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Fire Behaviour Knowledge in Australia

Knowledge gaps and Fire Behaviour Analyst (FBAN) training revision plan

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Important disclaimer

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1 Fire Behaviour Knowledge Gaps

1.1 Introduction

Research questions related to bushfire behaviour issues encompass a wide spectrum of disciplines dealing with plant physiology, combustion, heat transfer, atmospheric dynamics and chemistry just to name a few and also includes areas where these disciplines overlap. In Australia there have been many efforts to identify fire behaviour research needs and knowledge gaps (e.g. Cheney 1981; Catchpole 2002) and many conferences and workshops periodically devoted to the subject of bushfire behaviour knowledge (e.g. Cheney and Gill 1991; Gould and Cruz 2007). Much progress has been made in the last decade or so as evidenced by, for example, the presentations made at the CSIRO Bushfire Behaviour Science Symposium held 14-16 October 2013 in Canberra (Gould *et al.* 2013)[1] and the report produced by Sullivan *et al.* (2014).

The present review of fire behaviour knowledge gaps (which should be read in conjunction with the associated report on Fire Behaviour Knowledge in Australia (Cruz *et al.* 2014)) focuses on applied science questions, in particular those that describe knowledge gaps or research needs that have been identified as limiting our present capacity to understand and predict fire propagation and other bushfire behaviour phenomena in support of fire management activities such as wildfire suppression and prescribed burning. As a result, this review focuses on fire behaviour aspects only. Research into fire weather and fire weather indexing issues, such as atmospheric dry slots or the Haines Index, are not included in the present work.

In order to better understand end-user needs, we sent out a request to Australian land management agencies with Fire Behaviour Analyst (FBAN) capacity, inquiring about what they perceived to be their main knowledge gaps from the standpoint of predicting fire propagation and other bushfire behaviour phenomena. This report seeks to elucidate the principal findings garnered from these discussions.

To better synthesize the analysis of the survey results we divided the knowledge gaps into the following seven distinct components for the purposes of discussion:

- Fuel characteristics and availability
- Fire spread sustainability and build-up phase
- End-user identified need for new fuel type specific fire rate of spread models
- Extreme fire behaviour
- Fire behaviour models to support prescribed burning operations
- Accessory fire models
- Topographic effects on fire propagation

The papers by Cheney (1981, 1990), Catchpole (2002) and Sullivan *et al.* (2012) constitute excellent primers on the general subject of bushfire behaviour. Books such as Luke and McArthur's (1978) seminal work, *Bushfires in Australia,* Cheney and Sullivan (2008) on grassfire behaviour and Scott *et al.* (2014) should also be consulted for background information.

1.2 Fuel characteristics and availability

Brown and Davis (1973) noted that "The ignition, build-up, and behaviour of fire depends on fuels more than any other single factor. It is the fuel that burns, that generates the energy with which fire fighter must cope, and that largely determines the rate and level of intensity of that energy. Other factors that are

[1] Many of the presentations have now been posted online: http://www.bushfirecrc.com/research/event/2013-symposium

important to fire behaviour (that is, moisture, wind, etc.) must always be considered in relation to fuels. In short, no fuel, no fire!"

1.2.1 FUEL AVAILABILITY AFFECTING FIRE INTENSITY (FLAME FRONT SCALE)

Knowledge of how recent precipitation and long-term drought affect the availability of fuel to be consumed in flaming and post-frontal combustion is lacking. Past research has focused on large woody fuels consumed during glowing combustion (e.g. Hollis *et al.* 2011a,b) and fine fuels consumed in low intensity fires (e.g. McCarthy 2003). Key outstanding knowledge gaps include the understanding of how bark, twigs of different diameters and live fuels burn under different dryness conditions and how fire intensity feedback mechanisms influence this process. A better understanding of these processes will result in more accurate predictions of fire propagation in prescribed burning conditions, smoke production, and determination of the total energy released by a fire.

1.2.2 FUEL AVAILABILITY LARGE SCALE – LANDSCAPE CONNECTIVITY AS DETERMINED BY LONG-TERM DROUGHT AND SPATIAL DISTRIBUTION OF FUELS.

Expanding the spatial scale of the fuel availability knowledge at the local fire scale as described above (Section 1.2.1) to the scale of the landscape more generally, is essential for understanding the transition of fire events to conflagrations associated with large burned areas. Key to this is improved understanding of information on the spatial and temporal variation of rainfall events, the spatial variation in landscape moisture uptake and loss, and the impact these have on the connectivity of fuels at the landscape scale. Changes in landscape connectivity, driven by fuel abundance and availability, will also be affected by long-term rainfall deficit and heat-wave conditions which will drive the response in the moisture status of both live and dead vegetation.

1.2.3 IGNITION POTENTIAL AND LANDSCAPE FIRE PROPENSITY

Information gained on landscape connectivity and fuel availability at the landscape scale is essential for developing the understanding of ignition potential and thus the propensity for the incidence of fire over large regions of the Australian continent. This knowledge will be driven by an understanding of fire occurrence, both from anthropogenic and natural causes, that will vary according to ignitability of fuels (Plucinski 2014) and the potential for ignitions to result in self-sustaining fires.

1.3 Fire spread sustainability and build-up phase

Knowledge of the conditions that will enable the sustainable spread of fire and its initial build-up phase into a pseudo-steady state are required to better plan and conduct prescribed burn operations as well as predict the timing of major fire outbreaks in large ongoing fires.

1.3.1 FIRE SUSTAINABILITY IN SHRUBLANDS

One of the limitations to the accurate prediction of fire propagation in temperate shrublands is our lack of understanding of the conditions suitable for sustained propagation, known as "go/no-go" (Weise *et al.* 2005, Anderson *et al.* in preparation). In particular, for prescribed burning applications with ignitions conducted in a somewhat marginal burning environment, the knowledge of threshold conditions for sustained propagation is the most relevant fire environment metrics (Anderson and Anderson 2010; Cruz *et al.* 2013). At the low intensity end of the spectrum, fire behaviour will be most sensitive to small changes in fuel complex structure and fuel moisture and fire spread thresholds may vary between vegetation types and depend on time since last fire – mostly because of fuel continuity and the proportion of fine dead fuel. Research into this aspect of fire – fuel dynamics, should be focussed experiments extended to a number of distinct shrublands types to capture the effect of fuel complex structure. These will require a careful characterization of the lower levels of the fuel complex, namely the dead suspended fuels. Research into the impact of the type of ignition device on fire sustainability should also be considered. As with recent advances on our understanding on fire dynamics in Australian vegetation types (Cheney *et al.* 2012; Cruz *et al.* 2013), this research will require close collaboration between research organisations and end-user agencies.

1.3.2 FIRE SUSTAINABILITY IN FORESTS UNDER MARGINAL CONDITIONS (PRESCRIBED FIRE AND BACK-BURNING CONDITIONS)

Similar to the case for shrublands, our capacity to understand and predict the conditions that will lead to sustained fire spread in eucalypt forests is a significant knowledge gap that limits the successful application of prescribed burning and back-burning operations. Research into this topic will require an understanding of fuel availability (see Sections 1.2.1. and 1.2.2. above) and the effect of fuel moisture content on fire propagation under marginal burning conditions. Also relevant in this research topic is the understanding how multiple ignition sources and the ensuing interaction between separate flame fronts allow the damping effect of fuel moisture and/or low fuel availability to be overcome and the role to which the type of ignition device plays.

1.3.3 BREAKOVER/BREAKAWAY WILDFIRE CONDITIONS

One of the largest sources of uncertainty to FBANs conducting fire propagation simulations for fires burning over multi-day periods is the knowledge of the environmental conditions that will allow an inactive section of a fire perimeter to build up sufficient intensity to lead to a major fire run. Research into the drivers of fire build-up and its cumulative effect is required in order to be able to identify trigger points for high intensity fire propagation.

1.3.4 FIRE BUILD-UP/FIRE GROWTH

In spite of its recognition by McArthur (1967, 1968) many years ago , the spread of a fire in its initial build-up phase, from a point source ignition to reaching a pseudo-steady state (Figure 1.1), is still poorly understood and quantified, despite its importance for initial attack planning and dispatching (Alexander 2000). Recent research within a Bushfire CRC project has provided preliminary models for eucalypt forests under a narrow set of conditions most applicable to prescribed burning conditions (Sullivan *et al.* 2014). There is a need to further develop and evaluate these models and investigate their applicability to a wider range of fuel types and fire weather conditions (in particular the role of wind turbulence in influencing the rate of development of ignitions (Sullivan *et al.* 2014)), including those associated with high intensity wildfires.

1.3.5 FIRE PERIMETER GROWTH (ELLIPTICAL FIRE LENGTH-TO-BREATH RATIO, FIRE SHAPE)

Existing fire behaviour knowledge has focused on an understanding of the rate of spread of head fires advancing in the general direction of the wind. Geometric approximations that are currently employed in both manual and computerised methods to estimate fire perimeter propagation, which are not based on any physical mechanism, remain unvalidated and therefore cannot be extended to other situations (i.e. to incorporate the combined effects of slope and wind). Improved understanding of the mechanisms of fire perimeter shape growth useable in both manual and computerised methods is essential for improved estimate of fire perimeter locations, particularly prior to the arrival of critical wind changes associated with cold frontal passages (Harris *et al.* 2012).

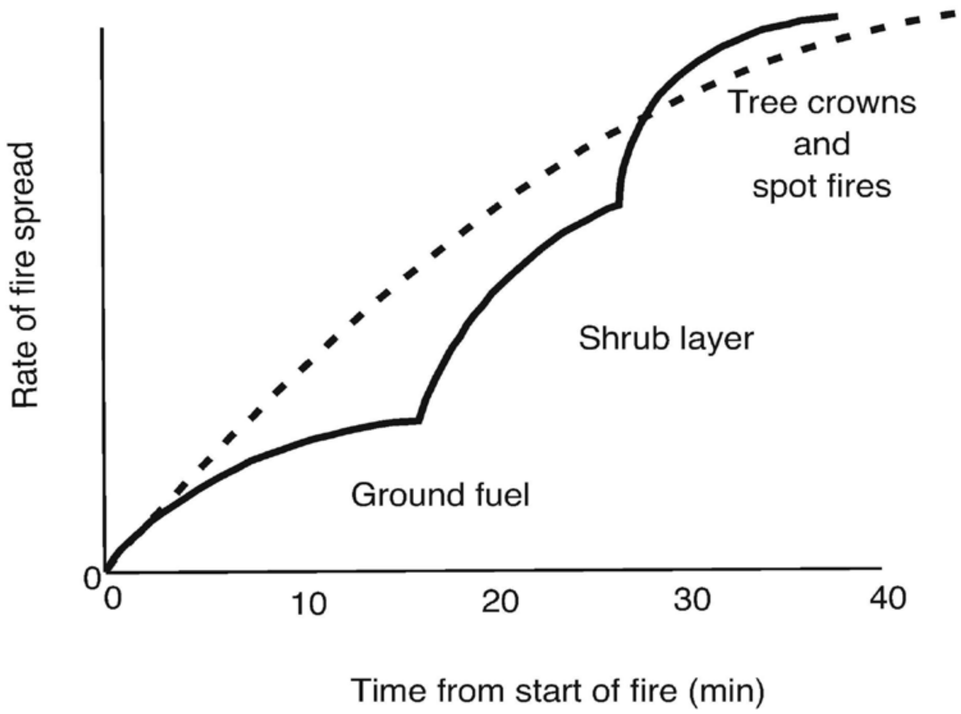

Figure 1.1. Stepwise increase in rate of fire spread as distinct fuel layers are involved in combustion processes (from McArthur 1967). Dotted line represents the idealised acceleration curve.

1.4 End-user identified need for new fuel type specific fire rate of spread models

As a result of our request, several end-user agencies identified a number of relevant fuel types for which no adequate models of fire rate of spread presently exist, either for prescribed burning and wildfire conditions. These include:

1.4.1 WET/DAMP EUCALYPT FOREST (INCLUDING RAINFOREST) (ACT, TASMANIA, VICTORIA, WA)

These are typically low flammability forests with low fire spread potential. These fuels types have more distinct fire spread thresholds than dry eucalypt forests which make them susceptible to widespread fire propagation only in certain years. High fuel loads and poor accessibility typically make fires in these fuel types difficult to suppression. The key knowledge gap here is to identify the fuel moisture content threshold conditions that will allow, for example, sustained fire propagation with respect to say the Keetch-Byram Drought Index (Keetch and Byram 1968) or Mount Soil Dryness Index (Mount 1972; Burrows 1987), with application for prescribed burning operations and wildfire suppression planning. This fuel type could also include the wet/mixed forest.

1.4.2 TEMPERATE, TYPICALLY COASTAL, SHRUBLANDS (NSW, TASMANIA, VICTORIA, SA, WA)

This has been identified as a problematic fuel type due to the high flammability of the fuel complex and its location within peri-urban areas. New models for fire spread are being finalized (Anderson *et al.* in preparation). Outstanding knowledge gaps are the determination of fire sustainability from weather conditions and fuel structure (or time since last fire) (see also Section 1.3.1).

1.4.3 SEMI ARID SHRUBLANDS/WOODLANDS (WA AND SA)

These are complex fuel types with a dynamic ephemeral grass understorey that responds to periods of above normal rainfall. Knowledge gaps in this fuel types are the quantification of the impact of the ephemeral grasses in breaching fuel discontinuities and the ensuing fire propagation.

1.4.4 COASTAL MALLEE (SA)

As with temperate shrublands, this is a problematic fuel type with fire spread thresholds distinct from semi-arid mallee as dealt with by Cruz *et al.* (2013). There is also a lack of information on fuel structure characteristics in this fuel complex.

1.4.5 YOUNG FORESTS, PARTICULARLY RECENTLY FIRE-KILLED FORESTS (ALPINE/MOUNTAIN ASH) (VICTORIA, NSW)

Fire-killed alpine and mountain ash forests occupy more than a million ha across mountainous topography in south-eastern Australia. Recent fire events have shown these fuels to have a propensity to reburn a few years after a stand replacement fire. Fire propagation in this particular fuel condition is poorly understood, partially because of dynamic fuel structural changes and the impact of episodic grassy understorey growth that provide flashy fuels that may allow fire to spread across areas of low litter accumulation.

1.4.6 EUCALYPT PLANTATIONS (BLUE GUM AND SIMILAR)

This fuel type has significant economic value and has been flagged in the past (Gould *et al.* 2001) as an important fire behaviour knowledge gap. The fuel dynamics associated with this type is well understood (Fernandes *et al.* 2011) but the plantation industry has been reluctant to fund further research on fire behaviour in such fuel types. Admittedly, from the point of view of operational fire behaviour prediction, this is likely to be a fuel type of marginal importance due to the current fragmented nature of plantations across the landscape.

1.4.7 INTRODUCED GRASS SPECIES (BUFFEL, GAMBA, AFRICAN LOVE)

There are a number of invasive grass species with a structure distinct from native grasslands. Identified as an important fuel type in Northern Australia (*WA, NT, Queensland*). Fuel dynamics in these vegetation types are largely unknown. High fuel loads can make fire suppression problematic. The response of fire spread to wind, fuel moisture and curing is unknown.

1.4.8 PERI-URBAN/RESIDENTIAL AREAS (IDENTIFIED BY VICTORIA AS PROBLEMATIC FUEL TYPE, BUT RELEVANT ACROSS AUSTRALIA)

Fuels and fire propagation in peri-urban fuels constitute a largely unresearched topic. Knowledge of fuel distribution and the definition of threshold fragmentation metrics are key to understanding and identifying the main drivers of fire propagation in this kind of environment, namely, what is the contribution of bushfire fuels to the overall fire propagation. Related to this issue is the determination of under what conditions existing fire spread models cease to perform well. A further research topic is the definition of the fire spread potential above which fuel fragmentation has no impact on fire propagation.

1.5 Extreme fire behaviour

Extreme fire behaviour is defined by AFAC (2012) as “A level of bushfire behaviour characteristics that ordinarily precludes methods of direct suppression action. One or more of the following is usually involved:

high rates of spread; prolific crowning and/or spotting; presence of fire whirls and a strong convective column."

Australia has the infamous distinction of holding a number of world records when it comes to observed free-burning fire behaviour:

- Fastest spread rates in grass, eucalypt and pine plantation fuel types (Keeves and Douglas 1983; Noble 1991; Cheney and Sullivan 2008; Cruz *et al.* 2012);
- Tallest flame height (Sutton 1984);
- Longest spot fire distance (Cruz *et al.* 2012); and
- Longest forward fire spread distance in a single burning period (Keeves and Douglas 1983; Cruz *et al.* 2012).

The environmental conditions necessary for extreme fire behaviour are known in a general way with respect to fuel moisture, wind and fine fuel loads (Cheney 1976; Burrows 1984). Predictability of extreme fire behaviour is difficult due to our lack of understanding of the driving processes and quantitative descriptions of the processes themselves. It also can be pointed out that the high energy release rates associated with extreme fire behaviour may lead to erratic fire-atmosphere interactions that further limit our understanding of the driving processes, in particular firebrand transport and the role of spotting and mass fire behaviour. Linked to this aspect there is a general tendency to reach conclusions about the processes involved in extreme fire behaviour without the benefit of repeated, systematic observations (Alexander 2009).

1.5.1 CROWNING IN EUCALYPT FORESTS

Some Australian eucalypt stand types are prone to crowning (e.g. McCaw *et al.* 1988). The basic index of the Australian Forest Fire Danger Meter (McArthur 1967) provides for the prediction of wildfire behaviour characteristics in terms of forward rate of fire spread, flame height, and spotting distance on level to gently undulating terrain in a dry eucalypt forest with fine fuel quantities of 12.5 t/ha (Luke and McArthur 1978). The meter also identifies the general conditions required for crown fire development in this fuel complex (Figure 1.2) based on the assumption that a flame height of 14 m constitutes the threshold between a surface fire and a crown fire. Nonetheless, an underprediction bias with the McArthur (1967) meter in regards to rate of fire spread has been identified in several studies (e.g. McCaw *et al.* 2008; Kilinc *et al.* in press). The onset of crowning in eucalypt forests is linked to a number of characteristics associated with extreme fire behaviour such as profuse, short-range spotting. An understanding of the conditions leading to the onset of crowning can be seen as key to gaining an understanding of extreme fire behaviour characteristics in eucalypt forests.

1.5.2 SHORT-RANGE AND MASS SPOTTING

Short-range spotting (spotting up to about 5 km) is a common occurrence in high intensity fire propagation associated with the presence of eucalypt stringybark species. McArthur (1967) describes this process as key to how a fire maintains overall rates of spread much higher than expected in the absence of spotting. Under certain conditions high density of embers can lead to mass fire behaviour or an "area ignition" effect.[2] As with other processes, such as long-range spotting, our heuristic understanding of the process exists. It is considered that key components for the maintenance of severe short range spotting propagation are the presence of long unburnt eucalypt forest with a significant number of species with fibrous bark, high wind speeds and low fuel moisture contents. What is lacking is a quantitative understanding of the process, namely firebrand density distribution with distance from the fire front and how distinct fires coalesce in a highly turbulent environment.

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[2] Defined by AFAC (2012) as "Ignition of several individual fires throughout an area, either simultaneously or in rapid succession, and so spaced that they add to and influence the main body of the fire to produce a hot, fast-spreading fire condition. Also called simultaneous ignition."

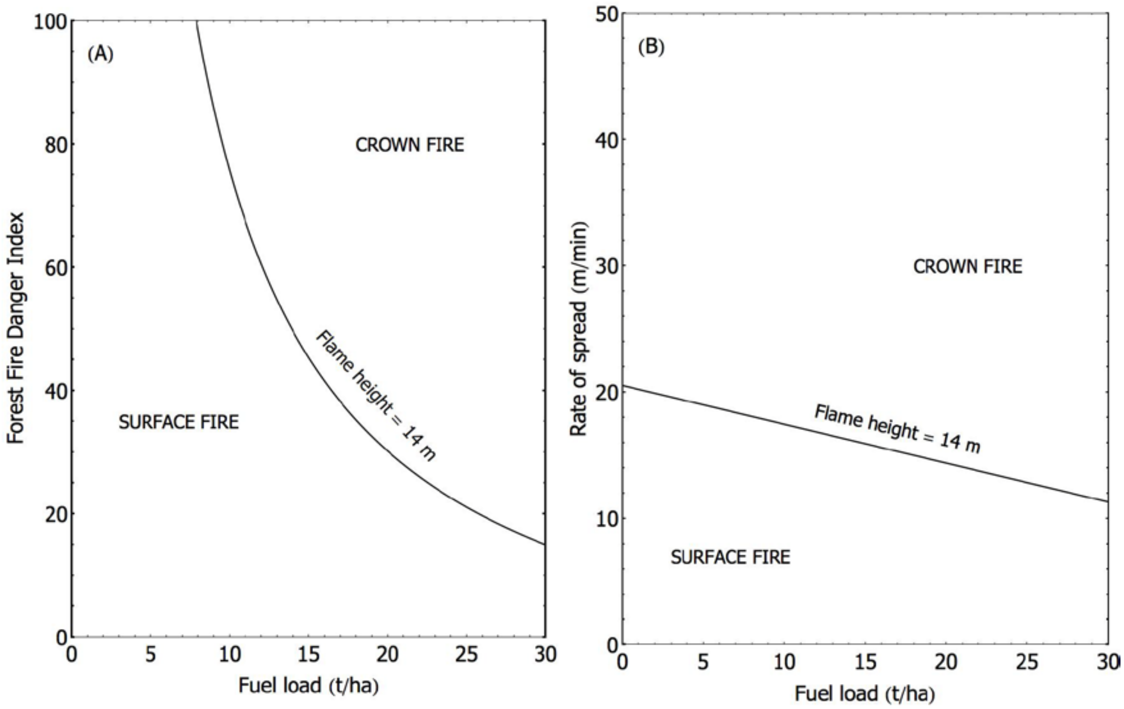

Figure 1.2. Graphical representation of McArthur's (1967, 1973) guide to sustained crown fire propagation in Australian eucalypt forests based on (A) rate of spread and fuel load and (B) the Forest Fire Danger Index and fuel load assuming that crowning occurs once flame heights exceed 14 m.

1.5.3 LONG-RANGE SPOT FIRE DISTANCES

The occurrence of long-range spot fires (i.e. > 5 km) is a common contributor to the large fire development in dry sclerophyll eucalypt forests (Figure 1.3). Spot fire distances up to 40 km have been verified on particular occasions in fires in southern Australia eucalypt forests (Hodgson 1967; Cheney and Bary 1969; McArthur 1969; Cruz *et al.* 2012). The process of long-range spotting can be seen as distinct from short-range spotting, requiring the presence of a specific different set of conditions. Long-range spotting requires an intense fire that maintains a strong upward motion in the buoyant plume to transport relatively large fuel particles several kilometres above the ground and high winds aloft to transport firebrands for extended distances downwind.

The firebrands responsible for long-range spotting are long streamers of decorticating bark from certain smooth-barked eucalypt species (Cheney and Bary 1969). The bark strips curl into hollow tubes that when ignited at one end can burn for as long as 40 minutes (Hodgson 1967; P.F. Ellis, personal communication). The long combustion times coupled with good aerodynamic properties (Luke and McArthur 1978; Ellis 2011) allows these firebrands to be a viable ignition source even when transported over long distances. Evaluation of spotting models is a difficult proposition (Albini *et al.* 2012), but it is well accepted that current spotting models are not necessarily appropriate for estimating the maximum spotting distance in light of past case studies (Figure 1.3 and Figure 1.4).

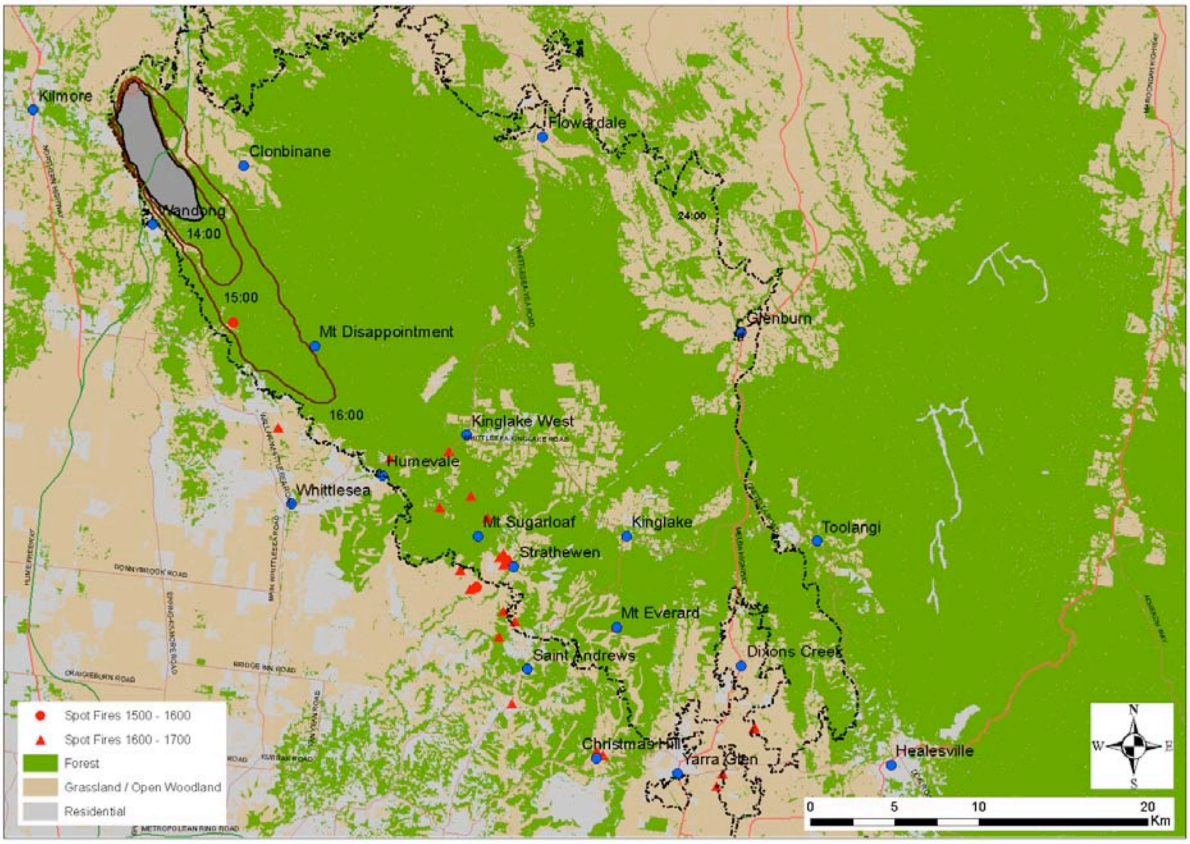

Figure 1.3. Detail of long distance spot fire ignitions identified between 15:00 and 16:00 h in the afternoon during the main run of the Kilmore-East fire, February 9, 2009 (from Cruz *et al.* 2012).

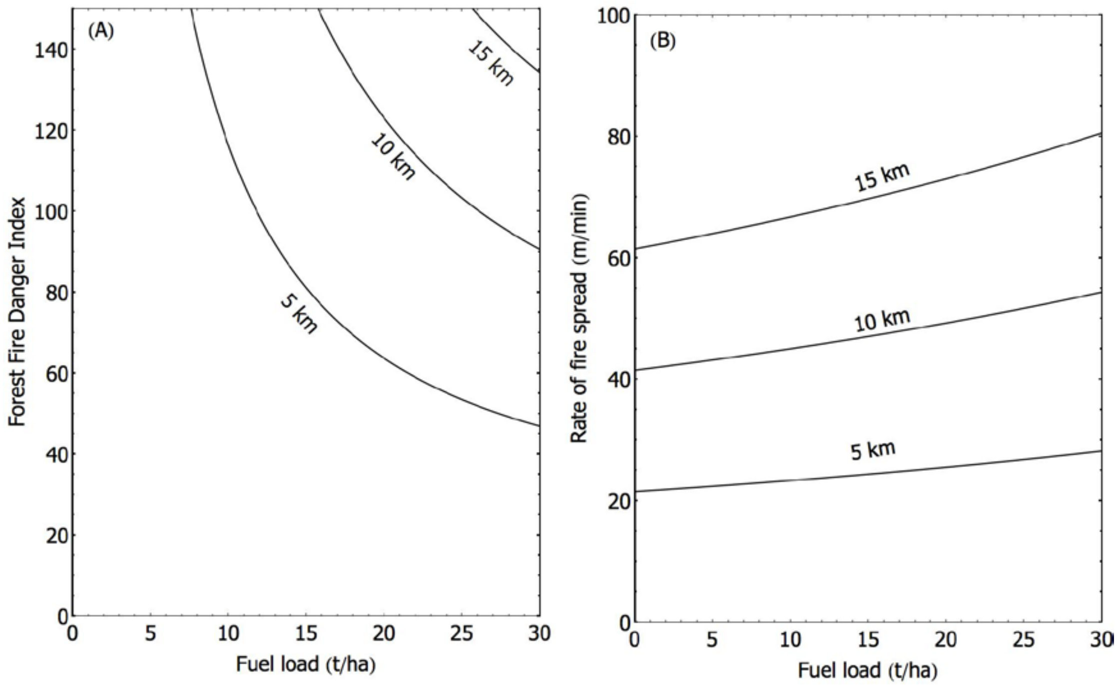

Figure 1.4. Spotting distance as predicted by the MacArthur (1967, 1973) Forest Fire Danger Meter according to the equation given by Noble *et al.* (1980) as a function of (A) the Forest Fire Danger Index and fuel load and (B) rate of fire spread and fuel load.

1.5.4 FIRE-ATMOSPHERE INTERACTIONS

Fire-atmosphere interactions are a large unknown in fire science and their impact on the spread of a fire, namely through feed-back mechanisms, not yet quantified. It is expected that significant fire-atmosphere interactions will require a fire with a spatially broad footprint releasing large quantities of energy to sustain a well-developed convection plume (Figure 1.5). While there are a number of meteorological case studies and speculations, it has not yet been definitively shown that a fire-atmosphere interaction has a strong effect on the propagation of a fire.

The qualitative evidence up to now suggests the fire-atmosphere interaction is a consequence of the burning conditions not a cause for atypical fire propagation. Evaluation of case studies and empirical based fire spread models in North America (Rothermel 1991; Alexander and Cruz 2006) and Australia (Cheney *et al.* 2012; Kilinc *et al.* in press) did not show a distinction in fire behaviour between fires with a strong convection build-up and others, such as so called wind-driven fires.

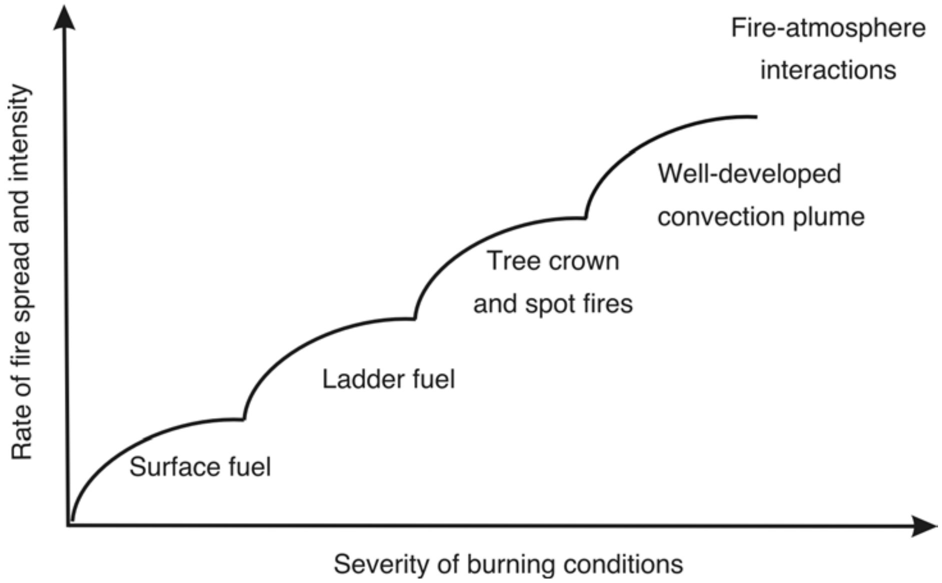

Figure 1.5. Effect of severity of burning conditions on the type of fire over the full spectrum of fire intensity. (from Alexander and Cruz 2013).

1.6 Fire behaviour models to support prescribed burning operations

Prescribed burning is defined by AFAC (2012) as "The controlled application of fire under specified environmental conditions to a predetermined area and at the time, intensity, and rate of spread required to attain planned resource management objectives". The planning and application of prescribed burns requires an understanding of the likelihood of successful propagation, potential fire behaviour and the prediction of the impact of fire in various ecosystem components (Burrows 1995, 1999; Tolhurst and Cheney 1999). Prescribed burn operations in eucalypt forests of south-eastern Australia rely on the use of coarse weather derived fire danger index metrics or the McArthur (1962) controlled burning guide at best.

It is somewhat of a contradiction that although prescribed burning has been identified as the most important tool available to land managers to reduce the likelihood of catastrophic fire development, the scientific support to judge prescribed burning behaviour on is still based on 50 plus-year-old fire behaviour research knowledge. The non-existence of models quantifying prescribed fire behaviour that incorporate the current state of knowledge is likely the most significant limitation to the application of scientific knowledge to support forest fire management in Australia. The two key knowledge gaps in regards to prescribed burning are discussed below.

1.6.1 MODELS FOR FIRE SPREAD SUSTAINABILITY IN DRY EUCALYPT FORESTS

As mentioned above, there is a need to develop the base knowledge and models to predict the likelihood of sustained fire spread and the associated burn patchiness and fuel consumption in these fuels. Models of these processes can then be used to more effectively plan and schedule prescribed burns. Furthermore, such models can be used to more precisely determine remaining fuel states for future fire spread prediction.

1.6.2 MODELS FOR FIRE SPREAD AND INTENSITY UNDER MARGINAL BURNING CONDITIONS IN DRY EUCALYPT FORESTS

New models for prescribed fire behaviour need to incorporate the latest knowledge on the effect of fuel structure and fuel moisture on fire propagation. This will enable more accurate prediction of fire potential that can be used to (1) ensure a burn achieves the aimed fuel reduction targets; and (2) plan for suppression requirements and predict the likelihood of an "escape" from a planned ignition prescribed burn.

1.7 Accessory fire models

The knowledge of a free-burning fire's rate of spread is central to being able to compute or estimate other fire behaviour characteristics (Figure 1.6). Accessory models are used to support a number of decisions, such as igniting a prescribed burn, set initial attack resources, estimate fire effect into a forest stand overstorey and determine smoke emissions. Two fire behaviour aspects were identified as needed better models to support fire management.

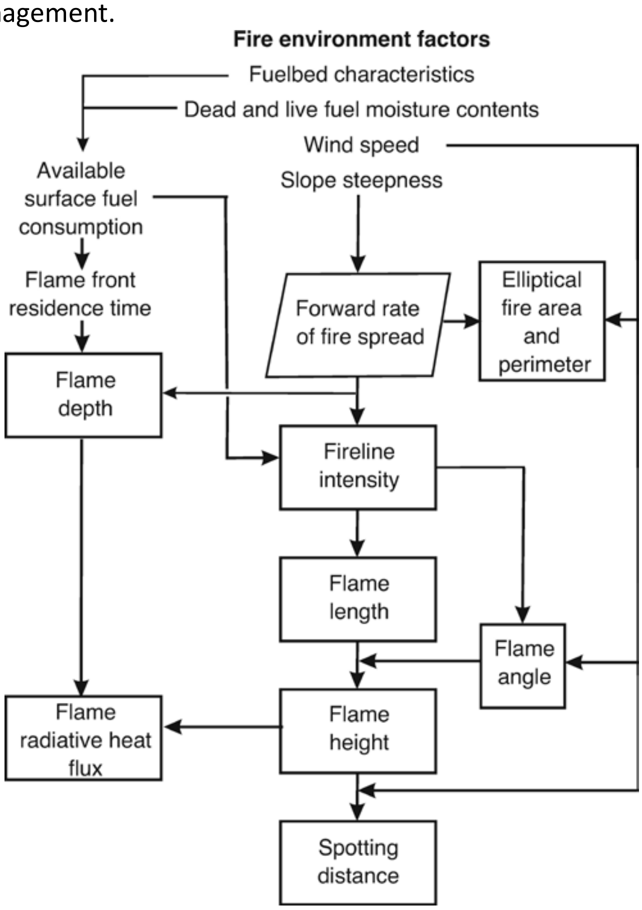

Figure 1.6. Flow chart illustrating the linkages that forward rate of fire spread has with the flame front dimensions and other characteristics of surface fire behaviour. Similar flow processes apply to crown fires in forests and shrublands but with the addition of available canopy fuel consumption to the determination of fireline intensity (after Cruz and Alexander 2013).

1.7.1 IMPROVED GENERIC MODELS FOR FLAME ZONE CHARACTERISTICS (FLAME HEIGHT, DEPTH, RESIDENCE TIME, RADIANT HEAT).

Models of flame zone characteristics such as flame height (Figure 1.7), depth and radiative output are used to inform a number of fire management decisions (e.g., Australian Standard 3959-2009). Unfortunately, the complexity of the flame processes made that current models use to predict flame zone characteristics are oversimplifications of narrow applicability. As Cheney (1990) noted “the flame characteristics associated with a specific fire intensity are only applicable to fuel types with the same fuel structure characteristics”. Illustrating this issue with published flame length models, Alexander and Cruz (2012a, b) showed a wide variability in the response of 20 distinct fireline intensity – flame length models depending on fuel types and studies.

There is a need for a more fundamentally-based generic model of flame characteristics that would describe the 3-dimensional structure of a flame as determined by the energy released and associated buoyancy forces, fuel structure and wind speed for both surface and crown fires.

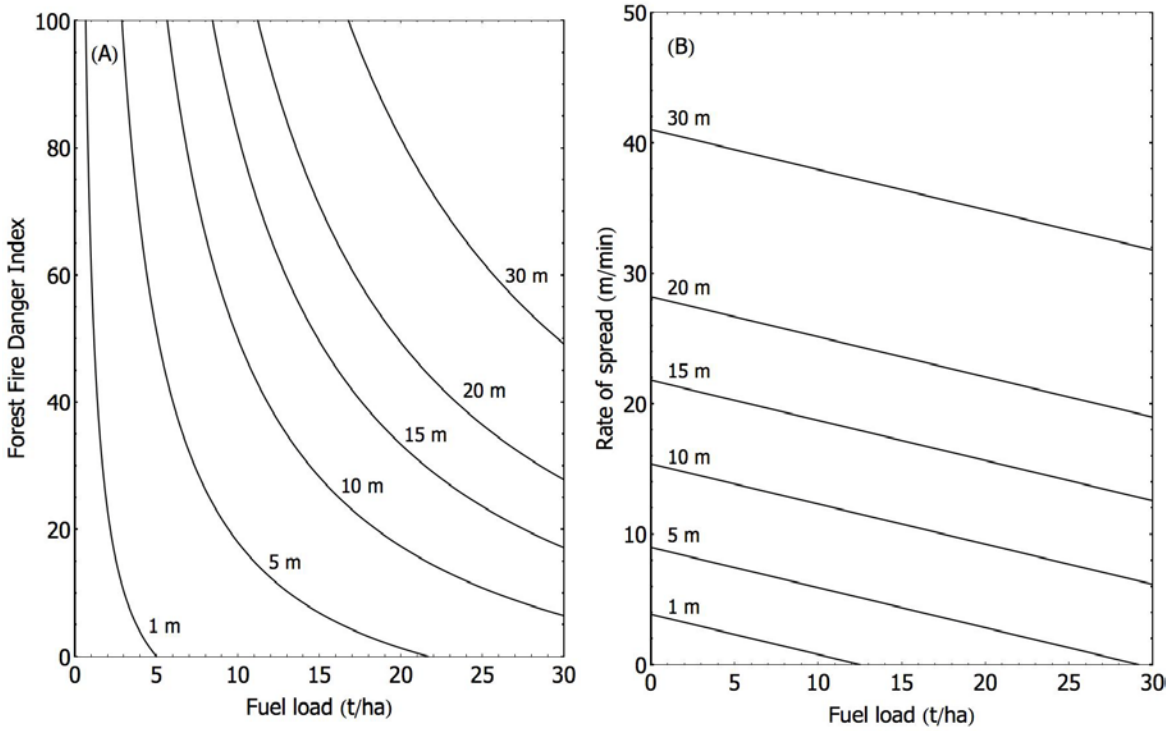

Figure 1.7. Flame heights as predicted by the MacArthur (1967, 1973) Forest Fire Danger Meter according to the equation given by Noble *et al.* (1980) as a function of (A) the Forest Fire Danger Index and fuel load and (B) rate of fire spread and fuel load.

1.7.2 IGNITABILITY AND CONSUMPTION OF ORGANIC SOILS AND PEAT (SUGGESTED RESEARCH NEED BY WA)

Fires in organic soils and peat spread slowly and almost unnoticed. Nonetheless, they have a disproportionate significance due to suppression costs and effects on sensitive ecosystem components (Wein 1981). Knowledge of its dynamics, namely the conditions that will allow a fire to start in these organic layers, are lacking. Comparably speaking, the relatively low occurrence frequency of these fires means that techniques for its containment and extinguishment are poorly developed.

1.8 Topographic effects on fire propagation

1.8.1 SLOPE STEEPNESS EFFECT

Slope is a variable with a dramatic effect on fire propagation, with fires spreading in positive slopes aligned with the wind known to increase their rate of spread several fold (McArthur 1967; Viegas 2004). Nonetheless, the characterization of the effect of slope steepness on fire rate of spread is still a major knowledge gap. One major issue is that in outdoor fires the slope effect is not constrained to the mechanical effect of slope steepness in increasing fire spread. There is a broad topographic effect associated with slope which interacts with the boundary layer meteorology. Wind flows tend to change with position on the slope, with stronger winds occurring closer to the ridge lines and lighter winds occurring at the valley bottom (Schroeder and Buck 1970; Forthofer *et al.* in press). Fuel structure tends also to change with position in the slope. The lower levels of a slope tend to be wetter and of higher productivity, causing fuels in these areas to have higher fuel loads, and fuel moisture contents (e.g. Potts *et al.* 1986; Raaflaub *et al.* 2011). Fuels near ridge tops tend to be more open and of lower height than fuels at lower elevations.

The difficulty in isolating the effect of fuel structure, fuel moisture and wind speed from a purely slope-driven effect has limited the suitability of field-based studies to determine the slope effect on shrubland fire propagation. Further research into this topic will likely require a combination of physical-based modelling with carefully conducted field experiments where a comprehensive quantification of the heat transfer processes are conducted.

Cheney (1981) points out that the slope function for adjusting rate of fire spread as discussed in Cruz *et al.* (2014) has certain limitations. He notes that "it may not hold above a slope angle of 30° as fuel discontinuities usually occur on steep slopes. Very steep slopes may include short sections of vertical rock face, as in the Hawkesbury sandstone formations in the Sydney area of New South Wales, which stop fire of moderate intensity, but a high-intensity fire can carry across these sections by spotting."

1.8.2 FIRE SPREAD PREDICTION IN COMPLEX TERRAIN

The prediction of fire propagation in complex topography poses a series of difficulties due to the effect topography has in creating an heterogeneous environment where fuel complexes, fuel moisture and wind flow vary in an intricate mosaic. General issues are known (Luke and McArthur 1978) but predictability of fire growth becomes highly complex. As such, it largely an issue of finding the correct inputs and the most adequate spatial scale at which to conduct accurate simulations. Recent advances in fuel type mapping, fuel moisture modelling (Sullivan and Matthews 2013) and wind modelling (Forthofer *et al.* in press) reduce the uncertainty in the main input variables driving fire simulations. Still, much of these tools are not available to end-users to run at a scale that would allow them to improve predictions of fire behaviour.

2 Fire Behaviour Analyst (FBAN) Training Revision Plan

The Fire Behaviour Analyst (FBAN) training revision plans presented here are based on the training material delivered at the Victorian FBAN training course held in July 2012. While subsequent FBAN courses have been delivered since that time, the material is substantively the same with only minor modifications by individual presenters.

The current curriculum was developed in 2007 and we believe it is time to update some of the lessons presented in the course to better focus on the knowledge needs of FBAN trainees and to include recent advances in fire behaviour science and knowledge. The revisions suggested in this section follow findings from the review of fire behaviour models and the personal experience of two of the authors' of this report (MGC and ALS) as lecturers in the course. The revisions should be seen as starting points for further discussion on the FBAN course contents.

The present section follows the order of delivery of material at the course but does not consider the exercises undertaken during the course.

2.1 Existing FBAN course outline

The course is divided into 20 sections as outlined in Table 2.1. The review plan will focus on the content of the fuels and fire behaviour science related lectures, namely, numbers 4, 5, 6, 11, 13 and 14.

Table 2.1. Outline of existing FBAN training course

#	ACTIVITY	CONTENT	TIME
1a	Role of Fire Behaviour Analyst	History, development future Importance to fire agencies and land managers in planning and emergency response The "Art and Science"	30 mins
2	Role in IMT (Planning).	Role in prescription development (Prescribed burning, backburning). Interface with BoM, field intelligence, operations, strategic planning. "Standard Products" – Fire Spread Predictions (best estimate), Potential Impact Zone (possible extent), documented basis for maps, commentary and implications.	15 mins
3	Processes	Review of pre-course exercise (Linton 1997) – basis of fire spread predictions, sources of information, interpretation, how data was used, factors considered, methods used. Process - gather intelligence (fire behaviour, assets/values at risk, suppression resources). Process - look ahead (fire prediction, weather, topography, fuels, fire size and behaviour) Process - suppression plan: objectives, strategies, options analysis, tactics, assess/review)	120 mins
4	**Fire behaviour**	**Elements of fire danger and fire behaviour models (overview)**	**45 mins**
5	**Fire behaviour**	**Grassland**	**30 mins**
6	**Fire behaviour**	**VESTA**	**45 mins**
7	Fire weather	Review pre-course weather exercise	30 mins
8	Fire weather	Bureau of Meteorology Products & Services (preparedness, situational awareness, going fires)	

#	ACTIVITY	CONTENT	TIME
9	Fire weather	The aerological diagram: Refresher and activity	90 mins
10	Fire weather	Weather influences on fire behaviour	45 mins
11	**Fire behaviour**	**Topographic effects on fire behaviour**	**45 mins**
12	Tools	Fire behaviour spreadsheet	30 mins
13	**Fuels**	**Assessment (Structure and continuity)** **Fuel moisture** **Fuel availability**	**60 mins**
14	**Fire behaviour**	**Buttongrass** **Heathland** **Mallee**	**65 mins**
15	Tools	McArthur's secrets revealed	60 mins
16	Tools	Bringing it all together Use of spreadsheet Preparation of documents and maps Communication of output	45 mins
17	Tools	Victorian system	60 mins
18	Tools	Suppression options Use of productivity guide Risk analysis	45 mins
19	Tools	PHOENIX-Rapidfire In-fire video analysis Setting assessment tasks Review of course--feedback	90 mins
20	Exercises	7 exercises	785

2.2 Suggested revisions to course material

2.2.1 GENERAL COMMENTS

The overall structure of the fire behaviour lessons is currently based on the fire danger meters for grass and forest. While this in the past has provided a useful starting point for discussing fire behaviour, many of the new fire behaviour prediction systems are sufficiently different that such a structure is inhibiting and distracting.

Many of the lessons have significant history included to provide context for each of the fire model categories. This history should be extracted and provided as part of the overall introduction to fire behaviour modelling (Lesson 4). Lessons then could then focus on matters pertinent for the prediction of fire spread in each fuel type (i.e. grasslands, shrublands, dry forest, etc).

As part of the teaching of these lessons, it is also recommended that short, specific exercises in applying the new knowledge in each lesson be used to cement the learning. This would be in addition to the existing more comprehensive exercises that are focussed on predicting the spread and behaviour of historical fire events.

2.2.2 LESSON 4: ELEMENTS OF FIRE DANGER AND FIRE BEHAVIOUR MODELS (OVERVIEW) – 45 MIN

General comment: This lesson lacks cohesion. There are a number of slides that seem to not fit very well in the lesson as they are not really relevant to the FBANs and there is not enough time to better explain the sub-topic (e.g., three slides on the Canadian Forest Fire Behaviour Prediction System).

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
Add two-three slides detailing differences and linkages between fire danger and fire behaviour	Remove US examples (two slides) and give more focus to Australian history
Add slide with purpose of fire behaviour models	Remove Poor experimental design slide
Add slides about general fuel types and models available	Remove Canadian system slides from this presentation
Add slides about fireline intensity calculation	Presentation of McArthur FFDM is out of place in this lesson as it is repeated late, unless the objective is to present a general structure of what is a fire spread model. However, McArthur model might not be the best example with which to start.
Add slides about flame characteristics and its estimation	
Expand on error in fire behaviour predictions	
Add more comprehensive content about spotting	

2.2.3 LESSON 5: GRASSLANDS – 30 MIN

General comment: This lesson generally achieves what it needs. However, comparisons of multiple models and graphs of model sensitivity distract from the key take home points. This lesson should always precede the lesson on fire prediction in dry eucalypt forest (currently called Vesta) as it introduces key concepts like fuel structure being more important than fuel load.

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
More detail on spinifex models	McArthur Mk 4 (and 5) as basis (structure and form) of lesson. Focus should be on CSIRO Grassland model as recommended model
Need to reformulate curing slides in light of new results from CFA grass curing project (when published)	Comparison of multiple grassland model functions (mostly McA Mk 4/5 and CSIRO)
Curing assessment; spatial variability in curing	Illustrations of model input sensitivity
Model limitations and uncertainty in outputs	History of model development (7 slides starting with NT experiments)
Expected variation and uncertainty in model output	Any mention of FDI
More discussion of threshold wind speed, particularly in discontinuous fuels.	
Effect of wind field turbulence on rate of spread predictions	
Firebreaks	
Flame height, suppression difficulty	

2.2.4 LESSON 6: VESTA – 60 MIN

General comment: This lesson needs to be reformulated to include new models in Cheney *et al.* (2012) (i.e. fuel hazard rating as well as hazard score versions). The detailed discussion of forest fuel strata needs to be done separately prior to discussion of prediction of fire spread in forest. The lesson needs to be renamed and focussed on prediction in native forest in general, rather than about a particular model. As models are improved or replaced, they can be slotted in without unnecessary restructuring of the lesson plan.

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
Add slides showing new model (i.e. hazard rating) outputs	History of reasoning behind the need for Vesta
Add slides showing model evaluation against independent data	Experimental details behind Vesta (6-8 slides)
Fire growth rate. More information about bounds of application of this model	Some of the fuel slides if this is discussed in the fuel section. Fuel discussion needs to be done prior to dry eucalypt forest fire model discussion
More information on FMC variability and effect on spread prediction	Comparison of multiple forest model functions (mostly McA Mk 5 and Vesta)
Effect of forest type on wind reduction factors	Illustrations of model input sensitivity, particularly hazard score

2.2.5 LESSON 11: TOPOGRAPHIC EFFECTS ON FIRE BEHAVIOUR – 45 MIN

General comment: Overall, this lesson delivers what it is supposed to. It could be streamlined a bit, use more local examples of topographic effects on fire spread. Some examples, such as the computational fluid dynamics modelling of wind flow in complex topography need to be put into better context.

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
Australian example of landscape moisture variation across complex topography	Pictures of fire in snow—it's just confusing
Better graphics illustrating mechanisms by which slope influences fire spread	Northern hemisphere example of FMC variation in landscape
Discussion of spotting and topography	Comparison slides between McArthur and Rothermel methods of combining slope with wind.
Place canyon/chimney effect in more Australian context and provide some detail	Sensitivity slides, wind/slope and FMC (2)
Revise downslope spread discussion to include new model kataburn	Forthofer wind in complex topography slides, they just add confusion, especially the fire spread maps
Discussion of difference between planar and linear estimates of rate of spread on slope and impact this has on predictions	
Discussion of methods for combining wind and slope and recommendation of using McA's rule of thumb	

2.2.6 LESSON 13: FUELS – 60 MIN

General comments: The fuels section is a comprehensive one comprising three main part: fuel assessment, fuel moisture and fuel availability. Currently this section is focused solely on eucalypt forest fuels. The discussion of other fuel types (e.g., grassland, shrublands) should be added to the lesson. The content could be improved by providing state specific fuel types in this particular lesson (the specific content would vary with the specific course location).

Furthermore, the course might benefit if this particular lesson was delivered earlier in the course, probably before lesson 5.

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
Discussion on fuel moisture estimation models	
Section on grassland fuels	
Section on shrubland fuels	
Section on pine plantation fuels	
Add slides on estimation of fuel moisture from models with some equations and limitations of models.	
Needs to be more generally applicable across wider fuel types and locations	

2.2.7 LESSON 14: SHRUBLANDS – 65 MIN

General comment: This lesson should be redesigned to focus on the most relevant models, namely to redo the mallee-heath and heathland sections to focus on the new model (Anderson *et al.* in prep). Equations from the old models should be removed.

SUGGESTED ADDITIONS	SUGGESTED SUBTRACTIONS
Slides (a few) on fuel characteristics in shrublands and highlight key shrubland fuel types in Australia – link with e.g. NVIS and Specht vegetation classification systems	Remove slope effect studies slides
Slides of limitations for each fire spread model discussed	
Slides (2) with main general features of shrubland fire propagation	
New section with new heathland model	
Re-do mallee-heath section to only focus in new model.	
Needs to be more generally applicable across wider fuel types and locations	
Woodland case needs better explanation	
Presentation should end with a slide of shrubland fuel types map and indication of where the models are applicable	

2.2.8 OTHER COMMENTS

There were a number of lessons from the original course materials from 2007 that have not been presented in the last few year's courses. Notably, these include the "Red book" lesson, the "Associated fire behaviour models" lesson and the "Pine plantation models" lesson. It is likely these lessons fell out of the course due to time constraints. Nonetheless, we believe the lessons still have an important role in the course and should be reintroduced. We suggest that these lessons be reorganized to reduce their delivery time and reincorporated into the course.

There are a number of other possible lessons that should be added to the current course curriculum. These include:

- Fire build-up:
  Experience with FBAN work showed that the course should have a lesson on fire build-up. There used to be some slides on this aspect of fire propagation in the "Basic fire behaviour" lesson that have since been removed. Some aspects of the fireline width in the grassland and Vesta lessons

could be merged into a build-up section. Such a lesson could also incorporate elements related to fire spread sustainability and trigger points for breakout conditions.

- Models for Prescribed burning operations:
  Prescribed burning models are available to FBANs through tables and the fire behaviour calculation spreadsheet. Nonetheless, there is no introduction to these models, or documentation, currently provided to the FBAN trainees. Given the suggested use of McArthur (1962) and other prescribed burning models under mild burning conditions, it would be advisable to have these models and their application introduced to the students during future courses.

It is arguable that the current lesson 10 (Weather influences on fire behaviour) should remain as the bulk of the topic should be covered by each of the fuel-specific fire behaviour lessons.

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