have worked in this role over longer periods (i.e. > 2 hours).

Crew leaders and crews conducting suppression operations on the fire will be able to provide valuable information on the difficulty and effectiveness of their actions. Experienced personnel will be able to provide useful comparisons to other incidents, including those in more typical grassland fuels. Suppression crews and crew leaders will also be able to provide information on the locations (parts of the fire and geographic locations) where they worked, the other units they worked with (including aircraft), the techniques they used, such as the methods used to apply water (e.g. from front mounted monitor, crew bay or external hose) and ignited back burns, and the specific roles, such as knock down and mop-up, they undertook. They can also provide information on issues that may have affected their operations, including access to fire and water points and fire behaviour changes in different fuel types.

Information from airborne aerial suppression coordinators, such as air attack supervisors, will be able to provide the details of the priorities and tactics used in the aerial suppression, including parts of the fire suppressed, how they integrated with ground suppression, and their effectiveness.

All three of these personnel types may be able to provide valuable data in the form of photography, videography and GPS data. Incident controllers may also have incident logs with information such as fire locations, resource deployments and weather observations. A guide for questions for these three personnel types is provided in Table 3.

Table 3. A guide for questions for key personnel. Sections 3-5 should be applied to individual phases of suppression (e.g. specific roles, assignments or sections of fire) and repeated for subsequent phases.

Field	**Fireground incident controller**	**Crew leaders and crews conducting suppression**	**Airborne aerial suppression coordinators**
1) Background information	Name, unit attached to, normal role, contact details, experience with fires in this fuel type		
2) Response	Time alerted for incident, time arrived on scene, other units on fireground at arrival, time commencing suppression		
3) Size up, priorities and objectives	a) What did the fire look like (extent, flame height, smoke characteristics)		
	b) What were the initial suppression priorities and objectives?	b) What were your objectives?	b) What were the initial priorities and objectives for aerial suppression?
4) Tactics and techniques	a) What tactics were selected and why? b) Were there any / what limitations were there to tactical options?	a) What roles (e.g. knockdown, mop up) were you tasked with? b) What other units were you working with? c) Where did you work (location with respect to fire and landscape)? d) What application techniques were used? (e.g. to apply water)	a) Where were aerial drops made (location with respect to fire and landscape)? b) Were aircraft working with ground units? c) Details of drops including load types and requested execution such as coverage levels and application (e.g. half on half off).
5) Limitations, difficulty and effectiveness	a) Did the operation go as planned? b) What was the effect of suppression on fire behaviour (e.g stopping flanks/ narrowing and slowing head, lessen impact of wind change)?		

	c) How did suppression compare to other fires that you have worked on?		
	d) Were there any unexpected issues that impacted or aided suppression (e.g. accessibility, water availability)? e) Did you persist with the planned tactic or have to change?	d) Were there any issues that may have affected or aided their operations, including access to fire and water points and fuel changes influencing fire behaviour?	d) Were there any issues that may have affected or aided their operations? e) What were the flying conditions like? f) Were the turnaround times reasonable?

2.3 FUELS

A wildfire will typically burn through a mosaic of fuel types and conditions. For the specific case of fires in cropland fuels, the emphasis should be on understanding the fuel's spatial distribution and assessment of its condition. T here are three predominant crop types in Australia—cereals (grains harvested from various grasses such as wheat, barley or oats), pulses (seeds harvested from legumes, generally in a dried state) and canola. For the purposes of fire reconstruction these fuels need to be described and quantified in a manner similar to those pastures or open grasslands. That is their current state at the time of a fire needs to be described in terms of at least their condition and curing. Further description, such as crop or stubble height, row spacing, sowing pattern, time since or to harvest, dead or alive and grazing activity should be noted if possible.

2.3.1 Fuel map

An accurate fuel map is critical to understanding fire spread patterns, suppression success or failure. It will probably not be possible to develop an accurate fuel map for the wildfire area during the main periods of fire propagation. As the fire will consume most fuels, observation of fuel features and sketch their distribution during the fire, albeit in a rough manner, will likely e very beneficial for developing the fuel/crop map for the fire area. Observers should try to note key fuel features and sketch their distribution ahead of the fire. This can be carried out in a portable GIS environment, hand drawn maps, or through annotated oblique aerial photographs. Features to include are described in the next two sections.

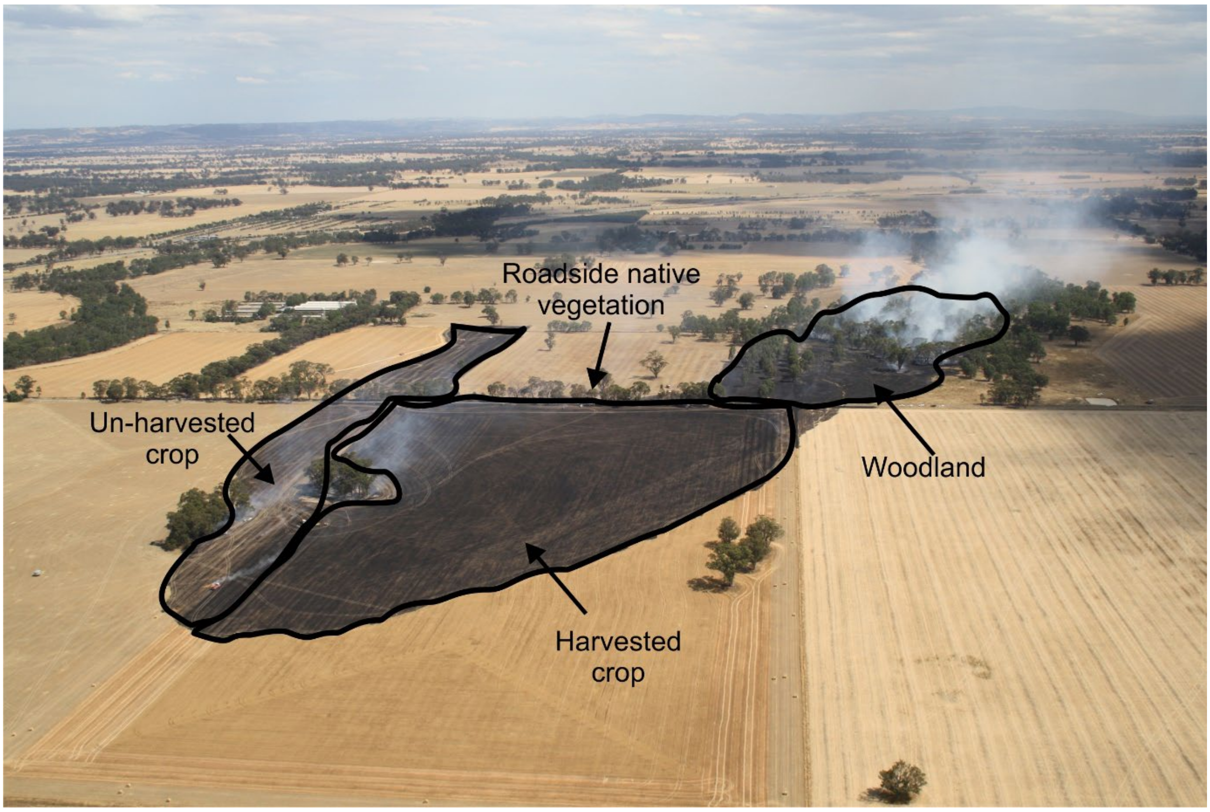

Figure 2. Sketch made of oblique aerial photo of fire in cropland depicting crop conditions and fuel types. Background photo from Wayne Rigg, CFA.

2.3.2 Crop type and condition

There are two primary conditions to be considered: harvested and not yet harvested. Prior to harvest the crop will likely form a continuous layer of fuel. In the case of cereals, this sward will have great similarities to continuous pasture or open grassland. After harvest, the height and bulk density of the fuel bed will be greatly reduced and, depending on the distance between rows and row alignment with wind direction, decreased horizontal fuel continuity might affect or even limit fire propagation.

Primary observation sources of the condition of crops burning during the fire event (crop type, condition, location, time) will be useful for validating other data sources accessed post-fire.

Table 4. Crop information relevant for reconstructing crop status as a wildfire fuel

Crop/fuel attribute	Description
Crop / grassland type	Cereal, pulse, canola, pasture or other. Note crop species if possible
Crop / grassland condition	Pre- or post-harvest; if grassland or improved pasture, note if natural, grazed or eaten out
Crop greenness / curing	Scale of curing 0 (green) – 100% (fully cured)
Height / spacing/continuity	Note height of crop or stubble and spacing between plants
Other fuel types	Note BFC fuel type (Appendix 5), particularly their occurrence along roads. If time available and size of unit warrants, conduct overall fuel hazard assessment.

Quantification of other fuel attributes such as load (biomass per unit area) and bulk density may assist in determining applicability of assumptions of fire behaviour after the fact.

2.3.3 Crop greenness/degree of curing

Prior to harvest, crops may still be green and growing and thus consideration of greenness status or degree of curing is required. Cereal crops tend to follow a senescing process akin to natural grasslands. For such crops one should quantify their degree of curing, or the proportion of dead material. This quantity can be estimated visually using the Victorian Country Fire Authority Grassland Curing Guide (CFA Fire and Emergency Management 2014). Observations of partially cured grassland areas, namely in locally anomalous areas such as in or next to gullies or creeks should be recorded. Variability on this scale is not captured at the spatial resolution of the satellite other than in the average over a whole 375 to 500 meter pixel.

Some crops (particularly pulses but also canola) are treated with a desiccant (similar to a herbicide) to kill off and dry out the crop (and also weeds) prior to harvest. Assessment of whether a crop has been treated and to what extent it has desiccated should also be noted.

2.3.4 Fuel moisture and its assessment

Fuel moisture content can be directly measured by sampling fuels and drying them in an oven, measured indirectly using portable instruments (such as Neosystems and Wiltronics fuel moisture meter) that derive the moisture content of a sample from gravimetric or electrical resistance, or estimated using a model.

During a wildfire event it will typically be impractical to sample fuel moistures over a broad spatial scale and along the temporal length of the fire. However, if the opportunity presents itself and resources are available, samples of live and dead fuel moisture should be made.

Three to four representative samples (20-30 g) of live or dead fuel should be collected and sealed in airtight containers (metal tins or plastic boxes, sealed with sticky tape if possible—do not collect samples in paper bags as moisture will be lost out of the sample bag.

Samples should be weighed (w_{wet}) as soon as possible after collection. Hand-held scales can be utilized for this. Samples should then be oven-dried for 24 hours at 105°C and then reweighed (w_{dry}). Fuel moisture (Mi) can then be determined as:

$$M_i = (w_{wet} - w_{dry})/w_{dry} \times 100 \qquad [3.2]$$

Operators should be careful to ensure that errors introduced by inorganic material (e.g. rocks) or effects of air movement over balances are minimised. Direct measurements of fuel moisture from oven drying samples provide the most accurate measurement of fuel moisture, and should be used if possible.

Estimates of dead fuel moisture should be made at hourly periods during the propagation of the fire, and after significant changes in the air mass (e.g., frontal passage or sea breeze arrival). Portable fuel moisture measuring instruments, such as Wiltronics, can be used, but users should be aware of possible difficulty in preparing the sample and should ensure that the calibration being used is applicable to the grass/crop type being sampled. It is advisable that specific calibrations are developed for dry grass fuels. Use of incorrect calibration can lead to errors.

2.4 WEATHER

The aim of measuring meteorological variables is to accurately define the conditions under which a fire is burning. Primarily weather, or meteorological quantities include: air temperature, relative humidity, wind speed and direction, but can also include rainfall, solar radiation, cloud cover and atmospheric stability. Changes in weather conditions may occur quickly and result in rapid and possibly extreme changes in fire behaviour. Hence, observations of weather must be accurate in time and space.

Given the unexpected occurrence and fast spread of cropland fires it is expected that the bulk of the weather data to be used in the case study analysis will come from already established Bureau of Meteorology Automatic Weather Stations (AWS). When feasible, the use of a Portable AWS (PAWS) close to the fire area will allow for more accurate understanding of the conditions driving the fire. PAWS setup up should follow WMO standards (WMO 1996), namely in regards to the effect of obstructions to the measuring of wind speed and direction and the periods over which observations should be averaged.

In the event of lack of AWS in the fire area, one should investigate the use weather stations from organizations other than BoM. Agri-business, wind farms, and certain land management or fire control agencies have automatic weather stations that can provide suitable data for the case study development.

Table 5. Relevant meteorological variables to quantify

Meteorological variable / condition	Comment
Air temperature	If measured using handheld devices it should be measured in the shade. Measurements should be conducted half-hourly or after the occurrence of particular events such as frontal change or arrival of sea breeze.
Relative humidity	If measured using handheld devices user should ensure sensor is calibrated. Measurements should be measured in the shade every half-hour or after the occurrence of particular events such as frontal change or arrival of sea breeze.
Wind speed	Should be measured in the open away from obstructions (see standard in Appendix 4). If using a hand-held device, measurements should be conducted over a period of 5-10 minutes, with average and gust speeds recorded. Measurements should be conducted every half hour following an established chronology.
Wind direction	Same as above
Cloud cover	Not always provided by BoM. Should be estimated in the field in eighths of cloud cover (i.e. oktas) where 0/8 is clear sky, 8/8 is completely overcast sky.
Atmospheric stability	On-site atmospheric lapse rate can be obtained from aircraft flying above the fire. Direct measurements can be obtained from

	launching a weather balloon. Estimated values can be obtained from meteorological models
Vertical wind profile	Direct measurements can be obtained from launching a weather balloon. Estimated values can be obtained from meteorological models

To complement AWS data, a fire observer can conduct periodic, possibly every 30 min, observations of temperature, relative humidity and eye level wind speed and direction within a few kilometres of the fire area. Handheld instruments, such as Kestrel®, or similar can be used to provide these point location measurements. It is important that these measurements are not influenced by the fire. Use of the Beaufort wind scale, observation of cloud cover, wind gustiness and wind changes (frontal passages, sea breeze, etc) also can provide localised information that is unlikely to be measured at an AWS.

See Appendices for standards to measure weather quantities.

2.5 BE PREPARED

A wildfire event, with its rapid propagation through the landscape and the hazard it poses to communities and firefighters alike has the potential to create somewhat chaotic situations. Attempting to collect data and stay informed of fire propagation dynamics during a wildfire event benefits from prior planning and the establishment of a network of contacts associated with fire suppression activities. In the it is provided an equipment checklist normally required to conduct most of the fire observations and measurement and estimation of environmental conditions. Detailed checklist of activities to conduct during and after the fire event are given also in the appendices section at the end of this guide.

3. DATA THAT CAN BE COLLECTED AFTER THE FIRE

Once the fire event is over and the fire has been extinguished the task of collecting the remaining critical information on the burning conditions, fuels and fire behaviour begins. While not as time sensitive as data collection during the fire event, these data are not indelible and must be collected as soon as possible after the fire. Physical evidence disappears and memories fade. It is important to get into the field around the fire as soon as possible to begin the collection of post-fire information before data collection becomes too difficult.

As indicative timing for collecting post fire data, the preferred period will be within a week after the fire. The further the data collection period extends beyond the first week after the fire, the lower the quality of the data. Most data will be of reasonable quality within 2 to 3 weeks after the fire, but expect the quality to be degraded with time. Field and interview data will be of limited value when collected 1 month or more after the fire.

Often fire events will occur simultaneously or on consecutive days, reducing the ability to respond to the post-fire investigation phase as rapidly as would be liked. In these instances, prioritisation and synergistic data collection are essential.

Interviews with key personnel involved in the suppression of the fire, namely air support and ground crews, plus members of the public that might have direct contact with the fire (e.g., farmers), should have priority while the events are fresh in their memory. If key firefighting personnel were alerted to the need for the collection of critical data before or during the fire event, ensure that these data (including photos, videos, etc) are collected during the post-fire interviews.

Table 6. Checklist for post fire key activities and data needs. See updated checklist in appendices

Order	Key post-fire activities
1	Contact agency duty officer/district contact for approvals
2	Contact Incident commander and relevant brigades for interviews Contact land owners
3	Acquire GIS information, including topography, vegetation maps, crop maps, etc
4	Acquire weather data
5	Acquire relevant fire intelligence data (line scans, photos, videos, sketches, fire logs)

3.1 FIRE PROGRESSION AND SUPPRESSION ACTIVITIES

Interviews with selected personnel involved in the fire should be undertaken to try to establish fire progression and time of fire arrival at know locations. Effectiveness of fire suppression actions and the resources involved in them should also be described and mapped.

There are three main perspectives that will provide valuable insights into the suppression operation, fireground incident controllers, crew leaders and crews operating suppression units (such as tankers) and those coordinating aerial suppression operations. A guide for questioning personnel in these roles is provided below in the field sheets (Appendix …).

Targeted requests for digital media should be made to gather available photographic and video evidence collected during the fire where appropriate considering investigations and public sensitivity. Review of radio log books as well as incident reports should be also carried out to find details of fire location with time. Fire cause and location should also be determined at this stage, if possible.

Interviews with local farmers involved in fire suppression or affected by the fire should also be undertaken. These interviews will be necessary to ascertain crop status. A call for digital media should also be made to local residences. See field sheet with interview guidelines to members of the public.

3.1.1 Post-fire footprint/burned area

The fire area should be flown after the event to take vertical or oblique photographs of the area impacted by the fire. This information can also be used in the interview process. The use of remote piloted aircraft (RPA), also known as drones or UAVs, can provide low cost detailed footage of the burned area. RPA footage can also be super-imposed over pre-fire imagery and GIS layers. Identification of zones where the headfire or flank fires crossed areas of fuel discontinuity, e.g., wide roads, should also be made.

Figure 3. Aerial oblique photo from a crop fire burning through a mosaic of crop conditions. Photo by Wayne Rigg (CFA).

3.2 CROP STATUS/FUEL DISTRIBUTION

Once the extent of the fire propagation is known, a priority task is to develop a map of the crops and fuel types that were involved. This will involve ground reconnaissance and interviews with land owners, such as farmers and land management agencies.

3.2.1 Crop information/fuels

The pre-fire status of the burned crops should be established after the fire while evidence is fresh. Part of this information can come from interviewing land owners and inspecting similar crops nearby that were unaffected by fire. As part of this work a map with the spatial distribution of crops and other fuels in the burned area should be made.

As described in Section 2.3.1, burned areas should be identified by crop type used, its condition (standing or harvested, desiccated, etc) and greenness/degree of curing. (Table 7). Identification of other relevant fuel types within the burned area should also be mapped.

After identification of the main crop types burned, i.e., the crop types that were most relevant for the fire propagation, an effort should be made to find published quantitative data on the physical structure of the crop. In the absence of such information an effort should be directed at sampling the structure of the target crop in their unburned condition in the vicinity of the fire. A methodology to sample crop fuel load and structure is given in the appendices. Photographs of nearby unburned crops should be taken.

Table 7. Post fire crop and fuel condition assessment

Fuel assessment activities	**Timing**
Contact and interview landowner	Within 2-3 days after fire
Establish main crops and crop history (e.g., prior crop, prior harvest method, etc)	Within a week after fire
Sketch a map with crop species, condition and distribution	Within a week after fire
Identify other relevant fuel types and barriers to propagation within the fire area	Within a week after fire
Determine if crop sampling is necessary; establish sampling areas with owner authorization	Within a week after fire
Conduct fuel sampling of relevant crops	Within 2 weeks after fire

In case some crops were not fully cured, sample of relevant live fuels should also be undertaken for live fuel moisture estimation on the immediate days after the fire. A curing map should be produced for the final fire area.

Areas burned by the fire with fuels other than crops, e.g, pastures, woodland, shrublands, should be described following the Bushfire Fuel Classification top tier description appendices.

3.2.2 Fuel moisture and its assessment

After the fire, estimation of the moisture content of dead grass fuels for the duration of the wildfire can be made using the equation suggested by Cheney et al. (1989) that mathematically describes McArthur's (1960) fuel moisture tables.

$$M_e = 9.58 - 0.205\,T + 0.138\,RH \qquad [4.1]$$

where M_e is the estimated dead grass fuel moisture content, T is air temperature (°C) and RH is relative humidity (%). This equation has been shown to perform well over a range of moisture contents present during wildfire events (Cruz et al 2016).

Estimates of dead fuel moisture should be made for hourly or half-hourly periods during the propagation of the fire.

Table 8. Post fire assessment of fuel moisture content

Activities	Timing / comment
Acquire detailed (30 m or less measuring interval) weather data from meteorological stations within the fire area.	Within 2-3 days after fire; might require local contact for information of non-standard weather stations.
Visit fire site to identify areas with live or non-fully cured fuels	Within 2-3 days after fire;
If non-fully cured fuels are deemed relevant, conduct fuel moisture sampling and assess curing level	Within 2-3 days after fire
Calculate time-series of fuel moisture content during fire event.	Within 2 weeks after fire

If it is believed that some of the important fuels were not fully cured or dead, then it would be advisable to collect samples of these fuels in the day after the burn if the weather conditions are similar. Three to four representative samples (20-30 g) should be collected and sealed in airtight containers (metal tins or plastic boxes, sealed if possible). Fuel moisture estimation should follow the process described in section 3.3.4. Similar protocol can be followed to obtain dead fuel moisture samples to calibrate estimated values.

3.3 WEATHER AND CLIMATE INFORMATION

Possible sources of weather and climate data should be established and mapped. This will include data from the Bureau of Meteorology AWS network and other possible sources (e.g., Department of environment; ranger or fire stations, industry, PAWS). Weather data should be collected at the lowest time interval possible. The BoM AWS network stores data every 10 minutes. Weather data to be collected should also include the days preceding the fire.

Weather data of interest is wind speed and direction, air temperature, relative humidity, cloud cover and precipitation. Information on other meteorological aspects such as solar radiation, barometric air pressure should not be discarded.

Climate data should also be collected for the nearby weather station. For this, daily values of wind speed and direction, air temperature, relative humidity, precipitation and drought codes should be determined.

If available from nearby locations, radar and Doppler data should be acquired.

3.4 TOPOGRAPHY

3.4.1 Digital elevation models (DEMs) or Digital Terrain Models (DTMs)

Information on topography can be found from digital elevation or terrain model (DEM or DTM). This information should be available from local land management agencies or organisations such as Geoscience Australia or Google Earth. Slope and aspect can be calculated from a DEM.

3.5 ASSESSMENT OF DATA RELIABILITY

Reconstructing the propagation of a free-spreading wildfire involves a high degree of uncertainty. The more information about the conditions and spread of a fire, the better the reconstruction will be. However, the diverse sources from which information can be collected (see following appendices) will have a broad range of reliability which will ultimately affect uncertainty in the reconstruction. In order to combine the information from these disparate sources data must be categorised by the reliability index given in Table 9) from 1 (most reliable) to 5 (least reliable).

Four classes of rating category are given: weather, dead fine fuel moisture content, fuel complex (type), and fire behaviour (rate of spread). For the most part, a rating category of 1 results from direct measurement or observation as part of a consolidated data collection regime. A rating category of 5 is inferred from observations or measurements made a large distance from the event or inferred from indirect or second-hand assessments.

When reconstructing a fire event sometime after data have been collected, the reliability index will allow you to weight potentially conflicting or contrary observations by their reliability.

Table 9. Summary of data reliability ratings and descriptions where 1 is most reliable and 5 is least reliable

Rating	Weather	Fine fuel moisture content	Fuel complex	Rate of spread
1.	Nearby (<25 km) meteorological station or direct measurements in the field with high quality instruments, and/or validated modelled wind field .	Point measurements made at time of fire and extrapolated to fire area taking into account topographic effects	Fuel characteristics inferred from a fuel age function developed for the particular fuel type/area.	Direct timing of fire spread measurements i.e. IR scans, aerial observations, observed reference points with photographs.
2.	Meteorological station within 50 km of the fire with no local effects (i.e. terrain, vegetation) on the wind field, and/or partially validated modelled wind field.	Single point measurements within or in the vicinity of fire area.	Fuel characteristics inferred from a visual assessment or measurements of nearby unburnt forest.	Reliable timing (within +/- 15 min) of fire spread by field observations with general reference points.
3.	Meteorological station within 50 km of the fires but there are local effects on the wind field or the data not representative of the fire area. Meteorological station > 50 km of the fire, reconstruction of wind speed for fire site. Unvalidated modelled wind field.	Estimation of fuel moisture through validated models taking into account topographic effects.	Fuel characteristics inferred from a fuel age curve for a forest type of similar structure.	Reconstruction of fire spread with numerous cross references.

4.	Spot meteorological observation near the fire.	Estimated fuel moisture for nearly (< 25 km) meteorological stations	Fuel characteristics typical of equilibrium level in the representative fuel type.	Doubtful reconstruction of fire spread.
5.	Distant meteorological observations at locations very different to fire site.	Estimated fuel moisture for distant (> 50 km) meteorological stations	Qualitative fuel type description	Anecdotal or conflicting reports of fire spread.

4. DOCUMENTING THE FIRE EVENT

After a fire event ends, the process of piecing together all the bits of information available and developing a coherent description of the fire propagation and behaviour begins. As mentioned before, there is not a defined recipe of how to make a wildfire case study. The depth of detail in a wildfire case study will depend on the information available and its relevance. Alexander and Thomas (2003) suggest the following outline to organise the available data:

1. Fire chronology and development
2. Fire environment
    a. Topography
    b. Fuels
    c. Fire climatology weather
3. Analysis of fire propagation and behaviour

4.1 FIRE CHRONOLOGY AND DEVELOPMENT

The description of the fire itself will rely on putting together all the available information about the fire, namely the cause of the fire and time of ignition, fire location with time, details on initial attack activity and other suppression, namely aerial fire suppression, actions. As a first step this data should be organised chronologically. From the knowledge of the fire events and their relevance, the fire should be divided into discrete phases that highlight the importance of particular periods of fire propagation. Each phase will then be populated with the available information, e.g., fire front and perimeter locations, fuel consumption patterns, etc.

As data is put together within a spatial and temporal context one starts to get an appreciation of how the fire developed thought the landscape. At the same time, one will note a number of inconsistencies in reported fire locations and exhibited fire behaviour. It is common for personal observations of a fire event to differ significantly between nearby observers, depending on a number of factors including the person's psychological state and experience. A person's recollection of an event may differ significantly from another's, and in the aftermath of a disastrous impact, what may be considered a 'true' account of it may not reflect the 'facts' of that event. Probably the most important component of the case study development is to recognise the value, or lack of value, in the available information. The individuals conducting the fire reconstruction will need to use care and their best judgement to identify the relevant data and to provide a rationale for the exclusion of any data. The categorization of data by reliability level will resolve some of the conflicting information.

The next step in the mapping of the fire propagation is to identify events, e.g., spotting occurrence, changes in fuel type in headfire region and wind direction changes, which might have a significant impact on the overall fire dynamics. From the available information it should be possible to delineate headfire, and perimeter, regions with time. This information will in turn allow to determine rates of fire spread and energy release for certain fire spread periods.

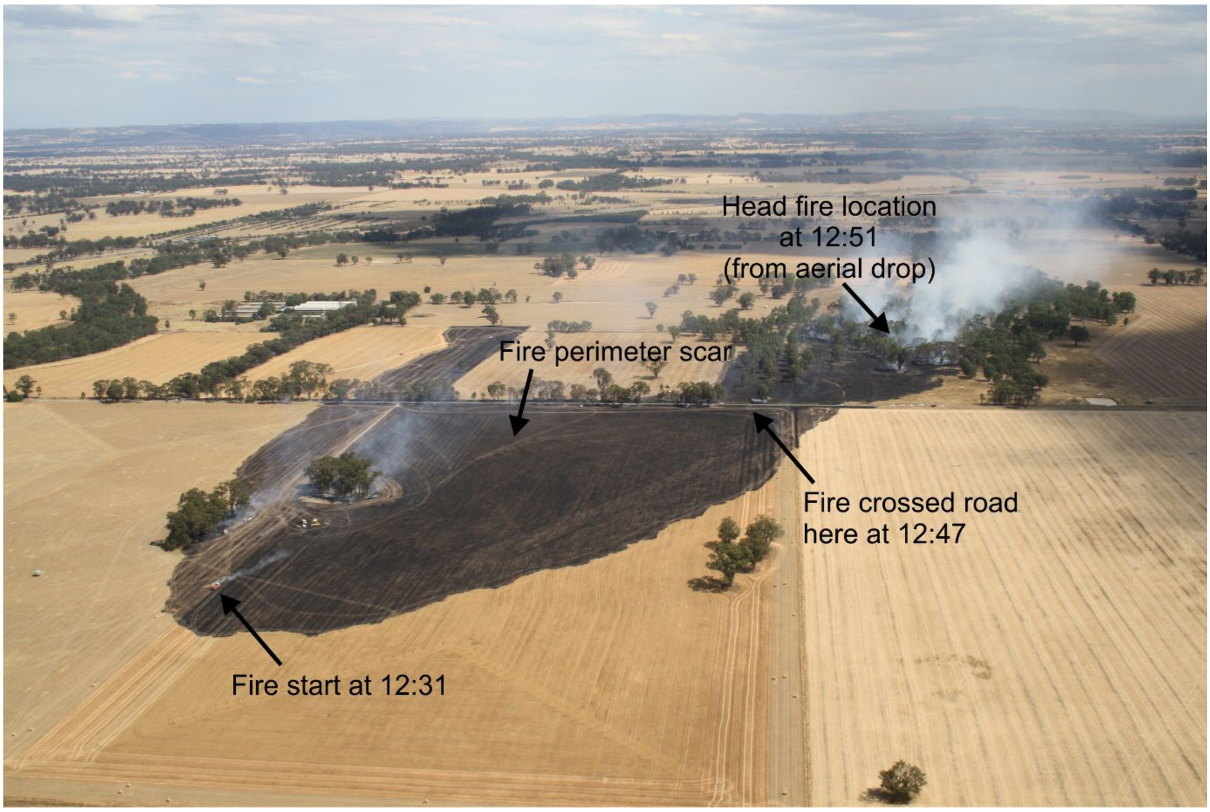

Figure 4. Hypothetical summary of important timing of fire propagation obtained from eye witnesses and logged information imposed in an oblique aerial photo of fire in cropland fuels. Background photo from Wayne Rigg, CFA.

4.2 FIRE ENVIRONMENT

This section aims to catalogue and describe the key environment variables responsible for fire propagation.

4.2.1 Topography

The availability of topographic information will vary from detailed DEM available to be analysed within a GIS environment to hard copy tomographic maps. The topographic information will be used to support the analysis of fuel distribution and fire propagation. Topographic maps can help understand why fuels change on the landscape and why changes in fire behaviour occurred, namely due to the presence of particular topographic features.

4.2.2 Fuels

In this section the aim is to integrate the spatial information on crops and other fuels with point sample or standardised data. The first step of this process is to identify, map and describe the main fuel types in the fire area. After determining the spatial distribution of crops, the effort of fuel description should focus on those that are most relevant (e.g., higher area burned, unusual fire behaviour, etc). The crop / fuel description addresses the various aspects determining the physical structure of the fuel bed (see Table 7 as example). Crop description should include: crop type (cereal, pulse, canola), condition (pre- or post-harvest), greenness and height (as per Table 7). In case it is not feasible to conduct a field assessment of nearby unburned crop characteristics, some nominal values are provided in Appendix 1.

4.2.3 Fire climatology and weather

This section aims to summarise all relevant climate information and the fire weather driving fire propagation. From location characteristics and the onsite fire environment and weather description provided by witnesses one needs to identify which of the nearby weather stations are representative of the fire area. Climatic information, such as drought status, time since last rain event, prior heat wave conditions, spring frosts, etc should be collated. Information on crop greenness, grass curing and other live fuels availability should be also summarized.

After selection of the representative weather stations, one needs to summarise the key weather variables at half-hourly intervals (or less if possible). This detailed weather description should precede the occurrence of the fire by a few days to identify factors that might have conditioned fuel susceptibility to ignition and combustion. Descriptions of other atmospheric characteristics such as stability, wind changes, wind gustiness, etc should also conducted for the duration of the fire event.

4.3 ANALYSIS OF FIRE PROPAGATION AND BEHAVIOUR

This section focus on analyse and discuss the key fire propagation aspects, namely how fire behaviour related with weather and fuel conditions. Analyses of the effect of suppression operations on the various stages of fire propagation, and how it influenced fire shape and spread rates, should also be included.

If possible, in this section one should also contrast fire propagation simulations conducted during the fire event and analyse model adequacy to the fire being studied. One should also analyse the adequacy of the fire propagation models against the observed weather and fuel condition. This helps to reduce the uncertainty in the operational fire propagation simulations due to the use of estimated weather conditions and fuel distribution.

All data used in the case study should be provided to ensure that follow up analysis can be conducted by others without missing relevant information.

4.4 WRITE-UP

- A case study write-up should follow the outline described above, plus an introductory section where the significance of the fire is explained, its main features described, and lessons learned analysed. The write-up format, language and contents will vary according to the audience. For example, the style of a peer reviewed publication will and should be quite different from an internal agency audience where lessons management is the priority. At a minimum, the write-up should contain:The context of the reconstruction – why the reconstruction was performed and who for

- Document control and guidance as to the sensitivity and data privacy
- Basic and clear reporting on what is and is not available from the reconstruction (i.e. any missing components from the above sections)
- A simple timeline of the fire
- A description of where the generated reconstruction dataset is and will be maintained for future access

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APPENDIX 1: CROP TYPE AND CONDITION

Agricultural crops cover approximately 22 million hectares in Australia, representing about 2.9% of land area. There are 10 primary crops farmed in Australia with the predominant being wheat (60.3% by farmed area nationally), barley (19.8%) and canola (7.8%). Cereals (gramineous species consisting of wheat, barley, oats and triticale) represent approximately 84.5% of cropland by area, pulses (field pea, chickpea, faba bean, lupin, lentils) cover about 7.7% and canola covers about 7.8% of croplands. Each state has a slightly different mix of crops but these are not greatly different from the national picture.

Cereals: Cereals are a class of grass-like crop that includes wheat, barley, oats and triticale. These generally have similar morphology when fully cured but may differ in planting, harvesting and management practices.

Pulses: Pulse crops are legumes and include field pea, chickpea, fava bean, lentil and lupins. These crops have similar morphology within the group but differ significantly from cereals and canola. Different management and harvesting practices may result in significantly different morphologies prior to and post-harvest. Some pulses are sprayed with a desiccant (like an herbicide) to kill off the plant (and weeds) and commence drying of the harvestable pulse for harvesting. Some pulses are pushed into windrows prior to harvest (e.g., fava bean), which changes the fuel bed and potentially fire behaviour.

Canola: Canola or rapeseed is considered neither a cereal nor a legume and is a tall (up to 1 meter), slender plant, that flowers prolifically.

For more details and assistance with identification of crops, Agriculture Victoria offers extensive resources on identifying crops, their varieties and region at: https://agriculture.vic.gov.au/crops-and-horticulture/grains-pulses-and-cereals/growing-grains-pulses-and-cereals.

APPENDIX 2: FUEL TYPE AND RESTRUCTURE ASSESSMENT AND SAMPLING GUIDELINES

Fuels exist in a variety of forms, states, sizes and arrangements making efficient and precise sampling a challenging process. Assessing fuel characteristics and structure can be a long and time consumed process depending on the fuel characteristics being measured and the precision required. For the purpose of case study documentation, it is envisioned that a cursory fuel assessment is conducted.

In the event that the fire occurred in a crop type that has not been quantified or well described it is suggested that destructive samples be conducted of unburned crop fuels representative of the crop burned. We suggest a maximum of 10 destructive samples per significant fuel type, with each sample consisting of the fuel collected within a sample square 0.25 m^2 in size. The sampling procedure starts with the (a) selection of representative locations of average condition or (b) definition of a transect with samples collected at a set distance along its length (Figure A1).

At each sample location, crop/fuel height is measured and all fuels within a 0.5 x 0.5 m sample quadrat are to be harvest (Figure A2 and A3) and sorted by elevated (vertically oriented) and surface (laying on the ground) status. Samples are then bagged and transported to a laboratory for determination of oven-dried weight (dried at a nominal temperature of 105°C for 24 hours). Special care must be taken when sampling surface fuels so to not to collect dirt and rock particles, which will bias the fuel sample to high fuel loads. A description of crop and plantation type, plus its condition (harvested vs unharvested) should be made.

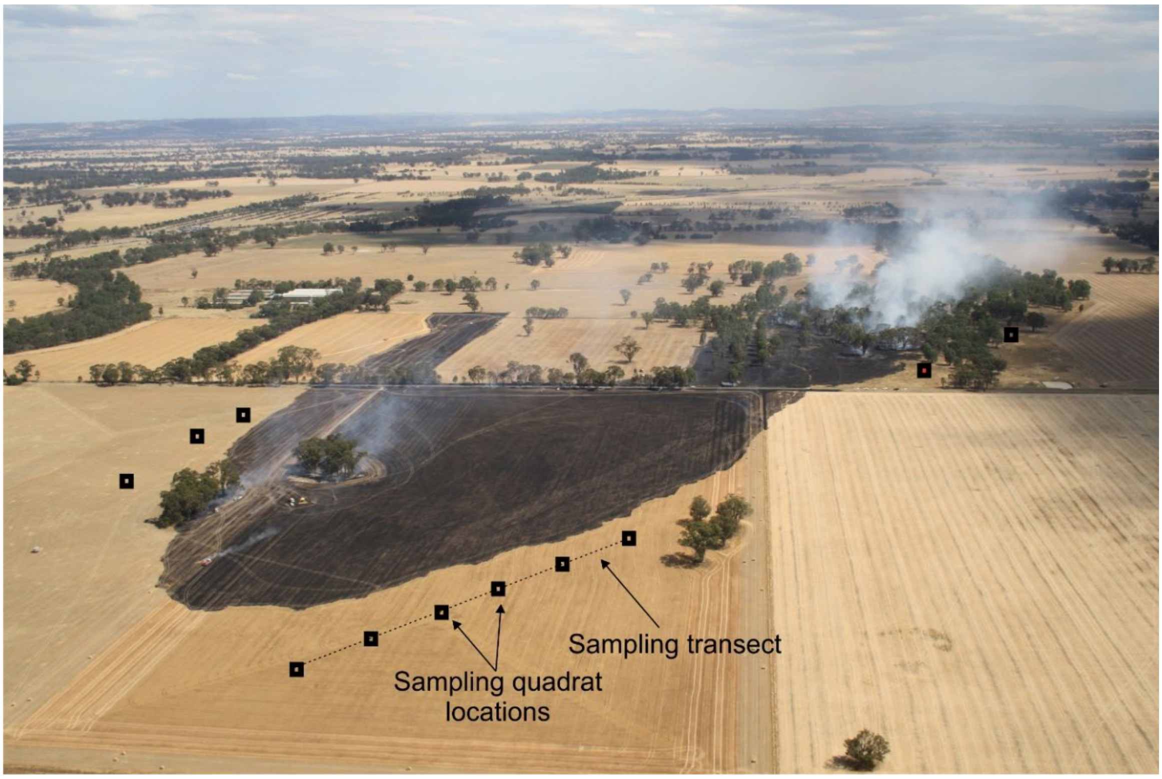


Figure A1. Example of location of fuel sampling quadrats used to quantify the fuel characteristics of various crop conditions representative of a wildfire. Background photo from Wayne Rigg, CFA.

Figure A2. Example of standing (vertically oriented) and surface (laying on ground) fuels commonly found in a crop area. Fuel assessment should sample the two fuel conditions separately.

Figure A3. Example of application fuel sample quadrat to estimate grassland fuel load.

Coarser estimates of fuel load without oven drying could be done by weighting the fuels in situ (e.g., with spring scales) and correcting the fuel weight with the estimation of the moisture content by Eq. 1 in Section 3.3.4.

APPENDIX 3: WEATHER OBSERVATION REQUIREMENTS

AIR TEMPERATURE

Air temperature is a relative measure of the warmth of the air and excludes the effects of radiative heating from sources such as the sun. It is measured in degrees Celsius (°C).

Air temperature can be measured using a variety of devices, from simple thermal liquid thermometers that need to be read manually to electrical thermocouples which measure the electromagnetic force generated by temperature gradients between the two ends of a circuit and which can be digitally recorded.

All types of thermometer must be freely exposed to the air but shielded (shaded) from solar radiation and moisture. In order to remove the influence of radiative heating from the sun and cooling from evaporating water, measurements should be made in the shade (for portable instruments) or in an instrument screen (if instruments are fixed) such as the Stephenson screen or Gill screen.

Air temperature should be measured in the shade at a standard height of 1.2 – 2 m above the ground. The instrument must be exposed to the air until it equilibrates with the ambient temperature. This is most easily achieved by taking successive reading at regular intervals, e.g. 30 seconds, until the reading stabilises.

AIR HUMIDITY

Humidity is a measure of the amount of water vapour in the air. Humidity can be given in terms of absolute humidity or relative humidity. Relative humidity is the ratio of the amount of water vapour in the air to the amount required to saturate the air at its current temperature. Relative humidity is usually expressed as a percentage. Absolute humidity is the mass of water vapour in a given volume or mass of air. There are several ways of describing absolute humidity, including the mass of water vapour per kg of air, or the pressure exerted by water vapour in the air. However, the most common measure of absolute humidity is the dew point temperature. Dew point is the temperature to which the air must be cooled before relative humidity reaches 100% and dew forms. A higher dew point means that there is more water in the air. Dew point is also important because it allows the recognition of changes in the water content of air masses and hence the potential for very low relative humidity or for dew to form overnight.

While dewpoint and other measures of absolute humidity give good technical description of humidity, in fire work we are most interested in the effect of humidity on fuel moisture and hence fire behaviour. Therefore, relatively humidity is the most common measure of humidity as is used for simplicity. Provided air temperature and one of relative humidity or dew point are record it is possible to convert between the two humidity measures using tables or equations. Relative humidity must be measured in the shade. Some electronic instruments are capable of reporting both relative humidity and dew point.

The use of a psychrometer is advised. If using an electronic hygrometer such as implemented in pocket weather meters, ensure it has been recently calibrated.

WIND

Wind is the most dynamic variable affecting fire spread and is the most difficult quantity to measure, apart from the fire itself, because it is highly variable in both space and time. Observations and models suggest that fire responds instantaneously to wind in a non-linear manner such that short-term variation in wind speed results in amplified variation in rate of fire spread. In addition, the source and direction of the wind may determine the nature of the humidity and temperature regime.

Wind speed may be expressed as meters per second, kilometres per hour, or knots (nautical miles per hour). It is essential that units be recorded because wind speeds in each of the three conventions are of similar magnitude, e.g. 10 m s-1 = 36 km h-1 = 19 kt. Wind direction is the magnetic direction from which the wind is blowing, from 0° to 360°. Since 0° and 360° could both indicate a wind from the north, 0° is reserved for calm conditions and 360° signifies a wind from the north.

Three categories of wind measurement are made in bushfire work, each of which require different measurement strategies but use similar instruments. The first is measurement of wind in the open away from the influence of fire. The second type of measurements is those made under the canopy in the absence of a fire. These are used to examine the wind in the forest and to relate it to the wind in the open. The third type is wind measurements made in the vicinity of a fire. The wind in the open is most useful for the spread of crop fires, but it can be worth noting under canopy winds as fires in croplands will often encounter trees at roadsides. Measurements in the vicinity of the fire can be used to investigate localised effects, but are typically not as useful for repeatability. For example, a fire spread simulation would only use open wind measurement away from the fire.

Because the wind speed varies rapidly in time an instantaneous reading is of little use and some form of average must be taken. For anemometers where the user must manually record the wind speed, a 2-minute or 10-minute average is recommended. This ensures that the measurement encompasses a period with gusts and lulls. Some electronic devices will calculate an average automatically but the user may be required to estimate the average. The record should include: wind speed to the nearest 1 km/h, the height of the measurement, and a description of the location including proximity to the fire and forest canopy cover, if any.

Wind direction should be recorded to the nearest 10°, from 10° to 360°. The same averaging methods should be applied as are used for the wind speed measurements. It is important to note that it is not correct to simply take the average of several wind direction observations. For example, the average of wind directions 350° and 10° is 360°, not 180°. Instead, it is necessary to add or subtract 360° from successive observations to ensure continuity within an averaging interval. Where possible it is preferable to calculate the vector components of the wind from speed and direction and average the components. If a wind vane is not available when making observations with a hand-held anemometer then wind direction may be estimated and recorded as a compass-point, e.g. N or SW.

When measuring instruments are not available it is possible to make a subjective assessment of wind speed and direction. Wind speed may be estimated using the Beaufort scale, which associates a range of wind speeds with the effect of the wind on trees and smoke (Table 10). Wind direction may be estimated by observing the motion of foliage or a streamer attached to a tall pole. Where possible the observer should stand below the streamer or foliage. The movement of clouds should never be used to estimate surface wind direction. Records of manual wind observations should include: Beaufort number, wind direction as a compass point, e.g. N or SW, and a description of the measurement location including proximity to the fire and forest canopy cover, if any.

Table 10. The Beaufort wind speed scale (adapted from WMO 1996)

BEAUFORT NO.	BEAUFORT DESCRIPTION	WIND SPEED EQUIVALENT AT 10 M ABOVE OPEN FLAT GROUND (KM/H)	SPECIFICATION FOR ESTIMATING WIND SPEED OVER LAND
0	Calm	<1	Smoke rises vertically
1	Light air	1 - 5	Direction of wind shown by smoke drift but not by wind vanes.
2	Light breeze	6 - 11	Wind felt on face; leaves rustle; ordinary vanes moved by wind.
3	Gentle breeze	12 - 19	Leaves and small twigs in constant motion; wind extends a light flag.
4	Moderate wind	20 – 28	Raises dust and loose paper; small branches are moved.
5	Fresh wind	29 – 38	Small trees in leaf begin to sway; crested wavelets form on inland waters
6	Strong wind	39 – 49	Large branches in motion; whistling heard in telephone wires; umbrellas used with difficulty.
7	Near gale	50 – 61	Whole trees in motion; inconvenience felt when walking against wind.
8	Gale	62 – 74	Twigs break off trees; progress generally impeded.
9	Strong gale	75 – 88	Slight structural damage occurs - roofing dislodged; larger branches break off.
10	Storm	89 – 102	Seldom experienced inland; trees uprooted; considerable structural damage.
11	Violent storm	103 -117	Very rarely experienced - widespread damage
12+	Hurricane	118 and over	Cyclonic

WIND MEASUREMENTS IN THE OPEN

The World Meteorological Standard for siting of wind speed measuring devices is at a height of 10 m above level ground in the open, where the open is defined as a cleared space at least 10 times the height of the nearest obstacle in radius. For greater accuracy, the WMO recommend a distance of 30 times the height of the nearest obstacle.

It may be difficult to find such a location in the proximity of a wildfire. However, it is important that the wind is measured at 10 m in as open a space as possible. This is because the Bureau of Meteorology base all wind measurements and forecasts on 10 m wind in the open and all operational fire behaviour models must use this information. Wind speed measured at heights other than 10 m can be converted to an equivalent '10-m' height through the implementation of assumptions about the nature of the boundary layer flow of air near the ground. The measured wind speed should always be recorded and corrections applied during data analysis.

Topography may significantly influence wind velocity and direction. It is important to select a site that is as free as possible of topographic relief. If this is not possible, the aspect and degree of slope must be recorded, along with the height above ground of the anemometer.

Topography, height and a description of the area surrounding of the instrument must be recorded and associated with any measurements. The aim when measuring the speed of the wind is to obtain a value that is representative of an area. In general, the area being represented should be as large as possible such that the representation is applicable to an area greater than that where the anemometer is located.

RAINFALL

Rainfall, and especially recent rainfall, is an important parameter in determining fuel moisture content. Rain is measured using a rain gauge or an automated device such as a tipping bucket. These devices catch the rain from a determined area and convert the total amount of water or depth of water to a depth of water per unit area in millimetres. The rain gauge should be located in an open area with no nearby obstructions. Ideally the gauge should be in an open area with radius at least twice the height of the nearest obstacle. Standard plastic rain gauges should be mounted on or close the ground above grass or gravel so that they will not intercept splash from the ground nor be overly affected by strong wind. Automatic tipping bucket rain gauges are usually placed on the ground.

APPENDIX 4: OTHER METEOROLOGICAL VARIABLES

SOLAR RADIATION

Solar radiation provides energy to heat fuels, aiding drying after rain and lowering the moisture content of fuels that are dry enough to burn. As a result, more intense fire behaviour can be expected on sunny days than on cloud days.

Solar radiation is measured using a pyranometer, an instrument which measures the amount of solar radiation intercepted by flat surface over a given period of time. In bushfire work solar radiation is most often measured in the open using a sensor incorporated into an automatic weather station (AWS). Care must be taken to ensure the pyranometer is mounted horizontally. It should be the highest instrument on the AWS and should have an unobstructed field of view.

An average value of solar radiation should be recorded to the nearest 1 W/m^2. The averaging time is usually the same as that used for other instruments on the AWS, typically 1 min, 10 mins or 1 h.

ATMOSPHERIC STABILITY

The profile of temperature and humidity in the atmosphere governs the vertical motion of air and the formation of clouds. These affect the development of the convection column above the fire, modifying the wind in the vicinity of the fire and the fire behaviour itself.

Depending on the rate at which measured air temperature change with height the atmosphere may be stable or unstable. In stable conditions fire behaviour is more likely to be steady, it is less likely that a convection column will form, and spotting distances will be shorter. In unstable conditions fire behaviour is more likely to be erratic, it is more likely that a convection column will develop, and long-distance spotting may occur.

Atmospheric profiles are routinely measured by meteorological agencies using radiosondes. To date atmospheric profiles have not usually been measured as part of experimental burns. If profiles measurements are not available, some information on stability may be deduced from fire behaviour observations (see Appendix 4)or from weather observations. Stable conditions are associated with steady winds and status clouds. Unstable conditions are associated with gusty winds and cumulus clouds with vertical development.

CLOUD COVER

Clouds affect fire behaviour by reducing the amount of solar radiation reaching the ground. They can also be a useful indicator of the stability and vertical structure of the atmosphere above a fire when profile measurements are not available. Clouds may also be produced by condensation in the convection column above the fire and are sometimes refer to as a 'pyrocumulus..'If the fire triggers a thunderstorm through this process and becomesvery tall (e.g. 8km +), the cloud is called a 'pyrocumulonimbus'.

Throughout the duration of the fire, the amount of cloud cover should be recorded as a fraction of an eight-point scale (0 - 8 octas), with 0 indicating clear sky and 8 indicating overcast conditions. Any significant change during the fire should be noted.

AUTOMATIC WEATHER STATIONS

An automatic weather station (AWS) combines instruments for measuring a range of meteorological quantities with a data logger into a single installation. An AWS normally measures at least air temperature, humidity, precipitation, and wind but may also include sensors for radiation, soil temperature and soil moisture. When selecting a site for an AWS care should be taken to choose a location where all the instruments can be used correctly. Wind measurements are usually the most demanding in this respect. The data logger can be programmed to record observations at a range of intervals, 1-min, 10-min or 1-hour intervals are appropriate for bushfire work. Averages should be calculated from samples taken at least every 10 s.

Portable AWS (PAWS) are automatic weather stations that can be easily moved and set up in desired locations and should provide similar level of data observations and quality as an AWS.

APPENDIX 5: MEASUREMENT OF TOPOGRAPHIC QUANTITIES

SLOPE

Degree of slope is the angle of rise above the horizontal and is measured in degrees by a clinometer. A positive value is an upslope, a negative value is a downslope.

Ensure that the clinometer is correctly oriented, and the internal mechanism moves freely. Sight through the clinometer over the slope to be measured to a location at the same height above ground level as the clinometer. This is most easily done by having another person stand at the location and sighting on their eyes or face and then taking the reading.

On most firegrounds, the slope will varyand it is necessary to take a number of clinometer readings. The number of measurements will depend on the number of fire behaviour measurements that will be made during the life of the fire being reconstructed. For example, if there will be only one measurement of fire behaviour made during the fire, then only one slope measurement needs to be taken. However, if fire behaviour will be measured more frequently, more slope measurements will be required.

Slope measurement should be made for the intended direction of fire spread. In most instances, this will be directly up hill in the direction of steepest slope. However, depending on burning conditions and wind direction, the fire may spread cross-slope or diagonally. A transect line through the centre of the fire will normally provide a good measure of the fires slope when small.

ASPECT

Aspect is measured by taking a compass bearing perpendicular to the slope and should be measured at the same location slope is measured.

HEIGHT ABOVE SEA LEVEL

An estimate of height above mean sea level (AMSL) can be obtained from a map or using a GPS and is generally satisfactory.

BUSHFIRE FUELS

A cropland wildfire, particularly a high intensity wildfire that has been burning for some time, will often involve fuels other than crops. It is important for these fuels to be identified where they play a role in affecting the behaviour and spread of the fire. The Bushfire Fuel Classification (BFC) system provides a consistent way for identifying these fuels across districts, regions and states.

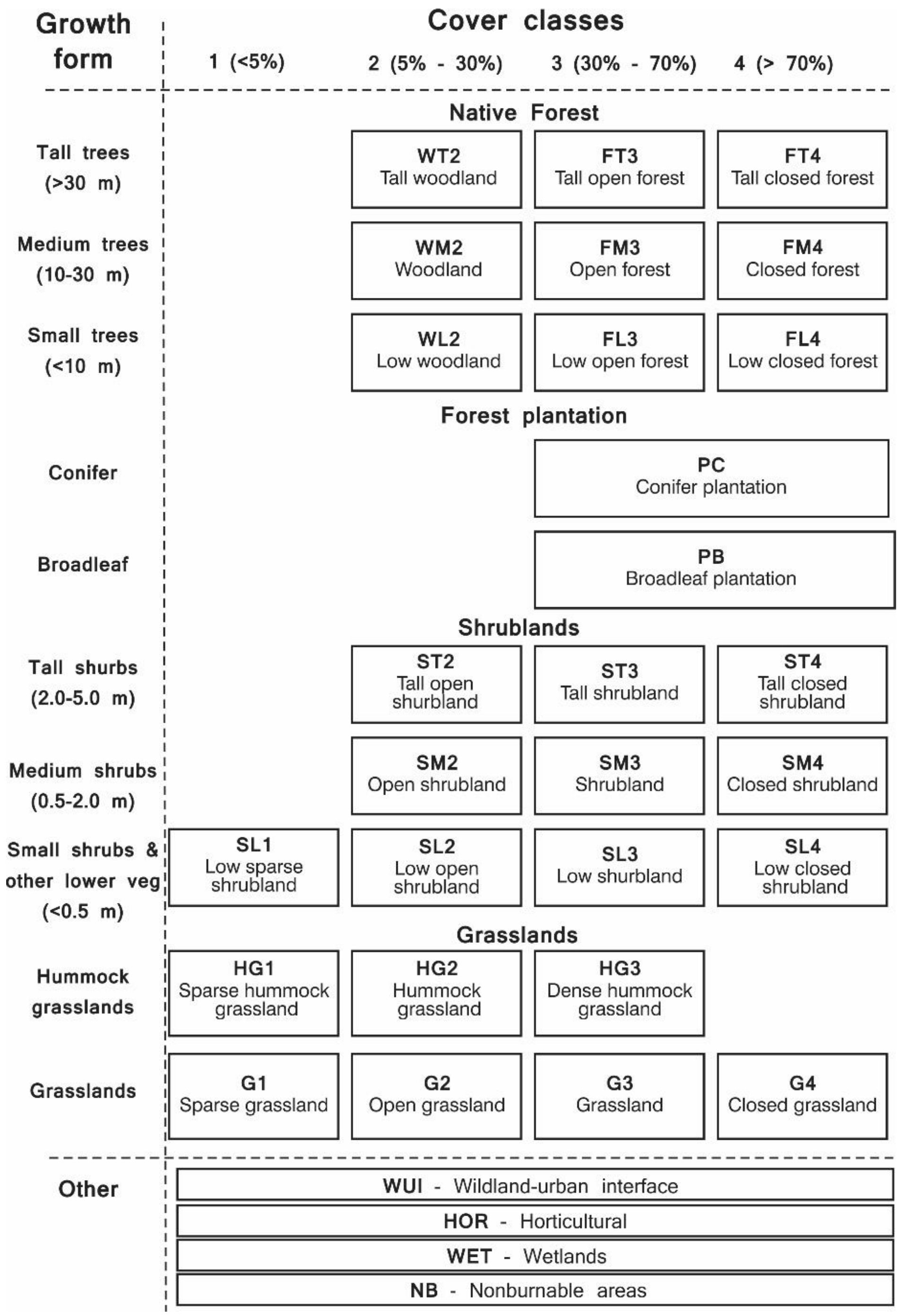


Figure A4. The national bushfire fuel classification system for identifying and quantifying bushfire fuels in Australia.

APPENDIX 6: CHECKLISTS AND PRINTOUTS

DATA COLLECTION CHECKLISTS

Pre-fire checklist

Item	Details	Completed	Further contact/ Follow up (phone/email)
Equipment			
	AWS is operational	☐	
	Fuel sampling kit complete	☐	
	Fuel moisture sampling kit complete	☐	
	Hand held weather station operational	☐	
	PPE	☐	
	Video / photographic camera operational	☐	
	Field sheets / forms	☐	
	Computer resources	☐	

Fire documentation checklist

Item	Details	Completed	Further contact/ Follow up (phone/email)
Incident information			
	Incident name	☐	
	Region/Location	☐	
	Incident controller	☐	
	Time of ignition	☐	
	Location (Lat/long, E/N)	☐	
	Detected by? When? How?	☐	
	Ignition source	☐	
	Fuel type/crop type at fire ignition.	☐	
Fire perimeter location at specific times			
	Infra-red line scans/FLIR imagery from aircraft	☐	
	Aerial photos/video from air observers	☐	
	Photos/observations from fire fighters	☐	
	Photos/observations from public/land owners	☐	
Other fire behaviour			
	Flame front characteristics (height, angle, active fuel layers)	☐	
	Spotting - time and location of occurrence as well as time of report to enable cross-validation	☐	
	Spotting - Suppression actions	☐	
	Note presence and effect of fire whirls on spread	☐	
	Note dominant colour of smoke plume from most active section of perimeter	☐	
	Note smoke plume angle of rise	☐	
	Note height of maximum rise of plume	☐	
Initial attack			
	Time of arrival on fire ground	☐	
	Fire size at initial attack	☐	
	Aerial suppression presence	☐	

Item	Details	Completed	Further contact/ Follow up (phone/email)
	Ground resources at initial attack	☐	
	Aerial drops, location and timing	☐	
Weather			
	Identify nearest Automatic Weather Stations (AWS) (Bureau of Meteorology (BoM) and other sources)	☐	
	At regular intervals access and download recent observations from each station.	☐	
	Install PAWS in safe but relevant location. Ensure location meets meteorological observation standards and is safe from fire. Log data at 10-min intervals.	☐	
or	Conduct weather measurements with handheld device at half-hourly intervals.	☐	
Fuels			
	Determine crop types likely to be affected	☐	
	Assess crop condition for crop types identified	☐	
	Obtain assessment of crop curing	☐	
	Obtain land use/vegetation map for fire area	☐	
	Direct sampling of dead fuel moisture content	☐	

Post-fire documentation checklist

Item	Details	Completed	Further contact/ Follow up (phone/email)
Fire progression			
	High resolution aerial photography should be obtained very soon after fire is controlled (remotely piloted aircraft or normal aircraft).	☐	
	Obtain fuel, vegetation, land use, infrastructure, roads and water features GIS layers for the burned area plus 50%.	☐	
	Assess of areas within burned area that were not consumed for fuel attributes/identification of why not consumed.	☐	
	Identify regions where headfire crossed regions of fuel discontinuities.	☐	
	Collect and consolidate infra-red linescan/FLIR imagery into time series	☐	
	Collect and consolidate photos and videos from all sources into time series by location taken.	☐	
	Collect and consolidate all information on suppression, vehicle/aircraft tracks, etc.	☐	
Fire behaviour			
	Interview air observer	☐	
	Aerial photos/video by air observers	☐	
	Fire perimeter/fire location sketches	☐	
	Interview key firefighting personnel	☐	
	Fire behaviour descriptions relative to crop type	☐	
	Video/photo sources	☐	
	Fire perimeter sketches	☐	
	Interview public – obtain video and photos	☐	
Weather			
	Obtain complete AWS datasets. Collect data as far back as available.	☐	

Item	Details	Completed	Further contact/ Follow up (phone/email)
	Consolidate AWS, PAWS and other weather data by location	☐	
	Contrast and validate AWS, PAWS and direct measurements obtained during the fires with hand held instruments. Assess applicability of such data to fire locale	☐	
Fuels			
	Construct map of fuel type for fire region, if not already extant	☐	
	Identify all predominant crop types (cereals/pulses/canola)	☐	
	Identify regions that are not croplands (note dominant vegetation types)	☐	
	Obtain information on crop condition and (harvested v. not harvested, wind-rowed, etc) for all paddocks in fire region:	☐	
	Local Department of Primary Industry harvesting data	☐	
	Interviews with landholders	☐	
	Construct map of crop condition	☐	
	Obtain information on crop degree of curing if not already obtained (particularly for non-harvested crops)	☐	
	BoM satellite imagery	☐	
	Observer network	☐	
	Direct observations of nearby unburnt paddocks	☐	
	Using AWS/PAWS weather streams, construct time series of dead fine fuel moisture content	☐	
	Validate against point measurements at appropriate times (if collected)	☐	
Topography			
	Obtain Digital Elevation or Digital Terrain Model for fire area	☐	
	Calculate slopes and aspects as required.	☐	

Summary of data reliability ratings and descriptions

Rating	Weather	Fine fuel moisture content	Fuel complex	Rate of spread / fire behaviour
1.	Nearby (<25 km) meteorological station or direct measurements in the field with high quality instruments, and/or validated modelled wind field .	Point measurements made at time of fire and extrapolated to fire area taking into account topographic effects	Fuel characteristics inferred from a fuel age function developed for the particular fuel type/area.	Direct timing of fire spread measurements i.e. IR scans, aerial observations, observed reference points with photographs.
2.	Meteorological station within 50 km of the fire with no local effects (i.e. terrain, vegetation) on the wind field, and/or partially validated modelled wind field.	Single point measurements within or in the vicinity of fire area.	Fuel characteristics inferred from a visual assessment or measurements of nearby unburnt forest.	Reliable timing (within +/- 15 min) of fire spread by field observations with general reference points.

3.	Meteorological station within 50 km of the fires but there are local effects on the wind field or the data not representative of the fire area. Meteorological station > 50 km of the fire, reconstruction of wind speed for fire site. Unvalidated modelled wind field.	Estimation of fuel moisture through validated models taking into account topographic effects.	Fuel characteristics inferred from a fuel age curve for a forest type of similar structure.	Reconstruction of fire spread with numerous cross references.
4.	Spot meteorological observation near the fire.	Estimated fuel moisture for nearly (< 25 km) meteorological stations	Fuel characteristics typical of equilibrium level in the representative fuel type.	Doubtful reconstruction of fire spread.
5.	Distant meteorological observations at locations very different to fire site.	Estimated fuel moisture for distant (> 50 km) meteorological stations	Qualitative fuel type description	Anecdotal or conflicting reports of fire spread.

CRITICAL OBSERVATIONS TO BE CONVEYED BY FIRST ATTACK PERSONNEL

On approach	Comment
Smoke colour (white, grey, dark grey, black)	
Size of smoke plume (small, moderate, huge)	
Angle of smoke plume (low (<15), moderate (>15 <40), large (>40))	
Direction of smoke spread (ordinal direction)	
Maximum height of plume (low, moderate, high)	
Smoke colour (white, grey, dark grey, black)	
On arrival	
Location of fire heel (GPS position, map grid coords)	
Size of fire	
Area (small (<1 ha), moderate (>1 ha <5 ha), large (>5 ha))	
headfire width (narrow (<20 m), moderate (>20 <50 m), wide (>50 m)	
flank length (short (<50 m), moderate (>50 <150 m), long (>150 m))	
Time since ignition	
Direction of spread	
Fire behaviour (rank: 0, 1, 2, 3 or 4)	
Immediate threats	
Potential for successful first attack	
Further resources required (quantity/type/immediacy)	
Current suppression activity	
Burning conditions:	
Wind speed/direction	
Terrain	
Fuel type/condition	

FIREFIGHTER INTERVIEW GUIDELINES

Be polite. Firefighters may feel that any investigation may be used to identify their negligence or deficiency of action. Reassure them that the investigation is purely about determining fire behaviour and what factors affected it and the difficulty of suppression in the fuel types encountered.

Interviewing the fireground incident controller

1.	Background information:	Name, unit attached to, normal role and association (e.g. brigade), contact details, firefighting experience including with fires in this fuel type, primary role on day of fire
2.	Response:	Time alerted for incident (How do you know what the time was? How certain are you of this time? NOTE: Every statement of time should be followed up by these sorts of questions Where did they first see the fire? (Get position on map and use map to facilitate following questions). Time arrived on scene, other units on fireground at arrival. Time commencing suppression
3.	Size up, priorities and objectives:	What did the fire look like (extent, flame height, smoke characteristics), In what vegetation was the fire burning at that time? In what direction was the fire spreading? Ask about time of arrival to landmarks (e.g., roads, river, house) How fast was the fire spreading? How tall were the flames? Was the fire spotting? Where? How far from the fire front? At what time was this? What were the initial suppression priorities and objectives?
4.	Tactics and techniques:	What tactics were selected and why? Where there any / what limitations were there to tactical options?
5.	Limitations, difficulty and effectiveness	Did the operation go as planned? What was the effect of suppression on fire behaviour (e.g stopping flanks/ narrowing and slowing head, lessen impact of wind change)? How did suppression compare to other fires that you have worked on? Where there any unexpected issues that impacted or aided suppression (e.g. accessibility, water availability)? Did you persist with the planned tactic or have to change?
6.	Other data	Do you have photos/videos? Obtain copies of the photos/videos Ask to see the camera with which the photos/videos were taken and check its time. Note difference from GPS standard at the time of the interview. Go through each photo/video with the firefighter to ascertain location, direction of view and fire position and direction of spread.

Sections 3-5 should be applied to individual phases of suppression (e.g. specific roles, assignments or sections of fire) and repeated for subsequent phases.

Interviewing crew leaders and crews conducting suppression

1.	Background information:	Name, unit attached to, normal role and association (e.g. brigade), contact details, firefighting experience including with fires in this fuel type, primary role on day of fire
2.	Response:	Time alerted for incident (How do you know what the time was? How certain are you of this time?

		NOTE: Every statement of time should be followed up by these sorts of questions Where did they first see the fire? (Get position on map and use map to facilitate following questions). Time arrived on scene, other units on fireground at arrival. Time commencing suppression
3.	Size up, priorities and objectives:	What did the fire look like (extent, flame height, smoke characteristics), In what vegetation was the fire burning at that time? In what direction was the fire spreading? Ask about time of arrival to landmarks (e.g., roads, river, house) How fast was the fire spreading? How tall were the flames? Was the fire spotting? Where? How far from the fire front? At what time was this? What were your objectives during this period?
4.	Tactics and techniques:	What roles (e.g. knockdown, mop up) What other units were you working with? Where did you work (location with respect to fire and landscape)? What application techniques were used? (e.g. to apply water)
5.	Limitations, difficulty and effectiveness	Did the operation go as planned? What was the effect of suppression on fire behaviour (e.g stopping flanks/ narrowing and slowing head, lessen impact of wind change)? How did suppression compare to other fires that you have worked on? Where there any unexpected issues that impacted or aided suppression (e.g. accessibility, water availability)? Did you persist with the planned tactic or have to change?
6.	Other data	Do you have photos/videos? Obtain copies of the photos/videos Ask to see the camera with which the photos/videos were taken and check its time. Note difference from GPS standard at the time of the interview. Go through each photo/video with the firefighter to ascertain location, direction of view and fire position and direction of spread.

Sections 3-5 should be applied to individual phases of suppression (e.g. specific roles, assignments or sections of fire) and repeated for subsequent phases.

Interviewing air attack supervisors

1.	Background information:	Name, unit attached to, normal role and association, contact details, firefighting experience including with fires in this fuel type, primary role on day of fire
2.	Response:	Time alerted for incident (How do you know what the time was? How certain are you of this time? NOTE: Every statement of time should be followed up by these sorts of questions. Where did you first see the fire? (Get position on map and use map to facilitate following questions). Time arrived on scene, other units on fireground at arrival. Time commencing suppression
3.	Size up, priorities and objectives:	What did the fire look like (extent, smoke characteristics)? In what vegetation was the fire burning at that time? In what direction was the fire spreading? How fast was the fire spreading? Was the fire spotting? Where? How far from the fire front? At what time was this?

		What were the initial priorities and objectives for aerial suppression
4.	Tactics and techniques:	Where were aerial drops made (location with respect to fire and landscape)? Were aircraft working with ground units? Details of drops including load types and requested execution such as coverage levels and application (e.g. half on half off)
5.	Limitations, difficulty and effectiveness	Did the operation go as planned? What was the effect of suppression on fire behaviour (e.g stopping flanks/ narrowing and slowing head, lessen impact of wind change)? How did suppression compare to other fires that you have worked on? Where there any issues that may have affected or aided their operations? What were the flying conditions like? (i.e. did they restrict the operation) Were the turnaround times reasonable? (i.e. did they restrict the operation)
6.	Other data	Do you have photos/videos? Obtain copies of the photos/videos Ask to see the camera with which the photos/videos were taken and check its time. Note difference from GPS standard at the time of the interview. Go through each photo/video with the firefighter to ascertain location, direction of view and fire position and direction of spread.

Sections 3-5 should be applied to individual phases of suppression (e.g. specific roles, assignments or sections of fire) and repeated for subsequent phases.

GENERAL PUBLIC WITNESS INTERVIEW GUIDELINES

Be polite. Show them your credentials. Start by explaining the context and authorisation for your interview- it's important that it is an approved activity with appropriate ethics, privacy and consent given that is appropriate to context. Be sure not to conflate any research activity with formal investigations for other purposes (e.g. fire investigation).

Do not interview witnesses in groups if you can help it. Try to interview each person in isolation in a quiet place. If you have to interview a group of witnesses, ensure that all individuals feel able to speak up and share. Don't let one or two witnesses badger, coerce or influence others. Ask quiet individuals specific questions. Offer to come back and speak with individuals later.

Be prepared to deal with grief/anger/frustration/animosity/lassitude. Be prepared to spend some time with the witness to extract necessary details and be gracious. Give them your business card with email address (and cloud storage address) to contact you with anything further they may recall.

FIRE RECONSTRUCTION'S FIELD PACK

Item	Comment	Check/ Comment
Radio	Critical for keeping situation awareness. Ensure spare battery and recharging capability	
Clinometer		
GPS		
Still or video camera (or camera phone)	Ensure with correct date/time + additional memory cards	
Laptop/tablet		
Spare USB flash drives	Ensure enough capacity to take copies of people's video/still files either directly or indirectly)	
Email account / cloud location	To where public can send imagery if (a or b) not possible with sufficient transfer capacity	
Fuel sample kit (backpack)		
Collapsible 0.25 m^2 quadrat		
Tape measure		
50 x Paper bags		
Marker pen		
Scale or numbered air tight containers (x 20)		
Access to large oven		
Calibrated and tested fuel moisture meter (e.g. Wiltronics)		
Fuel sample data sheets		
Fuel moisture		
Fuel hazard/load		
Maps	Appropriate map sheets or complete map book or appropriate GIS layers & GIS software on laptop/tablet	
Water/food		
PPE		
Notebooks + pens, scale rule, protractor,		
Portable meteorology equipment		
PAWS		
Fire weather kit	Includes Kestrel or similar hand-held device for measuring wind speed, temp and RH, and notebook for recording values at regular intervals if not auto-logged	
2 m tripod with attachment clip		
Handheld radio/comms for keeping situation awareness		

FUEL MOISTURE SAMPLING WORKSHEET

Fire Id/name:		Observer:	
Sampling location:		Date:	
Distance to the fire:			

Sample time:			
Air temp. (dry bulb)		Relative humidity	
Wet bulb temp.		Wind speed (km/h)	
Cloud cover (Oktas):			

Sample #	Container number	Wet weight (g)	Oven dry weight (g)	Moisture content (%)	Crop / fuel type:

Sample time:			
Air temp. (dry bulb)		Relative humidity	
Wet bulb temp.		Wind speed (km/h)	
Cloud cover (Oktas):			

Sample #	Container number	Wet weight (g)	Oven dry weight (g)	Moisture content (%)	Crop / fuel type:

Sample time:			
Air temp. (dry bulb)		Relative humidity	
Wet bulb temp.		Wind speed (km/h)	
Cloud cover (Oktas):			

Sample #	Container number	Wet weight (g)	Oven dry weight (g)	Moisture content (%)	Crop / fuel type:

FUEL LOAD AND STRUCTURE SAMPLING WORKSHEET

Fire Id/name:		Observer:	
Sampling location:			
Quadrat size			
Distance to the fire:			

Sample #	Fuel bed height (m)	Standing fuel: Bag number	Surface fuel: bag number	Dry weight (g) standing fuel	Dry weight (g) surface fuel	Crop / fuel type:

Comments

FIRE SPREAD OBSERVATION FORM

Fire Spread Observation Form

Sector

Observation Number

Observer

Observation Date

Observation Time

Estimated Fire Impact Date/ Time (if known)

Coordinates

Zone

Easting (6 digits)

Northing (7 digits)

GPS Waypoint

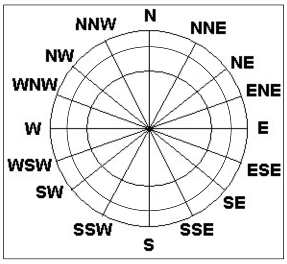
Location (Address or description)

Fire Activity/ Indicator (please circle and/or specify)

Point Of Origin	Head Fire	Transitional Zone	Point of Interest
Backing Fire	Flanking Fire	Multi Directional Fire	Witness Interview

Other:

Fire Direction (arrow)



Comments

DETAILED WEATHER REPORT

To SAVE this form, Print to CutePDF Writer (File > Print)

Author	Date	Time

Incident Name/Number

Location Coordinates	Locality Name

Topography Position	Site Exposure	Elevation (m)	Slope (Degrees)	Aspect (Facing)

Ridge, Mid Slope, GullyWell Exposed, Under Canopy N, NW, W, SW, S, SE, E, NE

Air Temperature (Celsius)	Dew point (Celsius)	Relative Humidity (%)	Temp Collect Method

Kestral 3000, Sling Psychometer Other

Wind Direction	Wind Speed (km/h)	Wind Gust (km/h)	Wind Collect Method	Wind Collection Height (m)

Kestral 3000, Skymate, Other 2m, 10m, Other

Weather Description	Cloud Cover

Fine, Rain in Area, Lightning or Thunder Clear, Overcast, Convection Cloud, Stratiform Cloud

Comments