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Fire Severity Patterns in the Victorian Fires of February 7th 2009: influences of weather, terrain and land use history

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Introduction

One of the principal issues of debate in bushfire management is the extent to which pre-fire management can reduce the risk of bushfire damage. There are a variety of scientific approaches that can be used to understand the drivers of fires and to measure the effects of landscape management. One of these is retrospective analysis (i.e. post-fire) of fire severity patterns.

Fire severity is a description of the damage to vegetation caused by fires. It can be mapped using remote imagery sourced from sensors mounted on aircraft or satellites. In essence, the method calculates the change in reflectance from vegetation caused by burning, by contrasting images taken before and after the fire. Fire severity is correlated with fire intensity (Hammill and Bradstock 2006; Keeley 2009) reflecting trends in indicators such as heights of scorch and consumption of foliage. Patterns of remotely-sensed measures of severity can therefore be related to these measures. This allows assessment of the influence of the relative effects of weather, fuels and terrain on fire behaviour to be carried out over large spatial scales.

The Department of Sustainability and Environment (DSE) created a severity map for the Victorian fires of 7th February 2009, with classes that identify a range of severities from crown consumption to litter fires. In this report we formally relate variations in patterns of severity to variations in weather, terrain and land use history (including prescribed burning) in the affected areas.

Recent studies have shown the weather, terrain and fuel characteristics can affect fire severity and inferred fire intensity in a variety of ecosystems. For example, in the western USA, fire severity in conifer forests has been shown to increase as a function of prior logging activities (Odion et al. 2004, Thompson et al. 2007) and fuel age (Collins et al. 2007). In Portugal, vegetation type and terrain have major effects on fire severity (Oliveras et al. 2009). Recent studies in Australia have illustrated that fire severity is substantially influenced by weather, vegetation characteristics and terrain in eucalypt forests (Chafer et al. 2004; Chafer 2008; Hammill and Bradstock 2006). In particular Bradstock et al. (2010) showed that weather was the predominant influence on fire severity in eucalypt forests in the Blue Mountains (NSW). Time since prior fire (a surrogate for age of fuel) and terrain also had significant effects. For example, probability of intense crown fires in severe weather conditions increased with time since fire in a non-linear manner.

The 2009 fires in Victoria provide an opportunity to use analyses of fire severity to further investigate the relative of importance of the fundamental drivers of fire behaviour and their implications for management. In particular, these fires allow offer the opportunity to examine responses in a wider range of eucalypt forest types and fire weather conditions (e.g. tall, moist forest types and weather of rare extremity) than previously reported in the literature.

Given these circumstances, this study addressed the following questions:

1) What was the predominant influence on fire severity and inferred fire intensity?

2) Was fire severity affected by time since fire and inferred fuel age?

3) Was fire severity affected by time since logging?

4) Was fire severity affected by terrain?

Contrasting levels of severity were examined in relation to these questions, following the approach used by Bradstock et al. (2010). This was done to interpret consequences of weather fuel and terrain for key aspects of fire management. Fires of low severity (i.e. confined to the understorey of forests) burn at intensities that are more amenable to suppression than fires of higher severity (i.e. those that substantially damage or consume tree crowns). By contrast, fires which consume tree crowns (highest level of severity) represent the upper extreme of fire intensity in eucalypt forests (> 10,000 kW m^{-1}). Fires of this severity are uncontrollable and are likely to pose the highest level of threat to adjacent people and property. Insights into the way in which probability of understorey and crown fires can be respectively increased and decreased under the circumstances of February 7th and later days are therefore pivotal to future management.

Methods

Effects of weather, terrain, time since fire and logging were analysed across four fires that burnt in February 2009 in southern Victoria. Point samples were taken across the burnt areas, and at each point a range of environmental variables were calculated, and fire severity was estimated using the spatial data provided by DSE. These data were then used to conduct statistical modelling to relate severity (response or dependent variable) to the other variables (predictor or independent variables).

Two types of fire were defined as discussed above: those that consumed or scorched the crown (called Crown Fire, class 1) and those that burnt only the litter (with possible light crown scorch) (called Understorey Fire). The resultant statistical models predict the probability that: i) the fire crowned, and; ii) the fire remained confined to the understorey, as a function of the predictor variables. This approach followed that of Bradstock et al. (2010) who noted the correspondence of on-ground indicators of intensity with these respective levels of fire severity. Thus understorey fires are likely to be suppressible (i.e. inferred intensity < 4,000 kWm^{-1}), whereas crown fires burn at inferred intensities well beyond the suppressible range.

Data
Four fires were used for this study: Kilmore, Murrundindi, Bunyip and Churchill (Fig. 1). The fires have been described in the Interim Report of the Royal Commission. The salient point for this analysis is that these fires all burnt in a southeast direction under extreme weather conditions on February 7th until a cooler and more humid southerly change in the evening caused the fires to veer to the northeast. Within these fires, areas burnt within three consecutive time periods were delineated to represent the discrete influence of contrasting periods of fire weather. These were: 1) the period prior the southerly change on February 7th; 2) the period after the southerly change, but before midnight on February 7th, and; 3) days subsequent to February 7th. These areas were delineated by using fire progression maps provided by DSE and Country

Fire Authority (CFA) with cross-reference to half-hourly weather records from BOM weather stations Kilmore Gap (#88162), Coldstream (#86383) and Morwell (#85280) as indicators of fire weather across the affected region. Trends in fire weather at these stations were also evident at other stations in southern Victoria (Sullivan and McCaw 2009). In all three of these stations, the southerly change began to have an effect at about 17.15. Thus, we used the are burned up to 17:00 to indicate the influence of pre-change weather, and the area burned from 18:00 to 24.00 to indicate the influence of post-change weather. The range of fire danger for the three periods (as described for the three stations in Table 1) was respectively Extreme, Moderate and Low.

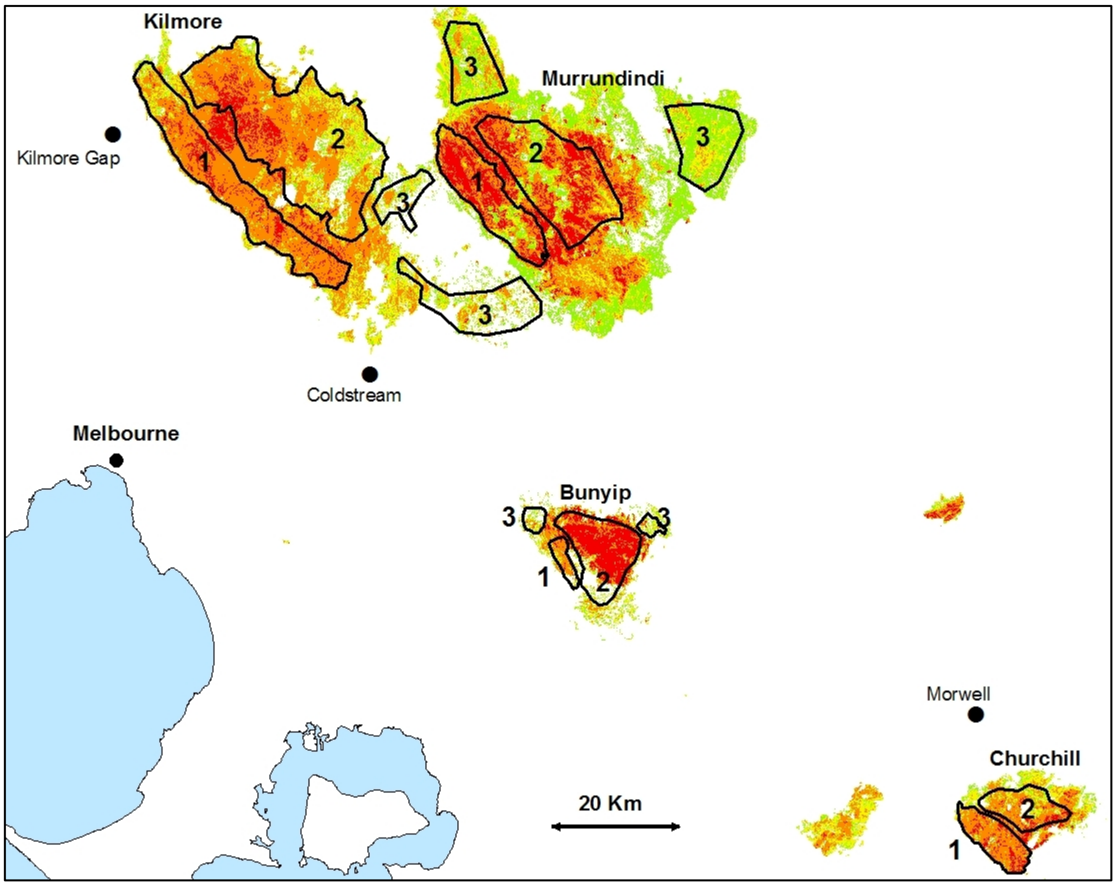

Figure 1: Fires, severity map and time periods used for analysis. The severity map is shaded from green (no understorey burnt) to red (crown burn). The numbered areas are defined as: 1 = Feb. 7th before southerly change; 2 = Feb. 7th after change; 3 = subsequent days. The weather stations Kilmore Gap, Coldstream and Morwell are also shown.

Table 1: Weather experienced during the three weather periods at three nearby weather stations.

Station	Period	FFDI Mean	FFDI Range
Kilmore Gap	Extreme (12:00-17:00)	131	81-189
	Moderate (18:00-0:00)	7.56	1.6 – 20
	Low (08/02/2009)	3.0	1.1 – 5.6
Coldstream	Extreme (12:00-17:00)	84.3	67-110
	Moderate (18:00-0:00)	9.6	3.4 -17
	Low (08/02/2009)	3.2	1.4 – 7.5
Morwell	Extreme (12:00-17:00)	96	67 -122
	Moderate (18:00-0:00)	10.0	4.5 – 25
	Low (08/02/2009)	3.9	1.9 – 7.8

Fire severity was mapped by DSE at a scale of 1:25,000, mostly from SPOT satellite imagery using the Normalised Burn Ratio (NBR) method (DSE 2009). The method involves estimation of change in vegetation reflectance (near infrared bands of radiation) derived by contrasting images from before and after the fires.

A grid of sample points with 500 m separation was created within these defined areas. This distance was chosen following the method of Bradstock *et al*. (2010), who found that this gave spatial independence to the sampling points. Environmental data was calculated for each of the points with GIS software using relevant layers of vegetation, terrain, and fire and logging history supplied by DSE.

A simplified, aggregated classification of vegetation was used to describe the dominant forest types. These were Dry forest; Damp forest and Ash forest. The classes were derived from maps of DSE's Ecological Vegetation Classes by combining classes with similar structure and species composition. The three classes covered 70% of the points initially selected for sampling. The total number of points sampled in these forest types was 4566.The remainder, consisting of woodlands, riparian and wetlands, were not used in the analysis. A 25 m resolution Digital Elevation Model (supplied by DSE) was used to calculate Slope, Aspect and Topographic Position. The latter was calculated as the elevation as a percentage of the range of elevations in a 500 m radius (i.e. local ridge tops = 100 and local valley bottoms = 0).

Digital fire and logging history maps were supplied by DSE and these were used to calculate Time Since Fire and Time Since Logging for each point (Fig. 2). Time Since fire was based on the date of either prior unplanned or prescribed fires (i.e. both sources of fire combined). Both of these variables had distributions dominated by long values (i.e. long time since burnt or logged) (Fig. 2). For the analysis, Time Since Fire and Time Since Logging were log-transformed to reflect the typical asymptotic post-disturbance recovery of fuels. Log-transformation of the logging data was also necessary because the distribution was strongly skewed toward unlogged sites with a nominal age of 130 years (82% are unlogged).

Table 2: Variables used in the analysis

Variable	Description and Values
Dependent Variables	
Fire Severity	DSE Fire Severity map for the fires of February 7th 2009, 1:25,000 scale. 1 - Crown Burn 2 - Crown Scorch 3 - Moderate Crown Scorch 4/5a - Light or No Crown Scorch. Understorey Burnt 5b - No Crown Scorch. No Understorey Burnt
Crown Fire	Reclassification of Fire Severity: Severity = 1 (True or False).
Understorey Fire	Reclassification of Fire Severity: Crown Not Burnt; Severity > 3 (True or False).
Predictor Variables	
Weather	Extreme – Before southerly change, FFDI ~100 Mod – After southerly change, FFDI ~ 10 Low – Subsequent days, FFDI ~ 3
Time Since Fire	DSE state-wide fire history mapping at 1:100,000 scale (see Figure 2a for values). Log transformed for analysis.
Time Since Logging	DSE state-wide logging history mapping at varying scales (see Figure 2b for values). Log transformed for analysis.
Slope	In degrees (derived from DEM)
Aspect	N, S, E, or W
Topo-position	% elevation compared to surrounding 500 m (0 = valley, 100 = ridge)
Forest Type	Vegetation simplified from 1:100,000 or 1:25,000 regional Ecological Vegetation Classes mapping into 3 dominant forest classes, combining EVC codes as follows: Dry Forest: CVU_0022, CVU_0023, HNF_0021 ,HNF_0022, HNF_0023, HSF_0022, HSF_0023 Damp Forest:HNF_0029, HSF_0029, Strz0029, VAlp0030 Ash Forest: HNF_0030, HSF_0030, Strz0030, VAlp0038, VAlp0039

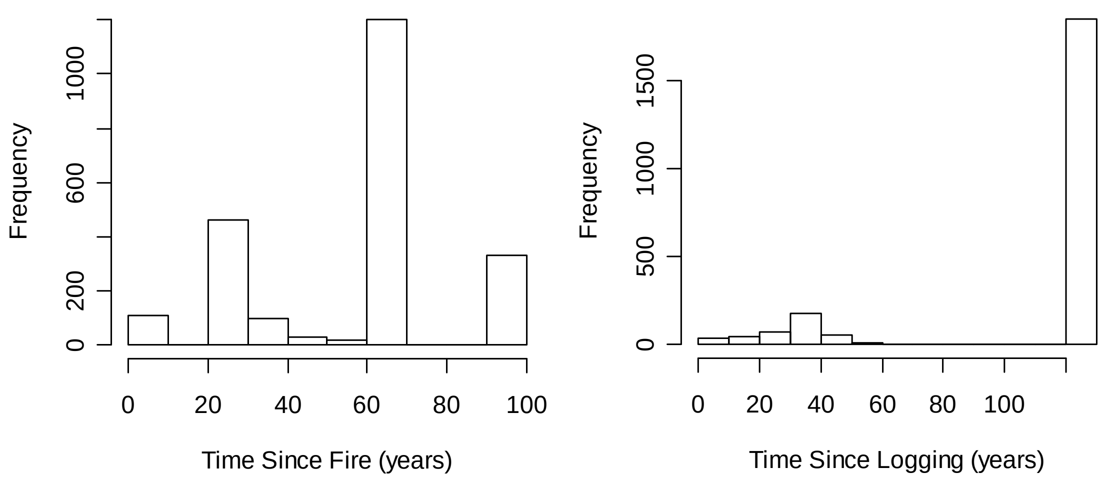

Figure 2: The distribution of a) Time Since Fire and b) Time Since Logging values among the sample points.

Analysis
Generalised Linear Modelling was used to develop predictive models of the drivers of fire severity. Two analyses were conducted: one for the probability of crown fire would burn the crown (Severity score = 1, Table 2); and one for the probability of understorey fire (Severity score > 3, Table 2).

In each case, the models were binomial (meaning the response variable was either 0 or 1), and a logit link function was used. In order to assess the accuracy of the models, approximately half of the points (n = 2288) were selected randomly for the models, and the other half (n=2278) were set aside and used to test the performance of the selected statistical models by comparing predicted severities with measured severities.

For each analysis, all possible combinations of the predictor variables were tested, and the best model and supported alternatives identified using Aikaike's Information Criteria (AIC) (Burnham and Anderson, 2002). Any model with an AIC value within 2 of the best model (ΔAIC) is considered to be a supported alternative. When alternatives are present, no one model can be considered to be the definitive model. Then five two-way interactions were tested on the best model, and retained if they reduced the AIC of the best model. These were the Time since Fire * Vegetation Type, Time Since Fire * Weather and Slope * Aspect. More complex, higher order interactions (e.g. three way interactions) were not considered. The significance of the selected models was tested using analysis of deviance. This is also provides some assessment of the degree to which the models account for variability in the data.

The selected models were used to make predictions of Crown Fire and Understorey Fire probability for all sample points excluded from the model selection process. For this subset, the accuracy of prediction from the selected models was assessed by calculating the Receiver Operator Characteristic Area Under the Curve (ROC AUC), and the percentage of correct predictions. To test whether the log-transformation of the Time Since Fire data was appropriate, two versions of the best model (with the transformed or untransformed variables) were compared using AIC.

Further testing was done to examine whether fire severity responses were influenced by spatial autocorrelation at the sample point spacing of 500 m. The detail of methods and results are not presented here, but the outcome indicated that the analyses described above are likely to be robust and not distorted by effects of spacing between samples.

Results

Trends in crown and understorey fire severity

The proportion of samples with a crown fire increased with increasing Time Since Fire (Fig. 3a). There was little evidence of any trend in the proportion of samples with a crown fire, in relation to Time Since Logging (Fig. 3b) though sample sizes in recently logged areas were small. The proportion of samples with an understorey fire was substantially higher in recently burnt areas (i.e. 3 years or less) compared with sites less recently burnt (Fig. 3c). The converse trend applied to Time Since Logging (Fig. 3d) with a higher proportion of samples in recently logged areas (i.e. 3 years or less) compared with sites less recently logged.

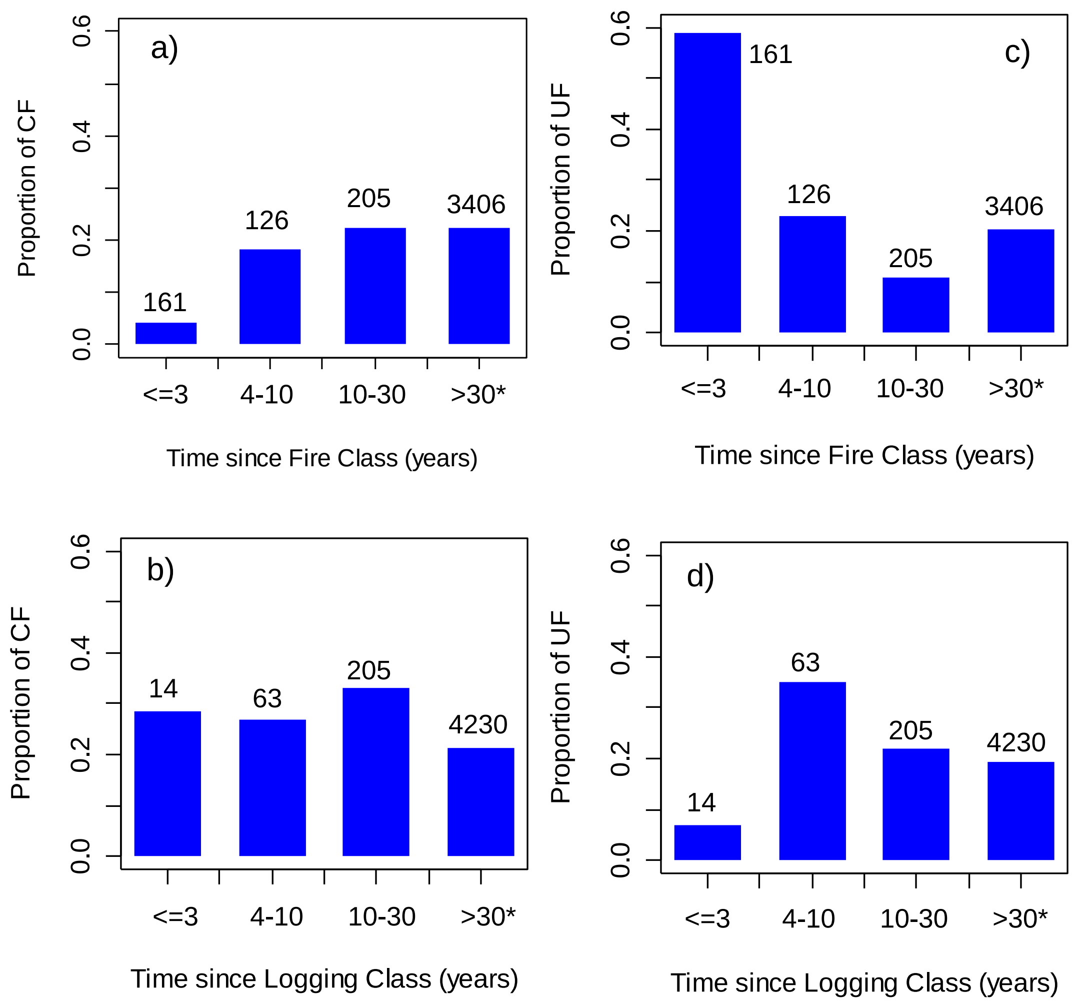

Figure 3: Proportions of sample points that experienced Crown Fire or Understorey Fire in classes according to Time Since Fire or Time Since Logging: a) Crown Fire/Time Since Fire; b) Crown Fire/Time Since Logging; c) Understorey Fire/Time Since Fire; d) Understorey/Time Since Logging. The sample sizes are shown above the bars.

Probability of Crown Fire

The analysis revealed significant effects of all of the variables considered and significant interactions between Time Since Fire and Forest Type and between Aspect and Weather (Table 3). Weather had the most pronounced effect on the likelihood of crown fire (Fig. 4). During Extreme weather, the likelihood was high, and in Low weather, it was very low, irrespective of other factors contributing to the likelihood. In the Moderate weather, likelihood was intermediate and influenced by the other factors, such as Forest Type or Time Since Fire. The likelihood of crown fire decreased with Time Since Fire in Ash forests (Fig. 4a) but increased in a non-linear manner in Damp and Dry forests (Fig. 4b). Dry forests had lower likelihoods (by about 0.1) across all weather and Time Since Fire values compared with Damp forests though the pattern of response to Time Since Fire was similar. The predicted likelihood of crown fire in the Damp and Dry forest was lower by 0.2 – 0.3 in Moderate Weather compared to extreme weather.

Time Since Fire effects in these forest types (about 0.1 to 0.2) were most pronounced in young fuels (less than 7 years). By contrast, in Ash forests, predicted fuel age effects were linear and larger. The raw data indicated that the fuel age effect is pronounced for approximately 3 years after last fire (Fig. 3a), whereas the predictions from the selected model suggested more prolonged effects in all forest types (Fig. 4).

Time Since Logging decreased the likelihood of crown fires, and the model predicted that long unlogged areas could reduce crown fire likelihood by about 0.2 to 0.3 (Fig. 5a).

The selected model predicted that high slopes had lower Crown Fire likelihood and Topo-positions toward the tops of ridges had slightly higher likelihood, though these effects were negligible (as illustrated for Topo-position in Fig. 5b). Aspect and Weather interacted (Fig. 6), so that before the change (during Extreme weather), easterly aspect had the highest predicted likelihood of crown fire and southerly the lowest (Fig. 6a). After the change, the northerly aspect had the highest probability of crown fire and westerly the lowest (Fig. 6b).

The selected model had an overall accuracy of 72% when used to predict the occurrence of crown fire in the portion of the data not used for initial analyses. Positives were correctly predicted in 63.9% of cases, and negatives correctly predicted in 74.5% of cases. The Area Under the Curve for the best model was 0.800.

Table 3: Best model for the Crown Fire analysis. Deviance = 521.5, df = 19, p<0.001 (21.6% captured). The values for Forest Type and Weather/Aspect combinations are additive (e.g. add 6.365 for Ash), the others are multiplicative (e.g. add -1.011*Time Since Fire). The model gives predictions for y, which is translated into a probability value using the logit function: p = Exp(y)/1+Exp(y).

Slope	Topo-position	Time since Logging	Forest Type	Time Since Fire	Weather by Aspect Combination
-0.012	0.011	-0.441	Ash: 6.365	-1.011	Ext/E: 0
			Damp: -4.865	0.195	Ext/S: -1.470
			Dry: -5.950	0.227	Ext/W: -1.310
					Ext/N: -0.989
					Mod/E: -1.051
					Mod/S: -0.10
					Mod/W: 0.484
					Mod/N : 0.339
					Low/E: -19.08
					Low/S: -17.52
					Low/W: -4.128
					Low/N: -4.504

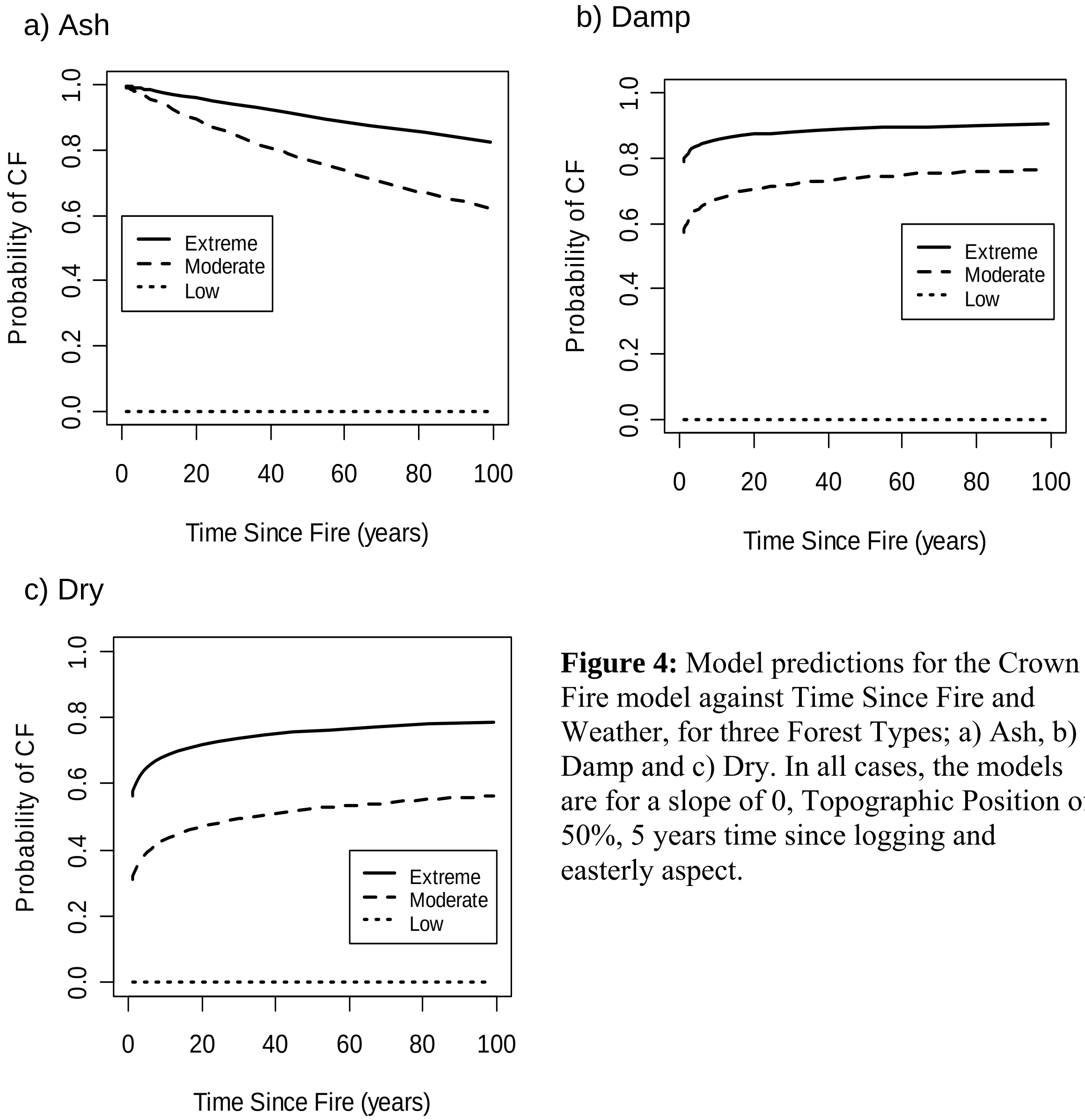

Figure 4: Model predictions for the Crown Fire model against Time Since Fire and Weather, for three Forest Types; a) Ash, b) Damp and c) Dry. In all cases, the models are for a slope of 0, Topographic Position of 50%, 5 years time since logging and easterly aspect.

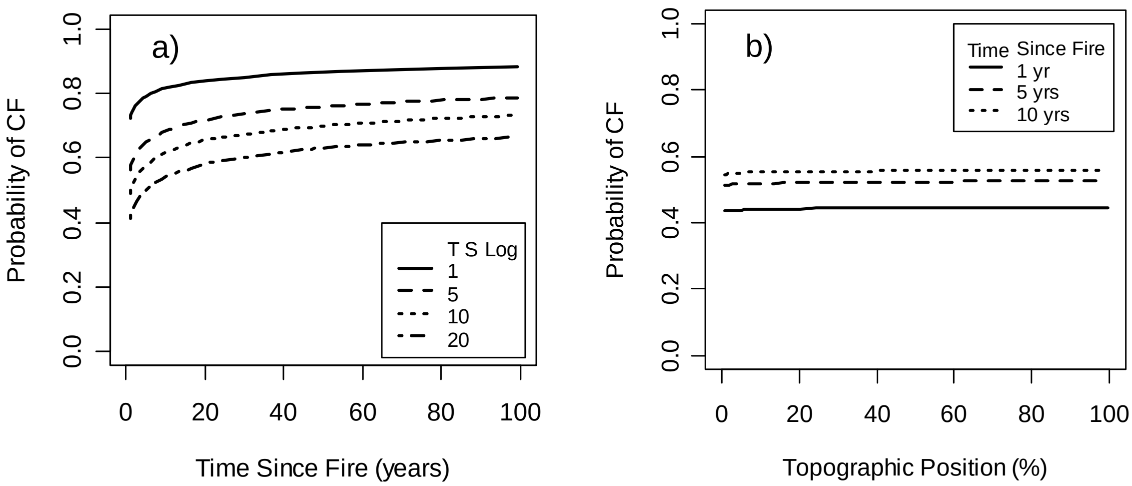

Figure 5: Model predictions for the Crown Fire model against: a) Time Since Fire and Time Since Logging (for cases with Dry forest, slope of 0, Moderate Weather, Topographic Position of 50%, 5 years time since logging and easterly aspect); and b) Topographic Position and Time Since Fire (for cases with a slope of 0, Moderate Weather, 5 years time since logging and easterly aspect).

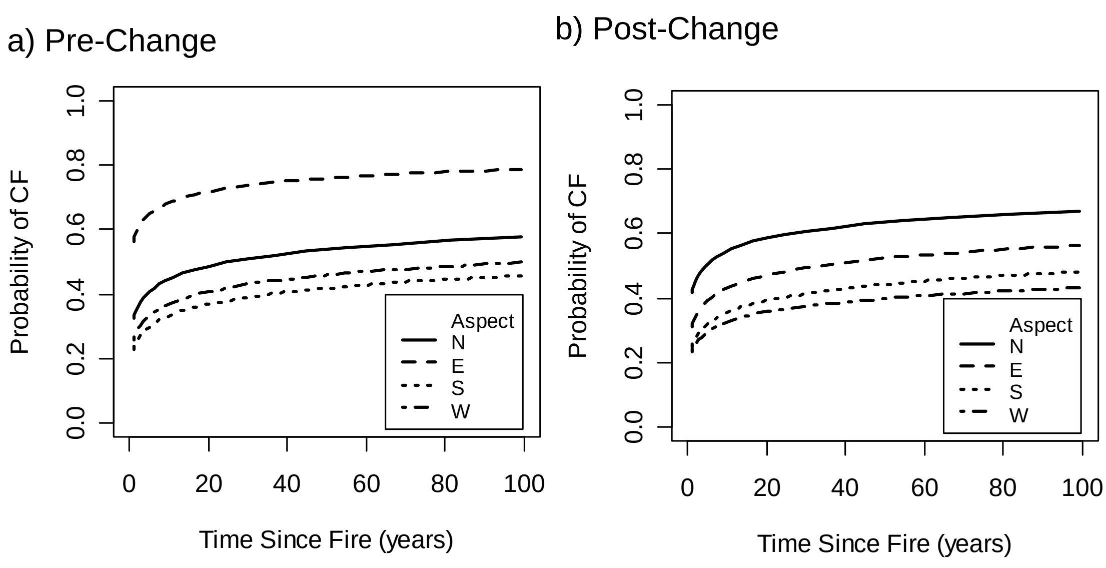

Figure 6: Model predictions for the Crown Fire model against Time Since Fire and Aspect for two weather periods; a) before the change (Extreme) and b) after the change (Moderate). In all cases, the models are for Dry forest, with a slope of 0, Topographic Position of 50%, 5 years time since logging.

Understorey Fire

The best understory model included effects of Weather, Time Since Fire and Forest Type and interactions between Time Since Fire and Weather, plus Weather and Forest Type (Table 4). Again, weather had the dominant effect, such that there was very high likelihood of Understorey fire in Low weather conditions and very low likelihood in Extreme weather (Fig. 7a). In Moderate weather, the other variables had an influence. Time Since Fire only affected understorey fire probability in the Moderate weather period, and the model predicted that such effects (i.e. higher probability of an understorey fire) were mostly confined to very recently burnt age classes (i.e. 1 to 5 year period post fire). Effects of Time Since Fire beyond 5 years were small and attenuated rapidly (Fig. 7a). In Low weather, Ash forests had a lower likelihood of understorey fire than the Damp or Dry forests, but in Moderate weather, the Dry forests had a higher likelihood than the Ash or Damp forests (Fig. 7b). In Extreme weather, all the forest types had a very low likelihood of an understorey fire.

Table 4: Best model for the Understorey Fire analysis. Deviance = 1004.5, df=11, $p<0.001$ (44.5% captured). The model gives predictions for y, which is translated into a probability value using the logit function: p = Exp(y)/1+Exp(y).

Weather	Forest Type	Intercept	Time Since Fire coefficient
Extreme	Ash	0	0.485
	Damp	-20.55	0.485
	Dry	-6.924	0.485
Moderate	Ash	0.474	-0.894
	Damp	-15.71	-0.894
	Dry	-2.079	-0.894
Low	Ash	1.783	-0.120
	Damp	-12.34	-0.120
	Dry	0.182	-0.120

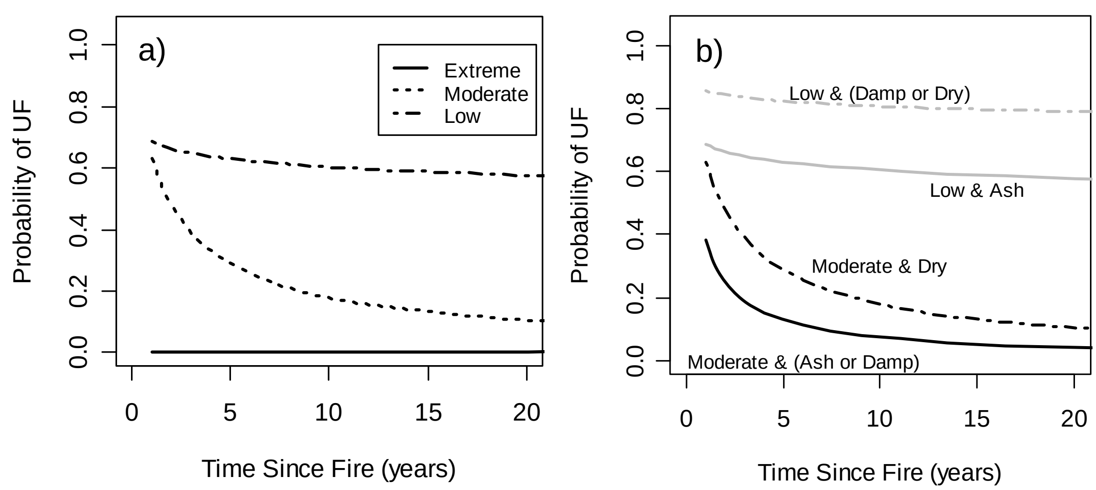

Figure 7: Model predictions for the Understorey Fire model against Time Since Fire: a) showing differences in Weather periods for Dry forest; and b) showing the interaction between Weather and Forest Type.

The selected model had an overall accuracy of 85.3% when used to predict the probability of an understorey fire in the portion of the data not used for initial analyses. Positives were correctly predicted in 85.5% of cases, and negatives correctly predicted in 84.9% of cases.

Discussion

What was the predominant influence on fire severity and inferred fire intensity?
Weather was the predominant influence on fire severity and inferred fire intensity in the areas examined in this study. This was evident in the range of variation in predicted probability of both crown and understorey fires (e.g. > 0.9 for understorey fire, Fig. 4; > 0.7 for crown fire, Fig. 7) in response to variations between categories of weather. Thus crown fires were likely in Extreme and Moderate Weather but effectively absent in Low weather (Fig. 4), whereas the opposite trend applied to understorey fires (Fig. 7)

Responses to other predictors were more muted. Responses to Time Since Fire varied across a maximum range of about 0.3 for crown fire (Fig. 4) and about 0.5 for understorey fire (Fig. 7). Aspect effects of crown fires varied across a range of about 0.3 (Fig. 6), Time Since Logging effects on crown fires varied similarly (Fig. 5a), whereas effects of topographic position and slope were very small (< 0.1 range, Fig. 5b crown fire only). Forest type also had major effects, not only in terms of the range of variation (up to 0.7 range for crown fires, Fig. 4; up to about 0.2 range for understorey fires, Fig. 7b) but also fundamental differences in the nature of response to Time Since Fire and Weather (Figs 4, 7b).

Was fire severity affected by time since fire and inferred fuel age?
Responses to Time Since Fire were strongly dependent on Weather and Forest type. Time Since Fire had negligible effects on both crown and understorey fire probabilities in Extreme weather, irrespective of Forest type (Figs 4, 7). By contrast, in Moderate or Low weather, crown fire probability increased in a non-linear manner with increasing Time Since Fire in Damp and Dry Forest types.

The nature of this latter response accords with known patterns of surface, fine fuel accumulation. Fuel accumulates rapidly in the immediate post-fire period (e.g. 5 to 10 years) in eucalypt forests but approaches a steady state after a longer period (Raison et al. 1983). The responses of crown fires in Damp and Dry forests followed this pattern. The higher probability of crown fire in Damp compared with Dry forests also reflects known patterns of fuel load (i.e. higher fuel loads likely in Damp forest). The interaction between Weather and Time Since Fire in Damp and Dry forest (e.g. higher crown fire probabilities under Extreme weather, Fig. 4bc) indicates that the effect of Weather is consistent across potentially differing fuel loads, as predicted by fire behaviour models (e.g. the McArthur Forest Fire model, Catchpole 2002).

By contrast, predicted probability of crown fire declined in Ash forest with increasing Time Since Fire, contrary to likely fuel accumulation patterns (Fig. 4a). This response reflects known patterns of stand development in *Eucalyptus regnans* (Mountain Ash) forests (Mackey et al. 2002). Mountain Ash lacks a strong capacity to resprout after intense fires. Thus trees are often killed and stands recover from fire through re-establishment of new cohorts from seed. Such regenerating stands grow rapidly. Fires are therefore more likely to reach the crowns of young stands than old stands, especially in severe weather. Trends in severity driven by accumulating surface fuels could be masked by age-dependent effects of tree height. By contrast, in Dry and Damp forests, dominant eucalypts are strong resprouters. Thus the height of the forest stand is relatively stable as a function of time after fire. This may mean that crown fire probability is more sensitive to fuel load variations as a function of Time Since Fire, in contrast to Ash forest.

Predicted effects of Time Since Fire on probability of understorey fire were strongly conditional on weather. Under Extreme weather, Time Since Fire and inferred patterns of fuel accumulation had no effect on understorey fire probability (i.e. predicted probability was uniformly close to zero). This result can also be considered to be consistent with predictions from fire behaviour models. For example, under a Forest Fire Danger Index of >100, the estimated fuel load required to produce a fire corresponding with this level of severity (i.e. inferred intensity < 4,000 $kWm^{-1}$is predicted to be small (e.g. < 0.8 kg m^2 of fine surface litter fuel; see equations in Noble et al. 1980 & Gill et al. 1987). There is evidence that fires spread more rapidly than predicted by fire behaviour models under such conditions (Sullivan and McCaw 2009). In theory this may further discount the level of fuel required to exceed the above range of intensity. Many unplanned and prescribed fires leave significant quantities of unburnt, residual litter fuels (e.g. Raison et al. 1983; Morrison et al. 1996). It is therefore plausible that levels of fuel sufficient to produce high severities of fire (i.e. not confined to the understorey) under the kind of weather experienced in southern Victoria on the afternoon of February 7th 2009, would be available soon after a prior fire.

Time Since Fire was predicted to affect probability of understorey fire under Moderate and Low weather in a manner that is consistent with patterns of fine fuel accumulation (Fig. 7a). Thus predicted probability of understorey fire declined in a non-linear way with Time Since Fire. The bulk of this effect occurred at small values of Time Since Fire (i.e. < 5 years) when fuel loads are expected to be relatively low in these forest types (Bradstock 2010). Such fuel loads would be expected to yield relatively high probabilities of understorey fire under Moderate and Low weather conditions, based on knowledge of fire behaviour. Differences in response of understorey fire probability among Forest types, in interaction with Weather (Fig. 7b) are consistent with differences in expected fuel load among these types.

Overall, Time Since Fire and inferred fuel age had asymmetric effects on fire severity. Probability of crown fires in Extreme weather was affected but not understorey fire probability (Figs 4, 7). This implies that relatively young fuel ages (e.g. < 10 years Time Since Fire) can reduce the intensity of fires in these conditions to some degree. Thus the potential intensity of fires may be reduced by fuel ages in this range, compared with older fuel ages, from a level where most of the tree canopy is consumed (i.e. crown fire, severity class 1) to that where tree canopies are partially consumed (i.e. partial crown fire, severity classes 2 to 3). The analysis implies, however, that the effect of fuels of low fuel age are insufficient to reduce fire intensities from levels where tree crowns are fully or partially consumed (i.e. severity classes 1 to 3), to level where fires are confined to the understorey (i.e. severity classes 4 to 5). This proposition could be further scrutinised by analysing trends in classes of severity that are intermediate to those examined here (i.e. severity classes 2 to 3, Table 2).

By contrast, in Moderate weather, low fuel ages ameliorate fire severity to a greater degree (Figs 4, 7), resulting in a potential, partial shift from fires in tree crowns (full or partial consumption) to fires confined to the understorey. In Low weather, complete crown fires (i.e. severity class 1, Fig. 4) are effectively absent, hence effects fuel age are confined to shifts between levels of lower fire severity.

Was fire severity affected by time since logging?
Time since logging affected the probability of crown fires but not understorey fires (Tables 3, 4). Probability of crown fires was predicted to be inversely related to time since logging (Fig. 5a). The temporal pattern of logging effects on crown fire probability was superimposed (e.g. Fig. 5a for Dry forest) on the non-linear pattern of response to Time Since Fire (i.e. inferred fuel age). The results therefore suggest that recently logged sites (e.g. < 10 years since logging) have a higher probability of crown fire compared with sites less recently logged.

There are several mechanisms that may account for this pattern. First, full or partial removal of the tree canopy may result in greater penetration of sunlight and wind to the understorey and ground surface (Lindenmayer et al. 2009). This may result in greater dryness of surface and near surface fuels and higher fuel temperatures, therefore elevating the availability of fuel to burn. Increased wind speed at or near the ground will tend to increase the rate of spread of fire, resulting in higher fire intensity and severity.

Second, residual slash may remain after logging and slash burning, thereby elevating surface and near surface loads (Lindenmayer et al. 2009). This may also result in an increase in intensity and severity soon after logging. Such effects may diminish over time as slash decomposes or is burnt in subsequent fires.

Third, regeneration of trees after logging follows a predictable pattern of increasing height growth following establishment of tree seedlings. Therefore in recently logged stands, regrowing cohorts of trees are short, whereas in older post-logging stands, trees may approach their unlogged height. Fires will therefore tend to burn regrowing tree crowns more readily in recently logged stands than in older or unlogged stands. In this regard, the fire severity response of logged Damp and Dry forests may exhibit some similarity to that followed naturally in Ash forests as a function of Time Since Fire (see above; Fig. 4a).

These explanations are not mutually exclusive and further on-ground measurements would be required to apportion effects among them.

Was fire severity affected by terrain?
Terrain affected the probability of crown fires, with a strong, predicted effect of aspect but negligible effects of topographic position (Figs 5b, 6) and slope. The aspects with highest probabilities of crown fire were altered by the passage of the weather change on February 9th (i.e. eastern aspects were supplanted by northern aspects Fig. 6). The effect of aspect initially appears to be counter-intuitive. Highest probability of crown fire may have been anticipated on western and northern aspects

(i.e. windward aspects) under the influence of fires driven by north westerly winds before the weather change. Similarly, after the weather change (i.e. south westerly winds) high probability of crown fire may have been anticipated on windward aspects. Instead, highest crown fire probabilities were predicted on lee aspects (Fig. 6) rather than windward aspects.

The very high wind speeds, both prior to and after the change (Sullivan and McCaw 2009), may offer an explanation for this effect. Strong winds tilt flames at a relatively acute angle. Thus the potential for flames to completely consume foliage of tree crowns in forests is reduced. Crowns may therefore tend to be partially rather than completely consumed (i.e. a potential shift from severity class 1 to severity classes 2 or 3). On lee slopes, effects of wind may be ameliorated by sheltering or alternatively vortices may occur which are synergistic with effects of slope on fire intensity. Fire severity could therefore be potentially maximised on lee slopes. Further analyses of trends in intermediate fire severity classes (i.e. classes 2 to 3, Table 2) would be required to test these explanations.

Assumptions and limitations of the analyses

The validity of the results described here are dependent on the robustness of the classification of severity across the range of environmental conditions used in the analysis. Remotely sensed measures of fire severity need to be validated via extensive, on-ground observations to ensure that resultant classifications of severity accurately demarcate trends in fire-caused vegetation change, and account for differences in structure among vegetation types (e.g. Hammill and Bradstock 2006). We assumed that the processing of the remotely sensed data and ground truthing by DSE has resulted in an accurate and robust classification.

The selected statistical models for probabilities of crown and understorey fires (Tables 3,4), while highly significant, do not account for the majority of variation in the response data, as indicated by the levels of Deviance accounted for in each case. The levels of variation accounted for in these statistical analyses are typical of those accounted for in large-scale studies in ecological and environmental science.

The nature of the selected models means that strong trends in the respective severity levels are evident in response to the predictor variables, but there is considerable variation around these trends. This could mean that there is likely to be some major explanatory factor or variable that is not accounted for in the analysis. On the other hand, this result could occur not because a major predictor is missing, but because the predictors and the responses are only crudely represented in the analyses. The latter explanation is more likely because all the known, main drivers of fire behaviour are represented (directly or indirectly) in the analyses. For example, weather is represented but only as a simple set of categories. Underlying the three classes of weather are complex variations and combinations of temperature, wind and humidity. In turn these characteristics of weather were not recorded across the entire fire ground. Instead reliance is placed on extrapolation from relatively few weather stations. All these steps of condensation of weather into a simple explanatory factor introduce error into the analyses. In a similar vein, there are major simplifications and sources of error that are inherent to the scale of mapping of severity and other major predictors.

More detailed analyses could, in principle, be expected to account for more of the variation in the response data. There are however, practical constraints that limit the scope of the analyses. The results presented here are a pragmatic compromise in this regard. Given these constraints, the trend revealed by the selected models can be considered to offer important and robust insights into the way these fires have been affected by variations in weather, fuel and terrain. This is evident by the ability of the selected models to successfully predict severity (i.e. > 70% accuracy, see above) in the independent set of data.

Effects of Time Since Fire and inferred fuel age were estimated on the basis of information on fire history that combined both prescribed and unplanned fires. The layer of fire history supplied for the analyses did not discriminate between these sources of fire. The area burned by prescribed fire over time may be considerably less than that burned by unplanned fire. Thus the method represents a generalised set of fuel age effects rather than a specific set of effects stemming from prescribed fire.

The effects of inferred fuel age on the severity of the 2009 fires in the study area are therefore more likely to reflect impacts of prior unplanned fires on fuel structure and recovery rates. The nature of this bias is important: on average, unplanned fires are typically more intense than prescribed fires. Residual fuel following unplanned fires can be expected to be lower than after prescribed fires (e.g. Morrison et al. 1996). Thus the intensity and severity of a fire may tend to be lower on average in an area previously burnt by an unplanned fire compared with a prior prescribed fire, assuming equivalence of timing. Inferences derived from the study about the “effectiveness” of prescribed burning need to account for this bias. Thus the trends toward either reduced probability of crown fire, or increased probability of understorey fire, as a function of increasing Time Since Fire (Figs 4, 7) are likely to be over-estimates of what can be expected following prescribed fire at similar times.

Conclusions and implications for management

Fires confined to the understorey (i.e. severity classes 4 and 5, Table 2) are likely to represent a range of intensities where fire suppression has some chance of being conducted in a safe and effective manner. Insights into the probability of an understorey fire revealed by the analyses (Table 4, Fig. 7) therefore indicate the degree to which suppression can be facilitated by manipulation of fuel. The analyses suggest the following:

1) Manipulation of fuel via prescribed burning, in the forests types studied here, is unlikely to alter (i.e. increase) the potential for successful suppression under weather conditions equivalent to the afternoon of the 7th of February 2009 in southern Victoria (i.e. Extreme weather, prior to the south westerly change at around 17.00 hrs, Table 1).
2) Manipulation of fuel via prescribed burning, may increase the probability of successful suppression under weather conditions equivalent to those experienced on the evening of February 7th (i.e. Moderate weather ,after the south westerly change, Table 1), in these forest types.
3) Manipulation of fuel will also increase the probability of successful suppression under conditions equivalent to those experienced from February 8th onward (i.e. Low weather, Table 1).

4) Effects of fuel manipulation, in terms of increased probability of understorey fire in the circumstances of 2) and 3) above, are likely to be concentrated into the immediate 5 year period following treatment (Fig. 7). Some effect will remain beyond 5 years but the relative increase in probability of understorey fire is likely to small (Fig. 7). Effects on capacity for safe and effective suppression will be commensurate.

Based on these conclusions it is unlikely that higher levels of prescribed burning would have increased opportunities for safe and effective suppression of these fires on the afternoon of February 7th 2009.

Following the south westerly change, late on that day, it is plausible that higher levels of prescribed burning may have increased the ability to undertake safe and effective suppression. Very high rates of treatment (e.g. 15 to 20 % of the landscape treated per annum) would be needed to maximise the potential for suppression under these circumstances (i.e. 4) above). Such levels are an order of magnitude or more above current rates of treatment. Other practical considerations, such as the size of the fires at the time of the weather change, ease of access and nature of available suppression resources would need to be considered, in order to assess the outcome of any alternative fuel reduction program in such circumstances.

Potential changes to the probability of crown fires may also ensue from prescribed burning, as indicated by relationships with Time Since Fire and Forest type (Fig. 4). Intense crown fires will contribute to spotting via propagation of embers. Mitigation of their intensity could therefore potentially reduce the size of fires (e.g. reduction in the range and density of long-distance propagation of embers and firebrands) plus the exposure of people and property to ember attack.

The results indicate that prescribed burning could potentially reduce ember propagation by reducing the probability of fires with complete crown consumption under conditions similar to those that occurred on February 7th 2009 (i.e. both before and after the change in weather) in Dry and Damp forest types in southern Victoria. Such effects are predicted to relatively long-lasting, though the bulk of any potential reduction in crown fire probability through prescribed burning may be concentrated in the initial10 to 20 year period after treatment (e.g. Fig. 4bc). Possible effects in Ash forest are less certain due to the inherent tendency for crown fire probability to decline as a function of time since fire.

The magnitude of any change in ember density and range of distance of propagation that could result from a shift in crown fire probability is unknown, due to the limited state of knowledge about relevant processes. For example, under extreme weather conditions equivalent to the afternoon of February 7th, fire intensity may be chiefly shifted by young fuel ages from complete consumption of tree crowns to partial crown consumption (see above). The degree to which this would alter ember propagation and consequent risk to people and property is unknown. The predictions about the effects of prescribed fire in this regard are therefore speculative.

Significant opportunities exist for extending the current analyses to improve knowledge about congruence between fuel age, fire weather, severity patterns and consequent losses of property and lives in areas affected by the 2009 fires. For example, the levels of damage could be analysed in relation to proximity of differing levels of fire severity. Such an analysis could be stratified according to differing weather conditions, forest types and fuel age classes in the manner used here. Analyses of this kind would yield immediate insights into the degree to which loss of property and lives can be mitigated by differing prescribed burning strategies.

A first step in such an analysis would be to examine the distribution of property damage and human injury in relation to the two types of weather that occurred on February 7th 2009 in the affected areas (see Fig. 1). As discussed above, the scope for prescribed burning to mitigate damage and losses is predicted to be inherently lower under the extreme weather conditions prior to the change on that day. A simple overview of this kind would indicate the relative degree to which losses could have been mitigated by differing prescribed burning strategies. We recommend that further analyses of this kind should be done as soon as possible.

The analyses presented here indicated that logging is unlikely to significantly change fire severity in ways that are likely to enhance the capacity for safe and effective suppression in these forest types. Recent logging was predicted to elevate the probability of crown fires in some forest types (e.g. Dry forest). While further on-ground observations may be needed to investigate the nature of these effects (see above), there appears to be little evidence to support the notion that extensive logging would mitigate potential for fires under the conditions that occurred on February 7th 2009.

In summary, weather was the predominant influence on the severity of these fires in southern Victoria. Fuel age effects produced by patterns of prior fires (prescribed and unplanned) and logging across these landscapes are also important but highly contingent on weather conditions, along with influences of terrain. Young fuel ages produced by prior burning may not enhance the potential for suppression in "worst case" fire weather conditions in the forest types considered in this study, but could mitigate the potential for propagation of embers. Potential for young fuel ages (e.g. < 10 years) to enhance suppression capacity is considerable in more moderate weather conditions. Logging appears to offer little potential to enhance suppression capacity.

Such results offer insight into the often intractable debate over the supposed "effectiveness" of fuel manipulation via prescribed burning and other means. Effects of fuel treatment on severity and inferred intensity of unplanned fires are not unilateral due to a dependence on the context; particularly the time elapsed since treatment and the weather conditions at the time (i.e. non-linear responses). It is therefore possible to select individual examples that illustrate widely divergent outcomes of fuel treatment on fire intensity/severity. Exploration and integration of effects over large spatial scales and ranges of environmental conditions, as afforded by remotely sensed data, is required to comprehensively evaluate when and where fuel treatments will alter fire behaviour, the degree of alteration and consequent effects on things that we value.

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