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RESEARCH ARTICLE

Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models

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Abstract

Context Fire behaviour research has largely focused on dry ecosystems that burn frequently, with far less attention on wetter forests. Yet, the impacts of fire in wet forests can be high and therefore understanding the drivers of fire in these systems is vital.

Objectives We sought to identify and rank by importance the factors plausibly driving flammability in wet eucalypt forests, and describe relationships between them. In doing so, we formulated a set of research priorities.

Methods Conceptual models of forest flammability in wet eucalypt forests were elicited from 21 fire experts using a combination of elicitation techniques. Forest flammability was defined using fire occurrence and fireline intensity as measures of ignitability and heat release rate, respectively.

Results There were shared and divergent opinions about the drivers of flammability in wet eucalypt forests. Widely agreed factors were drought, dead fine fuel moisture content, weather and topography. These factors all influence the availability of biomass to burn, albeit their effects and interactions on various

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dimensions of flammability are poorly understood. Differences between the models related to lesser understood factors (e.g. live and coarse fuel moisture, plant traits, heatwaves) and the links between factors.
Conclusions By documenting alternative conceptual models, we made shared and divergent opinions explicit about flammability in wet forests. We identified four priority research areas: (1) quantifying drought and fuel moisture thresholds for fire occurrence and intensity, (2) modelling microclimate in dense vegetation and rugged terrain, (3) determining the attributes of live vegetation that influence forest flammability, (4) evaluating fire management strategies.

Keywords Cognitive mapping · Conceptual models · Expert elicitation · Fire behaviour · Fire intensity · Flammability · Structured decision-making · Structured expert judgement · Wildfire · Wet forest

Introduction

The ability to accurately predict the spread of fires across different vegetation types is important for wildfire management and research. Empirical fire behaviour research has largely focused on dry ecosystems that burn frequently (Sullivan 2009), such as shrublands (e.g. Fernandes 2001; Bilgili and Saglam 2003; Anderson et al. 2015), dry forests (e.g. Fernandes et al. 2009; Cheney et al. 2012), woodlands (e.g. Gambiza et al. 2005) and grasslands (e.g. Cheney et al. 1998; Burrows et al. 2018). Fires in these systems occur across a broad range of weather conditions which provide frequent opportunities to implement experimental fires, safely observe wildfire behaviour and determine fire regimes from analysis of historic fires. In contrast, there has been far less research towards understanding the drivers of fire in wetter ecosystems that burn less frequently (Cochrane 2003), such as wet eucalypt forests, tropical and temperate rainforests. Despite the infrequency of fire in wet forests, predicting their likelihood and consequences is vitally important because the economic, social and environmental impacts of fires in these forests are often extremely high (Pivello 2011; Cruz et al. 2012).

Some of the most damaging fires in Australia's recent history, with significant loss of life and property, have involved intense burning in wet eucalypt forests, e.g. Black Saturday 2009 (Cruz et al. 2012), Ash Wednesday 1983 (Rawson et al. 1983), Black Tuesday 1967 (Solomon and Dell 1967). Wet eucalypt forests are highly valued for a range of ecosystem services—biodiversity (Lindenmayer 2009; Swan et al. 2018), carbon storage and sequestration (Fedrigo et al. 2014; Sillett et al. 2015), water supply and quality (Benyon and Lane 2013) and timber production (Florence 1996). Wildfires are important to maintaining ecosystem dynamics in wet eucalypt forests (Ashton 1981; Turner et al. 2009). However, fires that are too intense or too frequent jeopardise the ability of these forests to provide these ecosystem services (e.g. Benyon and Lane 2013; Bowman et al. 2014) and can threaten the lives and property of people living in proximity (e.g. Department of Environment Land Water and Planning 2015).

Current knowledge of the drivers and constraints on flammability in wet eucalypt forests is disparate, despite the potential impact of wildfires. Flammability is broadly defined as the capacity of biomass to burn and is measured by the combustion characteristics of the biomass, e.g. ignitability, flame spread rate (consumability), heat release (combustibility) and sustainability (burning time) (Gill and Zylstra 2005; Pausas et al. 2017). In this study we use wildfire occurrence and fireline intensity as measures of ignitability and heat release rate, respectively. There is broad agreement that global wildfire occurrence is driven by a common set of factors: amount of biomass, availability of biomass to burn, climate, weather and the ignition agent (Meyn et al. 2007; Bradstock 2010). However, the relative importance of each factor and the elements that drive variability within these factors differs between different ecosystems (Krawchuk and Moritz 2011) and at different spatial and temporal scales (Pausas et al. 2017). In wet eucalypt forests,

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there are many hypotheses about the relative importance of different factors driving fire occurrence and intensity and a lack of empirical data to test these ideas (summarised by Cawson et al. 2018). Such divergence of opinion is not uncommon in understudied systems, but it is problematic for fire management agencies who are still expected to make real-time fire behaviour predictions during wildfire incidents and manage fuel hazard in these ecosystems despite the lack of data or consensus.

With limited resources for research and numerous factors that could potentially influence fire occurrence and intensity in wet eucalypt forests, we need an efficient way of identifying which factors to prioritise for research. This could be done by identifying the epistemic uncertainties in our understanding of fire in wet forests; the uncertainties that result from a lack of knowledge (Regan et al. 2002). Epistemic uncertainties include model uncertainty arising from not knowing how things interact, subjective judgement because of our unique experiences and the way our mind processes information and experience, measurement error from lack of precision, systematic error resulting from biases in how we collect data, and also natural variation. Ideally research should be focused towards epistemic uncertainties which can be reduced by further data collection and which most hamper effective management and prediction (Runge et al. 2011). However, in order to do this, we first need to identify what uncertainties exist and the source of these uncertainties.

Unfortunately identifying epistemic uncertainties can be hampered by the vague and informal language that can be used to communicate ideas and theories (Regan et al. 2002). This informal use of language can lead to the perception there is disagreement (or agreement) when there is none. Identifying epistemic uncertainties can also be challenging because ecosystems vary in space and time, and people hold unique mental models which vary due to their unique experiences, as well as how their mind processes and makes sense of these experiences. Rarely do we have a complete insight into the mental models held by different people or the basis for them. This makes it difficult to understand where there is agreement and disagreement, and why. Without this understanding, research remains unfocused and may be targeting areas that are already well-understood or for which further data collection will not reduce critical uncertainties.

Conceptual models are graphical representations of an individual or groups' beliefs about causal relationships (Markóczy and Goldberg 1995). They consist of nodes that represent factors of perceived importance and arcs that represent relationships between factors. The direction and strength of influence can be assigned to the relationships. Conceptual models have been used successfully in several conservation and natural resource management contexts (Biggs et al. 2011), including in rangeland management (Abel et al. 1998) and in articulating dangers associated with climate change (Lowe and Lorenzoni 2007). Contrasting and comparing models elicited from a range of people can make alternative perspectives and experiences explicit, help remove linguistic ambiguity, and form the basis of discussions about the relative experiences and evidence shaping shared and divergent views (Walshe and Burgman 2010; Moon et al. 2019b; Shea et al. 2020). Possible biases and cognitive limitations stemming from a single model can be overcome by contrasting and comparing models elicited from multiple individuals and entrenched views that stymie innovation can be broken down. Conceptual models provide an invaluable framework for articulating perspectives and building a shared understanding where key epistemic uncertainties exist (Walshe and Burgman 2010). These uncertainties can be used to identify where investment in research may lead to the greatest advancements in our collective understanding of an ecosystem (Shea et al. 2020).

In terms of developing an understanding of flammability in wet eucalypt forests, conceptual models enable us to intellectually progress when there is little peer-reviewed research. Although there is generally a lack of empirical data about wildfire occurrence and intensity in wet eucalypt forests, there are many researchers and practitioners who hold substantial, but often undocumented and unexamined, knowledge and experience of fire in these systems. These substantial and unique experiences can be elicited into conceptual models to help identify known drivers of fire in these ecosystems and identify areas of disagreement. Currently, documented knowledge of these ecosystems tends to be communicated via peer-reviewed publication. This may be problematic as the scientific literature tends to disproportionately reflect the views of only a few within the academic community and is likely to reinforce the views of more well-established researchers or promote and reinforce existing models over alternative perspectives. It may therefore only capture a subset of views about the drivers of fire in these ecosystems, thus ignoring possibly important experiences by early career researchers, and those who do not publish in the academic literature, including fire managers and operational fire behaviour analysts. The elicitation of conceptual models can help to bring together a broad cross-section of the fire community to build a more complete understanding of flammability in wet forest ecosystems and thus overcome this bias.

In this study, 21 expert opinions were elicited to better understand the breadth of competing ideas regarding the key drivers of forest flammability, measured by fire occurrence and intensity, in the wet eucalypt forests of south-eastern Australia. This expert elicitation was then used to identify areas of consensus, and areas of disagreement, that could be used to frame research priorities towards a more robust understanding of fire in wet eucalypt forests. Specifically, the research questions were:

- What is the relative importance of the factors influencing forest flammability?
- What are the interactions and feedbacks between the factors influencing forest flammability?
- What research topics should be prioritised to progress our understanding of forest flammability?

Methods

Study area

Wet eucalypt forests (otherwise known as Tall open forests) are Australian native forests with a canopy of one or more *Eucalyptus* species (e.g. *E. regnans*, *E. delegatensis*, *E. denticulata*, *E. diversicolor*, *E. grandis*, *E. globulus*, *E. nitens*,, *E. obliqua*, *E. pilularis*) and a dense understorey of ferns, tree-ferns, broad-leaved trees and shrubs, many of which are mesic in character including rainforest species (Ashton and Attiwill 1994; Florence 1996; Tng et al. 2013). Mature forests have a canopy cover of 30–70%, are at least 30 m tall and commonly achieve heights of 70 m (Ashton and Attiwill 1994). These forests have a narrow ecological range occurring in areas of relatively high, reliable precipitation and are often on southerly aspects or in gullies (Wood et al. 2014). Wet eucalypt forests can be found in Queensland, New South Wales, Victoria, Tasmania and the south-west of Western Australia. In this study we considered wet eucalypt forests within south-eastern Australia (not in Western Australia) as this reflected the expertise of the workshop participants (Fig. 1). These forests harbour some of the tallest tree species on Earth and have an ecology, physiognomy and life history which is globally unique (Tng et al. 2012).

Workshop

To develop a conceptual understanding of the flammability in wet forests a 2.5 day workshop was held with 21 experts in fire behaviour and four facilitators. The aims of the workshop were to document current conceptual models of the drivers of flammability in wet eucalypt forests and use these models to identify research priorities. To do this, we broadly followed recommendations in the literature for eliciting individual and group conceptual models (Walshe and Burgman 2010). This involved identifying factors of importance, refining the list of factors and the descriptions of those factors, developing individual conceptual models, and then developing group models (Fig. 2). In the final stage of the workshop, participants were asked to pose a critical research question relating to flammability in wet eucalypt forests. The process is outlined in more detail below. The role of the facilitators was to design the format of the workshop, facilitate the development of conceptual models and collate the results. Facilitators did not attempt to influence the importance of variables, the conceptual models or research priorities. The participants were tasked with developing conceptual models of the drivers and constraints of flammability in wet eucalypt forests. Both facilitators and participants contributed to the authorship of this paper.

Selection of workshop participants

Workshop participants were recruited with different experiences and diverse perspectives and mental models of fire in wet eucalypt forests (Table 1). However, all participants required either research experience relating to fuel dynamics or fire behaviour in wet eucalypt forests or fire management experience

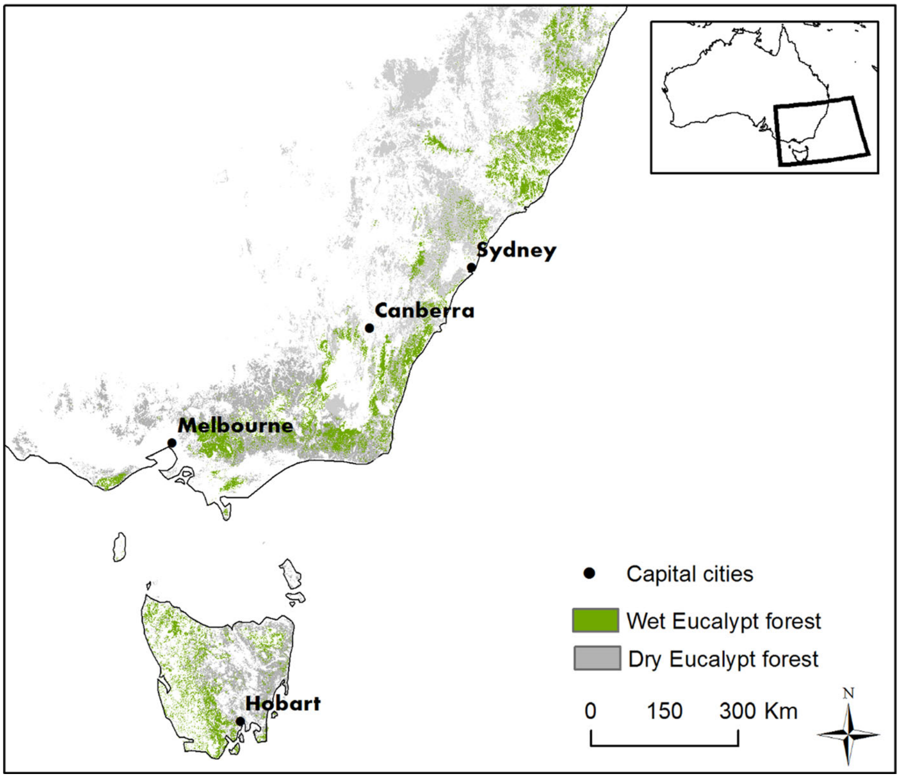


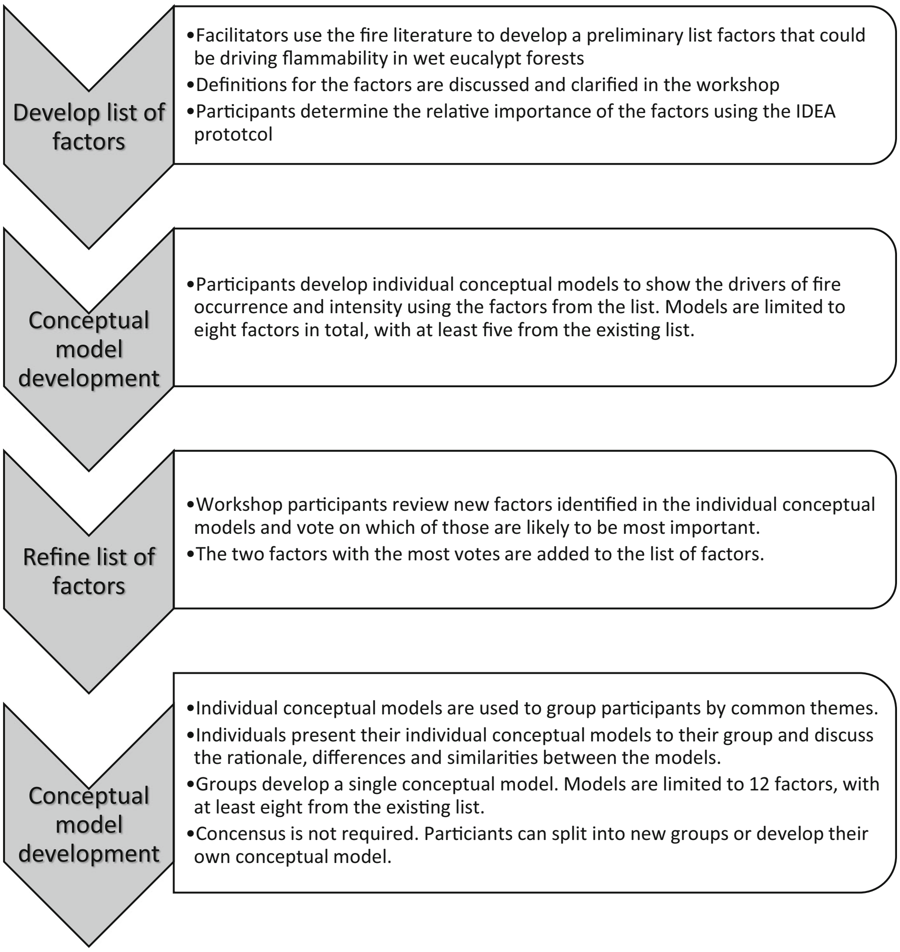
Fig. 1 Distribution of Wet eucalypt forest (otherwise known as Tall open eucalypt forest) in south eastern Australia. Spatial vegetation data sourced from TASVEG for Tasmania (Department of Primary Industries Parks Water and Environment 2013), Ecological Vegetation Classification for Victoria (Department of Environment Land Water and Planning 2016) and Vegetation formations and classes for NSW (Keith and Simpson 2011)

in wet eucalypt forests. Of the 21 participants, nine had experience as a researcher, five had experience as fire practitioners and seven had both. They came from ten different organisations—six research institutions and four fire agencies. Years of experience ranged from < 10 years (3 participants) to > 30 years (5 participants).

Identifying factors of importance

The first stage of the workshop was to derive a common list of factors influencing flammability in wet eucalypt forests. This was important so that the potential model components could be analysed for similarities and differences. The workshop facilitators derived an initial list from the fire science literature. Then, a structured expert elicitation method was used, termed the IDEA protocol (“Investigate”, “Discuss”, “Estimate” and “Aggregate”) (Hemming et al. 2018b) to quantify the relative importance of the factors, and to elicit additional factors of importance. During this exercise (a survey), the workshop participants were asked to consider fires in wet eucalypt forests they had previously experienced. The survey questions in our study considered four scenarios (see Appendix 1 for questions) relating to (1) the absence of fires exceeding 100 hectares in the landscape; (2) unburnt patches within a fire area; (3) low intensity patches within a fire area; and (4) high intensity patches within a fire area. The participants were asked to score factors by their relative importance for determining the fire outcomes described in the scenarios above.

The IDEA protocol requires experts to complete two rounds of a survey, with an intervening discussion phase. Participants were asked to complete Round 1 of the survey before the workshop commenced. During the workshop, participants were shown the group results of Round 1 and then a facilitated discussion considered the potential reasons for the variation in



- Facilitators use the fire literature to develop a preliminary list factors that could be driving flammability in wet eucalypt forests
- Definitions for the factors are discussed and clarified in the workshop
- Participants determine the relative importance of the factors using the IDEA prototcol

- Participants develop individual conceptual models to show the drivers of fire occurrence and intensity using the factors from the list. Models are limited to eight factors in total, with at least five from the existing list.

- Workshop participants review new factors identified in the individual conceptual models and vote on which of those are likely to be most important.
- The two factors with the most votes are added to the list of factors.

- Individual conceptual models are used to group participants by common themes.
- Individuals present their individual conceptual models to their group and discuss the rationale, differences and similarities between the models.
- Groups develop a single conceptual model. Models are limited to 12 factors, with at least eight from the existing list.
- Concensus is not required. Particiants can split into new groups or develop their own conceptual model.

Fig. 2 Process used to develop the conceptual models during the expert workshop

responses. After clarification, refined definitions for each factor were made.

The process led to several new factors identified as being potentially useful at the end of Round 1. To determine if any of these new factors should be included in the list for Round 2, participants were asked to vote for one additional factor. The two factors with the most votes (drought and dead-to-live ratio) were added for Round 2. Round 2 essentially involved repeating the same survey questions, drawing on any insights gained from the group discussions to adjust individual responses if desired. Agreed definitions for the key factors are presented in Table 2.

Development of conceptual models

Participants were asked to document their own conceptual model showing relationships between the factors and how they influence fire occurrence and intensity in wet eucalypt forests. This was done by posing the following question to the group:

> Across climatic conditions similar to what we have experienced over the last 20 years, imagine 1000 patches (100 ha in size) of wet eucalypt forests across south-eastern Australia. What will determine fire occurrence and fire intensity within these patches?

Fire occurrence was defined as the probability of a fire occurring that exceeds 100 ha. Fire intensity was defined using the definition of fireline intensity—rate

Table 1 Demographics of workshop attendees (excluding facilitators)

Organisations represented	Regional expertise	Type of experience	Years of experience	Gender
Research institutions:	Central Highlands (Vic) (8)	Researcher (9)	1–10 (3)	Male (18)
University of NSW (2)	Alps (ACT, NSW & Vic) (3)	Practitioner (5)	11–20 (7)	Female (3)
Aust National University (1)	Otway Ranges (Vic) (1)	Both (7)	20–30 (6)	
CSIRO (1)	Whole of SE Australia (3)		30 + (5)	
University of Melbourne (6)	Sydney basin (1)			
University of Tasmania (2)	SE Tasmania (1)			
University of Wollongong (2)	Whole of Victoria (2)			
Macquarie University (1)				
Land or fire management agencies:				
NSW Rural Fire Service (1)				
VicForests (1)				
Country Fire Authority (3)				
Dept. of Environment, Land, Water and Planning (3)				

The number of workshop participants within each demographic is shown in brackets

Table 2 Definitions for key factors potentially influencing fire occurrence and intensity in wet eucalypt forests

Factor	Definition
Amount of dead fine fuel	Tonnes per hectare of dead fine fuel (< 6 mm thick) in any fuel strata
Arrangement of fine fuel	Horizontal and vertical continuity of dead fine fuel (< 6 mm thick) and live fine fuel (< 2 mm thick) in any fuel strata
Dead fine fuel moisture content (Dead FFMC)	Mass of water per unit mass of dry dead fine fuel (< 6 mm thick)
Fire weather	Characteristics of the weather that affect fire behaviour, e.g. wind, temperature, humidity, rainfall, atmospheric instability
Fuel break	Gap in the horizontal continuity of fuel caused by a road, river or cleared vegetation
Ignition	An ignition source, e.g. lightning strike, human ignition, established wildfire
Live fine fuel moisture content (Live FFMC)	Mass of water per unit mass of dry live fine fuel (< 2 mm thick)
Species composition	Types of species within a vegetation community and their abundances
Topography (or terrain)	The natural shape of the landscape—slope, aspect, hillslope position, ruggedness
Dead to Live ratio	Ratio of the mass of dead fine fuel to the mass of live fine fuel
Drought	Prolonged period of abnormally low rainfall (rainfall deficit) over a period of months to years

These definitions were discussed in the workshop and the revised definitions used in Round 2 of the expert judgement exercise are shown here, including definitions for Drought and Dead-to-Live ratio, which were added after the Round 1 discussions

of energy output as a function of head fire width (Keeley 2009). Fireline intensity was chosen as the measure of rate of heat release because it is easily visualised and can be estimated from flame height (Cheney 1981). To limit the scope of the models and make them comparable, participants were asked to create models that included no more than eight factors, of which at least five should come from the list in Table 2. The purpose of developing individual conceptual models prior to grouping the participants was to capture individual experiences and reduce the potential for influence by more dominant group members during later stages of the workshop.

Facilitators reviewed the individual models and then created five groups based on the degree of similarity between individual models. Proposed groupings were presented to the workshop and participants were given the option to move between groups if they were dissatisfied with their allocation. Groups were told that consensus was not required and when disagreements could not be resolved, the group could split to develop separate models, which happened on only one occasion.

Each group was asked to develop a conceptual model that included no more than 12 factors, with at least eight factors from the revised list in Table 1. The number of allowable factors was greater than the previous exercise since groups were tasked with combining the individual models from a diverse group of experts. Group interactions were facilitated to refine the definition of terms, manage group dynamics and highlight inconsistencies in the groups' thinking. Participants were asked to illustrate the likely relationships (positive or negative correlations) between the factors in the model. For each link in the conceptual models, participants documented key scientific evidence supporting that link and knowledge gaps that could be addressed through research.

Identification of research priorities

Each group presented their model to the workshop and all participants were asked to consider the models developed and write down key points of difference between the models. At the end of the workshop all participants individually formulated a research question that they thought was a high priority to progress our understanding of flammability drivers in wet eucalypt forests.

Data analysis

Results from Round 2 of the expert elicitation exercise were analysed to identify key factors thought to be influencing flammability in wet eucalypt forests. Boxplots were used to show the relative importance of factors, based on the total score for each factor. As a secondary measure of relative importance, the individual conceptual models were analysed to identify the frequency with which each factor was used. The five conceptual models developed by groups of participants were recreated digitally and the factors within each model defined, where they deviated from the definitions in Table 2. Influential factors (with at least three outgoing links) and unique factors (specific to an individual model) were highlighted in each model. To compare the complexity of the group models we calculated average distance between variables (path length), maximum distance between variables and the total number of connections for all diagrams (as per Moon and Adams 2016). To more clearly identify commonalities and differences between the models, factors were grouped into five categories: biomass, available biomass, climate, weather, topography, fire and management. Then the frequency of links between those groups was analysed by combining all the models into a composite model. The composite model captures all the connections across the group models and weights those connections based on their frequency of occurrence. It can be used to clearly identify those model links that were identified as important by a large proportion of the workshop participants and those that represent more disparate views. Research questions posed by each workshop participant were mapped against the links in the composite model. This helped to determine whether the questions were informed by the agreements or disagreements between the models.

Results

Factors of importance

There was a broad range of responses for each factor influencing fire occurrence and intensity in wet eucalypt forests, although some patterns emerged (Fig. 3). Dead FFMC and fire weather were key factors identified in all scenarios of the expert judgement exercise as having an important influence on fire intensity and the absence of wildfires within a season. It should be noted that these two factors are not independent, as temperature and relative humidity (elements of fire weather) strongly influence dead FFMC. Drought was also frequently identified as a key determinant of fire occurrence and the presence of very high fire intensity patches within a wildfire. Amount of fine fuel, live FFMC and dead-to-live ratio were thought to have the least influence on

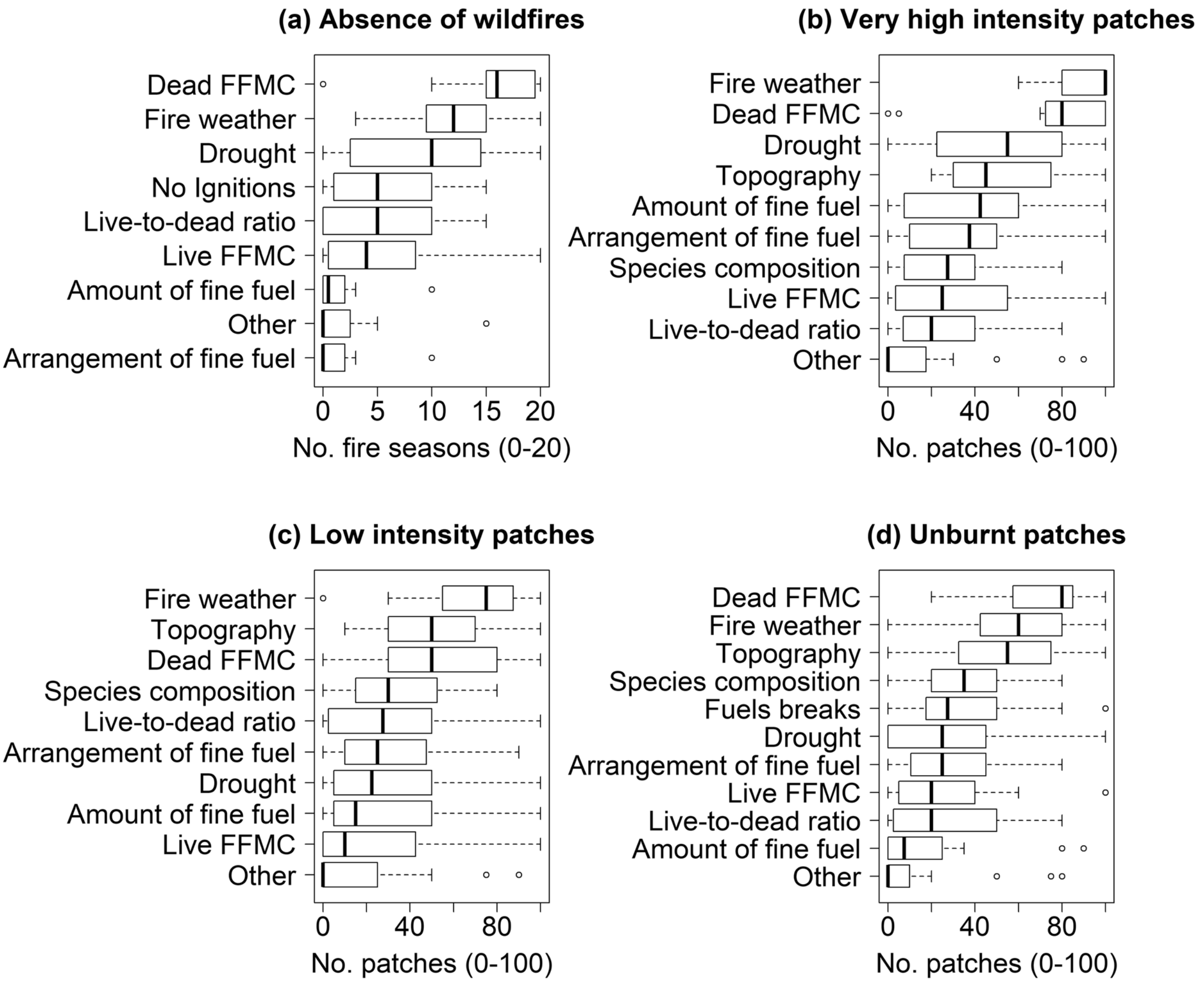


Fig. 3 Standard box and whisker plots summarising the responses from Round 2 of the expert judgement exercise. Participants were asked to estimate the number of fire seasons or number of patches in the landscape when each factor was influential in the context of **a** the absence of wildfire, **b** very high intensity fire, **c** low intensity fire and **d** unburnt patches within a fire area. Factors along the y-axes are ranked from most important (top) to least important (bottom) based on the medians for the box and whisker plots

flammability. The whiskers for many of the factors span a large proportion of the full range of each scenario, which indicates that there was a broad range of views on what influences flammability among the workshop participants.

Drought, fire weather and dead FFMC were used most often in the conceptual models developed individually by the workshop participants (Fig. 4). There were several new factors introduced in these models including available fuel, fire characteristics, suppression, time since disturbance and heatwaves. Fuel breaks were not used in any of the models.

Conceptual models derived by groups

There were several points of agreement, but also differences between the conceptual models developed by groups of workshop participants (Figs. 5, 6, 7, 8, 9; Table 3 and 4). Four factors out of a total of 25 were common to all models: drought, fire weather, dead FFMC and topography. In contrast, most models included several unique factors, despite steps taken earlier in the workshop to develop a standard list of factors and factor definitions (Table 3). Out of 71 different model links, only one link (topography → fire intensity) was common to all five models.

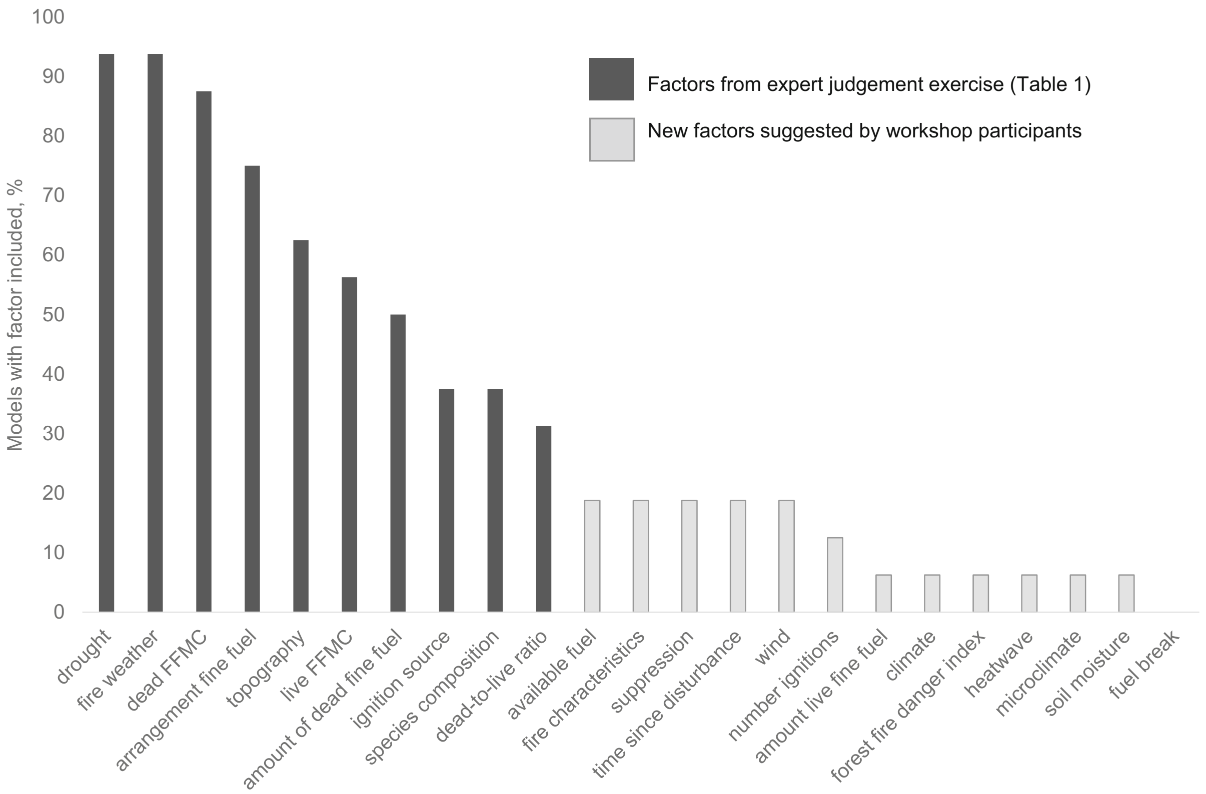


Fig. 4 Frequency of use for different factors in the conceptual models developed by individuals. The conceptual models indicated the drivers and constraints of fire occurrence and fire intensity in wet eucalypt forests. Each workshop participant developed their own model

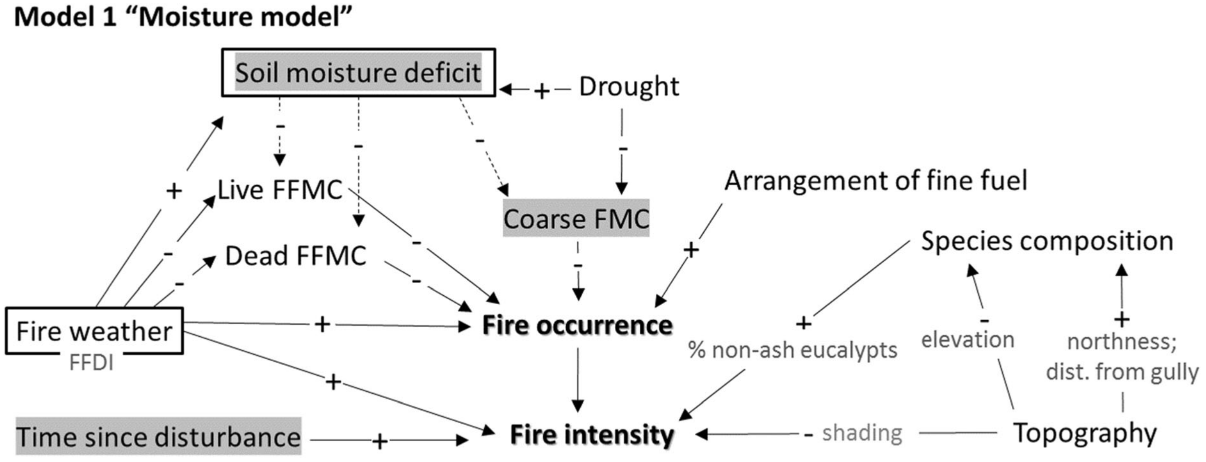


Fig. 5 Conceptual Model 1, the “moisture model”, predicting the probability of fire occurrence (fires exceeding 100 ha) and fire intensity. Factor definitions for this model are provided in Table 2. Dashed lines indicate speculative relationships between factors. The most influential factors (influencing at least three other factors) are surrounded by a black box. Factors unique to this model are shaded in grey

Only ten links were common to more than one model. In contrast, more than 50% of the model links within each model were unique. There were different views about the influence of topography on flammability,

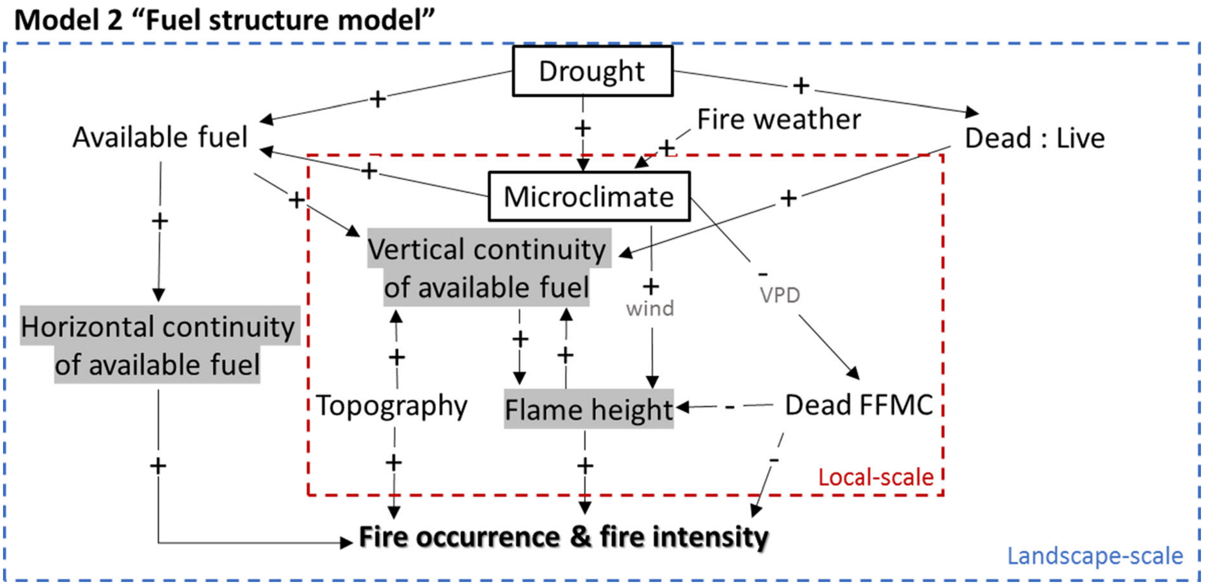


Fig. 6 Conceptual Model 2, the "fuel structure model", predicting the probability of fire occurrence (fires exceeding 100 ha) and fire intensity. Factor definitions for this model are provided in Table 2. The most influential factors (influencing at least three other factors) are surrounded by a black box. Factors unique to this model are shaded in grey

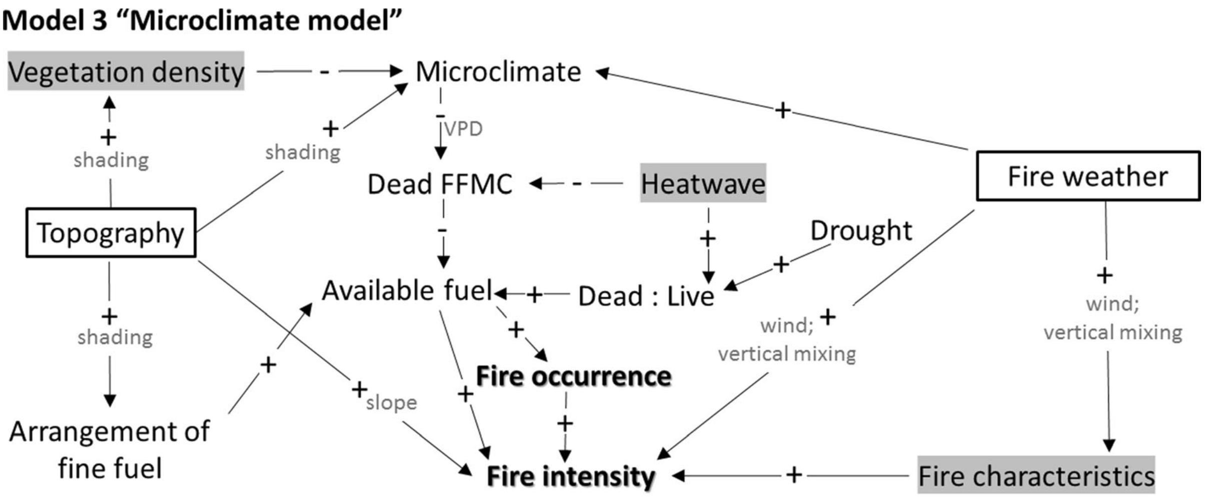


Fig. 7 Conceptual Model 3, the "microclimate model", predicting the probability of fire occurrence (fires exceeding 100 ha) and fire intensity. Factor definitions for this model are provided in Table 2. The most influential factors (influencing at least three other factors) are surrounded by a black box. Factors unique to this model are shaded in grey

despite it being a common factor to all models. The microclimate model (Model 3) was most complex, with an average path length of 4.6 and a maximum distance of seven between nodes. The species model (Model 4) was the least complex, with only six driving factors, an average path length of 2.9 and a maximum distance between nodes of four.

Model 1 is labelled the 'moisture model' because it focuses on the moisture content of different fuel elements (live fine fuel, dead fine fuel and coarse fuel) and the factors influencing the moisture content of those fuel elements (Fig. 5). Fire weather is one of the most influential factors in the model, driving moisture content as well as fire occurrence and intensity directly. Soil moisture deficit is another influential

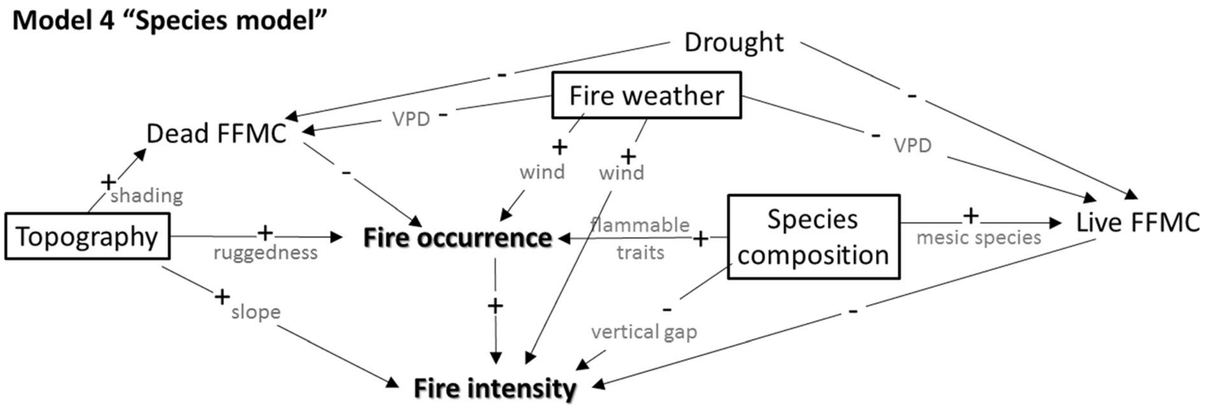


Fig. 8 Conceptual Model 4, the “species model”, predicting the probability of fire occurrence (fires exceeding 100 ha) and fire intensity. Factor definitions for this model are provided in Table 2. The most influential factors (influencing at least three other factors) are surrounded by a black box

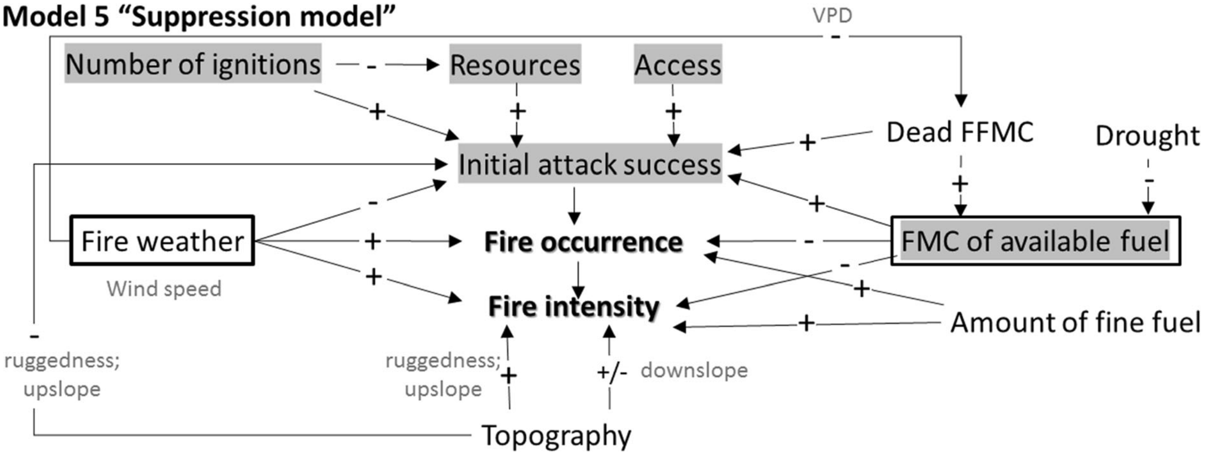


Fig. 9 Conceptual Model 5, the “suppression model”, predicting the probability of fire occurrence (fires exceeding 100 ha) and fire intensity. Factor definitions for this model are provided in Table 2. The most influential factors (influencing at least three other factors) are surrounded by a black box. Factors unique to this model are shaded in grey

factor, depicted as a linking factor between drought and fine fuel moisture. Soil moisture deficit is unique to Model 1; in contrast the other models tend to show direct links between drought and fine fuel availability or fine fuel moisture. Other factors unique to Model 1 are coarse fuel moisture content, which is also mentioned in Model 5 but not identified as a separate factor, and time since disturbance.

Model 2 labelled the ‘fuel structure model’ differentiates between the horizontal and vertical continuity of available fuel (Fig. 6). Drought and microclimate are the most influential factors, shown influencing the amount of available fuel across the landscape and other fuel dryness factors (e.g. dead to live ratio, dead FFMC). The influence of available fuel on fire occurrence and intensity is dependent on its continuity, with vertical continuity influencing flame height at the local scale and horizontal continuity influencing fire occurrence and intensity directly at the landscape scale. Flame height, another unique factor in the model, is considered explicitly because of its feedbacks with the vertical continuity of available fuel.

Model 3 labelled the ‘microclimate model’ depicts the downscaling of fire weather to microclimate, driven by topographic position and vegetation density (Fig. 7). Fire weather and topography are the most influential factors in the model, both influencing microclimate and fire intensity. Topography is shown

Table 3 Summary statistics for group models used to quantify the complexity of each model

	Average path length	Max distance between factors	No. factors	No. unique factors	No. links	No. unique links
Model 1 “moisture model”	3.5	5	10	3	20	11
Model 2 “fuel structure model”	4.5	6	10	3	18	15
Model 3 “microclimate model”	4.6	7	11	3	19	11
Model 4 “species model”	2.9	4	6	0	15	7
Model 5 “suppression model”	3.7	6	10	5	21	14

Average path length is the mean distance between factors in the models. Max distance between factors is the longest path length between factors. No. factors is the total number of factors in each model, excluding fire occurrence and fire intensity. No. unique factors is the number of factors that were exclusive to each model. No. links is the total number of links in each model. No. unique links is the number of links that were exclusive to each model

influencing the amount of available fuel via the arrangement of fine fuel. Fire weather is shown influencing fire intensity via fire characteristics. Fire characteristics is a unique factor in Model 3, included to show that the fire itself (e.g. plume size) can influence fire intensity. Heatwave is another unique factor, influencing the amount of fuel available to burn via the dead-to-live ratio and dead FFMC.

Model 4 is labelled the ‘species model’ because species composition is one of the most influential factors (Fig. 8). Species composition has a positive influence on fire occurrence when defined by the abundance of flammable traits. In contrast, species composition has a negative influence on fire intensity when defined by the size of vertical gap between fuel strata. Species composition is also depicted as having a positive influence on live FFMC when defined by the abundance of mesic species. Fire weather and topography are also influential factors, depicted as influencing fire occurrence and intensity directly and via fuel moisture content.

Model 5 is labelled the ‘suppression model’ because it includes initial attack success and factors that influence the effectiveness of fire suppression (number of ignitions, resources and access) (Fig. 9). The focus on fire suppression as a key process influencing fire occurrence and intensity in wet eucalypt forests is unique to Model 5. The most influential factors are fire weather and FMC of available fuel, both influencing fire occurrence, fire intensity and initial attack success. FMC of available fuel is a factor unique in this model, it includes all fuel elements (fine and coarse, even large logs) rather than just dead fine fuel.

Similarities and differences between the conceptual models are more easily seen when the factors are grouped into themes (Fig. 10) (see Table 4 for groupings). Available biomass is the most dominant theme across the models. It is depicted influencing fire behaviour directly and is predominately a function of weather and climate. Five model links appear in all models when the factors are grouped: available biomass → fire, climate → available biomass, topography → fire, weather → available biomass, and weather → fire. Conversely, model links that only appear once or twice indicate areas of divergent opinion. Even after grouping the factors into broad themes, there were nine model links that only appeared once (indicated by the ‘1’ on the arrows in Fig. 10).

Research questions

Most research questions posed by the workshop participants included some aspect of fuel moisture and understanding how fuel moisture relates to weather or fuel availability (see Appendix 2 for full list of questions). In mapping each research question to the composite conceptual model, we see that the questions are mostly focused on understanding the strongest links (Table 5). These were links that appeared most frequently in the conceptual models, rather than links that only appeared once or twice in the group models. Three topics encompassed most of the research questions: (1) the effect of weather on available biomass, (2) the effect of climate on available biomass, and (3) the effect of available biomass on fire.

Table 4 Definitions for factors depicted in the conceptual models

Theme	Factor	Model 1: moisture	Model 2: fuel structure	Model 3: microclimate	Model 4: species	Model 5: suppression
Available biomass	Available fuel	–	Amount of fuel dry enough to burn	Amount of fuel dry enough to burn	–	–
	Coarse fuel moisture content (FMC)	Moisture in coarse fuel, 6-50 mm diam	–	–	–	–
	Dead fine fuel moisture content (FFMC)	Table 2	Table 2	Table 2	Table 2	Table 2
	Dead to Live ratio	–	Table 2	Table 2	–	–
	Horizontal continuity of available fuel	–	Horizontal distribution of fuel that is dry enough to burn	–	–	–
	Live fine fuel moisture content (FFMC)	Table 2	–	–	Table 2	–
	Moisture content of available fuel	–	–	–	–	Moisture content of all fuel (dead, live, fine, coarse) that dry enough to burn
	Vertical continuity of available fuel	–	Vertical distribution of available fuel	–	–	–
Biomass	Amount of dead fine fuel	–	–	–	–	Table 2
	Arrangement of fine fuel	Table 2	–	Table 2	–	–
	Species composition	Table 2	–	–	Table 2	–
	Vegetation density	–	–	Plant area index for all vegetation strata	–	–
	Time since disturbance	Number years since logging or wildfire	–	–	–	–
Climate	Drought	Spring rainfall deficit	Table 2	Table 2	Table 2	Table 2
	Soil moisture deficit	Difference between actual and long-term average soil moisture	–	–	–	–
Fire	Fire characteristics	–	–	Plume size of fire	–	–
	Flame height	–	Vertical reach of flames	–	–	–
	Number of ignitions	–	–	–	–	Ignitions occurring at a similar time
Management	Access	–	–	–	–	Ease of access to fire for firefighters
	Initial attack success	–	–	–	–	Effectiveness of fire suppression early in fire development
	Resources	–	–	–	–	Firefighting suppression resources

Table 4 continued

Theme	Factor	Model 1: moisture	Model 2: fuel structure	Model 3: microclimate	Model 4: species	Model 5: suppression
Topography	Topography (or terrain)	Shading	Upslope gradient assuming fire moving upslope	Shading or upslope gradient assuming fire moving upslope	Shading, ruggedness or upslope gradient assuming fire moving upslope	Ruggedness, both upslope and downslope gradient
Weather	Fire weather	Table 2	Table 2	Table 2	Table 2	Table 2
	Heatwave	–	–	Consecutive days where humidity is low overnight	–	–
	Microclimate	–	Within forest weather	Within forest weather	–	–

Definitions were developed by each group or used from Table 2. '–' indicates that the factor was not used in that conceptual model. Factors are grouped into broader themes (first column) for used in a composite conceptual model

Discussion

There were some shared opinions about the factors driving and constraining flammability in wet eucalypt forests, but also divergent opinions, particularly with regards to the links between factors. Fuel availability (or available biomass) emerged as an important theme both in the conceptual models and future research directions, showing that it is of high importance to flammability, yet poorly understood in wet eucalypt forests.

Similarities between the conceptual models

Drought, fire weather, dead fine fuel moisture content and topography were considered the dominant factors influencing flammability in wet forests. This is unsurprising since these factors feature in empirical and physical fire spread models worldwide (e.g. McArthur 1967; Rothermel 1972; Forestry Canada Fire Danger Group 1992; Cheney et al. 2012). There was, however, variations in how these factors were defined and portrayed in the models.

Drought increases the likelihood of extreme wildfires (Sharples et al. 2016) by decreasing fuel moisture and increasing the availability of fuel to burn (Riley et al. 2013; Littell et al. 2016). Measures of drought used in fire prediction include the Keetch-Byram Drought Index (Keetch and Byram 1968) used in the McArthur fire danger rating system (McArthur 1967), the Soil Dryness Index used in the Forest Fire Behaviour Tables for Western Australian (Sneeuwjagt and Peet 1985) and the Drought Code used in the Canadian Fire Weather Index system (Van Wagner 1987). In drier forest types, drought increases the level of fuel availability and hence contributes to fire behaviour but isn't a prerequisite for fire occurrence (Littell et al. 2016). In contrast, longer term drying associated with drought may be a precursor for fires in wet forests because deep shade created by the dense understorey and higher levels of water storage within coarse debris and deep soils may buffer the effects of shorter duration rainfall deficits (Duff et al. 2018). While drought is acknowledged as important to flammability, the length of the drought required is not quantified in the scientific literature for wet eucalypt forests. Existing drought indices (e.g. Keetch and Byram 1968) used in Australia are known to both under- and over-predict fuel availability under certain

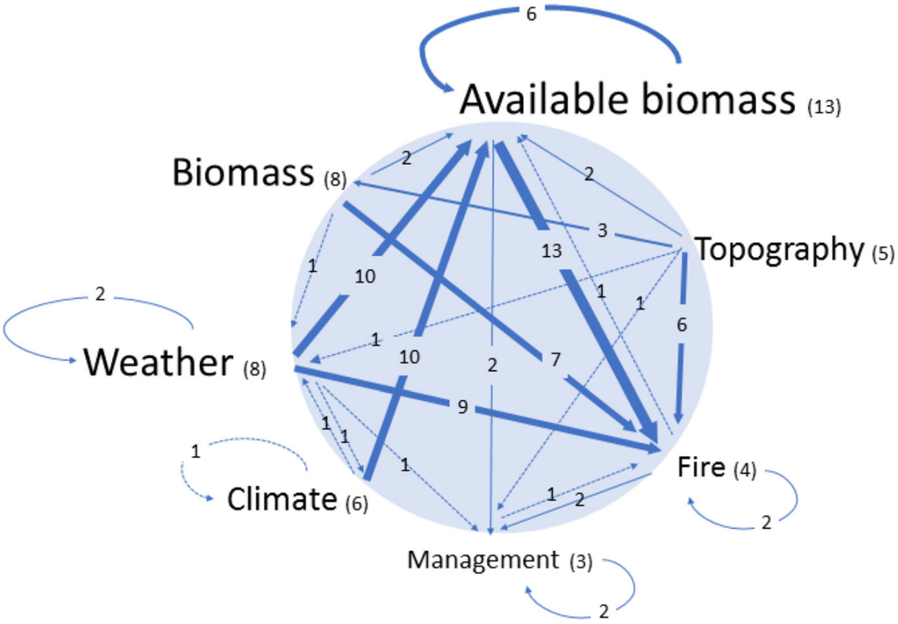


Fig. 10 Composite conceptual model to show dominance of themes driving fire occurrence and intensity in wet eucalypt forests, the strength and direction of relationships between those themes. In this model, factors from the group conceptual model are grouped into themes using the classification in Table 3. The number in brackets after each theme (and the font size) indicates the number of times that theme appeared across all conceptual models. The links between the themes and the direction of those links are shown by the arrows. The numbers on the links (and the weight of the arrow) indicate the number of times that the link appeared across all models

Table 5 Relationship between model links and research questions

Model link	Strength of link in composite model	Number of related research questions
Available biomass → Fire	13	6
Weather → Available biomass	10	12
Climate → Available biomass	10	8
Weather → Fire	9	1
Biomass → Fire	7	1
Topography → Fire	6	1

The table identifies model links that were addressed by a research question. The strength of the link is the number of times it appeared in the group models and therefore its weighting in the composite conceptual model

conditions, thus requiring manual adjustment by the fire agencies. New soil moisture metrics to indicate drought levels are being developed for Australia (Holgate et al. 2016; Kumar and Dharssi 2019) and should be tested as flammability metrics for wet eucalypt forest.

Fire weather influences the occurrence and intensity of fire (Bradstock 2010; Bradstock et al. 2010; Clarke et al. 2020). Across all vegetation types the occurrence of ignitions increases under worsening fire weather, which generally corresponds to hotter, drier and windier conditions (Syphard et al. 2008; Penman et al. 2013; Collins et al. 2015; Clarke et al. 2019). Higher wind speeds increase rate of fire spread and intensity, hence the difficulty of suppression (e.g. Rothermel 1972; Cheney et al. 2012). Vapour pressure deficit (or relative humidity) influences fire occurrence through its drying effects on dead FFMC (Viney 1991; Matthews 2014).

Local variations in broadscale fire weather, which manifest as fine-scale microclimates, were identified as important in several of the conceptual models. These fine-scale variations depend on a range of factors including elevation, aspect, hillslope position, vegetation density and tree height (Chen et al. 1999; Aussenac 2000; Sharples 2009; Holden and Jolly 2011; Sharples et al. 2012; Walsh et al. 2017). The effect of vegetation on microclimatic conditions is particularly important to understand in wet eucalypt forests given that the structural characteristics (e.g. dense understorey, tall trees, numerous vegetation strata) differ substantially from drier forests in terms of fuel moisture and wind speeds (Nyman et al. 2018; Moon et al. 2019a). Furthermore, there are dramatic changes in vegetation structure over the lifecycle of some wet forests (Ashton 2000), which contribute to microclimatic variations (Cawson et al. 2017; Burton et al. 2019). There is a growing body of research to quantify microclimatic conditions across a range of eucalypt forests including in wet forests (e.g. Walsh et al. 2017; Nyman et al. 2018; Slijepcevic et al. 2018; Moon et al. 2019a) and rainforests (Little et al. 2012; Peacock 2019).

Dead FFMC is a key determinant of ignitability, rate of spread and intensity (Keane 2015; Sullivan 2017) and globally the worst fire days coincide with very low dead FFMC (Sullivan and Matthews 2013; Nolan et al. 2016; Boer et al. 2017). Dead FFMC influences flammability directly or via its effects on fuel availability in all conceptual models. However, there is a relatively poor understanding of both the mechanisms driving dead FFMC in dense forests and the threshold moisture levels that lead to changes in fire occurrence and intensity. The deep litter beds characteristic of some wet eucalypt forests (Ashton 1975) likely mean it will be important to consider the role of moisture differentials through the whole profile of the litter bed (and not just the surface litter) and how they influence the total amount of available surface fine fuel (Sneeuwjagt and Peet 1985).

Topography effects fuel load, structure and moisture (Kirkpatrick and Nunez 1980), wind (Sharples 2009) and fire behaviour (McArthur 1967; Rothermel 1972; Cheney et al. 2012). The direct link between topography and fire intensity was the only relationship that appeared consistently across all five conceptual models. However, the mechanisms linking topography to flammability differed between models, reflecting multiple pathways by which topography can influence flammability and differences of opinion about which pathways are most important in wet eucalypt forests. It is uncertain whether relationships between topography and fire intensity are similar across all forest types or vary as a function of vegetation structure.

Differences between the conceptual models

Disparities between models may reflect individual experiences of fire in wet eucalypt forests that are yet to be formally studied but may hold important clues for understanding fire in these systems. Conversely, they could represent misinterpretations of the system, research biases or a lack of thought into the logic of putative interrelationships of variables driving the system. In some instances, differences between the models reflect differences in terminology for similar concepts, rather than true differences of opinion. The workshop commenced with a structured elicitation method (using the IDEA protocol) to derive a common list of factors and factor definitions. However, despite this process, some of these factors were redefined or different terminology were used to describe similar concepts in the models. As such, the difference between the models need to be acknowledged, but should be carefully scrutinised as potential avenues for further research.

Characteristics of the vegetation (other than its moisture content) were considered important to forest flammability in all conceptual models, but there were differences in how vegetation characteristics were depicted and therefore the implications for flammability. Some models depicted a positive association between fuel continuity (continuity of live and dead biomass) and forest flammability, which is consistent with the way fuel is considered in the fuel hazard assessment guides used in Australia (Hines et al. 2010; Gould et al. 2011). Vertical continuity (or the vertical gap) was singled out as a key mechanism influencing flame heights and fire intensity in wet eucalypt forests. This reflects discussions in the scientific literature about the relationship between stand age and fire severity in wet eucalypt forests (Price and Bradstock 2012; Attiwill et al. 2014; Taylor et al. 2014; Bowman et al. 2016). The abundance of flammable plant traits (e.g. leaf thickness, plant or canopy architecture, oil content) was another characteristic of vegetation identified as a driver of fire occurrence. Few studies have been able to quantify the influence of plant traits on flammability at field scales (Schwilk and Caprio 2011; Zylstra et al. 2016; Tumino et al. 2019). The amount of fine fuel was generally not identified as a key factor (included only in Model 5), presumably because the amount of fuel in wet forests (if available) is usually sufficient for fires to occur (Cawson et al. 2018) and therefore other features of the vegetation (e.g. continuity) were thought to be more important.

Empirical studies in eucalypt forests demonstrate relationships between live FFMC and fire occurrence (Nolan et al. 2016) and coarse fuel loads and fire intensity (Tolhurst et al. 2006; Hollis et al. 2010). Yet, live FFMC was only mentioned in three conceptual models and coarse FMC was only mentioned in two models. The absence of these fuel elements from most models may reflect uncertainties about their contribution to forest flammability and a need for further research to quantify their roles (Alexander and Cruz 2013; Sharples et al. 2016; Jolly and Johnson 2018). Live FFMC was a key theme that emerged among the research questions pitched by the workshop participants, despite not featuring in all the conceptual models, which further highlights that uncertainties about the role of this variable in influencing forest flammability should be addressed. Although the contribution of live and coarse fuel is not depicted in Australian forest fire behaviour models, coarse FMC is included in the US National Fire Danger Rating System (Bradshaw et al. 1984) and crown foliar moisture content is included in the US and Canadian systems (Bradshaw et al. 1984; Forestry Canada Fire Danger Group 1992).

Dead-to-live ratio is another factor that has not been the focus of much research (exceptions include Schwilk 2003; Dent et al. 2019) yet it is included in the Australian fuel assessment guides (Hines et al. 2010; Gould et al. 2011) and appeared in two conceptual models. It is likely to be closely aligned to live FFMC. Heatwaves were identified in one model as a potential mechanism driving dead-to-live ratios. Heatwaves are a common precondition leading to some of the worst fire days in wet eucalypt forest (Rawson et al. 1983; Sullivan and Matthews 2013). The potential effect of heatwaves on fuel drying and dead-to-live ratios has been highlighted in the literature, but not quantified (Jolly et al. 2015; Yeo et al. 2015; Sharples et al. 2016).

There are a limited number of studies on the effectiveness of fire suppression in general (although see McCarthy et al. 2003; Plucinski 2019). Fire suppression was only included in one model through initial attack success—the ability of firefighters to suppress an ignition in the early stages of fire development (Arienti et al. 2006). Initial attack success is influenced by several environmental factors (number of ignitions, fuel moisture, weather, topography), site accessibility and the number of resources available (Arienti et al. 2006; Plucinski 2012; Plucinski et al. 2012). There have been no studies about initial attack success specific to wet eucalypt forest, where dense understories and extreme fire intensities could alter the relationships.

Themes for future research

The research questions pitched by participants at the end of the workshop focused mostly on the factors and links that occurred across all models. Participants were more concerned with developing a better understanding of the widely agreed factors (the known unknowns) than resolving disagreements between the models (the disagreed unknowns). This result makes sense in the context of wet eucalypt forests, where empirical research is scarce for all factors. Most questions were about better understanding biomass availability, how it is influenced by weather and climate, and how it influences various dimensions of forest flammability. Biomass availability is a key determinant of fire in all systems, but in wet forests where the amount of fuel is often very high and therefore not limiting to fire, availability is known to be a particularly important driver.

After the workshop, further reflection on the alternative conceptual models and research questions provided a basis from which to identify four priority research areas towards a better understanding of flammability in wet forests. These research areas encompass both the research questions pitched during the workshop and some of the novel views that emerged during the workshop that may hold important clues for understanding fire in these systems.

1. Drought and fuel moisture thresholds (of a range of fuel elements) for fire occurrence and intensity. Drought and fuel moisture were both identified as key drivers of fuel availability and thus

flammability, but there is a lack of analysis specific to wet forests that quantifies the level of drought or moisture thresholds for fires to occur and intensify. Furthermore, there is a lack of understanding about the significance of live fine fuel moisture and coarse fuel moisture as drivers of flammability.

2. Microclimatic drivers of fire occurrence and intensity in dense vegetation and rugged terrain. Wet eucalypt forests have dense canopies, tall trees, several vegetation strata and they often occur in steep terrain, which means subcanopy weather can be very different to macroscale weather. Wind speeds and vapour pressure deficit (or relative humidity) were identified as key drivers of fire occurrence and intensity in wet forests, but models are needed to predict how those variables manifest beneath the forest canopy. In particular, the role of heatwaves was highlighted as a potentially important mechanism in wet forests that needs further scientific consideration.
3. Quantifying the role of live vegetation (biomass) in driving flammability, other than fuel moisture. There was wide agreement that some aspects of live vegetation are important to fire occurrence and intensity, but a disparity of views about the significance of different vegetation attributes—e.g. horizontal and vertical continuity, plant traits, dead-to-live ratio. Further research is needed to understand how these vegetation attributes influence fire occurrence and intensity, under what conditions they are important and how they change in space and time in wet forests.
4. Fire management strategies in wet eucalypt forests. Much of the research about fuel and fire management strategies in Australia focuses on drier forest types. Yet, a key question for land managers is how best to manage fuel and suppress fires in wet eucalypt forests, particularly in the urban interface or when there are high value assets like domestic water supply catchments. Such research will be pertinent in the face of climate change when we expect to see more fire in our wetter forests.

The elicitation approach

There is little advice in the literature about best practice for eliciting group models, despite conceptual models being proposed as a useful tool. This study developed an approach based on the advice and perspectives from a few select papers (Markóczy and Goldberg 1995; Walshe and Burgman 2010; Hemming et al. 2018a). Our approach was practical to apply and it may serve as a basis for future studies seeking to elicit multiple group conceptual models.

Individual steps throughout the workshop all contributed towards improved conceptualisation of the problem. The process of first developing a list of factors helped to stimulate creative thinking regarding possible factors of importance. Arguably, using the IDEA protocol to quantify the relative importance of key factors was not needed. Instead, experts could have been asked directly to nominate factors into a combined list, with factors then appearing most often in alternative conceptual models being of highest importance. However, the process, particularly the feedback given to the group about their estimates, clearly demonstrated and quantified disagreements about commonly cited drivers of flammability, inconsistent usage of terms and this acted as a motivator for the subsequent steps of understanding the reasons for this divergence.

The documentation of individual conceptual models before the discussion meant that experts first thought about their own ideas before comparing their models with their peers. In contrast, many group conceptual models are elicited without first eliciting individual models. Undertaking this step, provided a basis for a discussion that was centred around comparing, contrasting and understanding alternative viewpoints, rather than debating who was right and wrong. Placing a limit on the number of factors, forced experts to critically think about the factors that were the most important to include in a model. Placing constraints on the maximum number of factors in the models made it easier to compare models.

The subsequent phase of combining individual models into a group model was challenging and required facilitation. Workshop participants were grouped by facilitators based on their perceptions of natural groupings between models. This was necessary due to time constraints, but an alternative method may have been to have workshop participants selfassign into groups. Allowing workshop participants to split from their group if they felt the model did not reflect their true opinion, helped to overcome pressure to conform to ideas that individuals did not hold. Discussions during the development of group models helped to further reveal vague terms and concepts that required improved definition and provided opportunities to examine the rationale and evidence behind perceived causal links.

In the final stage of the workshop, participants compared the group models. This articulation of alternative conceptual models provided a basis from which to identify research priorities informed by the agreements and disagreements between the models. Importantly, the process captured the views and experiences of a broader cross-section of the expert community than may be represented in the academic literature. Therefore, the research themes are likely to encompass a more complete list than those currently documented in the academic literature.

Conclusion

Prior to this study, a range of factors had been proposed in the scientific literature as important to the flammability of wet eucalypt forests. Yet, there was no clear consensus about which factors were the most important drivers. Although an elicitation approach does not solve that knowledge gap, it does help provide a more balanced perspective by drawing on the experiences and knowledge of a broad range of experts.

The elicitation workshop provided an opportunity to evaluate all factors potentially influencing fire occurrence and intensity in wet eucalypt forests and determine their relative importance based on a range of experiences of fire in these systems. Such an extensive review would not be possible by examining the published literature, since there are very few studies about flammability in wet forests. Similarly, the cost would be prohibitive to evaluate all factors empirically. Despite the diversity of experts in the workshop, there was agreement about some of the key factors driving flammability in wet eucalypt forests—biomass fuel availability, weather, climate and topography. Biomass availability (or fuel availability) was identified as a key factor, being both of high importance to flammability in wet forests and poorly understood.

A set of research priorities towards a better understanding of the drivers and constraints of flammability in wet eucalypt forests were formulated by considering both the agreements and disagreements between the conceptual models developed during the workshop. Those research priorities focus on quantifying drought and fuel moisture thresholds in relation to fire occurrence and intensity; modelling subcanopy microclimate in dense vegetation; better understanding the role of live vegetation as a determinant of landscape flammability; and evaluating fire management strategies in wet forest. It is possible that the same research priorities might have emerged had we asked just one expert in the room to devise a list of priorities. However, it is also possible that we might have ended up with a list of priorities that were at odds with the broader view. By drawing on the collective wisdom of many experts using formal and informal techniques so that all experts can contribute, we can have greater confidence that the identified research priorities are based on the best available knowledge.

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