REVIEWER 1

General comments

The authors in their article present a research attempt to address the extreme fire behaviors (EFBs) as part of a potential phase of a widfire and to estimate their relative frequency in Australian forest environments. I consider the topic interesting for the Fire readers, as to my knowledge a few relevant papers have seen publicity to date. The authors however should present in their article a more robust literature based definition and clarify some issues related to the “extreme” term. Although Byram was the first who approached the phenomenon in 1954, the knowledge gap, as far as its definition is concerned and the aspects of fire behavior involved still remains. The paper includes some novelty, as there is no established definition for EFBs in the world literature as yet.

As reviewer correctly stated there are “a few relevant papers have seen publicity to date”. We cited all papers that we are aware of in relation to dynamic fire behaviours (DFBs, extreme fire behaviours previously). However, to improve readability and the definitions we have significantly enhanced the definitions in the introduction with the following text:

“Definitional issues are present for both extreme fires and DFBs. Tedim et al. [26] (p. 5) proposed the term extreme fire event instead of extreme fire. Based on a comprehensive literature review Tedim et al. [26] described extreme fire event as a combination of DFBs and the consequences of them. However, they considered only limited number of DFBs. There is still some confusion regarding extreme fire events and dynamic fire behaviours. Some researchers perceive them as the same event/process and some absolutely opposite (between them). At the moment, there are no standardised definitions for DFBs. In previous studies [19-21,27,28] authors used the term Extreme fire behaviours (EFBs). According to Collins’ dictionary [29] the term extreme is used “to describe situations and behaviour which are much more severe or unusual than you would expect”. This term related more to consequences rather than process itself. However, DFBs are not always EFBs. We propose to use the term Dynamic fire behaviour rather that Extreme fire behaviour. Werth, Potter, Clements, Finney, Goodrick, Alexander, Cruz, Forthofer and McAllister [21] defined DFB as “fire spread other than steady surface spread, especially when it involves rapid increases”. Thomas, et al. [30] described it as a phenomenon which “can involve significant and rapid changes in fire behaviour without significant changes in ambient conditions”. Viegas in his study [19] described DFBs as “a set of situations that are more like manifestations or forms of extreme fire behaviour rather than one particular form of fire behaviour”. It means that DFB is not a single process or event combining different phenomena, but a unique physical phenomenon. In this paper we define DFB as a

“physical phenomenon of fire behaviour that involve rapid changes of fire behaviour and occur under specific conditions [19] which has the potential to be identified, described and modelled.”

In general, extreme fire (or an extreme fire event) can involve one to several DFBs simultaneously [22,26].”

However, I think that a weak part of the study is the potential usefulness of the outcomes. The authors acknowledged that most of the identified types of EFBs (88%) have already been studied in detail. I strongly recommend the authors to provide more extended arguments to support the scientific value of their results. Perhaps a separate analysis of the “Conflagration” type of EFB, which covers 10% of all observations, would increase the scientific merit of the article. In addition, the potential contribution of each EFB to the burning area might lead to significant scientific findings.

We disagree with the reviewer’s comments on a number of points. Firstly, the paper contributes a great deal of new information to the literature. This includes the frequency distribution of DFBs; research prioritization for DFBs; data availability for the analysis of DFBs; and the first analysis of the lack of relationship between the occurrence of DFBs and fire size. Secondly, we do not understand how the reviewer came to the conclusion that “most of the identified types of EFBs (88%) have already been

studied in detail". This contradicts the text that stated only "Crown fires have been studied in detail". We modified the corresponding paragraph (lines 162-169 in the previous version) to clarify this point:

"Spotting, Crown fires, PyroEvs, Eruptive fires and Conflagrations were the most frequent DFBs observed. They can be more easily identified and detected, and fire managers are more likely to be familiar with them. Crown fires in conifer forests have been studied in detail, with several empirical models developed [46]. More recently, attention has been given to other DFBs; in particular PyroEvs [23,47], Spotting [48,49], Fire channelling [36] and Fire whirls [35,50]. Most of these studies are based on Computational Fluid Dynamics or conceptual modelling and they are not experimentally validated. Results from these studies cannot be translated into systems for prediction during fires for operational decision support at this point. Conflagrations and Downbursts have not been included at any physical or operational models to date."

Finally, the request to look at each EFBs contribution to burning area is something well outside the scope of the manuscript and would require understanding of the phenomena to model such data.

Specific comments

Abstract

In Lines 12 and 13 the authors refer to the role the EFBs play on fire impacts; an issue however that is not addressed in the article. It should be corrected.

Deleted.

Introduction

I suggest the authors to link the EFBs with fire severity, because this is commonly used in fire science.

While this might be of interest there are significant issues with trying such a process. Firstly, fire severity itself is a measure of fire behaviour with the higher categories indicating crown fire behaviour. Secondly, linking the EFBs with fire severity requires understanding the spatial extent of these phenomena and this is more challenging than understanding whether they occurred or not. Finally, the goal of this study was not to understand each DFB and provide the mechanisms of it, rather it was to understand the importance of DFBs in fire behaviour in order to prioritise future research efforts.

Lines 29 - 32. The authors should explain how they linked the fatalities they mention with EFB (in relation to the analysis that has been used in their manuscript). For example, Martinez-Harms *et al.* did not use the term "extreme", but the term "Large-scale". In addition, the increased fatality numbers sometimes occur in areas of intense human presence such as Wildland Urban Interface (WUI).

The reason of using different terms (e.g. Martinez-Harms *et al.* and others) is that there is no clear definition of extreme fires/mega fires/large-scale fires and agreement between researchers to use unified terminology. This confirms the importance of our study.
We have added the following paragraph to the introduction in response to this point:

"*Extreme wildfires create conditions pose disproportionate risks to environmental and human assets. Fire propagation can be significantly affected by dynamic feedback processes that result in unpredictable behaviour, the continual escalation of fire spread rates and intensities even when environmental conditions are consistent. These fires behave in a manner that goes beyond the suppression means and fire-fighters are unable to control the fire spread even in the most prepared and equipped regions [1]. The erratic behaviour and difficulty to control mean that these fires can burn larger areas and resulted in human losses. …*"

Line 31. I suggest the authors to use a more reliable source of information instead of the Wikipedia reference.

Corrected.

Line 52. I got confused with the terminology. In line 45 the authors state that several EFBs determine the “extreme” nature of fire, which is consistent. In line 52, they claim that EFB is not a single progress or event but a combination of phenomena. However, Viegas et al. (2012), suggest that EFBs may be expressed in several forms (manifestations) which is relevant to a set of situations. I think that there are some differences between the two expressions. It should be clarified.

Agree. These paragraphs have been rewritten:

“Definitional issues are present for both extreme fires and DFBs. Tedim et al. [26] (p. 5) proposed the term extreme fire event instead of extreme fire. Based on a comprehensive literature review Tedim et al. [26] described extreme fire event as a combination of DFBs and the consequences of them. However, they considered only limited number of DFBs. There is still some confusion regarding extreme fire events and dynamic fire behaviours. Some researchers perceive them as the same event/process and some absolutely opposite (between them). At the moment, there are no standardised definitions for DFBs. In previous studies [19-21,27,28] authors used the term Extreme fire behaviours (EFBs). According to Collins’ dictionary [29] the term extreme is used “to describe situations and behaviour which are much more severe or unusual than you would expect”. This term related more to consequences rather than process itself. However, DFBs are not always EFBs. We propose to use the term Dynamic fire behaviour rather that Extreme fire behaviour. Werth, Potter, Clements, Finney, Goodrick, Alexander, Cruz, Forthofer and McAllister [21] defined DFB as “fire spread other than steady surface spread, especially when it involves rapid increases”. Thomas, et al. [30] described it as a phenomenon which “can involve significant and rapid changes in fire behaviour without significant changes in ambient conditions”. Viegas in his study [19] described DFBs as “a set of situations that are more like manifestations or forms of extreme fire behaviour rather than one particular form of fire behaviour”. It means that DFB is not a single process or event combining different phenomena, but a unique physical phenomenon. In this paper we define DFB as a

“physical phenomenon of fire behaviour that involve rapid changes of fire behaviour and occur under specific conditions [19] which has the potential to be identified, described and modelled.”

In general, extreme fire (or an extreme fire event) can involve one to several DFBs simultaneously [22,26].”

Line 56. The EFBs are types of fire behavior. It should be revised. I wonder if there is really a need for predicting accurately some aspects of erratic (or extreme) fire behavior, such as, for example, phases of short duration. In addition, the crown spread rate, the onset of crowning as well as the spotting activity have already been described mathematically (see CFIS - Crown Fire Initiation and Spread).

This comment probably arises from unclear described definition (see previous comment). The DFBs are physical phenomena occur within fire and can contain several EFBs simultaneously.
We agree with the reviewer that Crown fire models in conifers have been described well however in other environments crown fires are not well understood. Our point is that the all other DFBs have not been fully described. For example, there are no data about generation of firebrands (firebrand flux), limited data about firebrand transport and ignition probability of firebrands. Again, the point of the study is not to define the relationships but a first step in understanding the rate of occurrence of DFBs in forested systems.

Line 64 and 66. The word “however” appears twice. The paragraph should be rephrased.

Corrected.

Line 68. I suggest the authors to add “expressions” or “manifestations” before extreme fire behaviors.

It has been added.

Materials and methods

The “extreme fires” term should be linked with burning area along with a relevant reference.

We believe that burning area is not a sole feature of extreme fires. Our findings showed that burning area does not correlate with number and type of DFBs.

I think that including also a diagram depicting the various terms used in connection with the applied methodology, would be very helpful for the readers.

We are unclear what the reviewer requested. A diagrammatic representation of terms seems unnecessarily complicated. We are happy to take further advice on this.

In addition, a brief description of the fire environment (the main types of vegetation) where fires occurred is necessary.

We have added information about fuel types:

“The fires occurred primarily in the following vegetation types [42]: Eucalypt Open Forests (48 %); Mallee Woodlands and Shrublands (16 %); Eucalypt Woodlands (15 %); Eucalypt Open Woodlands (5 %); Heathlands (4 %); Other Grasslands, Herblands, Sedgelands and Rushlands (4 %); Eucalypt Tall Open Forests (3 %); Other Shrublands (1 %).”

Line 76. How is the sample size sufficient for the research? The authors need to justify the sample size choice.

To address this, we have added:

“Sample size estimation showed that minimum 9 representatives require to get 2.6% relative standard error with 95% confidence level, population size 21, proportion of the population to have required attribute 0.99 (as experts survey only familiar fires) and confidence interval 0.05.”

Line 79. It remains unclear to me, why the knowledge/experience/understanding of crown fires was less important? I believe that the participants were experienced with all types of wildland fires. It should be explained.

We don’t understand how the reviewer came to this conclusion. Line 79 and the paragraph in which it occurred made no mention of crown fires.

Lines 99 - 120. Peer-reviewed articles or textbooks should be used to define the different EFBs manifestations.

The reviewer’s comment is unfounded. References [33, 40] (previous version of the article) are peer-reviewed articles, [18] is a textbook, [39, 41] are internationally recognised glossaries.

Line 107. I think that “Junction fires” would be a more suitable term than “Jump fires” (please see Ph.D thesis entitled “*Extreme Fire Behaviour Associated with the Merging of Two Linear Fire Fronts*” by Jorge Rafael Nogueira Raposo – 2016).

Agree. The term has been changed everywhere in the paper.

Results and Discussion

The results are based only in descriptive statistics. I think that adding inferential statistical analysis will improve the scientific merit of the manuscript. I mean, the results are clear for the 96 fires of the sample.

But what about the fire behavior in the 838 well recorded fires? Since the total burning area is provided, general outcomes could have been extracted. In lines 174 – 175 some correlations are mentioned. These could be described accurately (by reporting Pearson r or p-values numerically), even if no significant values are evident. Perhaps some other correlations could lead to significant findings. In addition, assessing a survey's validity is essential to ensure that meaningful data would be obtained. I recommend the authors to use Cronbach's alpha (CA) measurement (or other similar).

We have added additional analysis about types, number of DFBs and fire area:

"Relationship between occurrence of DFBs and fire size was not observed. Pearson's correlation coefficient and significance were r=-0.16 and p=0.079 respectively."

"There was no relationship between the number of DFBs per fire and fire size (Figure 3a) (Pearson's correlation coefficient r=0.25 and significance p=0.014)."

Insert example text

Lines 125 – 127. They should be deleted.

Deleted.

Lines 151 – 161. I agree with the mentioned limitations of the research, which may not cover the frequency of all aspects of EFBs. However, this must be incorporated in the title (for example, "*a survey*" or "*an expert-based approach*").

We are unclear of the requirement to include survey or expert-based in the title. Papers based on computer modelling or empirical data rarely include these words in the title. The comment seems to represent a bias against these approaches. We have included expert elicitation comments throughout the paper including the abstract, introduction, methods and results. Even a cursory glance at the paper will inform the reader how the data were gathered, we feel there is no need to include in the title.

Line 166. What does the abbreviation CFD mean? Canopy Fuel Density? It should be explained.

CFD - Computational Fluid Dynamics. It has been corrected.

Line 167. I disagree with the operational value of the prediction systems. Many of these systems have been incorporated in simple simulators which provide predictions in real time. In addition, the prediction systems can be applied before fire, so as to alter critical characteristics of the fire environment in order to prevent EFBs, such as crowning.

The reviewer's comment is inconsistent with the text which states prediction "during fires" whereas the reviewer is talking "before fire". Computational Fluid Dynamics or conceptual modelling (2-3D) include equations of conservation of energy, mass and momentum in integral or differential form. To solve such systems of equations, require significant amount of computational time (days and weeks) and they are very sensitive to input parameters and boundary conditions. To date we don't know any validated and tested operational model incorporated DFBs (except of crown fires in boreal forests).

Line 193. Comparisons should be based on statistical tests.

These results are part of the descriptive statistics.

Reviewer 2

The submitted manuscript, Frequency of extreme fire behaviours in Australian forest environments, provides a survey about the extreme fire behaviour manifestations, giving a better understanding and description of it. Also the most common forms of EFB are identified. This is a very important

contribution of the research community determining which EFBs should with high urgency be translated to fire models

In my opinion the article is ready to be published with the following small correction:

Please in line 30, correct the number of victims to 66, as reffered in the official report of Viegas et al. 2017

We appreciate your very positive review! The number has been corrected.

Reviewer 3

This paper presents results from a survey of fire and land management staff in Australia regarding their experiences with extreme fire behaviours (EFBs). The authors note there are no standardized definitions of EFBs and describe them as “physical phenomena of fire behaviour that may occur when fires burn under specific conditions.” This study used an expert elicitation approach to investigate the frequency and occurrence of nine recognized EFBs: spotting, crown fires, pyro-convective events, eruptive fires, conflagrations, jump fires, fire tornados/whirls, fire channelling and downbursts. Data were collected for fires that occurred between 2006 and 2016 and limited to those that exceeded 1000 ha in size.

The topic of this paper is an important one and I was pleased to see the author’s use of an expert elicitation approach to attempt to document EFBs, which are inherently challenging to document and assess – but which are often observed by practitioners during wildfire situations. For these reasons, I rated the paper highly with respect to novelty and potential interest to readers. Unfortunately, based on the information provided in the manuscript, I see no evidence that the authors have actually documented EFB frequency.

We have conducted additional survey to estimate the DFB frequency and added results into the paper, for example:

*“*Information on DFBs (or absence of them) was received for a total of 113 fires (Table 1, Appendix A). Each expert provided a unique list of fires with or without DFBs.*”*

*“*More than half of the fires considered in the survey had at least one DFB (overall 60 %). This value was consistent between states, with NSW having DFBs in 62 % of fires, VIC 61 %, SA 85% and TAS 57 %. Occurrence of DFBs versus fire size is shown on Figure 1.*”*

If my understanding of this study is correct, survey respondents (i.e., “suitable experts”) were provided definitions of EFBs and a list of fires in their jurisdiction and were asked to report observations of EFBs for the fires for which they were familiar. The main results of the study are summarized in Table 1, and include observation counts of nine different types of EFBs reported by experts and a self-reported classification of the observation type (direct, indirect, anecdotal). Figure 1 shows the proportion of observations collected for each EFB type, the percentage of fires with different quantities of EFB observations, and the lack of a relationship between EFB observation counts and fire size. Figure two reports the distribution of observations by quality of observation (direct, indirect, anecdotal). Unfortunately, none of this data tells me anything about the frequency of EFB occurrence. To understand frequency, we would need to know the number of EFBs observed relative to the duration of the observation period (the opportunity for observation). The survey did not appear to ask the questions necessary to determine how frequent these EFBs are – that would have required respondents to report "out of x days when I had opportunities to view EFBs of type y, I observed them z times."

We disagree with the reviewer. Perhaps such comments were raised as a result of misunderstanding of our results. Talking about frequency we meant relative frequency (or empirical probability) of an event which is the absolute frequency normalized by the total number of events, while the reviewer referring to the temporal frequency (the number of occurrences of a repeating event per unit of time). Moreover, saying that “none of this data tells me anything about the frequency of EFB occurrence” is not correct. Having the relative frequency the frequency distribution can be built (Fig 1a,b of the previous version). We have added clarification about frequencies to the methods section, as well as results of additional survey:

"The relative frequency $f_i = n_i/N$ (or empirical probability) of an event was used in our study. It was calculated as the absolute frequency n_i normalized by the total number of events N. The values f_i for all events *i* were plotted to produce a frequency distribution."

*"*Information on DFBs (or absence of them) was received for a total of 113 fires (Table 1, Appendix A). Each expert provided a unique list of fires with or without DFBs.*"*

*"*More than half of the fires considered in the survey had at least one DFB (overall 60 %). This value was consistent between states, with NSW having DFBs in 62 % of fires, VIC 61 %, SA 85% and TAS 57 %. Occurrence of DFBs versus fire size is shown on Figure 1.*"*

Instead, the authors are reporting observation counts disconnected from the observation duration or opportunity. For example, consider a situation where the respondent spent only a short time (say one day) observing a fire and reported 3 EFBs, while another observer spent 2 weeks observing the fire and also reported 3 EFBs – both observations appear equal in their contribution to frequency – but obviously the observation period of the first observer is truncated.

The reviewer again misinterpreted our findings. Our goal was not to identify temporal frequencies, but to find relative frequencies for the 10-year period. It is not possible to identify temporal frequencies with acceptable accuracy, as small nuances, such as time observing fire, cannot be incorporated into existing database. The only possible way is to define the frequency distribution for considered period. Moreover, we think it is not correct to link duration of fire with the number of dynamic fire behaviours. It is a function of weather, terrain, fuel and fire itself (Viegas 2012, Werth 2011 and 2016) rather than fire duration.

I'm also confused by the lack of any information about the fire environment conditions at the time of the observation – which could have provided very rich and useful details for understanding (and potentially predicting) EFBs. What fuel types were the fires burning in? What topographic conditions? What weather conditions? For example, we know atypical or extreme wind conditions are associated with many EFBs. Were the experts asked to report any of these fire environment attributes? That data would have been very interesting to see and could have provided a valuable characterization of the conditions under which EFBs emerge. As it stands, the authors are reporting only counts of observations that have no real meaning and are just an artifact of the respondents' personal experience record (i.e., if you could survey a different group of respondents, I'm not convinced you would get the same results).

We agree with the reviewer that such information could provide some insights into dynamic fire behaviours. However, the goal of our study was not to understand each particular case with DFB and provide the mechanisms of it. The goal was to understand the importance of DFBs in fire behaviour in order to prioritise future research efforts.

In short, I think the authors have missed the mark on this one, but I encourage them to persist in their efforts. It is possible that they could collect additional details from respondents that would enable a more comprehensive (and valid) assessment of EFBs.

In our opinion the reviewer missed the idea of our paper and tried to substitute it with their own. However, we think the comments are valuable and we have conducted additional survey to analyse the frequency of DFBs (see previous answers and results section).

Do to my significant concerns above, I did not proceed with documenting detailed comments aside from the two noted below.

L125-127 appears to be template text.

Deleted.

L131-135 Somewhat confusing - you don't appear to be surveying people about their overall experience (i.e., you are not asking respondents to identify all the fires they could comment on) so it is not clear to me why the overall number of fires (934) is being reported as the "fires surveyed." Presumably this was just a reference list to help respondents identify the fires they could speak to? Was that step even necessary? Could you have simply asked experts to self-identify the fires they had experience with? The fires analyzed in this paper are limited to 96 fires for which you received EFB details from respondents. The 10% value you are reporting seems to confuse what you did. It would be more useful to know the response rate – i.e., of the people who had expert knowledge of these fires and could have responded, how many actually did?

We agree that this paragraph is confusing. It has been rewritten:

"Responses were received from five experts from New South Wales (NSW, Table A1), four from Victoria (VIC, Table A2), and one each from South Australia (SA, Table A3) and Tasmania (TAS, Table A4). A list of 934 fires was used for surveying, 471 fires were from NSW, 130 from VIC, 281 from SA and 55 from TAS. No responses were received from Australian Capital Territory (ACT), Western Australia (WA), Queensland (QLD), and the Northern Territory (NT). Information on DFBs (or absence of them) was received for a total of 113 fires (Table 1, Appendix A). Each expert provided a unique list of fires with or without DFBs."