

Forest fuel bed ignitability under marginal fire weather conditions in *Eucalyptus* forests

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Abstract. Fires burning under marginal fire-weather conditions tend to be patchy in terms of their spatial coverage. This patchiness is partially driven by variability in the ignitability of the fuel bed. An understanding of fuel-bed ignitability through space and time would help fire managers to more effectively carry out prescribed burns to achieve desired levels of burn coverage in *Eucalyptus* forests. We sought to identify the key fuel-bed attributes influencing ignitability under marginal weather conditions. We recorded ignition successes and failures at 45 points within 5 operational prescribed burns and used the data to build logistic regression models to predict the probability of ignition as a function of fuel-bed attributes. Models were ranked using an information theoretic approach. The four highest ranked models explained 48–54% of the variance in ignitability. Surface fine-fuel moisture content (FFMC) and overall fuel hazard (i.e. fuel arrangement) were the strongest predictors of ignitability, occurring in all four highest ranking models. Both surface FFMC and overall fuel hazard were negatively related to ignition likelihood, contradicting a commonly assumed positive relationship between fuel hazard and flammability. Our field method to measure ignition success could be applied across more prescribed burns to develop operationally useful models of ignitability.

Additional keywords: fire behaviour, fire management, flammability, forest management, fuel hazard, fuel moisture, mosaic, patchiness, prescribed burning, wildfire.

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Introduction

Fires burning under marginal fire-weather conditions (e.g. during prescribed burns) are characteristically patchy in terms of their spatial coverage and severity (Knapp and Keeley 2006; Penman *et al.* 2007). Burning conditions are considered marginal when fire can be controlled with relative ease and self-extinguishment may occur overnight (Tolhurst and Cheney 1999). This generally occurs when there are low wind speeds, high relative humidities and low temperatures. Under such conditions, gullies and polar-facing slopes are typically less flammable and therefore more likely to remain unburnt or experience low intensity fire while ridges and equatorial-facing slopes are likely to burn at moderate intensities (Penman *et al.* 2007). This patchiness is often a desired outcome of prescribed burns, particularly when a burn occurs in an ecologically sensitive area where unburnt patches act as wildfire refuges (Robinson *et al.* 2013) or intercept erosive runoff (Cawson *et al.* 2013). Furthermore, areas of low flammability may be intentionally used as passive barriers to fire spread, during a prescribed burn – in essence, acting as boundaries (Tolhurst and Cheney 1999). To successfully implement prescribed burns and achieve a desired level of patchiness, fire managers need to be able to predict ignitability under marginal fire-weather conditions. Next to ignitability, other determinants of burn success are the fire intensity and proportion of hazardous fuels consumed.

Spatial and temporal variation in fuel-bed ignitability is likely a key determinant of patterns in fire coverage within prescribed burns. Ignitability, how easily the fuel ignites given an ignition source, is one important component of flammability (Anderson 1970). It has been studied extensively in the laboratory, primarily in relation to leaves and plant organs (reviewed by Varner *et al.* 2015; Pausas *et al.* 2017). In these studies, several factors have been identified as important to ignitability, including moisture content, chemical composition, leaf size and particle density. However, it is unclear how these laboratory findings apply in wildland environments because of differences in fuel-bed structure and heat fluxes between the laboratory and field (Fernandes and Cruz 2012; Varner *et al.* 2015). Few studies specifically measure ignitability in the field (one exception is Dimitrakopoulos *et al.* 2010) but the factors broadly recognised as important to ignition at this scale are fuel moisture, arrangement and composition. Fuel moisture influences the amount of heat required to raise the fuel to ignition temperature and is a core component of fire-behaviour models (Keane 2015; Sullivan 2017). Fuel arrangement (e.g. bulk density and continuity) has been shown to influence fire-spread rates (Cheney *et al.* 1992; McCaw *et al.* 2012) and hence is likely to influence the likelihood of an ignition to be sustained. Species composition may influence ignitability where there are differences in volatile oil content or structural differences between species

(e.g. leaf size, leaf arrangement) (Zylstra *et al.* 2016; Wyse *et al.* 2017). Understanding the drivers of ignitability at field scales is critical for predicting fire coverage.

Fire managers routinely collect information about fuel moisture in the field before deciding where and when to conduct a prescribed burn. Prescribed-burning guidelines provide moisture thresholds for successful burn implementation for surface fine fuel and sometimes profile fine fuel (e.g. [Sneeuwjagt and Peet 1985](#); [Forest Fire Management Victoria 2017](#)); guidance for hazard sticks may also be provided (e.g. [Marsden-Smedley 2011](#)). However, there is a lack of information about moisture thresholds for other fuel elements, e.g. dead elevated litter, bark or live vegetation. Fire managers also typically evaluate fuel quantity and structure within a proposed burn unit. In Australia, this is done using visual hazard guides ([Hines *et al.* 2010](#); [Gould *et al.* 2011](#)) where hazard scores are assigned to fuel strata on the basis of fuel amount, continuity and composition. Hazard scores (or the fuel loads derived from them) are input into fire-behaviour models to predict likely fire spread and intensity (e.g. [Cheney *et al.* 2012](#)), with an assumption of a positive association between hazard and intensity.

The aim of our study was to identify the key fuel-bed attributes influencing ignitability in eucalypt forest under marginal fire weather conditions. We hypothesised that surface fine-fuel moisture content would be the most important predictor of ignition success, but that ignition models could be significantly improved by considering the moisture content of other fuel components and fuel arrangement. To investigate this, we developed a methodology that can be applied during operational prescribed burns to link ignition outcomes to key attributes of the fuel being ignited.

Methods

We observed fuel bed ignitability within five prescribed burns undertaken for fuel management purposes in the Central Highlands region of Victoria, Australia (Table 1). Each burn encompassed several forest types (Department of Environment Land Water and Planning 2016) enabling us to measure ignition across a wide range of fuel conditions to find general patterns (Fig. S1 of the Supplementary material). Overstoreys were dominated by one or more *Eucalyptus* species. Understoreys in Wet and Damp forest typically included small tree species (e.g. *Bedfordia arborescens*, *Pomaderris aspera*) and ferns (e.g. *Cyathea australis*, *Polystichum proliferum*). Understoreys in Dry forest contained scleromorph species (e.g. *Monotoca scoparia*, *Hakea decurrens*). Litter beds were near continuous, with depths from 1 to 70 mm.

Burns were ignited with hand-held drip torches (3 : 1 ratio of diesel to unleaded petrol) from external edges and aerial incendiaries for internal ridgelines. We worked alongside hand-ignition crews, assessing fuel-bed attributes (fuel moisture, fuel hazard, vegetation type) at points, immediately before those points were ignited and then recorded ignition success or failure at each point. All ignition attempts were lit as backing fires (i.e. burning downhill or into the wind) (Tolhurst and Cheney 1999, p. 81). We assessed 45 ignition attempts over 8 burning days. Ignition attempts were considered independent if they were more than 500 m apart, more than 1 h apart or in different forest types.

Table 1. Details about the prescribed burns observed in the study

Daily weather observations were from Australian Bureau of Meteorology weather station located in Coldstream (37.72°S, 145.38°E). FFDI is the Forest Fire Danger Index (McArthur 1967). RH is the relative humidity

Burn name	Latitude and longitude	Burn size (ha)	Vegetation with observed ignitions	Date(s) of burn	Maximum temperature (°C)	Minimum RH (%)	Peak average wind speed (km h ⁻¹)	Maximum FFDI	Number of ignitions observed
McMahons creek – Whitelaw track	37.72°S 145.92°E	2616	Dry forest	13/03/2015	22	37	12	11	6
			Damp forest	14/03/2015	29	19	15	28	3
			Wet forest						
Reefton – Aldermans creek	37.74°S 145.97°E	2024	Dry forest	29/03/2016	19	56	12	6	7
			Damp forest	4/04/2016	25	38	5	8	5
			Wet forest						
Wesburn – Britannia	37.81°S 145.68°E	268	Dry forest	18/04/2016	25	39	11	11	7
			Damp forest	19/04/2016	25	32	11	15	5
			Wet forest						
Reefton – Contention Trig track	37.75°S 146.03°E	2015	Dry forest	5/04/2017	25	31	11	14	11
			Damp forest						
			Wet forest						
Toolebewong – Old Coach road	37.70°S 145.55°E	149	Dry forest	19/04/2017	26	42	10	11	3

Ignition attempts were deemed successful if burning was sustained and spread beyond the initial point(s) of ignition, and unsuccessful if the fire self-extinguished once flaming from the initial point(s) of ignition subsided. Field crews constantly modified their lighting techniques to accommodate changing fuel and weather conditions, so the degree of effort required to ignite the sampling points varied. The least intensive ignition method involved lighting individual spot fires with a spacing of 5 m. The most intensive ignition method involved strip lighting five strips of fires with 2-m gaps between each strip. If the fire did not sustain after maximum effort was applied, then ignition was deemed unsuccessful for that ignition attempt.

Fuel moisture was determined gravimetrically, with samples oven-dried for 24 h at 105°C (Matthews 2010). Fuel-bed components sampled were: (1) surface fine fuel – top 10 mm of leaf litter; (2) subsurface fine fuel – bottom 10 mm of leaf litter in contact with soil; (3) dead elevated fine fuel – dead leaves suspended in vegetation; and (4) live fine fuel – leaves of dominant grass or shrub species.

Fuel arrangement was assessed using the Overall Fuel Hazard Guide (as per Hines *et al.* 2010), which is a standard method for measuring fuel arrangement in Australia. Hazard scores for each fuel strata (surface, near surface, elevated and bark) were visually determined based on fuel amount, continuity and live-to-dead ratio. Those scores were then combined to determine an Overall Hazard Score (1, low hazard; 2, moderate hazard; 3, high hazard; 4, very high hazard; and 5, extreme hazard). In addition, we used Ecological Vegetation Groups (Department of Environment Land Water and Planning 2016) as a broad measure of fuel arrangement and species composition. Table S1 of the Supplementary material depicts fuel-bed attributes as a function of forest type.

Logistic-regression models of ignition success were built using all combinations of predictor variables but with the number of predictors in any model limited to three to avoid overfitting (56 different models were derived). The predictor variables were:

- surface fine-fuel moisture content (FFMC),
- subsurface FFMC,
- dead elevated FFMC,
- live FFMC,
- surface fuel hazard score,
- overall fuel hazard score, and
- vegetation type.

The logistic regression model had the following form:

$$\Pr(\text{Ignition}) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

where the logit $g(x)$ is given as:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_i x_i$$

$\Pr(\text{Ignition})$ is the probability of ignition, x_i are the independent variables and β_i are the coefficients.

All statistical analysis was done in the R statistical programming language (ver. 3.4.3, R Foundation for Statistical Computing, Vienna, Austria). Akaike's information criterion (AIC)

corrected for small sample size (AICc) was used to compare levels of support for models (Burnham and Anderson 1998). Each model was assigned an Akaike weight, which is the probability that the model is the most parsimonious. The highest ranked models (within two AIC units of the best model) are presented in the results. Model selection was undertaken using the R package glmulti (Calcagno 2013).

Goodness of fit was determined using $-2 \log(\text{Likelihood})$, McFadden R^2 (likelihood ratio index) and Hosmer and Lemeshow's goodness of fit test (Hosmer *et al.* 2013). Partial-residual plots (otherwise known as term plots) were derived for the highest-ranked model. In these plots, the predictor is plotted against the partial residual, which is a sum of the residual and the term for each predictor (or in other words, the part of the response not explained by the other predictors). These plots enable us to visualise the contribution of each predictor to ignition probability.

Results

The burns were conducted in autumn (March to May). Weather conditions were mild, with temperatures ranging from 16.5 to 28.2°C, relative humidity ranging from 22 to 79%, Forest Fire Danger Index (FFDI) (McArthur 1967) ranging from 1 to 24 and Keetch–Byram Drought Index (KBDI) (Keetch and Byram 1968) ranging from 101 to 140 (Table 1). Ignitions occurred in the surface or near-surface fuels, but where the ignition sustained, flaming often incorporated the shrub strata.

The model selection process identified four models that were within two AICc units of the best model (Table 2). All short-listed models produced an adequate fit to the data: Fadden R^2 ranged from 0.48 to 0.54; $-2 \log(\text{Likelihood})$ ranged from 26.82 to 30.51 and the Hosmer and Lemeshow goodness of fit tests were not significant ($P > 0.05$), which means there was no significant difference between the observed and expected frequency distributions of ignition. The highest-ranked model included three predictor variables: surface FFMC, dead elevated FFMC and overall fuel hazard. As shown in the partial-residual plots (Fig. 1), all three predictor variables negatively influenced the probability of ignition, which is expected for FFMC but surprising for overall fuel hazard. Surface FFMC and overall fuel hazard were stronger predictors of ignition than dead elevated FFMC, as indicated by their steeper slopes in the partial-residual plots and larger coefficients in Table 2.

Surface FFMC was included in all four of the highest ranked models. For the single parameter model (ranked 16th in Table 2; Fig. S2), the ignition probability was 0.75 when surface FFMC was 18%. Overall fuel hazard was included in all four of the highest ranked models. Overall fuel hazard only occurred over a limited range (from High to Extreme) and there were few ignition points where the hazard was in High or Very High categories, which likely limits its strength as a predictor. Although dead elevated FFMC, subsurface FFMC and vegetation type were all included in one of the four highest ranked models, their influence in these models was not statistically significant (i.e. $P > 0.05$).

Discussion

Fuel moisture was a strong predictor of ignition success. This is not unexpected considering numerous field and laboratory

Table 2. Models to predict ignition success as a function of fuel properties

This table depicts the highest ranked models using the corrected Akaike's information criterion (AICc); top ranked models within two AICc units of the top ranked model are shown. Additionally the single parameter model with ignition probability as a function of Surface FFM is shown (ranked 16th of 56 models considered). The Akaike weight (A_w), McFadden R^2 , $-2 \log$ Likelihood ($-2 \log$ Lik) and P -values from the Hosmer–Lemeshow (H-L) goodness of fit test results are displayed together with coefficients (β) for each model term and their statistical significance (z -value, P). The model in bold shows where the surface FFM is the only predictor was not among the highest ranked models but has been included in the table as a point of reference to demonstrate the value of using more than one factor to predict ignition. Probabilities are significant at: *, $0.01 < P < 0.05$; **, $0.001 < P < 0.01$; ***, $0.0001 < P < 0.001$

Rank	Model	AICc	Δ AICc	A_w	R^2	$-2 \log$ Lik	H-L	Predictors	$\beta \pm \text{s.e.}$	z -value	P -value
1	Ignition ~ 1 + surface FFM + dead elevated FFM + overall fuel hazard	35.82	0	0.22	0.5	26.82	0.5	(Intercept) Surface FFM Dead elevated FFM Overall hazard	25.70 ± 8.61 -0.44 ± 0.13 -0.13 ± 0.08 -3.06 ± 1.32	2.983 -3.245 -1.604 -1.314	0.00285** 0.00118** 0.10888 0.02064*
2	Ignition ~ 1 + surface FFM + subsurface FFM + overall hazard	35.91	0.17	0.21	0.5	26.91	0.4	(Intercept) Surface FFM Subsurface FFM Overall hazard	20.39 ± 7.52 -0.41 ± 0.14 -0.02 ± 0.01 -2.25 ± 1.21	2.709 -2.908 -1.764 -1.858	0.00674** 0.00364** 0.07779 0.06312
3	Ignition ~ 1 + surface FFM + overall hazard + veg type	36.68	0.93	0.11	0.5	27.7	0.9	(Intercept) Surface FFM Overall hazard Veg type (dry forest)	16.70 ± 6.43 -0.37 ± 0.14 -2.13 ± 1.10 1.67 ± 1.03	2.599 -2.597 -1.926 1.629	0.00935** 0.00942** 0.05416 0.10335
4	Ignition ~ 1 + surface FFM + overall hazard	36.7	0.86	0.14	0.5	30.51	0.4	(Intercept) Surface FFM Overall hazard	18.13 ± 5.79 -0.43 ± 0.13 -2.02 ± 0.94	3.134 -3.224 -2.155	0.00172** 0.00126** 0.03119*
16	Ignition ~ 1 + surface FFM	42.5		<0.01	0.4	38.21	0.3	(Intercept) Surface FFM	7.57 ± 2.23 -0.36 ± 0.11	3.387 -3.189	0.00071*** 0.00143**

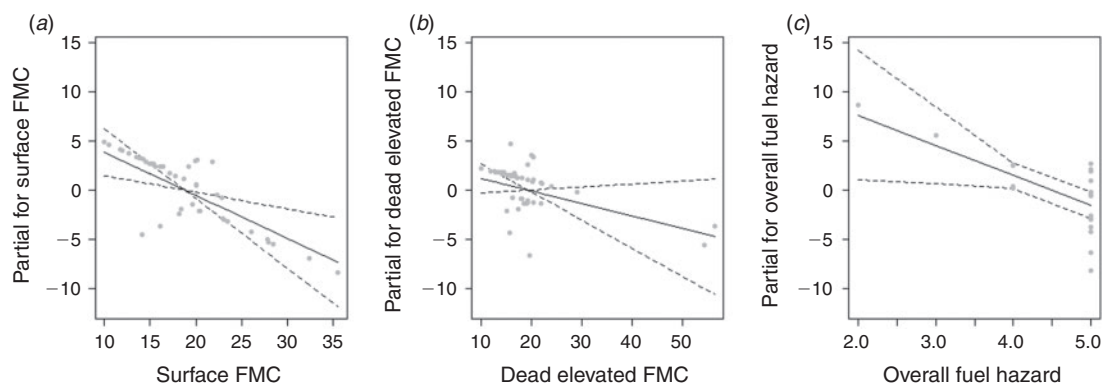


Fig. 1. Plots of partial residuals against (a) surface FFMFC, (b) dead elevated FFMFC and (c) 392 overall fuel hazard. Points are the partial residuals, solid lines are the fit between partial residuals and predictor variables and dotted lines are the standard errors.

flammability studies have identified fuel moisture as an important determinant of ignitability (e.g. Blackmarr 1972; Dimitrakopoulos and Papaioannou 2001; Plucinski and Anderson 2008; Dimitrakopoulos *et al.* 2010; Ellis 2015) and fire-behaviour models invariably include landscape dryness metrics (e.g. McArthur 1962; Sneeuwjagt and Peet 1985; Forestry Canada Fire Danger Group 1992).

Surface FFMFC was in all four of the highest-ranked models. This result supports our hypothesis that surface FFMFC would be the most important factor. Surface fuels are a key component of the fuel bed supporting the spread of fire (Gould *et al.* 2011; Keane 2015). Accordingly, if the surface fuels are too wet to burn then the fire will not be sustained. Additionally, surface fuels are the fuel component likely to have the greatest direct exposure to drip-torch ignitions (Tolhurst and Cheney 1999). The 18% surface-moisture threshold for a 75% probability of ignition corresponds with the upper end of moisture thresholds recommended for prescribed burning in eucalypt forests (Sneeuwjagt and Peet 1985; Tolhurst and Cheney 1999; Slijepcevic *et al.* 2015). Surface FFMFC is a function of both atmospheric conditions (varying at sub-daily timescales) and soil moisture (varying at weekly to monthly timescales) (Viney 1991; Matthews 2014). The strong relationship between surface FFMFC and ignition success suggests that both sub-daily and seasonal processes are important to ignition success.

Dead elevated and subsurface FFMFC were selected once each in the four highest-ranked models but their contribution in these models was not statistically significant. This result suggests dead elevated FFMFC and subsurface FFMFC are weak predictors of ignition. Given they represent the dryness of the air (dead elevated) and soil (subsurface), they are a function of the same drivers of surface FFMFC, so are likely to have limited independent variation.

Overall fuel hazard was in all four of the top ranked models, with increasing hazard associated with reduced ignition probability. This negative association between hazard and the probability of ignition seems at odds with the commonly assumed positive relationship between fuel hazard and flammability. Higher fuel hazards are associated with more intense fire behaviour (Hines *et al.* 2010; McCaw *et al.* 2012). Our results

suggest that, in areas of higher fuel hazard, the probability of successful ignition may be reduced. This could be due to high hazards representing areas of dense live vegetation. Under marginal burning conditions, there may be insufficient heat to ignite dense live vegetation. Therefore, rather than adding to the intensity of the fire, dense near-surface and elevated fuels may act as a heat sink that retards fire spread. Furthermore, in our study, the locations with higher fuel hazards often occurred in wetter, more productive parts of the landscape where mesic species were more abundant than scleromorphic species; mesic species may be intrinsically more difficult to ignite (Dickinson and Kirkpatrick 1985; Gill and Moore 1996). A limitation of using overall fuel hazard in this study was that it was measured as 'Extreme' at most ignition points, potentially limiting its predictive ability. Future studies should consider using more specific measures of fuel structure and composition rather than hazard scores to provide a potentially more precise indication of the factors driving ignition.

Other indicators of fuel arrangement – surface hazard and vegetation type – were also considered in the model selection process. Surface hazard did not appear in the highest ranked models, potentially because it was accounted for already within overall fuel hazard. Vegetation type appeared in one of the highest ranked models, suggesting that there may be some other characteristics of the vegetation not captured in the overall fuel-hazard score that influence ignition (e.g. species composition or the amount of solar radiation). However, because vegetation type only appeared in one high-ranking model, support for it as a predictor of ignition success was weak relative to overall fuel hazard.

Although our highest ranked models for ignition explain a reasonable amount of variation in the data, there is a large portion that remains unexplained. That unexplained variation could be due to other factors not measured in the study such as localised weather conditions, litter-bed composition, solar radiation, dominant plant species and fuel-structure attributes not captured by fuel hazard. Further research is required to explore other variables that might explain ignition and strengthen our ability to predict fuel attributes at spatial scales (100–500 m) relevant to prescribed burning.

Conclusion

Models to accurately predict fuel bed ignitability under marginal burning conditions have the potential to improve the efficiency of prescribed burning operations. We developed a method for measuring ignitability in operational prescribed burns and found that surface FPMC and overall fuel hazard were important determinants of ignition. Further data collection is needed to build operationally useful ignition models.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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