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Forest road and fuelbreak siting with respect to reference fire intensities

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Abstract

Forest roads and permanent fuelbreaks are an important part of fire suppression infrastructure, but due to maintenance and environmental costs many forest agencies seek to reduce the extent of these networks. The question of which roads should be retained or where fuelbreaks should be established is contentious, and few quantified methods exist to aid management decisions. This study uses GIS procedures and develops a metric for road network vulnerability, which may be used to determine the relative effectiveness of a road network or a particular fuelbreak as a fire control line. The method constructs 'reference fire' intensities, and compares the fire intensity at roadsides or fuelbreaks with the overall forest average. In the case study area in Victoria's Central Highlands (southeast Australia), average fire intensities on the forest road network are found to closely match the forest average, indicating that roads in their current locations are not skewed towards more dangerous parts of the forest. The fuelbreak network however is likely to face fire intensities substantially greater than those in the average forest area.

Key words: Fire infrastructure; GIS; Eucalypt; Australia; wildfires.

Resumen

Ubicación de pistas forestales y áreas cortafuegos con respecto a la intensidad de incendios de referencia

Los caminos forestales y las áreas cortafuegos permanentes son una parte importante de la infraestructura de extinción de incendios, pero debido a mantenimiento y los costes medioambientales muchos organismos forestales buscan reducir el alcance de estas redes. Nos preguntamos qué caminos y pistas deben mantenerse o dónde deben establecerse las áreas cortafuegos y surge el debate. Hay muy pocos métodos cuantitativos para ayudar a tomar estas decisiones de gestión. Este estudio, utiliza procedimientos basados en SIG y desarrolla un indicador de vulnerabilidad de una red vial, que se puede utilizar para determinar la eficacia relativa de dicha red, o de un área cortafuegos específico, como una línea de control de incendios. El método establece intensidades de referencia del fuego y compara la intensidad de los incendios en las pistas o las áreas cortafuegos con el valor promedio (de intensidad del incendio) en otros lugares de esa masa forestal. En el área de estudio, en las Tierras Altas Centrales del estado de Victoria (sudeste de Australia), las intensidades promedio de fuego en la red de caminos forestales resultaron semejantes a la media de los bosques, lo que indica que las carreteras en sus ubicaciones actuales no están sesgadas hacia las partes más peligrosas de la masa forestal. La red de áreas cortafuegos, sin embargo, si hace frente a intensidades de fuego significativamente mayores que las de otros lugares de la superficie forestal.

Palabras clave: Infraestructura; SIG; eucalipto; Australia; incendios forestales.

Introduction

Forest roads are sited in particular locations for a variety of reasons, including timber harvesting, fire control, through routes, recreational purposes or as access to points of interest such as lookout towers, scenic viewpoints, water sources etc. The road network of any forest area is largely a result of its historical use, and as such may not be perfectly optimized for current or future purposes. The aim of this study is to examine a means of quantifying the topographic suitability of a road network as fire control lines with respect to fire intensity, and to use this methodology to examine the relative merit of proposed permanent fuelbreaks in a case study area.

Previous work (Eastaugh and Molina, 2011) developed methods for describing the topological character-

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istics of forest road networks, in terms of road network coverage, efficiency and convenience. These three metrics describe the ability of a forest road system to provide access to all parts of the forest, to do this with a minimum length of roading, and to allow efficient transport between different parts of the road network. In fire control however a road is often called upon to be more than just an access way, and is commonly needed as a fuelbreak or backburn initiation line.

Different parts of a landscape will have different fire intensities under identical prevailing wind conditions, due to differences in fuel loads, fuel moistures and local wind conditions. To some extent all of these factors are influenced by topography. Roads sited in parts of the landscape with high fire intensities are less likely to provide safe locations for fire control lines, reducing the overall utility of the road network.

The use of permanent fuelbreaks as a forest protection measure has been a contentious issue in southeast Australia for many years. Some authors hold that such breaks are too often ineffective due to the extreme spotting behaviour of fires in this environment (e.g. Lyne (1918); Cheney (2008)), while others (Stretton (1939); Gill (2008)) note the usefulness of roads as permanent fuelbreaks — although both qualify their statements to some degree. The Victorian Department of Sustainability and Environment (DSE) has recently embarked on the construction of 600 kilometers of permanent fuelbreaks in Victorian forests, 108 kilometres of which are within or on the edge of this study's area of interest. The primary aim of the fuelbreak network is to assist in the protection of Melbourne's water supply catchment (DSE, 2009), predicated largely on the time saving achieved through having permanent breaks in place rather than needing to construct them as a fire approaches.

No road or fuelbreak network could be designed to cope with all conceivable fire circumstances, and there is very little certainty of what the next fire in any area will be like; weather conditions and ignition points may be guessed at, but not with any degree of certainty. Stochastic methods of fire scenario development such as those used by Lindenmayer and Possingham (1995) may be useful as scientific model inputs but their reliance on random factors limits their utility as management planning tools. To provide an objective means of rating a road or road system it is then necessary to develop repeatable 'reference' fire conditions that road options may be judged against. It must be stressed that these reference conditions, while within the realms of practicality, are not definitive and are only suitable for comparing roading options within the bounds of this study. The methodology however is readily transferable to other areas and perhaps to other purposes.

The procedure used here is an extension of Martínez-López's (2002) work in modeling fire 'death zones'; areas where higher fire intensities are likely to pose an unacceptable risk to firefighters. The methodology developed here differs in that we construct representative average fire conditions using a range of wind scenarios rather than selecting the historic conditions of one particular day. Results here are presented at a finer resolution than Martínez-López (2002), who was concerned with a binary 'over or under' delineation of fire intensities rather than the more continuous scale needed here.

This study aims to develop a means of comparing possible locations for roads or fuelbreaks with respect to their *comparative* safety and effectiveness, not to attempt to calculate fire intensities for any particular single given circumstance. We wish to: i) develop a quantifiable metric for road or fuelbreak locations comparative exposure to higher fire intensities, ii) determine whether the road and fuelbreak networks in our study area are likely to experience higher, lower or similar fire intensities to the general forest area, and iii) demonstrate a means of graphically comparing comparative fire intensity along fuelbreaks to aid management decisions regarding routing and fuel reduction treatments.

Data and methods

Location and site description

The study area for this paper is an approximately 123,000 ha part of Victoria's Central Highlands, about 120 kilometers northeast of Melbourne, southeast Australia. Several major bushfires have been experienced in the region, with fires in 1939, 1983, 2003, 2007 (DSE, 2007), and 2009 (Teague *et al.* 2010). The topography is hilly, rising from 230m ASL at Lake Eildon to a 1480m ASL on Lake Mountain. The valleys to the western edge of the study area are farmed, but the bulk of the area is state-owned forest. Native vegetation is a mix of dry and wet sclerophyllous eucalypt forest. Lower altitudes are predominantly *Eucalyptus obliqua* L'Herit. and *E. radiata* Sieber., with *E. regnans* F. Muell. and *E. delegatensis* R.T.Bak. higher. Smaller areas of *E. pauciflora* Sieber. may be found at the highest altitudes. The area contains 1,506 kilometers of forest

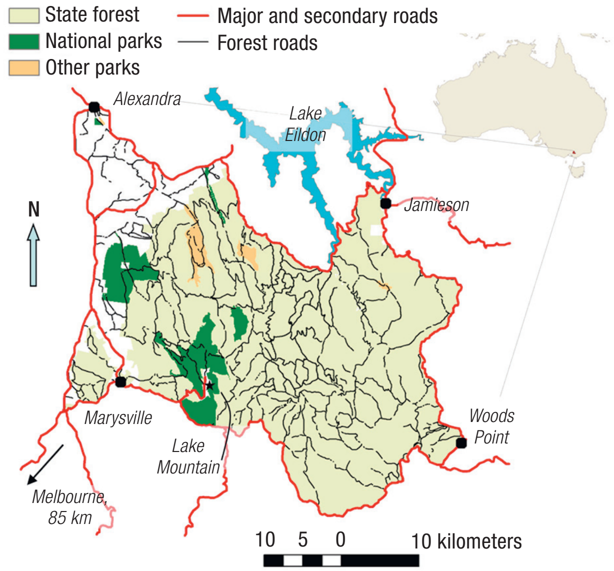

Figure 1. Location and road layout of the study area in the Victorian Central Highlands.

roads controlled by the Victorian Department of Sustainability and Environment, as well as other (more major) public roads.

This area was tragically impacted by wildfire on February 7, 2009. A fire originating from the west was pushed by a northwesterly wind through the extreme southwest of the study area, and then a southwesterly change brought fire back through Marysville and beyond (Teague *et al.*, 2010). Approximately half of the forest area was burned (Fig. 2).

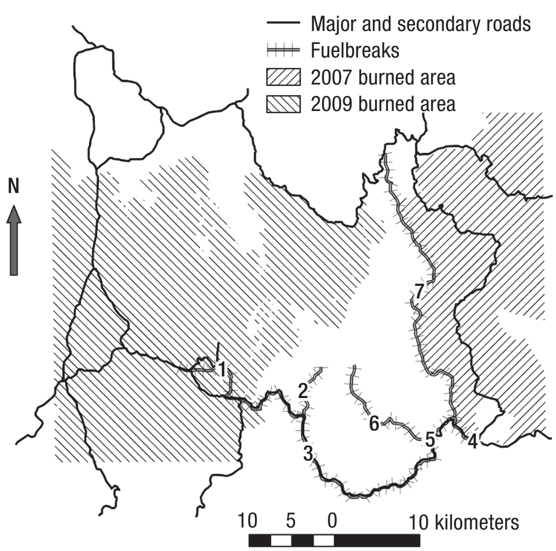

Figure 2. Recently burned areas and fuelbreak locations. 1 Paradise Plains, 2 Morris Track, 3 Yarra Track, 4 Walhalla Road, 5 Matlock to Triangle, 6 Frenchman's Spur, 7 Ryan Spur.

Proposed fuelbreaks

108 kilometres of permanent fuelbreaks have been planned within the case study area (Fig. 2), most of which were actually constructed during the 2006/2007 Alpine bushfires. The breaks have been labeled here according to the DSE's 'work unit' description. The fuelbreaks are intended to be 20 to 40 metres wide, with scattered trees and low vegetation coverage (DSE, 2009).

Reference fire

To judge the suitability of road locations with respect to fires, fire 'reference conditions' have been established. It is important to note that these conditions do not represent any specific likelihood of fire conditions, but rather present a defined, repeatable means of assessing fire-related attributes of the road and firebreak network. Necessary inputs to develop this reference fire were topographic details, fuel loading and weather conditions. No fire spread modeling was undertaken; the procedure used FlamMap (Finney, 2006) to determine the fire intensities at all locations in the case study area, as dependant on the given inputs. FlamMap is a fire behavior mapping and analysis programme that computes potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over a landscape for constant weather and fuel moisture conditions. The programme integrates fuels, weather and topographical information and is considered ideal for this type of analysis (Stratton, 2004). FlamMap is designed to use inputs in the same form as the popular dynamic fire simulator FARSITE (Finney, 1995; 2002).

Topography

Topographical data is drawn from the 20 m resolution digital elevation data supplied by the DSE (Jim Miller, per comm. 20 January 2009). As shown in Figure 3, the area is characterised by a large upland with a series of closeset ridges in the western half, with more complex topography and one major north-south ridge in the east. The area is bounded on the south by the main ridge of the Great Dividing Range; the forests south of the study area are conserved as the water catchment for the city of Melbourne.

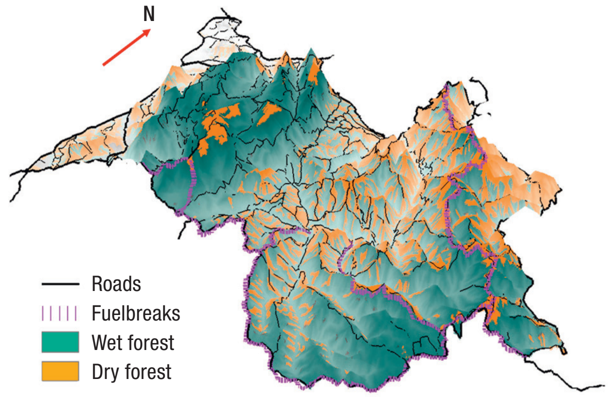

Figure 3. Fuel zones and topography. The exaggerated perspective view shows the mountain ridges to the east and west, and the valley between.

Fuel loads

Based on the DSE's online 'Forest Explorer' database (DSE, 2008) the area was divided into two classes; essentially 'wet' forest and 'dry' forest. Wet forest is taken to be those areas with an Ecological Vegetation Class (DSE, 2010) of 7, 8 and 9 ('wet or damp forests', 'riparian forests' and 'rainforest') and all others were classed as dry forest. Although this is a rather broad generalization, a more precise classification is probably impossible without substantial fieldwork. The occurrence of wet or dry forest is strongly influenced by topography (Fig. 3).

FlamMap uses Anderson's (1982) 13 fuel models, and after extensive searches of the literature (Eastaugh, 2009) it was decided that fuel model 10 "timber (litter and understory)" best reflected average conditions in the dry forest of the case study area and fuel model 12 the wet forests. Although fuel model 12 is intended to model 'medium logging slash', it was considered that this model better represented the high fuel loads typical of Victoria's wet forests than other alternatives. Table 1 shows a metric version of the parameters given by Anderson (1982) for these fuel models.

Table 1. Fuel model parameters[a]

Fuel Class	Total fuel load under 75 mm diameter (t/ha)	Dead fuel load under 6 mm diameter (t/ha)	Live fuel load, foliage (t/ha)
10	27.7	6.9	4.6
12	79.7	9.2	0

[a] Converted to metric units from Anderson (1982).

As an indication of fuel loads found in similar environments in prior studies, Tolhurst *et al.* (1992) measured average values in a Victorian dry schlerophyll forest of 13.9 t/ha < 6mm diameter, 2.4 t/ha from 6-25 mm and 71.1 t/ha over 25 mm. In wet forests in Tasmania Marsden-Smedley and Slijepcevic (2001) found fuel loads (< 25 mm) to be in the range of 12.4 – 20.3. Paul and Polglase (2004) cite figures for fine fuel loads of between 12 and 31 t/ha in *E. regnans* forests, not including bark. Gould *et al.* (2007) suggest fine fuel loads (< 6mm) of 16 to 18 t/ha in dry eucalypt sites in southwest Australia, 25 years after last burning. Different study methodologies and reporting formats make direct comparisons of studies difficult.

Weather conditions

Temperature, wind and relative humidity conditions for fuel moisture conditioning are taken from the meteorological station at Lake Eildon, on the north edge of the study area (BOM, 2009). Fuel moisture conditioning uses data recorded for the 5 days from February 2nd to February 6th 2009 (Table 2). In the author's experience, these figures are reasonably representative of peak summer conditions in the study area.

Local winds for the development of the reference fire intensities are simulated with 'Wind Ninja' software (beta version downloaded from http://www.firemodels.org/). Wind Ninja (Forthofer, 2007) is a mass-consistent fluid flow dynamics model that estimates the modifying effects of topography on synoptic winds. Simulations are run for 8 prevailing wind directions (N, NE, E etc), each with prevailing wind velocities of 10, 20, 30, 40, 50 and 60 kilometers per hour. Along with the 'no wind' case, this gives 49 wind fields.

Calculation procedure

Fuel moistures are estimated using subroutines in the FARSITE fire model (Finney, 1995) based on the inputs described above. FlamMap is then run to determine fire intensities in all parts of the forest under each of the 49 wind fields. The reference fire intensities are the result of averaging together all of the 49 runs. This procedure gives equal weighting to all 49 scenarios, and thus highlights areas that are likely to experience relatively higher fire intensities in the case of future fires under unknown weather conditions.

Table 2. Daily weather observations at Lake Eildon for February 2nd to February 6th 2009

Date	Temps, °C		Rain, mm	9:00 am			3:00 pm		
	Min	Max		Temp	RH%	Wind[a] kph	Temp	RH %	Wind[a] kph
2/2/2009	18.4	34.2	0	23.5	59	4	31.2	42	4
3/2/2009	17.0	34.8	0.4	20.9	84	7	30.9	44	7
4/2/2009	15.6	36.4	0	19.6	78	4	35.0	30	4
5/2/2009	17.8	39.6	0	23.7	71	7	38.2	21	11
6/2/2009	14.4	39.2	0	18.6	82	4	37.2	28	24

[a] Wind speeds are recorded at a height of 10 metres.

For spatial interpretation this result can then be classified according to Table 3, to give ‘fire intensity zones’ for the public forest area. Only zones 3 to 9 are represented in this study. Zones were delineated on the basis of values given by the Bush Fire Front Inc. (2007), with each of those divided into two. The descriptors for each zone given here should be considered comparative only; this study does not attempt to predict fire intensities that may occur in an unknown future ‘real world’ scenario, or for any given past occasion.

A metric for road network vulnerability (R_{VUL}) is developed as a ratio of the intensities to be expected on the network (or any part of it), compared to the intensities to be expected over the area as a whole. As FlamMap and the GIS used for calculations work on a raster basis, it is a simple matter to determine the fire intensity in each individual raster cell, and sum the cell counts for each intensity value. Road network vulnerability is then calculated as:

$$R_{VUL} = \frac{n_f}{n_r} \frac{\sum_{i=1}^{n_r} I_i}{\sum_{j=1}^{n_f} I_j} \quad [1]$$

Where:

n_r is the number of raster cells traversed by the road or roads;

n_f is the number of raster cells in the forest;

i is each raster cell traversed by the road;

j is each raster cell in the forest, and

I is the intensity of reference fire in each cell.

Note that this calculation procedure does not rely on the zone classification in Table 3, but uses the intensity figures for each raster cell. The same procedure can be followed to give an R_{VUL} value to the fuelbreak network.

Results are presented forest area, and the road and fuelbreak networks in each intensity zone from Table 3, and also at a finer intensity resolution through the use of kernel smoothing (Wand and Jones, 1995). This is done with the binned kernel density estimate of the probability density method with Gaussian kernels, using a ‘k’ value determined by the oversmoothed bandwidth selector (Ripley, 2009). Calculation of smoothed values use individual raster cell values of fire intensity rather than the amalgamated zones. These results are presented as smoothed histograms of the proportions of their length or area in each 100 kW/m bin range.

Table 3. Intensity Zones

Zone	Suppression difficulty[a]	Intensity (kW/m)
1	Attack on the headfire is relatively easy	0 - 250
2		251 - 500
3	Direct attack usually succeeds, but headfire must be “pinched in” from the flanks	501 - 1,100
4		1,101 - 1,700
5	Direct attack not likely to be successful on head or flank fires	1,701 - 2,600
6		2,601 - 3,500
7	Crown fires occur - suppression impossible	3,501 - 5,200
8		5,201 - 7,000
9		7,001 - 14,000
10		> 14,001

[a] From Bush Fire Front Inc (2007).

Results

Figure 4 shows the spatial distribution of regions with higher or lower comparative fire intensities and the location of the fuelbreak network. Only zones 3 to 9 are represented in this study area. Higher intensities tend to be found in the higher-altitude area in the west, in wet forest zones, and particularly on exposed ridges. The proportion of forest area, road network and firebreak network in each intensity zone is presented in Figure 5.

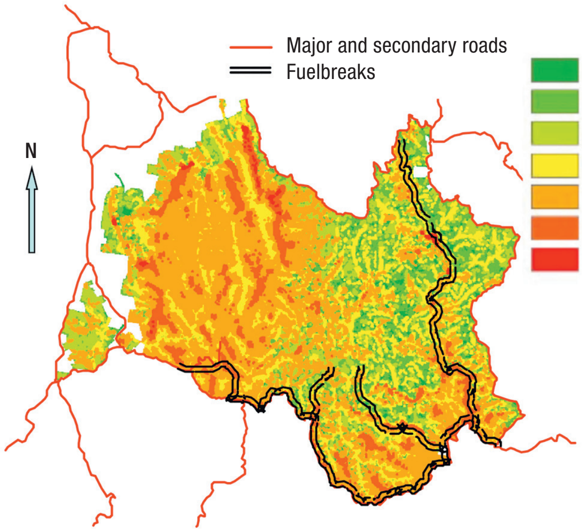

Figure 4. Intensity zones resulting from reference fire.

The choice of bin ranges in Figure 5 hides strong bimodality in the data, particularly for the forest area and fuelbreak network results. This bimodal distribution is most likely at least partly due to the choice of only two fuel models for the study. This may be seen in the kernel smoothed representation of the results for forest area, road network and firebreaks as provided in Figure 6.

Using equation 1, the road network, fuelbreak network and each individual fuelbreak may be given a quantified figure for vulnerability (Table 4).

The vulnerability of each fuelbreak may be examined in more detail by presenting individual kernel smoothed representations (Fig. 7). These show the relative influence of high or low vulnerability portions of each fuelbreak on

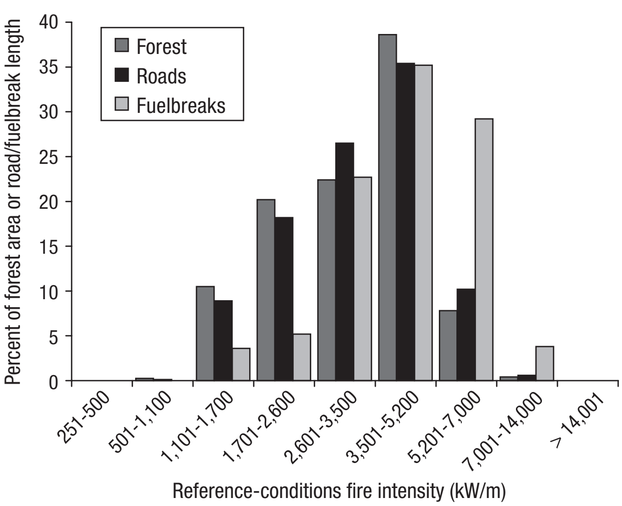

Figure 5. Percentage of land, roads or fuelbreak in each intensity class.

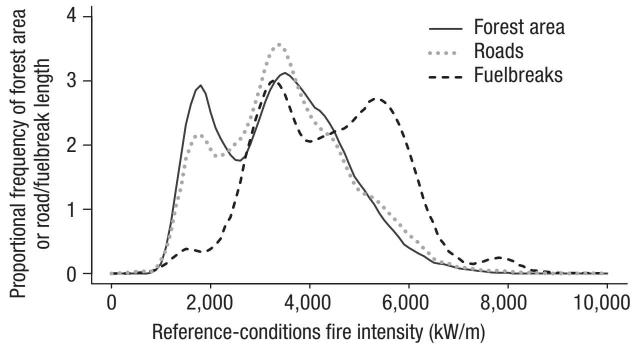

Figure 6. Smoothed frequency representation of reference fire intensities.

the overall vulnerability of each, and is of use in identifying whether improvements in R_{VUL} could be easily made, or if the location of the whole firebreak is of concern.

Discussion

The overall vulnerability of the road network in the case study area very closely reflects the range of fire intensities in the forest area, which suggests that the historical development of the road network in this area has not resulted in roads being preferentially located in high-risk areas. This was a somewhat surprising result, as it was expected that the common approach of constructing roads on ridgelines would have skewed roads into the higher intensity zones. This clearly opens many options for roads being used as fire control lines, as the fire intensity at roadsides will in general be no higher than that in the broader landscape. Naturally this applies only when weather conditions and fuel moistures are such that the fire is fightable. Although some road sections may be in high-risk areas, the procedure as outlined here for the fuelbreaks could be used to identify those which should be not be used for fire control (Martínez-López, 2002).

Table 4. Vulnerability

	R_{VUL}
Forest area	1.00
Road network	1.03
Fuelbreak network	1.30
Frenchmans spur	1.04
Morris track	0.94
Paradise plains	1.44
Matlock to Triangle	1.43
Walhalla Road	1.54
Yarra Trail	1.51
Ryan spur	1.33

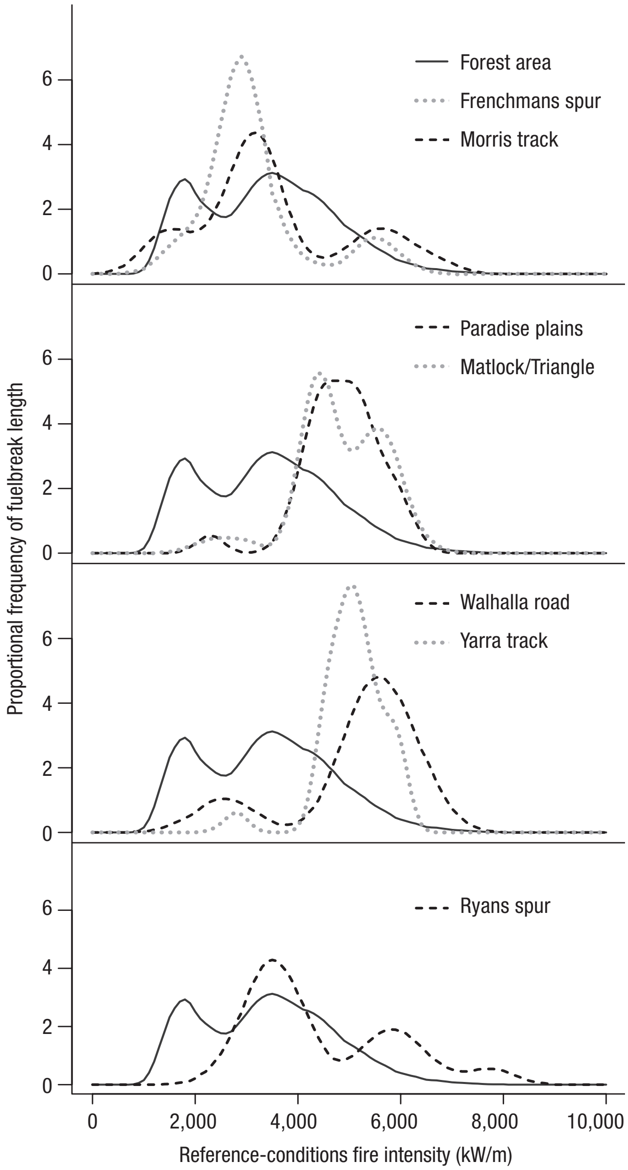

Figure 7. Smoothed frequency representation of reference fire intensities on each fuelbreak.

The fuelbreak network overall is heavily slanted towards high fire intensity areas. This results mainly from the locations of the 'Yarra track' and 'Walhalla road' portions of the network, and part of 'Ryans spur'. In essence, fires at these locations are likely to be on average more intense than fires in other parts of the forest. The high vulnerabilities of these sections suggests that substantial fuel reduction work (more regular prescribed burning or biomass removal programmes) would be needed in the surrounding area if these breaks are to be more appropriate fire control lines than other parts of the road network.

While the results for vulnerability in Table 4 clearly indicate which fuelbreaks are comparatively more likely to prove inadequate, the breakdown of these results in Figure 7 gives more detail that may usefully guide management decisions. For example, the relatively poor result for Ryans spur (R_{VUL} = 1.33) is largely driven by a small proportion of the fuelbreak being in a very high fire intensity area. Relocating this portion of the Ryans spur fuelbreak would give a substantial improvement in vulnerability, and make this fuelbreak a safer control line, with a better chance of being effective. The low vulnerability of Morris track (R_{VUL} = 0.94) gives confidence that this particular fuelbreak is more likely to be an effective control line than other alternatives, all else being equal. Although R_{VUL} is based only on fireline intensities, future studies could perhaps also consider convection processes that may compromise suppression efficiency and safety, such as smoke columns or convective heat transfer towards specific roads at midslopes (Molina *et al.*, 2009).

The delineation of fuel loadings into only two classes in this study reduces the precision of the results, but without extensive field measurements it is difficult to determine how fuel loads should be distributed across different areas. The use of Ecological Vegetation Classes may not be an appropriate descriptor, and prior studies give little guidance as to how regions may be classified for fuel levels, or what parameters would be appropriate inputs to a fire model driven by Rothermel (1972) equations. More accurate descriptions could also be given if information on past fuel treatments (i.e. fuel reduction burning) and forest management history was included. –One possibility for this would be to use LiDAR or other remote sensing methods, which are expected in the near future to allow managers and scientists to estimate fuel loads and structures more accurately (Morsdorf *et al.*, 2003; Allgöwer *et al.*, 2006; Mutlu *et al.*, 2008). Better input information could possibly allow for the extension of the work to provide consideration of the most likely wildland fire propagation patterns, including local interaction of particular weather synoptic patterns with topography as described for European conditions by Castellnou *et al.* (2010).

Conclusions

Contrary to expectations, the road network in this study area is not noticeably skewed towards areas which would expect higher intensity fires (such as ridgelines).

Substantial portions of the fuelbreaks however are likely to experience fire intensities greater than the forest average, and consideration should be given to relocating some parts of these, and carrying out intensive fuel reduction measures adjacent to the fuelbreaks in other areas.

Although this study has been able to show how fire intensities will vary across the forest as determined by fuel and topographic factors, the precision of the results is limited by the assumed fuel distributions and parameters. Although it is unrealistic to expect forest management agencies to keep constantly updated fine-scale details of fuel loads in all parts of their forests, urgent consideration should be given to studies which could relate fuel loads to other, measured factors such as forest vegetation groups or remote sensed data. A further possibility would be to develop modeling to predict the development of fuel loads in different environments as a function of topography, forest types, time since previous fire and management operations.

Notwithstanding the low precision of this study, the methodology presented has shown how topographic and fuel data may be used to inform fire management preplanning and infrastructure development through the use of a quantified metric for vulnerability.

Acknowledgements

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References

Allgöwer B., Stähli M., Bur M., Koutsias N., Koetz B., Morsdorf F., Finsinger W., Tinner W., Haller R., 2006. Long-term fire history and high-resolution remote sensing based fuel assessment: Key elements for fire and landscape management in nature conservation areas. *Forest Ecology and Management* 234(Sup.1), S212-S212.

Anderson H.E., 1982. Aids to determining fuel models for estimating fire behavior. USDA Forest Service General Technical Report INT-122, lntermountain Forest and Range Experimental Station, Ogden, Utah. 22 pp.

Bom, (2009) Lake Eildon, Victoria February 2009 Daily Weather Observations. Bureau of Meteorology, Melbourne. [on line]. Available in http://www.bom.gov.au/climate/dwo/200902/html/IDCJDW3040.200902.shtml [17 May 2009].

Bush Fire Front Incorporated, 2007. Glossary of Bushfire Terms. Bush Fire Front Incorporated. [online]. Available in http://bushfirefront.com.au/glossary-bushfire-terms [17 May 2009].

Castellnou M., Larrañaga A., Miralles M., Molina D.M., 2010. Improving Wildfire Scenarios: Learning from Experience. In: EFI Research Report no. 23."Fire Paradox", Project no. FP6-018505, European Commission, pp. 121-133.

Cheney P., 2008. Can forestry manage bushfires in the future? Australian Forestry 71 (1), 1-2.

DSE, 2007. Significant fire years. [online]. Available in http://www.dse.vic.gov.au/DSE/nrenfoe.nsf/childdocs/-D79E4FB0C437E1B6CA256DA60008B9EF?open [18 May 2009].

DSE, 2008. Forest Explorer. Department of Sustainability and Environment. [online]. Available in http://nremap-sc.nre.vic.gov.au/MapShare.v2/imf.jsp?site=forestexplorer [16 May 2009].

DSE, 2009. Strategic Fuelbreaks - Protecting Melbourne's Water Catchments. Department of Sustainability and Environment. [online]. Available in http://www.dse.vic.gov.au/DSE/nrenfoe.nsf/LinkView/4D206C6380DB36C1CA257313000B4922F64FFCC9CD5F38734A256DEA00140C30 [16 May 2009].

DSE, 2010. Ecological Vegetation Class (EVC) benchmarks for each bioregion. [online]. Available in http://www.dse.vic.gov.au/dse/nrence.nsf/linkview/43fe7df24a1447d9ca256ee6007ea8788062d358172e420c4a256dea0012f71c [07 December 2010].

Eastaugh C.S., 2009. Optimising forest road networks for fire suppression. Masters Thesis. University of Lleida, Spain and the University of Joensuu, Finland. 50 pp.

Eastaugh C.S., Molina D., 2011. Forest road networks: Metrics for coverage, efficiency and convenience. Australian Forestry 74, 54-61.

Finney M.A., 1995. FARSITE: A Fire Area Simulator for Fire Managers. USDA Forest Service Gen Tech Rep PSW-GTR-158. United States Forest Service, Albany.

Finney M.A., 2002. Fire growth using minimum travel time methods. Canadian Journal of Forest Research 32(8), 1420-1424.

Finney M.A., 2006. An Overview of FlamMap Fire Modeling Capabilities. USDA Forest Service Proceedings RMPS-P-412.

Forthofer J.M., 2007. Modeling wind in complex terrain for use in fire spread prediction. Masters thesis. Colorado State University, USA. 123 pp.

Gill A.M., 2008. Fire and adaptive management. Department of Sustainability and Environment, Melbourne. 82 pp.

Gould J.S., Mccaw W.L., Cheney N.P., Ellis P.F., Knight I.K., Sullivan A.L., 2007. Project Vesta - Fire in Dry Eucalypt Forest: Fuel structure, fuel dynamics and fire behaviour. Ensis-CSIRO, Canberra ACT and Department of Environment and Conservation, Perth WA. 218 pp.

Lindenmayer D.B., Possingham H.P., 1995. The conservation of arboreal marsupials in the montane ash forest of the Central Highlands of Victoria, south-eastern Australia, VII. Modelling the persistence of Leadbeater's possum in response to modified timber harvesting praqctices, Biological Conservation 73(3), 239-257.

Lyne H.J., 1918. Forest fires in coastal areas. Australian Forestry Journal 1 (3), 28.

Marsden-Smedley J.B., Slijepcevic A., 2001. Fuel characteristics and low intensity burning in *Eucalyptus obliqua* wet forest at the Warra LTER Site. Tasforests 13 (2), 261-279.

Martínez-López E.R., 2002. Gestion de grandes incendios forestales en el valle del Rialb y la Sierra de Aubenc. Masters thesis. University of Lleida, Spain.

Molina D.M., Blanco J., Galan M., Pous E., García J.B., García D., 2009. Incendios Forestales: Fundamentos, Lecciones Aprendidas y Retos de Futuro. Editorial AIFEMA, Granada, Spain. 256 pp.

Morsdorf F., Meier E., Koetz B., Itten K., Allgöwer B., 2003. High Resolution Airborne Laser Scanning for Forest Fuel Type Mapping. EARSEL - 4th International Workshop: Remote Sensing and GIS applications for Forest Fire Management.

Mutlu M., Popescu S.C., Stripling C., Spencer T., 2008. Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. Remote Sensing of Environment 112(1), 274-285.

Paul K.I., Polglase P.J., 2004. Prediction of decomposition of litter under eucalypts and pines using the FullCAM model. Forest Ecology and Management 191, 73-93.

Ripley B., 2009. Package 'KernSmooth'. [online] http://cran.r-project.org/web/packages/KernSmooth/KernSmooth.pdf [23 Mar 2011].

Rothermel R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Stratton D., 2004. Assessing the Effectiveness of Landscape Fuel Treatments on Fire Growth and Behavior. Journal of Forestry Oct/Nov 2004, 32-40.

Stretton L.B., 1939. The report of the Royal Commission to inquire into the causes of and measures taken to prevent the bushfires of January, 1939, and to protect life and property. Government Printer, Melbourne 36 pp.

Teague B., Mcleod R., Pascoe S., (2010) 2009 Victorian Bushfires Royal Commission final report volume 1: The fires and the fire-related deaths. Parliament of Victoria, Melbourne. 361 pp.

Tolhurst K.G., Flinn D.W., Loyn R.H., Wilson A.A.G., Foletta I., 1992. Ecological Effects of Fuel Reduction Burning in a Dry Sclerophyll Forest. Department of Conservation and Environment, Melbourne. 56 pp.

Wand M.P., Jones M.C., 1995. Kernel Smoothing. Chapman and Hall, London. 212 pp.