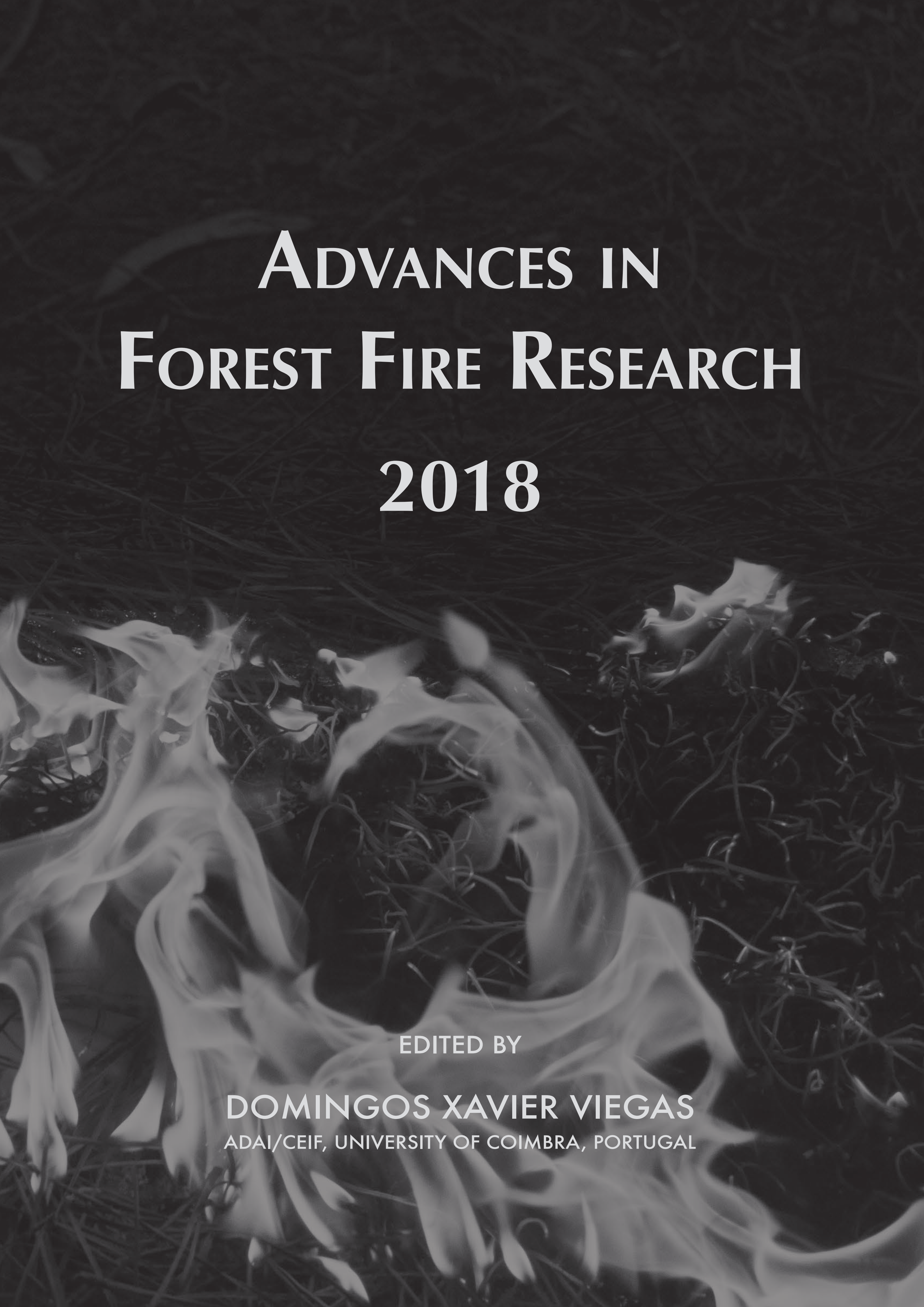

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Flammability at field-scales: conducting research in prescribed burns

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Abstract

To better understand the role of plant flammability in driving landscape-scale fire behaviour and fire regimes, field-scale flammability research needs to occur. Yet, experimental fires are costly to implement and research within wildfires is both logistically challenging and potentially dangerous. As an alternative, we propose that operational prescribed burns undertaken for land management purposes should be exploited for flammability research.. In some parts of the world, large areas are burnt annually, providing extensive opportunities for research. In this paper we describe three broad methods that can be used to measure different facets of flammability in prescribed burns. We compare the strengths and potential limitations of each method before finally providing ten principles for conducting effective flammability research in prescribed burns. We conclude that operational prescribed burns are a largely untapped resource that could be used to better understand links between plant flammability and landscape-scale fire behaviour.

Keywords: burn observation; fire agency; fire management; flammability; fire behaviour; forest; fuel; ignition; prescribed burn

1. Introduction

Plant flammability is an important determinant of fire behaviour and fire regimes (Gill and Zylstra 2005; Pausas *et al.* 2017). Flammability is broadly defined as the capacity of vegetation to burn and is often measured in terms of the specific combustion characteristics of the vegetation (ignitability, combustibility, consumability and sustainability) (White and Zipperer 2010; Varner *et al.* 2015). Research shows that the flammability of a plant or plant part (e.g. leaf) depends on a combination of plant traits (Varner *et al.* 2015; Pausas *et al.* 2017). Yet, there is very little understanding about how these plant traits interact and combine to influence the flammability of whole vegetation communities (Schwilk 2015; Varner *et al.* 2015; Cawson *et al.* 2018). Such knowledge is needed to better predict fire behaviour, manage fire risk across landscapes and predict future changes to fire regimes and landscape flammability.

A large body of flammability research has been conducted in laboratories (e.g. Dickinson and Kirkpatrick 1985; Dimitrakopoulos and Papaioannou 2001; Plucinski and Anderson 2008; Ganteaume *et al.* 2013; Possell and Bell 2013). Laboratory-based flammability studies have several advantages over field-based studies (Table 1) – confounding variables are better controlled; large quantities of data can be collected in relatively short time frames; research can proceed irrespective of seasonal climatic conditions; and costs may be less. The challenge is in translating research results derived in the laboratory to field-scale fire behaviour. Practicalities of working within a laboratory mean that the scale of research is often restricted to individual leaves, plant parts or reconstructed fuel beds and the heat source applied to the vegetation may not be representative of wildfire conditions (White and Zipperer 2010). As such, laboratory-based flammability research has been criticised for having limited applicability to field-scale flammability and fire behaviour (Fernandes and Cruz 2012).

Table 1 - Evaluation of research environments for measuring flammability. The research environments are evaluated against criteria from 1 (highest performing) to 4 (lowest performing).

Evaluation criteria	**Research environment**			
	Laboratory	**Experimental fires**	**Wildfires**	**Prescribed burns**
Safety	1	3	4	2
Cost	2	4	3	1
Ability to control for confounding variables	1	2	4	3
Ability to replicate measurements	1	3	4	2
Ability to represent wildfire conditions	4	2	1	3
Vulnerability of study outcomes to weather	1	3	4	2
Control over timeframes for data collection	1	3	4	2
Bureaucratic complexity	1	3	4	2
Average ranking	**1**	**3**	**4**	**2**

At a field-scales, experimental fires have historically been an important component of fire behaviour research with the data yielded from these experiments the foundation of widely used empirical fire behaviour models (Alexander and Quintilio 1990; Cruz *et al.* 2015). Plant flammability is generally considered in these experimental programs in terms of total biomass and dead fine fuel moisture content, with most other plant traits not considered. Experimental fire programs could be extended to better address research questions relating to community-level plant flammability (e.g. Schwilk 2003; Fraser *et al.* 2016). However, such experimental fires can be expensive to implement, difficult to replicate and their success is highly dependent on weather conditions during the experimental period (Cruz and Gould 2009). Another field-based alternative is research conducted within active wildfires. Such research would certainly be representative wildfire conditions. However, safety concerns, bureaucratic hurdles and logistical issues make this research difficult to design and implement (Table 1). Even the collation of wildfire statistics and observations from fire agencies can be challenging (Duff *et al.* 2014).

An alternative for obtaining field-scale flammability measurements is to conduct flammability research in operational prescribed burns in partnership with fire agencies. Prescribed burns are carried out by fire agencies for wildfire mitigation or ecological purposes in a range of vegetation types. Globally, the extent of prescribed burning varies widely by region depending on the risk of wildfire, political and social acceptance of fire in the landscape, fire ecology of the ecosystem and government budgets. However, in some parts of the world prescribed burning programs are well established (Fernandes *et al.* 2013; McCaw 2013; Forest Fire Management Victoria 2017; US Forest Service 2018). These prescribed burning programs provide many potential opportunities for flammability research to occur, even when the research budget is modest. For example, in Victoria in south-eastern Australia, on average 900 prescribed burns are conducted annually (data from 2012 to 2016) (Figure 1) (Department of Environment Land Water and Planning 2016). The main limitation of this research is that the most extreme fire conditions will not be captured. Additionally, there are several limitations of working within prescribed burns that may impede research success if not well managed.

The purpose of this paper is to provide guidance for planning and executing flammability research in operational prescribed burns. We reflect on our experiences of conducting research in prescribed burns in south-eastern Australia by outlining three broad approaches for obtaining data about field-scale flammability. We then outline 10 key principles for maximising the chance of a successful research project in an operational prescribed burn.

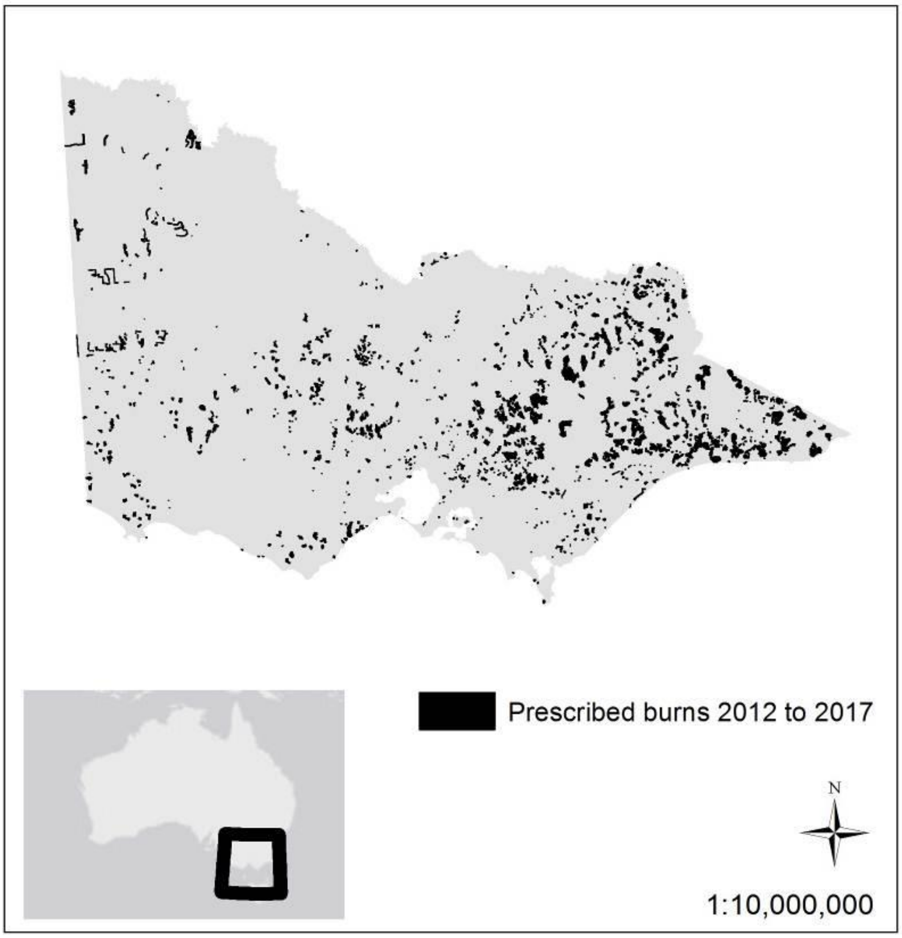

Figure 1 - Prescribed burns in Victoria, south-eastern Australia over a five-year period from 2012 to 2017. Data source: data.vic.gov.au

2. Methods for quantifying flammability at field scales

Here we describe three broad approaches to quantify flammability within prescribed burns:

1. *Direct observation of burning* – fuel, weather and burning characteristics are observed directly as researchers work alongside the lighting crew
2. *Pre- and post-burn plots* – plots established pre-burn to assess vegetation condition prior to the burn and the same plots are reassessed after the burn
3. *Analysis of maps of burn outcomes* – maps of burn extent or fire severity (often derived by the fire agency) are used to analyse burn outcomes at landscape scales

Table 2 outlines the suitability of each method to quantify the flammability (ignitability, combustibility, consumability and sustainability) of vegetation at field-scales.

Table 2 - Suitability of methods to measure field-scale flammability in prescribed burns. 'Yes' indicates the method quantifies the flammability variable. 'No' indicates the method does not quantify the flammability variable.

Flammability variable	Direct observation of burning	Pre- and post-burn plots	Analysis of maps of burn outcomes
Ignitability (ease of ignition)	Yes	Yes	Yes
Combustibility (flame spread rate or mass loss rate of fuel during burning)	Yes	No	No
Consumability (proportion of fuel consumed, correlated with heat release)	Yes	Yes	Yes
Sustainability (duration of flaming and/or smouldering)	Yes	No	No

2.1. Direct observation of burning

Direct observation of burning involves measuring ignition success and burning characteristics while working alongside a lighting crew on the day of the burn and/or using sensors to record burning characteristics. Fuel attributes (fuel moisture content, fuel hazard, surface fuel load, dominant species, plant architecture, live-to-dead ratio) can be measured immediately ahead of the fire fighters and then the ignition process and resultant fire behaviour can be observed. Ignitability can be measured in terms of ignition success or failure with ignition deemed successful if burning is sustained beyond the initial points(s) of ignition. Combustibility can be quantified by recording the rate of spread; in the context of a prescribed burn this is usually the rate of spread of backing fire. Sustainability can be estimated by the flaming duration. Consumability can be determined by destructively sampling the litter bed pre- and post-burn in small plots (e.g. 0.1 m^2).

Table 3 outlines the strengths and limitations of this research method. A key strength is fuel moisture content can be measured directly, rather than relying on predictions, because the researchers are within the plots immediately prior to burning. Additionally, fire behaviour can be measured directly, rather than inferred from char heights or crown scorch. A potential limitation is that the fire behaviour may be influenced by edge effects, as plots usually need to be situated on the burn boundary to enable safe access in dense vegetation. Additionally, burning characteristics (i.e. flames heights and rate of spread) may be a function of the lighting pattern in addition to the fuel, weather and topography.

Table 3 - Direct observation of burning – strengths and limitations

Strengths	Limitations
Fuel moisture content is measured directly, rather than relying on predictions	Fire behaviour influenced by ignition technique and edge effects as well as the fuel condition.
Fire behaviour is measured directly rather than relying on reconstructions based on char height	Measurements are done under time-pressure, so must use rapid assessment techniques
Minimal pre-burn field work is required, though pre-burn reconnaissance is valuable	Pseudo-replication is a potential issue. Temporal or spatial separation of plots necessary
Flexible approach – can be done at short notice in any burn rather than being limited to burns selected in advance	Daily number of plots achieved is highly variable depending on rate of ignition (from 1 to 10 plots per day for a single research group)
	Method may not be suitable for observing ignitions or fire behaviour that is not near the burn perimeter or areas of safety
	The ability to travel between parts of the burn being ignited may be limited by operational and safety constraints

(a) **(b)**

Figure 2 - Direct observation of burning in prescribed burns in Victoria, Australia. (a) Observing ignition success from burn edge. (b) Observing fire development from spot ignition.

Technologies such as fire proof camera boxes, thermocouples and drones can be used in *Pre- and post-burn plots* to provide more detail about fire behaviour, timing of ignition and duration of burning (Figure 3). However, such technologies are in their infancy and can be difficult to deploy in steep, densely vegetated terrain. Battery operated devices such as cameras within fire proof boxes and thermocouples attached to loggers can be difficult to switch on when the plots are far from a road. Replication may also be an issue since these devices are expensive and therefore a research team may only be able to access a small number. There are often restrictions on the use of drones within prescribed burns if other aircraft are also being used by the fire agencies. Furthermore, dense canopies and thick smoke limit the usefulness of drones as visibility is greatly reduced.

(a) **(b)**

Figure 3 - New technologies for flammability studies in prescribed burns. (a) Fire proof boxes for camera and data loggers to observe flaming inside the burn. (b) Drones to observe rate of spread inside burn.

2.2. Pre- and post-burn plots

Vegetation condition within each plot can be measured in advance of the burn (e.g. fuel hazard, species composition, plant architecture, live-to-dead ratio) and indicators of fire behaviour after the burn (char height, scorch height and leaf freeze). Ignitability may be estimated based on the proportion of the plot burnt, for plots where there is evidence that there had been an ignition attempt. Destructive fuel sampling can be used to measure consumability.

Advantages of using pre- and post-burn plots are that researchers do not need to attend the burn (Table 4). Additionally, plots can be located further from the edge of the burn, reducing edge effects. However, the trade-off is that fuel moisture and fire behaviour are not measured directly, which means inferences must be made using measures such as canopy cover or predictive models for fuel moisture and char heights for fire behaviour. Additionally, because plots need to be installed in advance of the burn, there is a greater likelihood that some effort will be wasted because burn plans inevitably change.

A variation of this method is where there is some experimental manipulation within the plots, e.g. lighting techniques are modified to achieve different fire intensities (Cawson 2012) or fuel structure is modified to isolate the effects of different fuel components on flammability (Schwilk 2003). Such experimental manipulations may enable a better insight into causal mechanisms but can also add to the complexity of the research design. In the context of fire behaviour studies conducted within prescribed burns, any added complexity introduces further risk that the study will not succeed.

Table 4 - Pre- and post-burn plots – strengths and limitations

Strengths	**Limitations**
Plots can be in the middle of the burn, to avoid edge effects Plot layout can be planned to achieve a balanced design across fuel types and terrain features Researchers do not need to be present during burning	Investment of time and effort in pre-burn measurements may be wasted if the plots are not burnt Difficult to determine ignition time for plots and therefore relate weather to fire behaviour Difficult to determine the nature of fire at a plot (i.e. backing, flanking, head fire) Plots cannot be accessed during the burn, so there is an inability to measure fuel moisture or fire behaviour directly

2.3. Analysis of maps of burn outcomes

Post-burn maps may be coupled with vegetation and fuel moisture maps in flammability studies to determine thresholds for ignition and fire behaviour under different weather and fuel moisture conditions (e.g. Nolan *et al.* 2016; Duff *et al.* 2018 in wildfire studies). These retrospective analyses are useful for obtaining broad-scale measures of ignitability and consumability (using fire severity as a proxy), but other flammability variables cannot be quantified with this data.

Advantages of using this method are that a landscape scale analysis can be done with data that are often freely available. However, without specific details about each burn the use of the data is limited.

Table 5 - Analysis of maps of burn outcomes – strengths and limitations

Strengths	**Limitations**
Data are often freely available from fire agencies No field work required, reducing data collection costs for research project Landscape scale analysis possible, potentially incorporating many burns	Typically lacking specific details about the burn such as ignition patterns, pre-burn vegetation and moisture conditions and when the burn occurred Only able to quantify ignitability, not combustibility or sustainability. No direct measures of fuel measure or fire behaviour Often mapping accuracy is not assessed and may vary between burns

3. Key principles for effective flammability research in prescribed burns

Drawing on our experiences working within prescribed burns, we have devised ten key principles for getting the best outcome from research in prescribed burns.

1. *Safety first*. Don't compromise on safety when designing and executing your method. Falling trees, hot ashes and the fire itself can make some methods unsafe to implement.
2. *Collaborate with fire managers.* Research will be best supported if it can be shown to have relevance to operational practice. Managers can be valuable for obtaining insights to support research design and application.
3. *Work within operational objectives.* Managers have different priorities to researchers, and need to consider burn effectiveness, logistics and safety. Designing projects that do not disrupt operational activity are more likely to succeed. It is important to work within burn protocols and recognise when it is appropriate to leave the fire ground.
4. *Focus your efforts on burns that are high priority for management.* Not all planned burns are likely to be completed in any one year. Undertaking pre-burn assessments in burns that are of high management priority will boost the chances that research plots are burned. It can also be valuable to consider the parts of burns that will be higher priority for ignition.
5. *Spread the risk.* Burns may be cancelled or altered at short notice. Hedge the risk of sites not being burnt by choosing multiple burns rather than a single burn and undertaking higher numbers of plots with less intensive measurements.
6. *Get appropriate firefighter training and approvals.* Not only is it safer to be properly trained, but it makes it easier for fire agencies to allow researchers into the burn.
7. *Stay informed.* Ensure communication channels are maintained with fire managers before, during and after the burn. Use contacts within the fire agencies and public notification systems to know when your burn is likely to occur. Ensure that you fit within the burn's communication plan.
8. *Be on standby for rapid deployment.* Often there is little notice before a burn is ignited (less than 24 hours), so equipment and people need to be ready to go.
9. *Be a help on the fire ground*. Make sure your work is not impeding the burn effort and if possible, find ways to contribute to the burn.
10. *Give something back*. Provide your findings to those you worked with to show the value of your collaboration. It can be helpful to do this informally.

4. Conclusion

Operational prescribed burns provide valuable opportunities for researchers to quantify plant flammability at field-scales, even with a modest research budget. However, for this research to be effective the potential limitations of working within prescribed burns must be managed. Central to a successful research program is the maintenance of mutually beneficial working relationships with the fire agencies conducting the burns. Such relationships may also enhance the operational applicability of the research to fire management.

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