20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013
www.mssanz.org.au/modsim2013

The effect of fire channelling on fire severity in the 2009 Victorian fires, Australia

O.F. Price [a], **J.J. Sharples** [b]

[a] *Centre for Environmental Risk Management of Bushfires, Biological Sciences, University of Wollongong, Australia.*
[b] *Applied and Industrial Mathematics Research Group, School of Physical, Environmental and Mathematical Sciences, University of New South Wales Canberra, Australia.*
Email: oprice@uow.edu.au

Abstract: Empirical studies of the 2003 fires in Canberra have highlighted a phenomenon called fire channelling, whereby a fire spreads rapidly laterally across lee-facing slopes, thus increasing the rate of spread and the power of the fire. Analyses of wind, terrain and fire data have identified thresholds in slope and aspect relative to the wind, which define necessary conditions for the phenomenon to occur. It is expected that areas affected by fire channelling will burn with high severity. Separate empirical analysis of fire severity patterns in the Victorian fires of 2009 identified higher prevalence of crown fire on leeward slopes as compared to that on windward slopes.

In this study, we reconcile these observations by using the thresholds to identify where fire channelling was likely to have occurred in the 2009 fires, and reanalysing the severity patterns to quantify the extent to which high severity corresponded to the identified fire channelling prone areas. The sample is 4500 regularly spaced points (500 m separation) from four time periods within four fires.

Fire channelling prone parts of the landscape were identified using a binary function $\chi(\sigma,\delta)$, which depends on a threshold slope σ and a threshold aspect discrepancy δ. Fire channelling prone parts of the landscape were defined as those satisfying $\chi(\sigma,\delta) = 1$, with other parts of the landscape characterized by $\chi(\sigma,\delta) = 0$. Values of $\chi(\sigma,\delta)$ were calculated using three different DEM resolutions: 30 m, 90 m and 240 m. In each case a binary grid was obtained across the landscape, which was then used as a predictor of fire severity. Initial analyses considered $\chi(\sigma,\delta)$ as the only predictor of fire severity, but subsequent analyses followed a full model selection process as was done by Price and Bradstock (2012), though in this case with $\chi(\sigma,\delta)$ replacing aspect. This approach identified the best model and supported alternatives, including testing all two-way interactions between variables. The best model obtained in this way was compared with the model developed by Price and Bradstock (2012) (i.e. with aspect).

The analyses revealed that locations identified as prone to the fire channelling phenomenon were more likely to experience crown fire, and that this effect was most obvious at larger spatial scales. At the largest spatial scale considered, crown fire occurred in 27.2% of fire channelling prone points and 20.5% of non-fire channelling prone points (33% greater). The binomial regression analyses also indicated that when fitted on its own fire channelling proneness was a significant predictor or fire severity. Overall, the effect of fire channelling on fire severity was substantial and amounted to an 11% increase in crown fire likelihood. Given that the analyses entailed a comparison with all parts of the landscape, including windward slopes where the highest likelihood of crown fire would normally be expected, the effect is very important.

Combined with information arising from other extreme bushfires, including the 2003 Canberra fires, the analyses considered here suggest that fire channelling may be a common phenomenon in large and intense fires. The fire channelling phenomenon therefore poses some serious challenges for firefighting, fire spread prediction, the management of environmental assets and risk planning. Given the effects of fire channelling on fire severity demonstrated by this study, this will be particularly pertinent in high-value water catchments. The results of the analyses also have significant implications for the management of soil erosion and biodiversity conservation in rugged terrain after large fires.

Keywords: *Fire severity, fire channelling, Black Saturday*

1. INTRODUCTION

It is generally accepted that the intensity of a spreading fire increases when it travels up a slope and decreases when it travels downslope. This effect is captured in fire behavior models, including those commonly used in Australia and North America (Sharples 2008). In the Australian McArthur fire behavior model (McArthur 1967; Gill *et al.* 1987), fire intensity is modeled as $I = hWR$, where h is a constant for the heat content of fuel, W is the fuel load (tonnes/ha) and R is the fire Rate of Spread. R itself is predicted as $R = 0.0012\ FW\ e^{0.069\theta}$, where F is the Fire Danger Index and θ is the slope. These equations predict that fire intensity on a 10° incline is approximately double and on a 10° decline is approximately half of that on level ground for any given fuel load or weather condition. Fire behavior models provide the basis for bushfire risk planning among fire agencies worldwide. For example, in Australia, new houses in bushfire prone areas are required to comply with construction standards and vegetation setbacks that include the slope between the house and nearby vegetation (Standards Australia 2009).

One of the reasons that commonly used fire behavior models may misrepresent the effects of slope is that they were developed under a restricted range of values for each of the parameters. In particular fire behavior under extreme weather was not included because such fires are difficult to control or measure. The exploration of topographic effects was similarly constrained by a small range of situations. In recent times a number of studies have highlighted cases where fires on slopes have behaved in a manner that is at odds with the behaviour predicted by models such as those outlined above (Price and Bradstock 2012; Sharples *et al.* 2012).

Wildfires burning under extreme weather often exhibit complex behaviour, which may not be predicted by current operational models. Most importantly for this study, Sharples *et al*. (2012) found several locations where the 2003 Canberra fires spread very rapidly across the prevailing wind direction on lee-facing slopes. They conjectured that this phenomenon is most likely due to the interaction between the fire and the separated flow at the top of the lee slope, and can result in fire spread in either direction across the slope (rather than down it). Sharples *et al*. (2012) referred to this phenomenon as 'fire channelling'. In locations prone to fire channelling, fires can spread faster and with higher intensity than on the windward slope. If this is a general phenomenon in wildfires, then it might necessitate a change in fire management and especially fire risk planning, so that among other things, fuel reduction treatments are prioritized in locations where assets are downhill from the most likely direction of fires. In this context it is important to emphasise that fire channelling is a coupled fire-atmosphere effect (Simpson *et al.* 2013) and that such effects are generally not accommodated by operational fire spread models.

Circumstantial evidence that fire channelling has occurred in instances other than during the 2003 Canberra fires comes from a number of photographic accounts (Sharples and McRae 2011) and through the analysis of fire severity patterns in the 2009 Victorian fires (Price and Bradstock 2012). Here, we further scrutinize these fire severity patterns and directly investigate their association with the fire channelling phenomenon. Specifically, an analysis similar to that conducted by Price and Bradstock (2012) is used to test the hypotheses that areas prone to the fire channelling phenomenon are more likely to have experienced crown fire than non-fire channelling prone areas and that the effect of fire channelling on crown scorch was greater under higher wind speeds. The significance of the effect of wind speed on the likelihood of crown fire in fire channelling prone areas can be tested using data for the 2009 Victorian fires because distinct weather patterns were observed during the fires.

2. DATA AND METHODS

Sharples *et al.* (2012) derived the following model to identify parts of the landscape that are prone to the fire channelling phenomenon:

$$\chi(\sigma,\delta) = \begin{cases} 1 & \text{if } \gamma_s \geq \sigma \text{ and } |\theta_w - \gamma_a| \leq \delta \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where γ_s is the topographic slope, γ_a is the topographic aspect, and θ_w is the direction the wind is blowing towards, so that for a westerly wind $\theta_w = 90°$. The model is defined by the parameters σ and δ. The parameter σ is the 'slope threshold' and the parameter δ is the 'aspect discrepancy'. In plain terms, the model identifies parts of the landscape steeper than σ and with a topographic aspect within δ of the direction the prevailing winds are heading. Strictly speaking, the above formula defines terrain conditions that are necessary for fire channelling to occur, but which are not sufficient in general.

Working with a digital elevation model (DEM) of 250 m resolution, Sharples *et al.* (2012) found that σ = 10.5° and δ = 40°. For a DEM with different resolution the slope threshold must be adjusted to reflect the

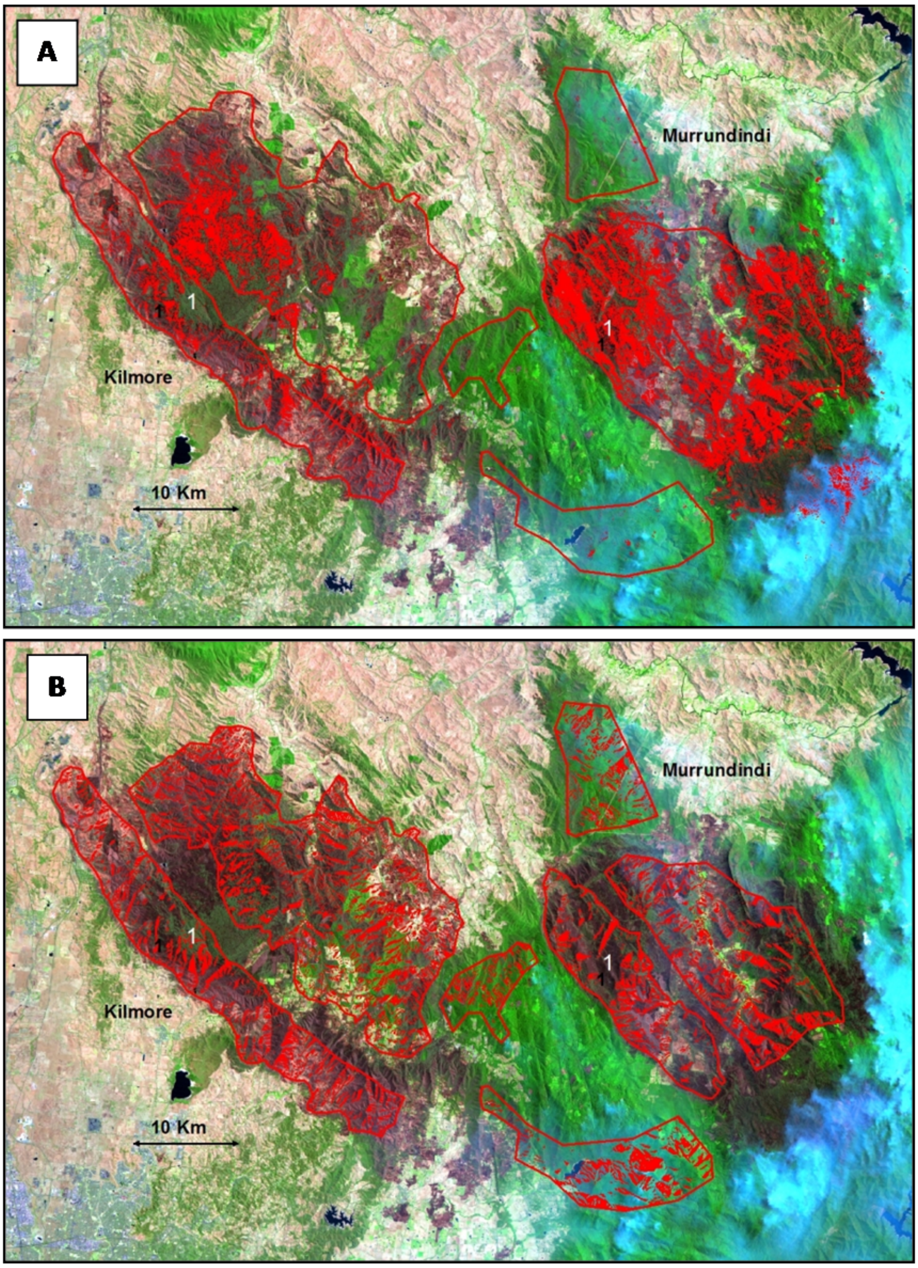

Figure 1. The two largest fires (Kilmore and Murrundindi), indicating A: the areas that experienced crown fire and B: the areas identified as prone to fire channeling (at 240 m scale). The polygons labeled 1 were burnt under catastrophic weather and a NW wind and other areas under a southerly wind at lower fire danger.

change in scale (McRae 1997). Thus for a 30 m resolution DEM, the slope threshold is adjusted to σ = 23.2° and the fire channelling prone parts of the landscape are defined as those grid cells with topographic slope γ_s and topographic aspect γ_a satisfying:

$$\gamma_s \geq 23.2^\circ \quad \text{and} \quad \theta_w - 40^\circ \leq \gamma_a \leq \theta_w + 40^\circ .$$

Thus for a westerly wind, grid cells that have both a slope above 23.2° and an aspect between 50° and 130° would be identified, for example. Note that the DEM scaling algorithm is isotropic and the directionality in the landscape is identified by the channelling algorithm

This approach was applied to identify the areas burnt by fires in the 2009 Victorian fires that were prone to fire channelling, and to analyze whether this phenomenon contributed to the occurrence of crown-consuming fire in those fires. Price and Bradstock (2012) analyzed the drivers of crown fire for a grid-sample of 4500 points in four of the fires by constructing statistical models of crown fire as revealed by fire severity mapping against a set of predictor variables including weather periods, topography and fuel age (time since fire). Fire severity maps indicate the extent of vegetation removal and in this case, the highest class of severity indicated fire in the forest crown, which is also indicative of a high intensity fire that is insuppressible. The 500 m separation between sample points was chosen to exceed the mean ridge-valley distance (Price and Bradstock 2012). The statistical models were binomial models (McCullagh and Nelder 1983) where the probability of crown fire occurrence (*cf*) is given by:

$$cf = \frac{\exp(l)}{1+\exp(l)},$$

where *l* is the linear predictor:

$$l = a_1 x_1 + a_2 x_2 + \cdots + a_n x_n,$$

and $x_1,\ldots,x_n$ are the predictor variables in the model (e.g. weather, time-since-fire, $\chi(\sigma,\delta)$). The model parameters $a_1,\ldots,a_n$ are to be determined by the data.

Due to difficulties in reconstructing the actual progression of the fire, weather was classified into periods. In the afternoon of February 7th 2009, a fierce wind (mean speed 54 km h^{-1} at Kilmore BOM station) blew from the northwest and the fire danger was rated as Catastrophic. At about 18:00 the weather changed to a cooler, southerly wind (mean speed 27 km h^{-1}) with a fire danger rating of Moderate and after midnight the weather calmed further to a rating of Low. One of the weather periods considered by Price and Bradstock (2012) was transitional between the Catastrophic and Moderate fire weather classes, and for this period we could not confidently assign a wind direction. This weather class was excluded from this study (removing 7.3% of the sample points).

The data considered by Price and Bradstock (2012) is reanalyzed here by first calculating the value of $\chi(\sigma,\delta)$ given by equation (1) at each grid cell belonging to a 30 m resolution DEM, and testing its significance as a (model) predictor of crown fire occurrence. Initially, $\chi(\sigma,\delta)$ was considered as the sole predictor. Subsequently a full model selection process (Burnham and Anderson 2002) was performed, as in Price and Bradstock (2012), but substituting $\chi(\sigma,\delta)$ for aspect. The rationale here is that $\chi(\sigma,\delta) = 1$ is hypothesized as providing a refined descriptor of the effect described by aspect in the original models of Price and Bradstock (2012). The method identified the best model and supported alternatives, including testing all two-way interactions between variables. We compared the best model with the model developed by Price and Bradstock (2012) (i.e. with aspect), but since the transitional weather period had been excluded, that model had to be re-fitted to the reduced data. In the present case 2978 randomly selected points were used to develop the models and 1523 points were retained for accuracy assessment.

As mentioned above, identifying areas prone to fire channelling depends on the scale of the data used for the prediction. In particular, the threshold slope σ present in equation (1) differs depending on the resolution of the DEM used to calculate $\chi(\sigma,\delta)$. Moreover, at present it is not known whether the fire channelling phenomenon adheres to a particular topographic scale: for example, it is not known if a small hollow in the side of a hill (discernible in a 30 m resolution DEM but not in a 250 m resolution DEM) is a relevant feature for the occurrence of fire channelling. To address this issue, we calculated slopes at three different spatial resolutions by smoothing the 30 m DEM to 90 m and 240 m, and using the threshold slope value appropriate for each scale (23.2°, 15.9° and 10.5°, respectively), to calculate $\chi(\sigma,\delta)$. The statistical modeling methodology described above was repeated for each of these different topographic scales.

3. RESULTS

Crown fire was found to be more common in fire channelling prone areas ($\chi(\sigma,\delta)=1$) than in non-prone areas ($\chi(\sigma,\delta) = 0$), and this effect was most obvious at larger spatial scales. Using the 240 m resolution DEM, crown fire occurred in 27.2% of fire channelling prone points and 20.5% of non-fire channelling prone points (33% greater). At the 90 m and 30 m DEM resolutions the differences were similar but smaller (27.6% and 21.8% for 90 m resolution and 26.3% and 21.6% at 30 m resolution). Considering the three weather periods separately, the Catastrophic and Moderate periods had similar likelihood of crown fire. At the 240 m resolution 38.4% and 37.1% of fire channelling prone points had crown fire, respectively (n=219 and 488), but no fire channelling prone points in the Low weather class had crown fire (n=268).

Table 1. Estimates table for the best model at 240 m scale.

	Estimate	*Std. Error*	*z value*	*p*
(Intercept)	5.231	1.080	4.845	0.000
Topo-position	0.009	0.003	3.739	0.000
Log (Time-Since-Logging)	-0.457	0.075	-6.100	0.000
Log (Time-Since-Fire)	-1.004	0.246	-4.079	0.000
Forest Type Damp	-3.818	1.015	-3.761	0.000
Forest Type Dry	-4.561	0.976	-4.675	0.000
$\chi(\sigma,\delta)$ 240 m: = 1	**0.443**	**0.116**	**3.816**	**0.000**
Weather: Moderate	-1.920	0.599	-3.205	0.001
Weather: Low	-18.179	19.596	-0.928	0.354
Log(Time Since Fire):Forest Type Damp	0.965	0.242	3.994	0.000
Log(Time Since Fire):Forest Type Dry	0.958	0.232	4.125	0.000
Log(Time Since Fire):Weather Moderate	0.413	0.146	2.831	0.005
Log(Time Since Fire):Weather Low	3.032	4.610	0.658	0.511

The larger scale resolution also performed better in the statistical modelling. When fitted on its own, $\chi(\sigma,\delta)$ was not significant at the 30 m and 90 m resolutions (p = 0.85 and 0.17, respectively), but was significant at the 240 m resolution (p = 0.0006), capturing a low 0.37% of total deviance. $\chi(\sigma,\delta)$ was not selected in the best model for the 30 m resolution, though it was present in a supported alternative model (ΔAIC = -0.157). At the 90 m resolution it was selected in the best model though the model without it was a supported alternative (ΔAIC = 0.811). At the 240 m resolution, $\chi(\sigma,\delta)$ was selected in the best model and delivered a considerable improvement in *AIC* (ΔAIC = 12.3). This model (Table 1) contained no significant interactions between $\chi(\sigma,\delta)$ and other variables. Among other things, this indicates that the increase in crown fire likelihood in fire channelling prone areas was the same for Catastrophic and Moderate weather periods, while the Low period cannot be compared since no crown fire occurred in that period anyway. The model captured a total of 20.3% of the total deviance, which was higher than the model without it (19.9%) but lower than the model using aspect as presented in Price and Bradstock (2012) (22.0%). The effect of $\chi(\sigma,\delta)$ is slightly stronger in this model than when it is fitted on its own (the estimate is 0.443 compared to 0.355 on its own).

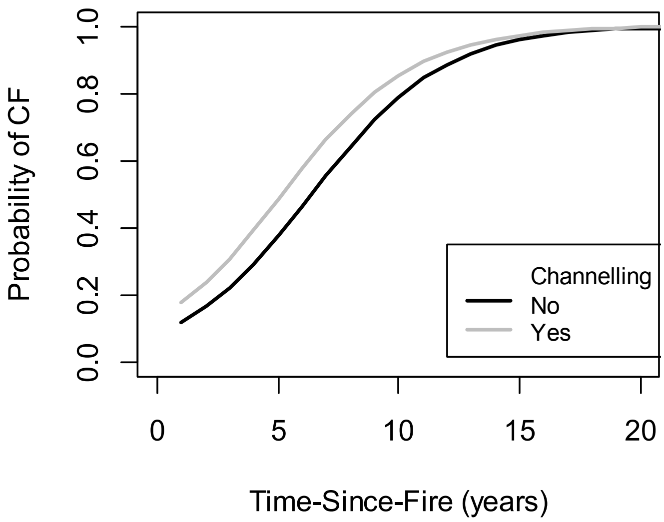

Figure 2. The effect of $\chi(\sigma,\delta)$ on crown fire likelihood in the final model. The plot shows the probability of crown fire occurring at increasing time since past fire and for areas that were or were not identified as fire channelling prone. Other variables in the model are held at set levels: i.e. Dry forest type, Moderate Weather, mid-slope topographic position, 30 years post logging.

According to the model, channelling proneness increases the likelihood of crown fire by 0.11 in conditions where other factors do not make crown fires either very likely or unlikely (e.g. at intermediate levels of fire weather, time since fire etc), as illustrated for increasing time since fire in Figure 2. The model had an overall accuracy of 72.7% for predicting crown fire occurrence in the third of points reserved for accuracy testing using the optimal threshold for the predicted likelihood of 0.28 (omission rate 33% and commission rate of 28%).

4. DISCUSSION

Locations that were identified as prone to the fire channelling phenomenon were found to be more likely to experience crown fire. Combined with the evidence from the 2003 Canberra fires, this suggests that fire channelling may be a common phenomenon in large and intense fires. The effect is substantial: an 11% increase in crown fire likelihood. Considering that this is a comparison with all parts of the landscape, including the windward slope, which would have been expected to have the highest likelihood of crown fire, the effect is important.

The effect of fire channelling was equal in magnitude for Catastrophic and Moderate weather periods, which suggests rejection of the hypothesis that the effect of fire channelling on crown scorch was greater under higher wind speeds. However, it is important to note that the winds were strong during both the Catastrophic and Moderate weather periods. Indeed, the mean wind speed for each of these periods was above 25 km h^{-1}, which is the threshold wind speed suggested by Sharples *et al*. (2012) for fire channelling to occur. No effect of fire channelling on crown scorch was found during the Low weather period, but no areas experienced crown fire in that weather period in any case. Moreover, additional exploratory analyses revealed that during the Low weather period the likelihood of the fire remaining in the understory (low severity) was not influenced by fire channelling proneness either. These findings support the notion that winds above a threshold speed are required to initiate fire channelling, but beyond that the actual wind speed does not influence the strength of the effect. The effect of the interaction of wind speed and fire channelling on fire severity should be subject to further inquiry as additional data relating to extreme bushfires comes to hand.

Fire channelling is only one of many factors that influence whether or not a crown fire will occur, and according to our analysis, it is not the most important one. Weather and fuel load and arrangement are the primary drivers, but once these factors produce conditions suitable for crown fire, the topography may become very important in determining the actual fire behavior. Topographic position also had a positive effect in this model and taken together with the channelling proneness effect, it suggests that locations near the top of lee slopes are the most prone to crown fire.

The fire channelling effect found here was not as strong as the leeward slope effect found in Price and Bradstock (2012). This may be because the method we used to identify channelling prone areas did not accurately reflect where it actually occurred in the fires. Clearly, there is scale issue here, because larger scales appear to correlate with greater accuracy, but there could be several other topographic factors at play. It is also important to note that equation (1) only identifies conditions of wind and terrain that are necessary for fire channelling occurrence. The full set of environmental conditions sufficient for fire channelling occurrence is yet undetermined, and so at present equation (1) likely identifies some locations where fire channelling didn't occur.

Furthermore, as described by Sharples *et al*. (2012) equation (1) should only be taken as identifying regions where fire channelling can be initiated. The effects of fire channelling, which include dense spotting and subsequent deep flaming, are likely to occur for some distance downwind of the regions identified by equation (1) and such effects are likely to have an impact on fire severity. More research is needed to accurately discriminate parts of the landscape that are likely to be impacted by fire channelling, though Sharples *et al*. (2012) suggest a downwind extent of 2-5 km as appropriate. Extension of the current work will therefore consider the inclusion of grid cells downwind of regions satisfying $\chi(\sigma,\delta) = 1$. It could also be that a number of processes contributed to the strong leeward effect on fire severity found by Price and Bradstock (2012). Sharples (2008) reviewed several possibilities, but there may be others.

The above points notwithstanding, the substantial effect of fire channelling on fire severity indicated by the results of this study has major implications for bushfire management, both in terms of risk planning and fire response. Planning attempts to identify those assets at most risk and prioritize these for treatment (such as prescribed burning). At present, areas uphill from large forest patches would be the priority but the present analysis suggests that in some cases, the downhill areas are at more risk. Effective fire suppression relies on intelligence about the location, rate and direction of spread of the fire and its intensity. The fire channelling phenomenon is unlikely to be anticipated by fire managers that are not acquainted with the phenomenon, and so decisions on how and where to suppress a fire may be misdirected in fires where it occurs. Fire spread simulators are now routinely used for operational response to fires, and since they generally do not accommodate coupled fire-atmosphere effects such as fire channelling (Simpson *et* al. 2013), they are likely to mispredict the behavior of affected fires. Clearly this phenomenon is only associated with rugged terrain, but considering that most of the remnant forest in eastern Australia is in such situation (either mountainous National Parks or steep slopes within settlements), it will be a widespread problem.

REFERENCES

Standards Australia, S, (2009). AS3959-2009: Construction of buildings in bushfire prone areas. SAI Global Limited, Sydney, Australia. 129.

Burnham, KP, Anderson, DR (2002). 'Model selection and multimodel inference: A practical information-theoretic approach.' (Springer-Verlag: New York:)

Gill, AM, Christian, KR, Moore, PHR, Forrester, RI (1987). Bushfire incidence, fire hazard and fuel reduction burning. *Australian Journal of Ecology* **12**, 299-306.

McArthur, AG (1967). 'Fire Behaviour in Eucalypt Forests.' (Commonweath of Australia, Forestry and Timber Bureau Leaflet 107: Canberra, ACT)

McCullagh, P, Nelder, JA (Ed. DVH D. R. Cox (1983). 'Generalised linear models.' (Chapman and Hall: London)

McRae, RHD (1997). 'Considerations on operational wildfire spread modelling. , Bushfire '97: Australian Bushfire Conference.' Darwin, 8-10 Juley 1997. (CSIRO Topical Ecosystems Research Centre:

Price, OF, Bradstock, R (2012). The efficacy of fuel treatment in mitigating property loss during wildfires: insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia. *Journal of Environmental Management* **113**, 146-157.

Sharples, JJ (2008). Review of formal methodologies for wind-slope correction of wildfire rate of spread. *International Journal of Wildland Fire* **17**, 179-193.

Sharples, JJ, McRae, RHD, Wilkes, SR (2012). Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channelling. *International Journal of Wildland Fire* **21**, 282-296.