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Welcome from Editor

It is my pleasure to bring to you the compiled papers from the Science Day of the AFAC and Bushfire CRC Annual Conference, held in the Sydney Convention Centre on the 1st of September 2011.

These papers were anonymously referred. I would like to express my gratitude to all the referees who agreed to take on this task diligently. I would also like to extend my gratitude to all those involved in the organising, and conducting of the Science Day.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Science Day ran four steams covering Fire behaviour and weather; Operations; Land Management and Social Science. Not all papers presented are included in these proceedings as some authors opted to not supply full papers.

The full presentations from the Science Day and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

Richard Thornton

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Progress in understanding springtime fire weather in Tasmania

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Abstract

In recent decades, there has been an increase in the occurrence of dangerous fire weather events during the Tasmanian springtime. To understand this phenomenon, a climatology of Tasmanian fire weather has been constructed, establishing objectively the extent of changes in typical spring fire weather and allowing comparison with any changes to fire weather in other seasons. The data reveal little change in fire weather characteristics of other seasons, suggesting that the observed increase in springtime fire weather is not an artifact of site or instrumental changes. Individual case studies of events have been examined, identifying features of the synoptic and mesoscale situations that have led to dangerous springtime fire weather behaviour. The events studied had a number of similar aspects, including the occurrence of very dry air, but differences included the origin of the driest air in each event and local antecedent rainfall. Currently, a synoptic climatology is being assembled of weather patterns corresponding to high-end events. It is hoped that this will enable an expansion on insights gained from the case studies, and improve the predictability of dangerous springtime fire weather events.

Introduction

A project is currently underway to better understand Tasmanian springtime fire weather. Springtime fire weather is a well-recognised phenomenon in many parts of the world, including the Eurasian boreal forests, parts of the United States and the Australian sub-tropics, but is less well understood in Tasmania, where the primary fire danger peak occurs in summer and early autumn (Luke and McArthur 1978). Anecdotal reports over many years suggested that a secondary peak in the seasonal fire danger occurs in Tasmania during spring, and an attempt is being made to characterise and better understand the phenomenon.

Much of the following has been published or is in the process of publication. This presentation draws together those publications into a single document for the AFAC Conference, wherein the results have not, for the most part, been aired before.

The structure of the presentation breaks naturally into the areas covered by each of the three publications to date that have followed from the project. First, long-term synoptic weather observations for a number of Tasmanian locations are examined, to objectively confirm the existence and nature of the springtime peak. Secondly, high temporal resolution fire weather observations from several Tasmanian automatic weather stations (AWS) are analysed, highlighting the variability of fire weather diurnally. Case studies of critical springtime fire weather events follow in the third section, where the dynamics of individual events are highlighted. Finally, some preliminary aspects of a synoptic climatology of Tasmanian springtime fire weather events are mentioned, as an indicator of current work on this project.

Climatology of Fire Weather in Tasmania

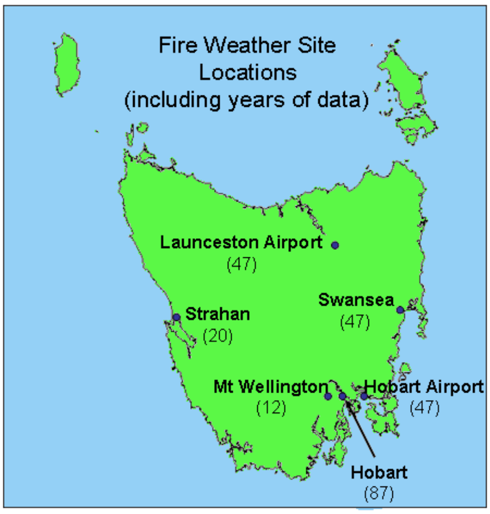

Figure 1. Location of sites used to derive fire weather climatology

Digitised three hourly synoptic weather observations from five Tasmanian sites (see Figure 1) were used to derive a climatology of Mark V McArthur forest fire danger index (FFDI) across the state. At Swansea, on the east coast of Tasmania, observations were available only at 1500 LCT (Local Clock Time). Details of the derivation of the FFDI values are contained in Fox-Hughes (2008). Briefly, FFDI values were obtained using the drought factor calculation of Griffiths (1999) with Soil Dryness Indices (SDI) providing longer term dryness information.

The data revealed a number of interesting features of the fire danger climate of Tasmania. Firstly, there is indeed an objectively identifiable springtime peak in fire danger, but it is largely confined to eastern and southeastern Tasmania. The Strahan and Launceston

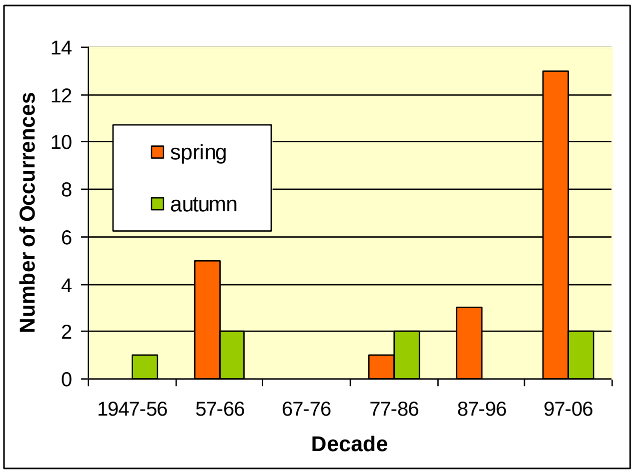

Figure 2. Comparison of spring and autumn counts of FFDI 40 or more at Hobart City, binned by decade.

Airport data gave little indication of elevated FFDI values before November. In southeastern Tasmania, at both Hobart City and Hobart Airport observation sites, approximately one in every two fire weather seasons (nominally October through the following April) were characterised by a springtime peak, where a springtime peak here was defined as a monthly highest value in October or November which exceeded that for the following month by at least 10. Of particular interest, when the longest-running record, that of Hobart City, is examined, it is clear that there has been a recent increase in the number of “high-end” events, those with peak FFDI of 40 or more during the spring. This is not simply an artifact of, for example, the observation site or instrumentation used, as no such trend is evident in FFDI during other seasons (Figure 2), and the pattern is repeated with the Hobart Airport site, within the constraint that the Airport record is shorter (all required data digitised from 1960).

Another interesting feature of the data was the comparison between high and low-level stations. Only about a decade of data was available for Mt Wellington (1260 m elevation), but there was a clear difference between the diurnal patterns of fire danger at the low level Hobart City and Airport sites and Mt Wellington (across all seasons). The elevated site

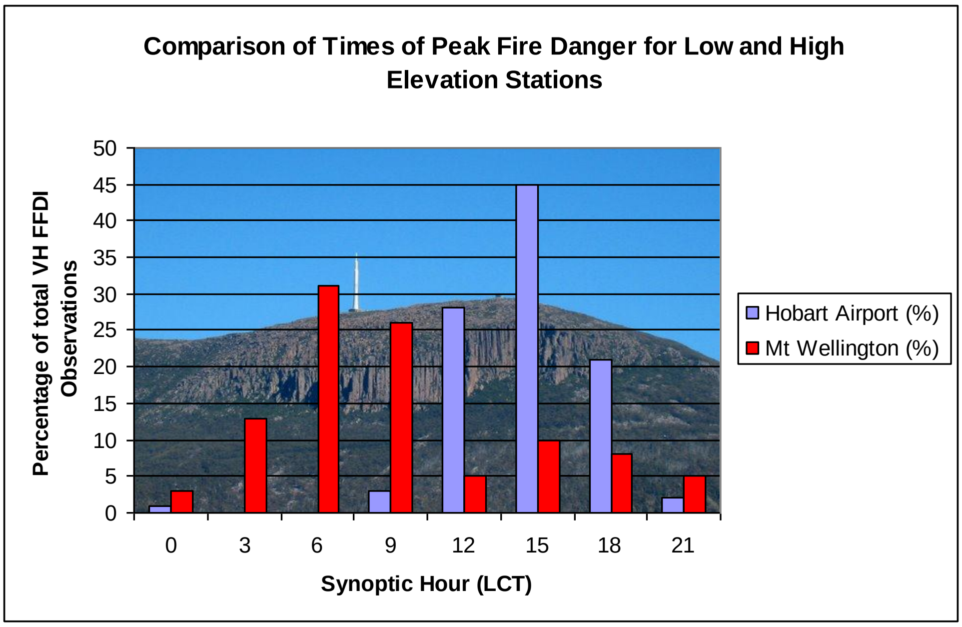

Figure 3. Comparison of peak fire danger between Hobart Airport and Mt Wellington, as the percentage of VH FFDR at each station falling at each 3 hour synoptic time.

experienced a fire danger peak much earlier in the day than did the lower lying stations. Figure 3 illustrates this difference, plotting the percentage of Very High FFDR (forest fire danger rating) experienced by Hobart Airport and Mt Wellington at each three hourly synoptic observation time.

High Resolution Data and Findings

The differences in diurnal fire danger between stations to some extent evident in the synoptic data suggested that there is value in examining more frequent fire weather observations. Such data, at hourly or half-hourly resolution, have become more readily available with the widespread introduction of AWS in the last two decades. The high temporal resolution data suggest the degree of accuracy of estimates of daily peak FFDI based on synoptic or 1500 LCT-only observations, and are therefore useful in calibrating the outputs of climate studies which are in most cases based on infrequent observations. The AWS observations also provide an indication of the value that may be gained from high temporal resolution forecasts of fire weather now becoming available with the Nexgen Forecast and Warning System being introduced across Australia by the Bureau of Meteorology.

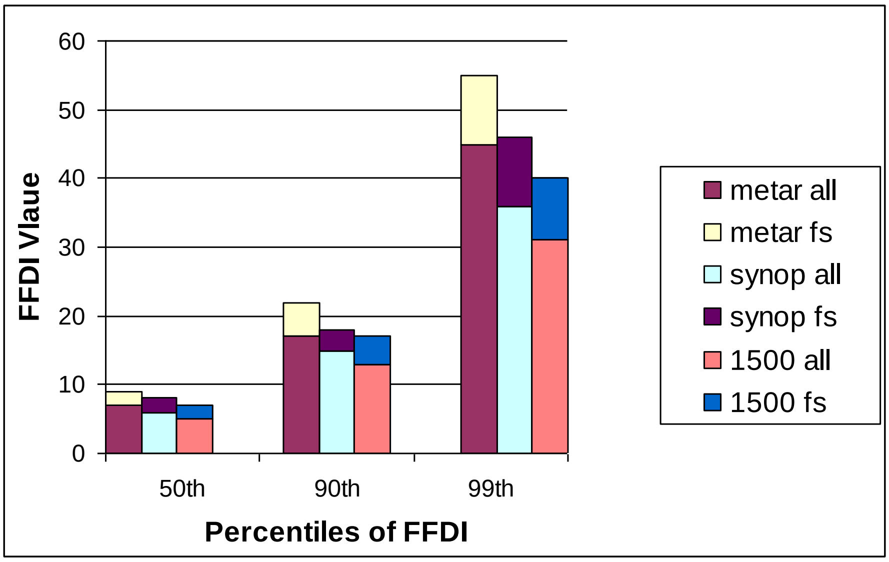

Figure 4. Stacked clustered column plots of 50th, 90th and 99th percentile FFDI at Hobart Airport. "All" observations include those through the year, while "fs" include October-March fire season observations. The columns represent "metar" (half-hourly), "synop" (three hourly and 1500-only observations.

Half-hourly data from three stations were examined: Hobart (19 years data available), Launceston and Devonport Airports (approximately 12 years each), across all seasons, with FFDI calculated following the method outlined above. Further details of the data specification are available in Fox-Hughes (2011a). The results of the study clearly indicate, unsurprisingly, that infrequent observations under-estimate the peak values of FFDI. Figure 4 displays a stacked cluster column plot of key percentiles of peak daily FFDI for Hobart Airport, across the entire year ("all" in the figure legend) and within a nominal fire season October to the following March ("fs"). Columns represent "metar" (half hourly), "synop" (three hourly) and 1500 LCT-only observations. For each percentile, across the whole year and within the fire season, the frequent observations give a higher peak daily FFDI. Further, as the percentile increases (and fire danger becomes more critical) the disparity between measures of peak daily FFDI increases.

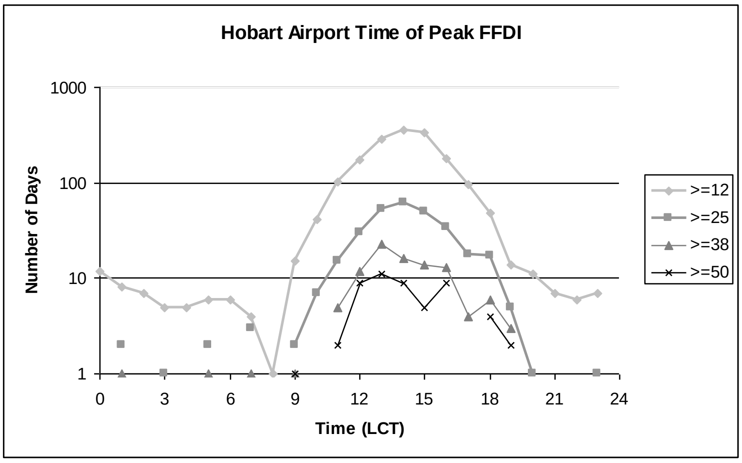

Figure 5. Frequency analysis of times of Peak FFDI for various FFDI ranges at Hobart Airport, plotted with a logarithmic y-scale to better resolve the plots displaying differing ranges of FFDI.

Availability of frequent observations allows an analysis of diurnal trends that is more detailed than that already seen with the synoptic dataset thus, for example, time of day of peak FFDI can be identified quite precisely. At Hobart Airport, the daily peak is early to mid-afternoon, but almost 50% of days when FFDI reached 38 (the level at which Tasmania Fire Service generally considers a Total Fire Ban) peak FFDI was recorded at a time other than 1500 LCT. When observations are restricted to progressively higher FFDI values, the Hobart Airport time of peak FFDI begins to drift to earlier in the day (Figure 5). Within the dataset considered, peak FFDI of at least 12 occurs near 1500 LCT, that of 38 is a little after 1200 LCT, while the relatively few days with peak FFDI reaching or exceeding 50 suggest a most likely time of the peak closer still to 1200 LCT. It is likely, then, that the higher the peak FFDI experienced during the day, the earlier it is likely to occur. While Launceston Airport generally records lower fire danger than Hobart, a similar trend is evident in the data from that station.

The high resolution dataset allows examination of fire weather event duration. Figure 6 suggests that higher FFDI events tend to be of shorter duration. This was explicitly investigated in the study. Figure 6 plots the measured duration of a number of FFDI ranges for Hobart Airport, where the duration of, for example, a FFDI 38 event is the length of time from first report during a day of FFDI at least 38 to the final report (even if the FFDI dipped below the criterion in the interim). It is clear from Figure 6 that higher FFDI events tend to be shorter in duration, and more likely to be missed by synoptic, and particularly 1500 LCT-only, reporting schedules.

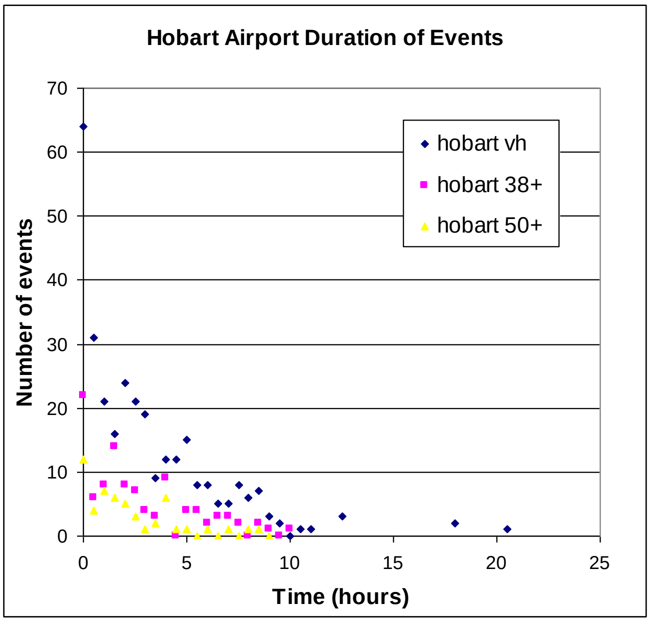

Figure 6. Plot of event duration vs. event count for several ranges of FFDI recorded at Hobart Airport using the high temporal resolution dataset. The ranges are: FFDI Very High (VH - 25) or higher, 38 or higher and 50 or higher.

Significant Event Case Studies

Aggregate data paint a useful picture of broad fire danger patterns, but there is much to be gained from examination of individual events. Two events were selected for study from the databases of fire danger discussed above, and are documented in detail in Fox-Hughes (2011b). Both were exceptional springtime fire weather occurrences. On 7 November 2002, approximately 40 scrub fires occurred in southeast Tasmania ahead of an early evening frontal passage. FFDI peaked sharply in the evening over 100, as mean wind increased above 60 km/h and dewpoint temperature dropped below -10 °C. Several days leading to 12 October 2006 were significant fire weather days in their own right. By about 1100 LST 12 October, FFDI in southeast Tasmania had climbed above 100, remaining above that value for much of the day, while dewpoint temperature dropped as low as -17 °C (and relative humidity 4%), wind hovered close to 50 km/h and an 800 ha fire burnt along Hobart's eastern shore.

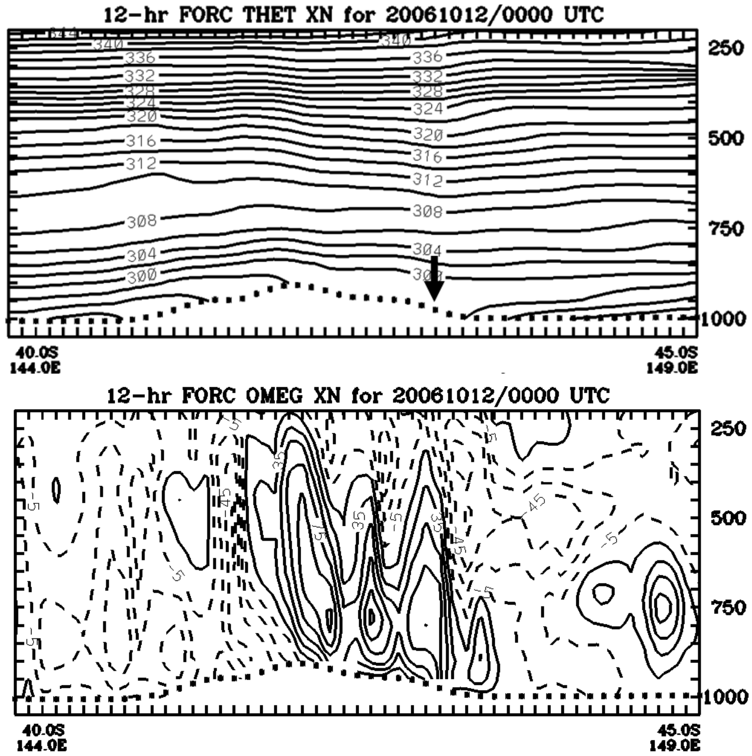

Figure 7. 12 hour forecast cross-sections along the line 40.0 °S 144.0 °E to 45.0 °S 149.0 °E from the 1200 UTC 11 October mesoLAPS numerical model run, valid 0000 UTC (1100 LCT) 12 October. Approximate location of Hobart is indicated by the arrow in the top panel. (a) Potential temperature isentropes, in K, at intervals of 2 K (b) Vertical motion, in hPa hr^{-1}, negative values dashed and contour interval 20 hPa hr^{-1}

Both events were characterised by exceptionally low humidity, with some similarities in the mechanisms acting to deliver such dry air. Air was advected over Tasmania from the drought-stricken Australian continental interior ahead of approaching cold fronts, and slowly descended around the flanks of high pressure systems. That air was further dried and warmed by the action of a foehn effect as the northwesterly trajectory of the airmass in both cases took it over the Central Plateau of Tasmania. This is illustrated by Figure 7 for the 12 October case, where a vertical cross-section is taken through a 12 hour operational numerical weather prediction (NWP), from 40 °S 144 °E to 45 °S 149 °E, i.e. northwest to southeast across Tasmania. In Figure 7(a), a sharp increase with height can be seen on the upwind (left hand side) of the model Tasmanian topography, indicating the presence of a marine boundary layer, while on the downwind slope the air was well-mixed, evident from the lack of increase in potential temperature in the lower layers. These features suggest the presence of a foehn effect, as the airmass upwind of the topographic barrier presented by the Central Plateau slid over the boundary layer air, descending and warming in its lee, as described in Sharples et al (2010). In Figure 7(b), dashed isopleths of vertical motion indicate negative (i.e. upward) motion upwind of the Plateau, while positive (downward) motion is indicated in the lee of the topography, as would be expected in the operation of a foehn wind.

The case studies suggest a potentially useful discriminator for extreme fire weather days. Figure 8 displays a plot of 850 hPa windspeed and dewpoint depression for Hobart Airport. The two cases fall at the extremity of the plot, together with a number of other points. Of the 12 extreme points falling outside the criteria of windspeed no more than 25 m s^{-1} and dewpoint depression no more than 20 ^{o}C, only two were not dangerous fire weather days. These two days were notable for extensive cloud cover.

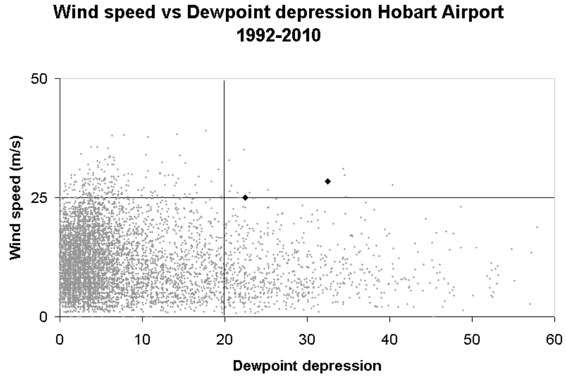

Figure 8. Scatterplot of Hobart Airport 850 hPa wind speed (m s^{-1}) and dewpoint depression (^{o}C) from routine 2200 or 2300 UTC (0900 local time) radiosonde soundings between 1992 and 2010. The two case study values are indicated by black diamonds. Threshold values of 25 m s^{-1} and 20 ^{o}C are represented by gridlines

The two cases differ in the local antecedent ground moisture conditions and in the origin of the driest air on each day. In November 2002, rainfall had been close to average in the preceding few months, but October 2006 followed several months of exceptionally dry conditions. There is good evidence that dry air advected on 12 October 2006 from the continental interior, where it was already very dry, without substantial modification. On the other hand, the sharp spike in FFDI and its underlying weather parameters on 7 November 2002, some hours after diurnal mixing, suggest the intrusion of air from another source. Again, NWP data suggest a mechanism for the origin of the driest air on this day. Figure 9 presents an 18-hour model forecast cross-section through 47 ^{o}S 140 ^{o}E to 41 ^{o}S 150 ^{o}E, across southern Tasmania (shown in the lower right of figure, the position of Hobart indicated by an arrow), and through the approaching trough associated with the cold front mentioned earlier. Red lines indicate potential vorticity in vorticity units (PVU, units 10^{-6} K kg^{-1} m^{2} s^{-1}), between -0.7 and -2.1 PVU, while solid black lines indicate humidity between 10 and 60%. The bunching of PV isopleths near the top of the figure indicates the location of the tropopause. A tropopause depression is evident in the upper left of the figure, identifying the location of the trough at upper levels. Of particular interest, a channel of low relative humidity coinciding with an area of high PV extends from the depressed tropopause towards

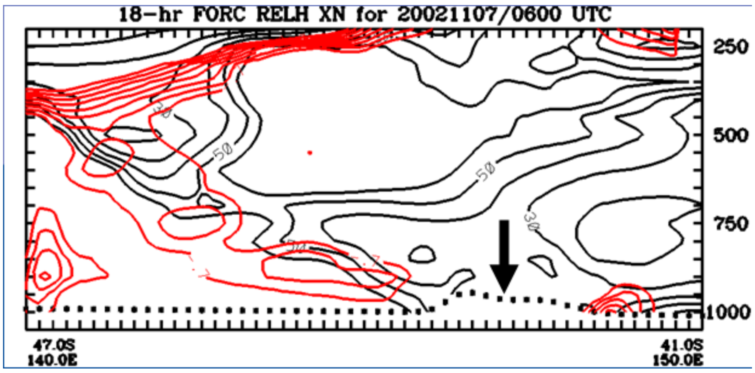

Figure 9. 18 hour model forecast of relative humidity (black), at intervals of 10%, between 10 and 60%, and potential vorticity (red), at intervals of 0.2 PVU between -0.7 and -2.1 PVU along 47 ^{o}S 140 ^{o}E to 41 ^{o}S 150 ^{o}E.

Tasmania. High momentum air (stronger winds) accompanies this feature (not shown in this figure), all of which strongly suggests that a stratospheric intrusion of very dry, higher momentum air reached close to the surface ahead of the cold front on 7 November 2002. Once it reached the boundary layer, it would have quickly mixed to the surface, as described in Mills (2008), Charney and Keyser (2010), and in other references, and caused the observed rapid increase in FFDI.

Towards a Synoptic Climatology

The two case studies examined indicate that there is more than one mechanism acting to cause elevated FFDI during springtime in Tasmania, so any explanation of the recent increase in dangerous fire weather events will need to address this fact. Recently, a synoptic climatology study has commenced, attempting to place these events into a broader context. Ultimately, it is hoped that the study will identify features of the broader atmospheric flow conducive to dangerous springtime fire weather events, allowing an increased degree of preparedness on the part of forecasters and fire agency staff. There are indications, for example, that many such events are preceded by sustained airmass descent through a considerable fraction of the atmosphere upwind of Tasmania. As an example, on 22 November 1997, Hobart Airport recorded FFDI 48 ahead of the passage of a cold front (the overwhelming majority of dangerous spring fire weather events on Tasmania are prefrontal). Examination of the trajectory of the airmass prior to it reaching southeast Tasmania reveals airmass descent through more than 5000 metres in the preceding10 days, and approximately 2000 metres in the final 48 hours (Figure 10). Such a trajectory is unusual in general, but not uncharacteristic of the events being studied, and may offer clues to the meteorological precursors of such events. Certainly, the airmass would warm substantially, and become drier during such a period of descent, preconditioning the air for a dangerous fire weather event.

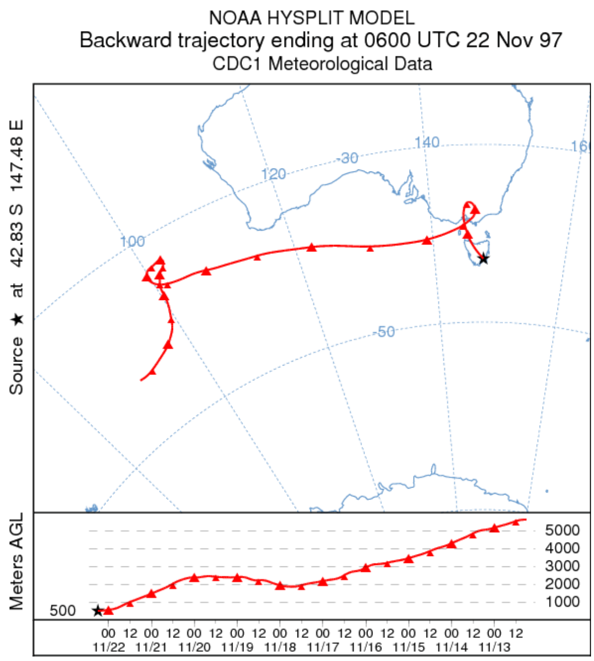

Figure 10. Airmass trajectory for the 10 days leading to 0600 UTC (1700 LCT) 22 November 1997. Figure courtesy of NOAA Air Resources Laboratory, using NCEP/NCAR reanalysis data.

Conclusion

Progress has been made in the study of Tasmanian springtime fire weather events. Much of the output has been published in the peer-reviewed literature, or is about to be published. A number of results are of immediate practical use, or useful background, for operational forecasters and fire agency staff, including:

- Existence of a springtime fire weather peak, in eastern and southeastern Tasmania roughly one year in two
- Increase in occurrence of dangerous springtime events in recent decades
- Documentation of the character of diurnal variability of fire weather in Tasmania
- Nature of the mechanism of dry air transport over Tasmania during (at least some) fire weather events during springtime.
- A discriminator for dangerous fire weather days, based on readily available 850 hPa weather parameters.

Further, there are promising leads in extending the work already done, to define precursor conditions likely to lead to days of dangerous fire weather in spring in Tasmania.

References

Charney, J. J., and D. Keyser, 2010: Mesoscale model simulation of the meteorological conditions during the 2 June 2002 Double Trouble State Park wildfire. *Int. J. Wildland Fire*, **19**, 427–448.

Fox-Hughes, P., 2008: A fire danger climatology for Tasmania. *Aust. Meteor. Mag*., **57**, 109-120.

Fox-Hughes, P. 2011a: Impact of more frequent observations on the understanding of Tasmanian fire danger. *J. Appl. Meteor. Climatol.*, doi: 10.1175/JAMC-D-10-05001.1

Fox-Hughes, P. 2011b: Springtime Fire Weather in Tasmania, Australia: Two Case Studies. *Wea. Forecasting*, accepted for publication.

Griffiths, D. 1999. Improved formulae for the drought factor in McArthur's Forest Fire Danger Meter. Aust. Forestry, 62, 202-6.

Luke, R. H., and A. G. McArthur, 1978: Bushfires in Australia. Australian Government Publishing Service. Canberra, Australia, 359 pp.

Mills, G., 2008: Abrupt surface drying and fire weather Part 2: a preliminary synoptic climatology in the forested areas of southern Australia. *Aust. Meteor. Mag*., **57**, 311-28.

Sharples, J. J., G. A. Mills, R. H. D. McRae, and R. O. Weber, 2010: Foehn-like winds and elevated fire danger in southeastern Australia. *J. Appl. Meteor. Climatol.*, **49**, 1067-1095.

An extreme fire processes cycle model for the February 2009 Victorian Fires

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Abstract

Following the aftermath of Black Saturday, the most significant bushfire event in Victoria since Ash Wednesday in 1983, the spread and behaviour of eight of the most significant fires on the day were reconstructed from multiple data sources.   A chronology of events was created using an enhanced fire isochrone approach which was cross-linked between GIS and Google Earth platforms to interpret and map fire spread and behaviour.

Conditions on Black Saturday produced extraordinarily complex fire behaviour; of note was the rapid development of masses of spot fires, which quickly coalesced into deep large convection columns that created strong pyro-convection and formation of pyrocumulus clouds a great distance into the atmosphere (in some cases approaching 12 kilometres above sea level). The mass fire behaviour and large convection columns were most evident in rugged forested terrain where fuels in both dry and wet forest types were completely available for combustion following a sustained period of drought and a severe summer heat wave, producing a continuous fuel bed for rapid fire spread.

Based on a comparison of the forest-based fire case studies, four distinct phases in fire development were recognised: (1) initial fire run and laying out of spot fires; (2) coalescence of spot fires, leading to mass fire convection and development of pyrocumulus cloud; (3) dissipation or weakening of pyro-convection; and (4) the final decrease in fire convection following a cool change or a lack of fuel.

These fire developmental stages are not as yet fully documented or understood by either the technical fire research or operations, or by rural communities at large.

Keywords: Fire behaviour, fire reconstruction, convection column dynamics, fire processes cycle

Introduction

Following a period of prolonged drought, heat-waves, and severe fire weather conditions, 15 major bushfires, along with some small fires suppressed early on, broke out in the Australian state of Victoria on 7th February, 2009. The desiccating conditions caused both live and dead fuels in dry, damp and wet eucalypt forests to be highly flammable and combustible that saw each fire ignition spread rapidly into large, convection-driven forest fires that burned actively into the late evening. Based on the video and ground evidence gathered as part of the fire reconstruction project, extreme fire behaviour experienced on this day included crowning fire in eucalyptus forest, dense ember production ahead of the fire front, medium and long distance spotting from firebrands (between 2 and 15 km), multiple head fires and fire whirls, either as vertical or horizontal rotors).

The combination of these fire behaviour attributes produced rapid and extreme rates of energy release forming active buoyant pyro-convection above most of the fires. This ‘Black Saturday’ saw 345,000 ha of land burnt, along with 173 Victorian lives lost and 4,200 homes destroyed (Teague *et al*., 2010), making it one of the largest fire impacts in Victoria, akin to Ash Wednesday on 16th February 1983 (209,830 ha, 32 fatalities and 2680 homes destroyed) and Black Friday on January 13th, 1939 (2,000,000 ha, 71 fatalities and over 650 homes and other buildings destroyed).

Out of the 15 fires on the day, eight fires in the central and eastern parts of the state were selected for detailed fire reconstruction (Figure 2): Beechworth–Library Road, Bendigo–Bracewell Street, Bunyip–Ridge Track, Churchill, Kilmore East, Murrindindi, Redesdale–Coliban Park Road, and the Dargo–White Timber Spur fires. With the exception of the Bendigo–Bracewell Street fire, these eight fires burnt more than 8,000 ha each. Six out of the eight fires burnt through substantial proportions of native forest, being primarily located in rugged mountainous or hilly terrain.

Amongst these eight fires studied, there was considerable variation in the landscape mosaic of eucalypt forest, plantation, and grassland types, as well as in the shape of topography through which these fires burnt. The largest of all the fires on Black Saturday, the Kilmore East and Murrindindi fires, burnt through a roughly equal proportion of dry, damp, and wet eucalypt forest types located in mountainous relief in ranges to the north and north-east of Melbourne, as well as grassland in the Kilmore, Wandong, Yarra Glen, and Glenburn precincts. The Churchill–Jeeralang fire burnt through predominantly eucalypt and pine plantation forest types on steep, hilly country in the Strezlecki Ranges in southern Victoria. The Bunyip-Ridge Track fire initially burnt through dry and damp eucalypt forest and undulating to flat relief, and then through partially to fully cured grasslands before finally burning up into wet eucalypt forest on to the more hilly Hells Gate North and South ranges in central western Gippsland. The Dargo–White Timber Spur fire burnt on the edge of the Dargo Plains high country through a mosaic of montane and sub-alpine grassy and shrubby forest in steeply dissected escarpment in central northern Gippsland. Further to the west in the Central Goldfields region of Victoria, the Redesdale–Coliban Road and Bendigo–Bracewell Street fires burnt through mainly grassland fuels interspersed with patches of dry grassy and litter dominated eucalypt forests. In the north-east of Victoria, the Beechworth–Library Road fire burnt through dry and damp eucalypt forests on mountainous plateaux and ridges, broken up by broad flat to undulating grassy valley floors.

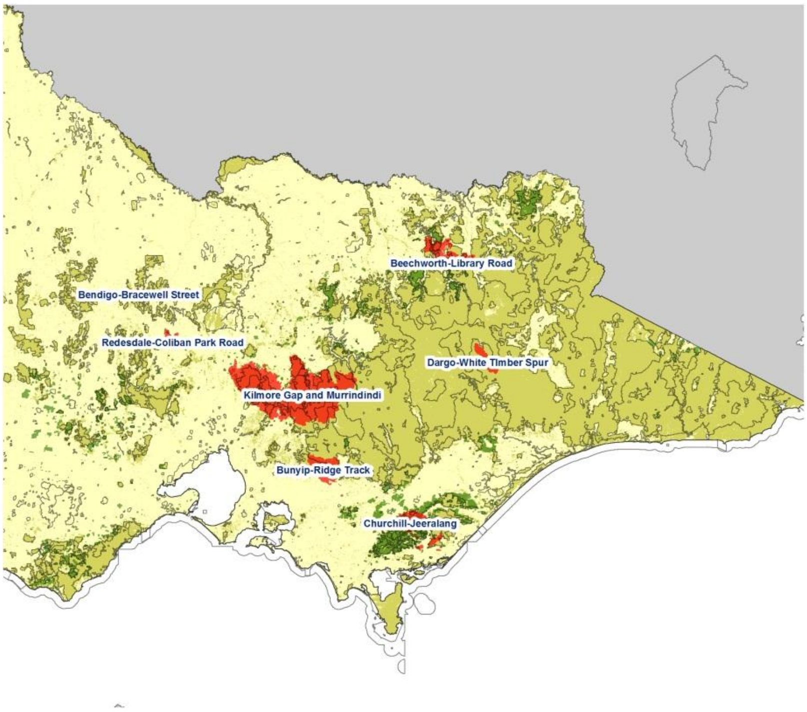


Figure 2. Black Saturday Fires under study

The conventional two-dimensional models of fire behaviour based on estimations of surface fire rate of spread do not account for the convection column and spotting behaviour observed on Black Saturday (McArthur, 1966, McArthur, 1967). An alternative fire developmental phase model is proposed in this paper, which is based on the analysis of detailed fire reconstructions produced by the project, and the vegetation-fuel landscape conditions, and fire weather on the day, a simplified model of the phases of fire development is proposed in this paper.

Fuel and Fire Weather Conditions

To provide some context for the proposed fire process model, the fuel and fire weather conditions on Black Saturday are compared to other significant fire seasons and fire events in Victoria in order to show how severe the landscape and atmospheric conditions were on that day.

Applying critical thresholds of severe drought to a 130-year time series of Soil Water Deficit (SWD) in both wet and dry sclerophyll forests identified historically critical sets of landscape dryness during fire seasons in southern Victoria (Gellie *et al*., 2010b). The results from this exploratory study based on the periods of extreme SWD above those critical dryness thresholds, showed that the 1938/39 and 2006/07 fire seasons were the most severe in the 126 year historical record. The 2008/09 fire season was more associated with fire seasons with less severe landscape dryness, such as 1897/98, 1926/27, 1943/44, 1967/68, and 1982/83. However, this analysis does not take into account the medium-term cumulative effects of a sixteen-year drought spanning the fire seasons from 1996 to 2009 that could have caused a draw-down in soil and vegetation moisture.

Based on anecdotal evidence and the completeness of fuel consumption collected from field interviews and landscape-based photographs, eucalypt litter in dry and damp eucalypt forests had dried throughout their respective fuel bed profiles. Grass, fern, or herbaceous species had fully cured in the dry forests and in many of the grassland areas. The finer coarse woody fuels (between 6 and 75 mm in diameter) such as larger branches and twigs had dried through to the centre. Bark fuels in common rough-barked eucalypt species, such as *Eucalyptus obliqua* (Messmate Stringybark) and *Eucalyptus dives* (Broad-leaved Stringybark) were dry deep into the inner bark. In the Kinglake–Mount Disappointment area, patches of dry eucalypt forest were observed to have orange coloured canopies on exposed northern and western aspect, indicative of drought stress. In wet sclerophyll forest, the litter and herbs were fully available for combustion, while the tall eucalypts and shrubs retained some level of moisture. As a result, fuels available for combustion across all eucalypt forest types were at an all-time high during the 2008-09 fire season, reaching 3–5 kg m^{-2} based on all the live and dead fuel elements (Gellie *et al*., 2010b). At the landscape level, this meant that fire was able to spread unhindered across all eucalypt forest types. The lack of moisture at this time of the fire season blurred the distinction between dry, damp, and moist eucalypt forests.

The fire weather on Black Saturday was largely driven by a deep pre-frontal continental heat trough that drew air from a very stable heat pool over central and western Australia. According to *Parkyn et al.* (2010), the atmosphere on Black Saturday was highly conducive to large-scale three dimensional fire behaviour based the atmospheric instability estimated from atmospheric soundings on the day. As a result, most of Victoria on that day was exposed to an atmosphere with an extremely hot, dry and very windy fire weather conditions in a mixed layer 5500 m deep. Typically, temperatures in excess of 45^0C, relative humidity ranging between 8 and 12% and strong to gale force winds between 45 and 55 km hr^{-1} were found at elevations below 400 m. At higher levels in the mixed layer, winds were blowing at 70 to 100 kilometres per hour (Bureau of Meteorology, 2010). Drawing on historical records, *Parkyn et al.* (2010) claimed that the conditions on Black Friday in 1939 were similar to those on Black Saturday, except that the strength of the winds were more likely to have been 35–45 km hr^{-1} prior to the arrival of the south-west change. The other factor on Black Saturday was the strength of the southerly change on the day, but not as strong or prolonged as that experienced on Ash Wednesday in 1983. The result was that fires burning in dry and wet eucalypt forest had sufficient vertical convective energy to resist mixing despite these strong winds, and the plume was thus able to penetrate above the mixed layer to heights well over 8000 m, and sometimes to over 11,000 to 13,000 m.

Method

A detailed outline of the fire reconstruction methodology has been previously set out in (Gellie *et al*., 2010a). High resolution 15 cm post-fire digital aerial photography was used as a base mapping reference. It also contained fire severity information, which was used to locate fire fronts and their fire behaviour. Spread and behaviour of the fires under study were documented with series of isochrones between 5 and 20 minute intervals for the Beechworth–Library Road and Bunyip–Ridge Track fires. For the other fires, which had less available evidence to reconstruct their spread and behaviour, fire spread and behaviour was documented at a slightly less detailed time scale, with 10 minutes to an hour between isochrone lines.

As well as mapping the surface fire spread in the form of fire isochrones, video and radar-based images were available to study the convective dynamics of six out of the eight fires studied. Fire chronologies and narratives for all the fires were developed in the report, along with a detailed analysis of fire weather, energy release patterns, and spotting dynamics. In addition to the fire reconstruction datasets, BOM radar data was made available to enable analyses of fire convection column dynamics. Although coarse in resolution, the radar data was used to plot the position of the fire and to detect the pulses of energy being out by the fire. There were some limitations to the radar data. For instance, it was not always available and some of the fires were just too far for the radar to pick up sufficient detail of the smoke plumes. For instance, the Laverton high resolution Doppler radar was not operational to monitor the Kilmore and Murrindindi fires between 1430 and 1800 hours, due to a mechanical fault. The Sale radar data was used to track the position, height and density of smoke plumes from the Bunyip–Ridge Track and Churchill–Jeeralang fires.

Based on all the evidence available, patterns and processes evident from these fires were developed into a conceptual model of an extreme fire process cycle on Black Saturday.

The Extreme Fire Processes Cycle Model

The conceptual basis of this model is that the fire environment is an interconnected, three-dimensional realm of interactions between landscape terrain, vegetation-fuel, and fire weather, all determining components of fire spread and behaviour across the landscape. The fuel structure, arrangement and continuity not only vary significantly across a spatial context, but also changes according to seasonal climate. The availability of individual components of the forest played a major role in determining the ease of ignition and onset of either intense sub-canopy or crown fires in eucalypt forest on the 7th of February. This can be directly related to the high water soil deficit levels brought on by drought and heat-wave conditions and intensified by severe surface weather conditions embedded in a pre-frontal continental heat trough. Fuels in wet eucalypt forest types were in a seasonally dry state, and when paired with the existing dry eucalypt forest types formed a continuous available fuel type stretching across multiple broken terrain features.

Fires spread rapidly from ridgeline to ridgeline leaving pockets of unburnt areas to fill in behind while the main front played catch-up to the spot fires ahead. Instability in the atmosphere that day introduced a third-dimension to the Black Saturday story, demonstrating the drastic impact that strong upper level winds and very dry atmospheric moisture conditions of passing air masses can have on energy release and associated convective energy of fire plumes. The fires themselves also affected local atmospheric conditions, by firstly altering stability and lifting condensation levels as forest fuels combusted, releasing significant quantities of heat and moisture was released and secondly altering the wind fields up to 10 km downwind.

In any fire process model, rate and duration of combustion are critical factors in determining a fire’s rate of spread and intensity at any point around its perimeter. The duration and intensity of the flaming zone is very much related to the architecture, fuel geometry, and loading of the individual fuel elements. The standard form of fire intensity is the widely used and accepted Byram's formula of fire line intensity (Byram, 1959):

$$BHFI = QMR \qquad \text{Equation 1}$$

where BHFI is equal to fire line intensity (kW m^{-1}), Q is the effective heat content of the fuel (kJ kg^{-1}), M is equal to the fuel load consumed in the flaming front (kg m^{-2}), and R is the rate of spread (m sec^{-1}).

Instead, one can use Byram's alternative form of fire reaction intensity which has units of area instead of lineal fire front:

$$I_R = \varepsilon QMd\tau_R w \qquad \text{Equation 2}$$

where I_R is equal to the reaction intensity (kW m^{-2}), ε is equal to combustion efficiency, d is equal to the depth of combustion zone, τ_R is equal to the flaming residence time, and w is the width of the head fire.

Reaction intensity (I_R) is a measure of the rate of combustion of fuels in a forest. A large number of fuel bed factors, including size and geometry of fuel elements, their architecture, and their bulk density affect the combustion rate of forest fuels. The most significant factor that affects mass loss in a fuel element is a fuel particle's thickness or diameter (Burrows, 2001), the finest fuels, such as eucalypt, grass, and ferns, burnt up the quickest but within a short time other fuels become involved in combustion, such as twigs and fine branches, as well as tree bark, and live shrub and tree foliage. Combustion rate values (I_R) for eucalypt forest fuel beds are almost non-existent in the literature yet determine fire spread rate and convective heat output around a fire's perimeter.

From evidence gathered during field interviews and from photographs taken during the fire (Figure 3), the mix of fine and coarse dead fuels, near-surface fuels, bark, and sometimes live canopy fuels had a τ_R of 1.5–3 min, extending the previously estimated τ_R of 45–60 sec by ~1.5–2.0 minutes. Combustion rates for a typical set of fuel elements involved in flaming combustion are presented in Table 1.

Table 1 Parameters and combustion rate for fuel elements in a Messmate Stringybark Forest

Fuel Element	Fuel Load	Percentage of fuel element consumed	Combustion Efficiency	Potential HW	Flaming Residence times	Combustion Rate
	(kg m^{-2})			(KJ)	(sec)	(KW m^{-2})
Litter	1.50	75%	90%	18,730	45	415
Ferns	0.40	75%	90%	5,000	30	165
Twigs with a mean diameter (6-25mm)	0.35	62%	90%	3,610	140	25
Bark	0.43	75%	90%	5,370	20	270
Total for a sub-canopy fire	**2.68**			**32,710**		**875**
Canopy	0.80	85%	65%	8,180	12.3	665
Total for a canopy fire	**3.48**			**40,890**		**1540**

Note: The estimates for percentage of fuel consumed, combustion efficiency, and potential QM are best estimates. For instance Q is taken to have value of ~18,500 and 22,500 for dead and live fuels (Pompe and Vines, 1966). The estimates for flame residence times are based on Burrows (2001) and Pompe and Vines (1966).

If one assumes that τ_R of the litter fuels determines the period of flaming combustion and was equal to 45 seconds (Pompe and Vines, 1966), being three times longer than 10 seconds for dry eucalypt leaves the experiments undertaken by Burrows (2001) because of differences in the bulk densities of the two fuel elements. The estimated combustion rates for the litter and the other fuel elements are based on the relative proportion of each fuel element consumed in that 45 second period. Combustion rate for rough-barked fuels is problematic as the mass loss rate depends on the thickness and density of the bark flakes, which increase in density towards the tree core, and being vertical, is highly efficient as the flames run vertically up a tree. Essentially the overall combustion rate for a sub-canopy fire in a Messmate Stringybark forest is estimated to be ~870 kW m^{-2}. A significant contribution of this I_R value came from the litter and fern fuel elements. This combustion rate estimate assumes that all the fuel elements burnt at the same time. If not, then the estimate of combustion rate would be lower and the effective τ_R. would be extended, which is possible based on the observations of flame residence time being extended to nearly 3 minutes on some of the Black Saturday fires. A canopy fire had almost double the I_R value, with a value of ~1500 kW m^{-2} because of the highly efficient combustion of openly packed eucalypt canopy foliage. Thus, crown fires in a dry rough-barked dominated eucalypt forest would have contributed more convective energy and atmospheric moisture within smoke plumes of the forest fires than a sub-canopy fire in a dry, damp, or a wet eucalypt forest on Black Saturday.

As witnessed on Black Saturday, combustion zones at the head of each spot fire or major finger of fire were deep (estimated to have been 60–150 m in depth) depending on forest type and exposure to wind and down-draft currents within and ahead of a convection column. These deep flame zones (usually at the sub-canopy or above the forest canopy) contributed to rapid fire acceleration and large amounts of convective energy available within each fire. The presence of vertical flames (or flame detachment) also contributed to the large amounts of energy release even on steep slopes (Dold and Zinoviev, 2009). A major contributor to this phenomenon was the presence of rough-barked eucalypts enhancing flames in the forest sub-canopy.

Figure 3 Deep combustion zones and detached flames on a forested slope during the Kilmore East fire at ~1630 hours (Photo credit: Richard Alder)

The process of fire spread on Black Saturday can be described in four generalized phases during the south-east runs under north-west winds: (1) formation of incoherent spot fire plumes; (2) plume consolidation; (3) plume weakening; and (4) plume dissipation (Figure 4).

(a) Phase 1

(b) Phase 2

(c) Phase 3

(d) Phase 4

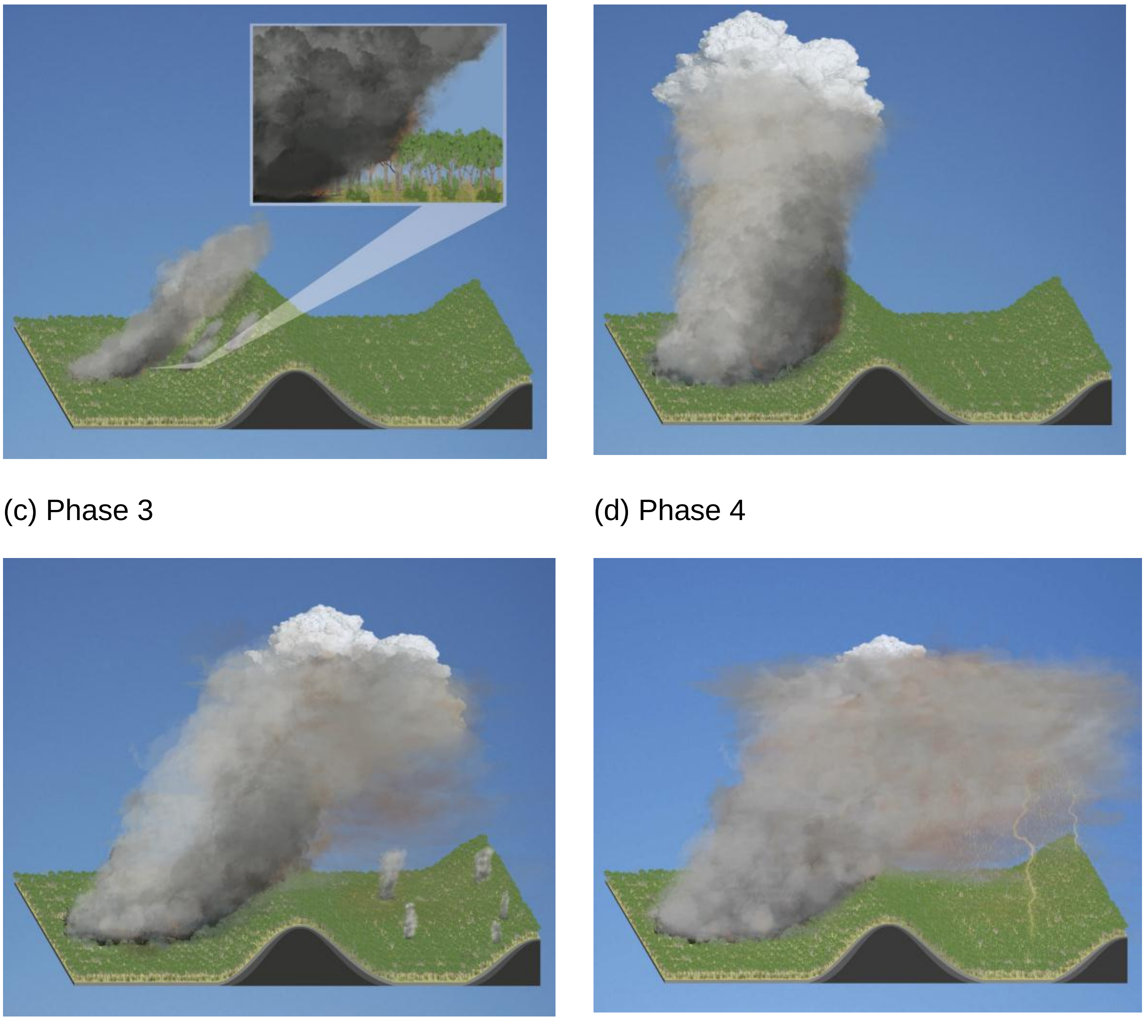


Figure 4 Key Phases in the extreme fire processes cycle model during the six most significant Black Saturday fires.

Note: This cycle pertains to the Beechworth–Library Road, Bunyip-Ridge Track, Churchill–Jeeralang, Dargo–White Timber Spur, Murrindindi, and Kilmore East Fires.

In the first phase, a series of short distance spot fires spaced 500 to 2000 meters apart were laid out and established quickly under the influence of turbulent winds (Figure 4 (a)). If the terrain was configured as a series of ridges at right angles to wind direction, rate of spread would be temporarily stalled as the fire went over the ridge, leading to an interruption in the plume's convective energy supply. This is when firebrands were cast out from the smoke plumes, leading to more spot fires becoming established downwind at distances between 1 and 5 km ahead of the initial fire. This meant that the fire jumped five to seven kilometres ahead, even though some of the area in between remained unburnt. Explanations of fire behaviour, based on atypical fire spread and fire channelling, were found at one location on the Bunyip–Ridge Track fire (Sharples and McRae, 2011). However, for the rest of the time, the propagation mechanism of short–medium distance spotting encountered in this phase was the dominant fire spread process.

In the second phase, individual spot fires developed into larger fires and merged with others nearby. Spot fires that landed at the base of ridges with steep slopes actively crowned uphill and contributed to quickly developing and strongly rising convection columns. The separately developing spot fires in very high available forest fuels, coupled with very low fuel moisture contents, steep forested terrain, and strong turbulent winds on Black Saturday produced deep flaming zones, often involving eucalypt tree crowns that led to more vertical smoke plumes (Figure 4 (b)). Combustion rates slowed as live canopy fuels in the canopy became actively engaged in combustion, creating dark red flames and darker and denser smoke columns (Byram, 1959). At these times, convective energy would increase to the extent that in the larger fires, such as the Murrindindi and Kilmore East fires, a near vertical core between 2000 and 4000 m high above the ground would be established, retaining potential spotting firebrands within the convection column. This effect could last from several minutes to several hours, depending on the extent of forest being burnt out.

During this phase the head of the fire usually did not travel as a coherent front. In most cases the spread of the fire was made of several convective areas centred on the earlier spot fires laid out in Phase 1 ((Figure 4 (a)). This often led to chaotic and fingers and runs developed related to drawing in and eventual coalescence of multitudes of individual spot fires. This is documented in detail for the Bunyip–Ridge Track fire, which shows four or five convective cores on either side of the power line easement and were drawn together by the processes described above.

Once the fires were fully established, a mature convection column formed (Figure 4 (b)). As the column built, forward and lateral spread of the fire slowed as a result of inward flow from entrainment or convective indrafts. If sufficient energy was produced during this stage a pyrocumulus cloud formed above the mixed layer. On the Kilmore East and Murrindindi fires, pyrocumulus clouds formed and lasted for several hours as a result of crown fires at the base of their convection columns. The combustion of live canopy fuels released additional energy into the column, contributing to the development of clouds at its peak. In this phase, longer distance spotting occurred only if the fire's convection was overridden by strong winds.

In the third phase, energy release from convection plumes was either interrupted or slowed, usually related to consumption of all the fuel in the area or the fire reaching the top of a ridge or plateau (Figure 4 (c)). At this point, a few longer distance spot fires (ranged from 6 to 20 kilometres) were initiated downwind, associated with ribbon bark firebrands from the damp or wet forest types becoming detached from the column and carried downwind in the dry air aloft. The transition back to a wind-driven smoke plume often occurred quickly (Figure 4 (a)), sometimes occurring within five to ten minutes. Flank fires now under less control and influence of the central convective core, would spread out at a faster spread rate, with the north-eastern flank becoming more exposed to wind shifts, sometimes leading to the creation of new runs of fire as spot fires landed beside the main flank. By these propagation processes, energy release at this point increased along the flanks without the restraint of the central convection column.

(a)

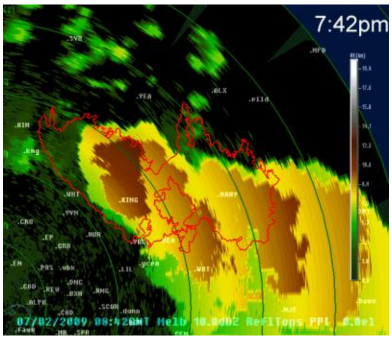
(b)

Figure 5. Energy release influencing convection column dynamics on the Churchill- Jeeralang Fire. (a) intensifying convection column at ~1445 hours and (b) temporary weakening of column at ~1452 hours. Photo credit: J. Wilson.

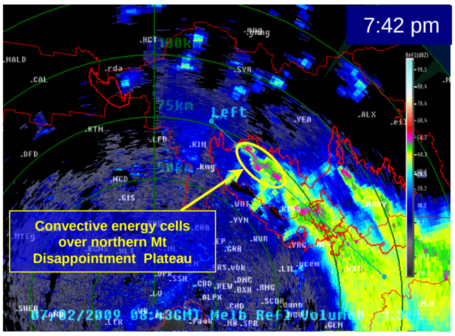
Phases 1 to 3 in the fire developmental cycle were repeated continually until a fire entered the fourth phase as the result of either: (1) major breaks in topographic relief; or (2), the fire spread from forest into grassland (a change in fuel type); or (3), a significant wind shift or a persistent wind change; or(4), a reduction in fire intensity from the combined effects of higher fuel moisture content and lower wind speeds associated with the passage of the cool change; or (5), some combination of all of the above circumstances (Figure 4 (d)). In the first case, the fire plume weakened at the top of an escarpment causing the pyrocumulus cloud atop the convection column to dissipate quickly, usually resulting in short and medium distance spotting between 5 and 12 km. In the second case, scattered spot fires would emerge downwind following the collapse of the fires' main convective centres, causing medium-distance spotting of between 3 and 5 km, resulting in several fingers of fire spreading independently through mixed grassland. On occasions, long distance spotting between 8 and 13 km, and sometimes 18–22 km downwind occurred. In the third case, mass fall-out of fire brands and embers along the north-easterly flank would create an eruptive energy release associated with the newly created set of head fires between 100 and 300 m to the north of it. During the south-east run, this would often create a parallel run of fire alongside the initial run.

After the persistent south-west wind change, pulses of convective energy were seen on the BOM radar trace at intervals between 6 and 15 minutes in the Kilmore East and Murrindindi fires (Figure 6). This time scale was much finer that used in the fire reconstruction of these fires (usually 60 minutes, occasionally 10–30 minutes), suggesting that in future fire reconstruction studies, fire dynamics will need to be based on field fire intelligence closely monitoring the fire processes involved.

(a) Top of smoke plume



(b) Highest within plume radar values



(c)Vertical plume profile

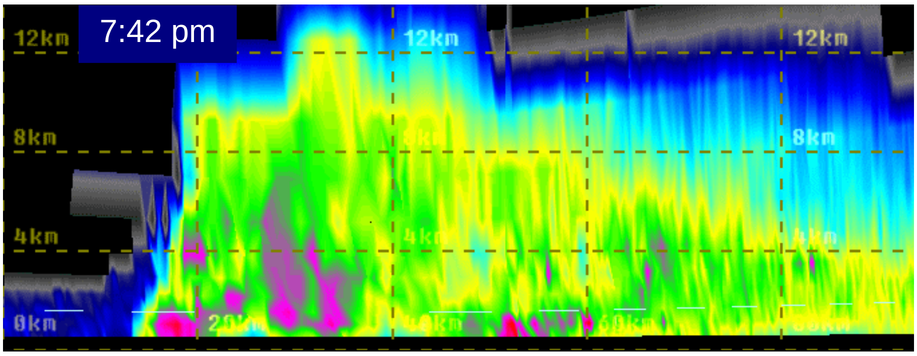


Figure 6. Interpretation of smoke plumes of Kilmore East and Murrindindi fires: (a) top of smoke plume, (b) highest within smoke plume radar values, and (c) vertical plume profile based on 1942 hour high resolution Laverton radar image. Credit: Bureau of Meteorology

Note: The vertical cross-sectional profile in (c) is along the blue line in (b) orientated NW to SE.

The dominant propagation mechanism in this case was mass fallout of spot fires at distances between 500 and 3,000 m, which would then coalesce in areas between ~300 and ~1,200 ha in size, producing energy releases varying between 1,000 and 4,000 GW[1], enabling the convection column to attain elevations over 12,000 m (Figure 5 (c)).

In the fourth case, the convection column would gradually dissipate, lagging 1–2 hours behind the cooler and moister air mass conditions and moderating wind speeds associated with the south-west change. In the fifth case, there happened to have been a combination of a persistent wind shift and a major change in wind direction that caused a fire storm over Marysville between 1900 and 1930 hours, which created an energy pulse that created a smoke plume reaching 8,000–9,000 m, which was ~3,000 m lower than the peak top height of the column over the Kilmore East fire, the surface fire energy being located over the northern parts of Mount Disappointment Plateau.

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[1] Estimate based on area growth and fuel consumption in each significant time step involving surface and canopy crown fires in the pink areas highlighted within a yellow oval outline in Figure 6 (b). Combustion rates were estimated to have been between 800 and 1,200 kW m^{-2} (refer back to

Table 1 which suggests a possible maximum estimate of ~1,500 kW m^{-2}).

Conclusion

A conceptual model of an extreme fire process cycle has been developed from six fire reconstructions of six Black Saturday fires, which were three dimensional in nature, involving live and dead forest fuels, set in complex hilly or mountainous terrain, and involving extreme fire weather embedded in turbulent air masses conducive to the development of deep smoke plumes and pyrocumulus. The proposed model is similar to that developed by Wade and Ward (1973) for the Bomb Range fire in Pond Pine-pocossin fuels in coastal northern Carolina. Both these studies reveal a more complex suite of spread and spotting mechanisms than have hitherto been described in most fire reconstruction studies, with the exception of (Chatto *et al.*, 1999). This model of extreme fire processes goes well beyond the conventional explanations of two-dimensional surface fire behaviour in eucalypt forests (McArthur, 1967, Luke and McArthur, 1978).

Improvements to this conceptual model will come from more detailed fire intelligence and analysis of the integrated dynamics of forest fuel combustion, chaotic fire spread, smoke plume development, and fire brand spotting processes. This is more likely to occur when fires burn in highly combustible drought-induced fuels burning under severe to extreme fire weather conditions. Analysing fire behaviour of severe to extreme fires at this level of detail will lead to a better understanding of the underlying fire processes and may lead to better fire simulation models that can better emulate the fire processes involved.

References

BUREAU OF METEOROLOGY (2010) Meterorological Aspects of the Kilmore East Fire on 7th February 2009. Melbourne, Victoria, Australian Government.

BURROWS, N. D. (2001) Flame residence times and rates of weight loss of eucalypt forest fuel particles. *International Journal of Wildland Fire,* 10**,** 137-143.

BYRAM, G. M. (1959) Chapter 6. Combustion of Forest Fuels. IN BROWN, A. A. & DAVIS, K. P. (Eds.) *Forest Fire - Control and Use.* McGraw-Hill Book Company.

CHATTO, K., TOLHURST, K. G., LEGGETT, T. & TRELOAR, A. (1999) Development, behaviour, threat and meteorological aspects of a plume - driven bushfire in West-Central Victoria: Berringa fire February 25-26, 1995. *Research Report No. 48.* Department of Sustainability and Environment.

DOLD, J. & ZINOVIEV, A. (2009) Fire eruption through intensity and spread rate interaction mediated by flow attachment. *Combustion Theory and Modelling,* 13**,** 763-793.

GELLIE, N. J. H., GIBOS, K. E., G., M., T., W. & SALKIN, O. (2010a) Reconstructing the spread and behaviour of the February 2009 Victorian fires. *3rd Fire Behaviour and Fuels Conference.* Spokane, Washington, International Association of Wildland Fire, Birmingham, Alabama.

GELLIE, N. J. H., GIBOS, K. E. & JOHNSON, K. (2010b) Relationship between severe landscape dryness and large destructive fires in Victoria. IN VIEGAS, D. X. (Ed.) *VI International Conference on Forest Fire Research.* Coimbra.

LUKE, R. H. & MCARTHUR, A. G. (1978) *Bushfires in Australia,* Canberra, Australian Government Publishing Service.

MCARTHUR, A. G. (1966) Weather and Grassland Fire Behaviour. *Leaflet No 100.* Canberra, Forest and Timber Bureau, Commonwealth Government.

MCARTHUR, A. G. (1967) Fire Behaviour in Eucalypt Forests. *Leaflet No 107.* Canberra, Forest and Timber Bureau, Commonwealth Government.

PARKYN, K., YEO, C. & BANNISTER, T. (2010) Meteorological Lessons learnt from Black Saturday. *Proceedings of 2010 AFAC Conference, Darwin.*

POMPE, A. & VINES, R. G. (1966) The influence of moisture on the combustion of leaves. *Australian Forestry,* 30**,** 231-241.

SHARPLES, J. J. & MCRAE, R. H. D. (2011) Atypical bushfire spread driven by the interaction of terrain and extreme fire weather. IN THORNTON, R. (Ed.) *AFAC 2011 Conference.* Sydney.

TEAGUE, B., MCCLEOD, R. & PASCOE, S. (2010) The February 2009 fires: final report, The Victorian Bushfires Royal Commission Melbourne, VIC.

WADE, E. D. & WARD, D. E. (1973) An analysis of the Bomb Range fire. *Res. Pap. SE-105. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 41 p.*

Sensor Network & Weather Data Stream Mining

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Abstract
Interest in environmental studies and awareness reflects sustainable growth. This in effect results in growing volume and speed of environmental data acquired from field sensors and systems. Real world environmental spatial data have the form of being vast, high-dimensional, raw, sparse, and lends itself to being dynamically streamed. Data with such characteristics calls for handling approaches and methodologies different from traditional ones in support for valuable environmental information. This paper proposes an efficient machine learning algorithm with less than 10% error bounds to extract bushfire hazard information from high arrival rate weather data streams using the resource-constrained wireless sensor network (WSN). The aim is to provide high spatial and temporal resolution bushfire hazard report. This could be achieved by employing dense multi-point and low cost weather sensors. The bushfire hazard prediction model of the Canadian fire weather index (FWI) system is implemented via in-network distributed computing. Simulation results indicate the potential of this approach to efficiently handle weather data stream mining with significant improvement in both temporal and spatial resolution.

Keywords: Wireless Sensor Network, Bushfire Hazard Prediction, Data Stream Mining, In-Network FWI Processor.

Introduction

Interest in environmental studies and awareness reflects sustainable growth. This in effect results in growing volume and speed of environmental data acquired from field sensors and systems. Real world environmental spatial data may have the form of being vast, high-dimensional, raw, sparse, and lends itself to being dynamically streamed. Data with such characteristics calls for online handling approaches and methodologies different from traditional ones in support for valuable environmental information and knowledge. Traditionally, environmental datasets are gathered and stored in a database from where different exploratory algorithms are run off-line to extract useful knowledge. Traditional algorithms and methodologies may either require extensive resources to cope with data arriving in a stream over time or fail to interact with events in real-time. In such systems with streaming data, exploratory algorithms such as automatic pattern detection and data summary are required to perform in an on-line fashion where knowledge is extracted from the data stream on the fly and raw data either be dropped or archived at a later stage.

This paper proposes an efficient machine learning algorithm with high performance in extracting bushfire hazard condition from high arrival rate weather data streams. The approach uses resource-constrained wireless sensor network (WSN). The proposed approach extracts clusters of highly likely bushfire hazard locations from distributed weather data streams. Based on a sliding window time model, the algorithm extracts clusters with a single pass over the current window of stream and scales well with limited memory and computational resources. The proposed approach is based on cluster network topology whereby the data routing protocol coordinates the weather stream learning process of the individual nodes in the network to achieve a global weather stream mining goal in an efficient manner. The bushfire hazard prediction model of the Canadian fire weather index (FWI) system is implemented here using in-network processing of fire indices.

Wireless Sensor Network (WSN)

A wireless sensor network (WSN) consists of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. Sensor nodes are normally small, inexpensive, consume low-power and have processing and communication capabilities. While each sensor node is limited in processing power, cloud of large number of nodes has the ability to measure a given physical environment in greater details. Besides computational power, sensor nodes are also energy and communication range limited [1]. Therefore designing and operating large WSN would require scalable architecture and energy-aware algorithms. The scalability objective is usually achieved through grouping sensor nodes into clusters whereby each cluster would have a leader node referred to as cluster-head (CH) [2].

Wireless network topology and wireless network protocol also play important role in the design of WSN. Network topology refers to the underlying physical or logical connectivity among the network devices [3]. The network protocol defines rules and conventions for communication between network devices.

The concept of Wireless Personal Area Network (WPAN) is developed for implementing short range and low power wireless network of devices. Wireless Sensor Network (WSN) is one of the technologies to realize WPAN. This allows for setting up low cost, low power and low data transfer rate wireless network in a particular area by deploying several network nodes [4].

Wireless Personal Area networks WPAN (IEEE 802.15.4 Standard Protocol) are designed for applications with relaxed throughput requirements and low power consumption. Among these standards are the low rate WPANs (IEEE 802.15.4/LR-WPAN) also known as ZigBee. This is intended to serve a set of industrial, residential and medical applications with very low power consumption and cost requirements. ZigBee is superior to other WPANs such as medium rate WPAN (IEEE 802.15.1/Bluetooth) and high rate WPAN (IEEE 802.15.3). The later is specifically suitable for communication of voice or images on WSN.

Weather data stream

A data stream is a real-time, continuous, ordered (implicitly by arrival time or explicitly by timestamp) sequence of items. It is impossible to control the order in which items arrive, nor it is feasible to locally store a stream in its entirety [5]. A data *stream* is a sequence of data records called *tuples*. A *tuple* is similar to a row in a database table and contains fields of parameter values. A field is similar to a column in a database table. In a high-volume streaming application, the data streams flow into the application and are processed in real time. Figure 1 illustrates a stream of weather data tuples:

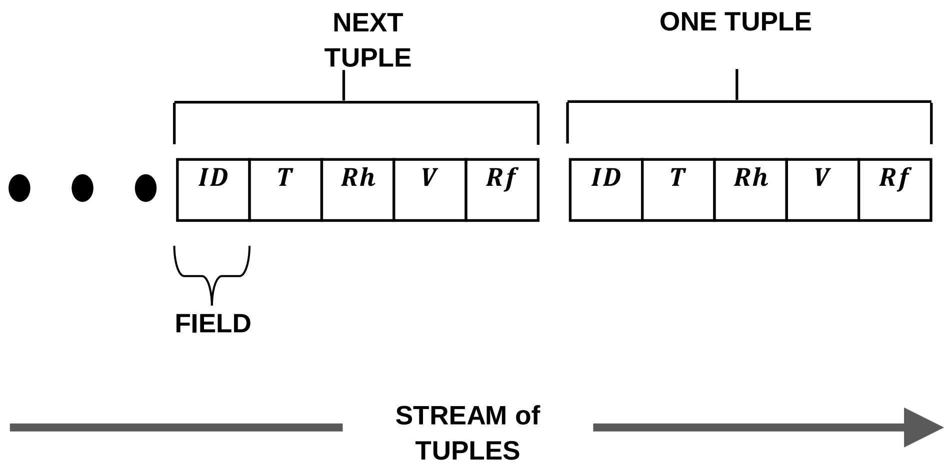

Figure 1: Weather Stream Tuples.

Data stream is a continuous sequence of tuples where each tuple has a timestamp automatically added at the time of arrival. When the source of such tuples is a weather station or the fields of the tuples constitute weather parameters, we can call the data stream a weather data stream. Here the weather data stream consists of Air temperature (T), relative humidity (Rh), wind speed (V), and rain fall or precipitation (Rf).

This study considers wireless sensor nodes as the sources of weather data streams. Hence the weather data stream is inherently distributed. The sensor nodes are linked in a two-tiered cluster topology such that the weather data stream arriving at CH nodes may exhibit bursty data rates. In this context, a weather data stream w is an unbounded sequence of elements $\langle w,t \rangle$, where w is weather data, and t is a monotonically increasing timestamp indicating the arrival time of the elements. w is a vector of weather values, $w = (T, Rh, V, Rf)$.

Bushfire hazard prediction model

Bushfire hazard prediction considered here is based on the indices of the Canadian Bushfire Weather Index (FWI) system. The FWI system is the most comprehensive and thoroughly researched bushfire modeling system [6]. It has been successfully applied in various types of forests. The FWI system models the complex relationships between the forest weather variables (fire weather observations), the forest floor moisture profiles known as Fuel Moisture Codes, and the Fire Behaviour Indices. The six standard components of the FWI System provide numerical ratings of relative wildland fire potential. The system is dependent on weather parameters only and does not consider differences in risk, fuel, or topography. It provides a uniform method of rating fire danger across wildland. The FWI system [7] is used as a representative system to demonstrate the capability of the WSN in bushfire hazard prediction.

Distributed weather stream mining framework

Weather data stream mining is the science of extracting useful information from continuously arriving large sets of weather data stream. A commonly used data mining technique, clustering, will be used to extract useful information from the weather data streams which in conjunction with the FWI bushfire model provides a mechanism to predict bushfire hazard. Clustering is the classification of datasets (objects) into different groups by partitioning sets of data into a series of subsets (clusters). Clustering algorithms seek to group data with maximum similarities inside the same cluster and have maximum dissimilarities between different clusters.

While WSN nodes are capable of probing and acquiring weather data steams at high temporal & spatial resolutions, they have known resource constraints to process the acquired data stream efficiently. Energy, computational power, memory, and bandwidth are main constraints of WSN’s. Requirements for processing bushfire hazard prediction at individual nodes impose memory, computational power and energy needs beyond that available. On the other hand, transmitting the weather data stream to a central location will drain the available energy and bandwidth resources available for the WSN. Therefore a frame work is designed where the weather stream mining for bushfire hazard prediction tasks are broken down into smaller sub-tasks. This is then distributed on individual nodes to process so that the weather data stream mining process can be embedded within the sensor network. This approach distribute the responsibilities on the sensor nodes, the cluster heads and the network sink for achieving the necessary processing of the FWI.

Sensor nodes processing sub-task

Initially, the sensor nodes transmit a tuple of their stream to their respective CHs and wait for the CH’s response. The CHs respond to each sensor node by transmitting cluster structures and related operational boundaries to the members of their group. Following this initial transmission, the sensor nodes continuously compare their incoming stream with the received local cluster. If their input steam falls within a given tolerance of their local cluster, then the sensors categorize the new stream as belonging to the local cluster and avoid transmission. However, if the new input stream deviates significantly from the local cluster, then they transmit the new tuple to their CH and wait to receive the new local cluster structure.. Therefore the sensor nodes, following the initial transmissions, only transmit their input streams whenever there is significant drift in their acquired stream content.

Cluster heads processing sub-task

The basic idea of stream processing at this level is to identify local clusters of the streams generated by all member nodes. Processing here assists sensor nodes to optimize communication by sending them their local cluster structures so that sensors will transmit new input streams only when they detect significant deviation in their streams and request an update. Cluster head processing also optimizes cluster head-to-Sink communication by transmitting cluster summary of their local streams to the Sink rather than the whole local stream.

CHs form and maintain a short table of Tuples of their member nodes- known as Local Stream Base (LSB) shown in Table1. Initially the CHs, does clustering of the Tuples in the Local Stream Base using subtractive fuzzy cluster mean (SUBFCM) algorithm [8] and multicast the local cluster to the associated member nodes. CHs further send local clusters and associated node ID's to the Sink for computation of global clusters for location based event cluster mapping. During subsequent stages, if CHs receive a stream Tuples from member nodes (i.e when the new incoming streams significantly deviate from the local clusters), they update the LSB. If a certain number of set desired update requests ∊ are received, then the CHs re-cluster the stream Tuples in LSB and update each member nodes and the Sink.

Let $\langle w,t \rangle_i (i = 1,2,3,...,m)$ be the tuples a CH initially received from its m member sensor node. CHs using the SUBFCM algorithm partition $\langle w,t \rangle_i$ into different clusters, c_i, where i is the number of cluster centers determined automatically by the SUBFCM algorithm. The cluster centers are then used as inputs to the FWI mathematical models to produce the bushfire hazard prediction indices; fuel codes and fire behavior indices. The SUBFCM algorithm uses the streams from the LSB table and writes the output into the CHs output vector table, a snap of which is shown in Table 2.

Sink processing sub-task

The network sink, being the most capable node, undertakes the most computation intensive task. Sink processing is mainly carried out to extract the global sensor stream clusters based on the local clusters received so far and to present the sensor stream mining results. The sink also facilitate sensor stream analysis to a user. It maintains a table of stream clusters and associated node IDs of all previous transactions- now known as Global Stream base (GSB). On every communication with CHs the Sink updates its GSB and performs global stream clustering.

Table 1: Snippet of CHs' local stream base (LSB)

Member ID	Temperature	Relative humidity	Wind speed	Rain fall	time
1	T_1	Rh_1	V_1	Rf_1	t_1
2	T_2	Rh_2	V_2	Rf_2	t_2
3	T_3	Rh_3	V_3	Rf_3	t_3
-	-	-	-	-	-
n	T_n	Rh_n	V_n	Rf_n	t_n

Table 2: Snippet of CHs' output vector table

Cluster Center	Member tuple	Member node id
c_1	$\langle w,t\rangle_1, \langle w,t\rangle_3$	1, 3
c_2	$\langle w,t\rangle_2, \langle w,t\rangle_4 \langle w,t\rangle_5$	2, 4, 5
-	-	-
c_x	$\langle w,t\rangle_x$	x

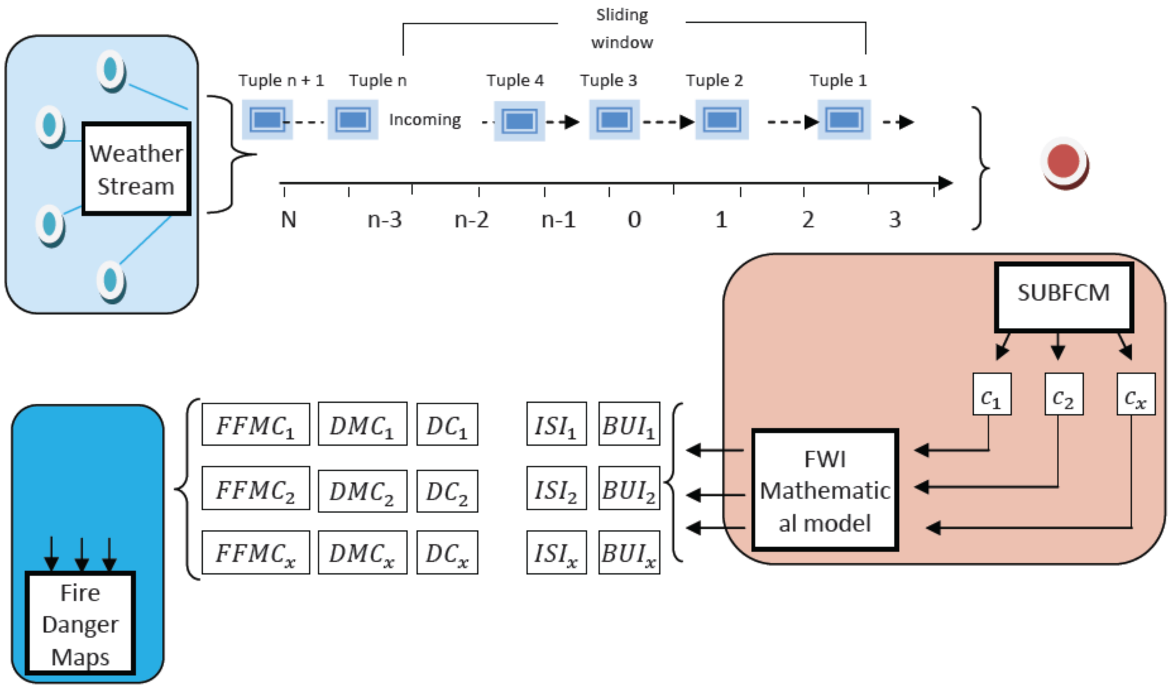

Figure 2: Distributed weather data stream mining flow diagram

WSN architecture

Cluster based WSN architecture is a key aspect of this work as it enables in-network distributed weather data stream mining. Clustering in a WSN adds scalability, reduces computational complexity of data gathering and routing protocols and enhances network performances [9]. Using clustering in a WSN helps WSN resource constraints, by allowing organization of the sensors in a hierarchical manner, grouping them into clusters and assigning specific task to the sensors in the cluster, before moving the information to higher levels [10]. The more capable nodes are located in strategic places to allow them to act as CHs and lower capacity sensors are placed around the CHs to sense the weather parameters and send it to the sink via their CHs. In our current organization there is no CH selection phase as the CHs are predetermined making the clustering protocol simple and efficient. Cluster formation is based on sensor nodes initially broadcasting join requests and listening for responses from CHs within the communication range. The nodes then join the nearest CH based on the received signal strength indicator (RSSI) and form clusters. The CHs only allow a maximum number of member nodes as optimal for stream mining algorithm. This forms a dynamic and robust cluster network whereby nodes can migrate to an alternative cluster upon either failure of current CH or association of the sensed data streams with the current CHs structure. In the data transmission phase or steady-state phase, CHs transmit the weather stream multi-hop to a sink. Hence the protocol forms a hierarchical structure to enable distributed stream mining and prolonged network lifetime. The cluster architecture is shown in figure 3 below.

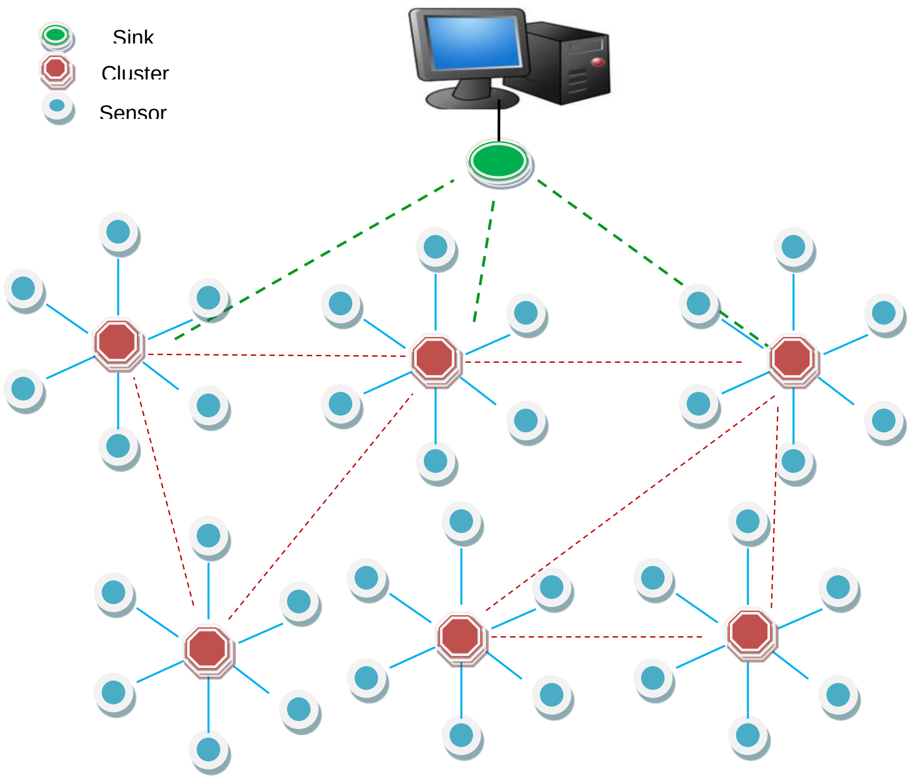

Figure 3. The WSN cluster architecture

Simulation setup

The distributed weather data stream mining model is developed using MATLAB environment. Three different types of weather data stream processing model objects are created using MATLAB representing sensor node, CH, and sink sub-tasks. The modular algorithms running within these objects described in sections *Bushfire hazard prediction model* and *Distributed weather data stream mining framework* are also programmed using MATLAB script language. These are the SUBFCM clustering and the FWI prediction algorithms.

TrueTime 2.0 beta 6 is used to model and simulate the wireless sensor network. TrueTime is a MATLAB/SIMULINK based network modelling and simulation tool. TrueTime provides customizable Kernel model, analogue input model, wireless network protocol model, location, and battery models. For the purpose of this study, the Kernel model is customized to represent Texas Instruments (TI) MSP430F2274 Microcontroller used to host the weather data stream mining application. The wireless network model is also customized to represent Chipcon's CC2530 IEEE 802.15.4 radio transceiver along with ZigBee wireless protocol stack. The analogue input model is used to represents temperature, relative humidity, precipitation, and wind speed sensor inputs. The sensor nodes battery model is made to represent standard two AAA size alkaline batteries, which normally powers the physical TI's MSP430 and Chipcon's CC2530 radio transceiver. The Kernel model further provides a simple interface for algorithms and models developed in Matlab or Simulink to run on. The location of each node can also be set through the x and y inputs or can be interfaced to GPS modules for dynamic localization. However, for this purpose we determined the locations as no mobile node is considered. The simulation parameters setting are shown in Table 3 below.

Table 3: Simulation parameters settings.

The WSN-WFHP Model Parameters

Model Parameter	Value	Model Parameters	Value
Network Type	ZigBee	Receiver signal threshold (dBm)	-85
Network Number	1	Path-loss exponent	3.5
Number of Nodes	19	ACK timeout (sec)	.0004
Data rate (bits/s)	25000	Retry limit	5
Minimum frame size (bits)	16	Error coding threshold	0.03
Transmit power (dBm)	0		

Results and Analysis

Real weather data sets recorded at several meteorology stations in South Island, New Zealand, obtained from National Institute of Water and Atmospheric Research (NIWA) is used as benchmarks to validate the system performance. These data sets consist of weather parameters (Temperature, relative humidity, Rainfall and Wind speed) along with their corresponding Canadian FWI indices (FFMC, DMC, DC, ISI, BUI, and FWI) collected hourly for the years 1994 to 2004. The data contains burst mode weather stream as each element is acquired periodically at one hour time intervals. During simulation, for the purpose of model validation on a continuously incoming weather data stream rather than the burst mode, the data is fed to the sensor nodes in intervals from every 10 seconds to every one second incrementally.

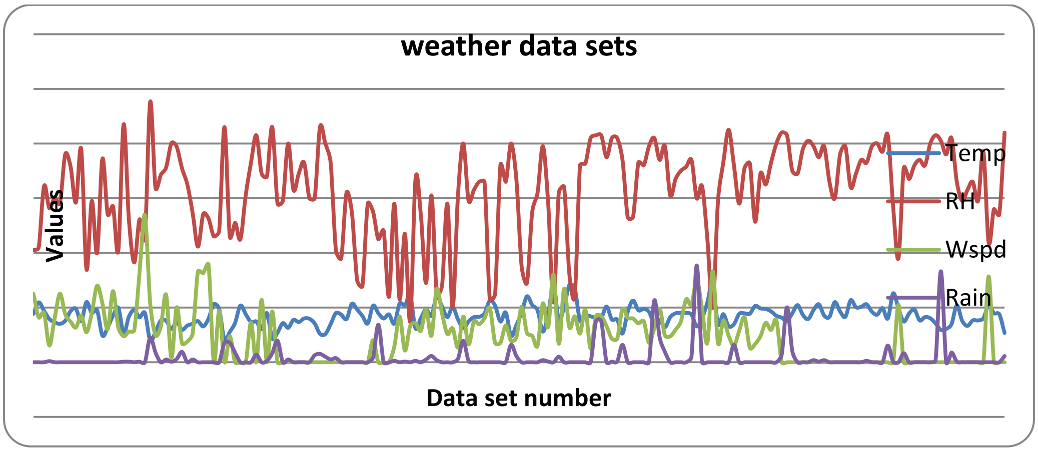

Figure 4: plot of weather data stream sets used for testing the system

Experiment 1

A model consisting of two clusters, with 9 sensor nodes in each cluster apart from the CH nodes is simulated. A weather data stream consisting of 180 records (Figure 4) is fed to each sensor model every 10 seconds and simulation continued for 30 minutes. The model computed FWI results are plotted along with the actual FWI values in figure 5. This experiment is repeated varying data feed periods from 9 seconds down to 1 second. The resulting average errors of FWI and FFMC indices are plotted against the stream periods in figure 6.

Experiment 2

This experiment is setup to investigate if the ZigBee network parameter, data rate, has an effect on the accuracy of the results generated by the model. The ZigBee network data rate is varied from 50 to 250kbps. The average FWI error against the weather stream data period repeated at different network data rates is shown in figure 7.

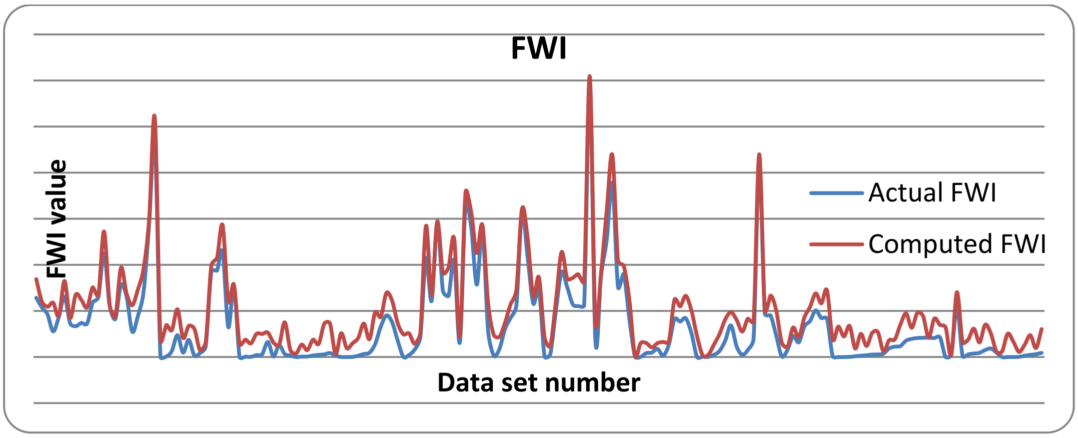

Figure 5: Plot of actual FWI values versus the computed FWI values

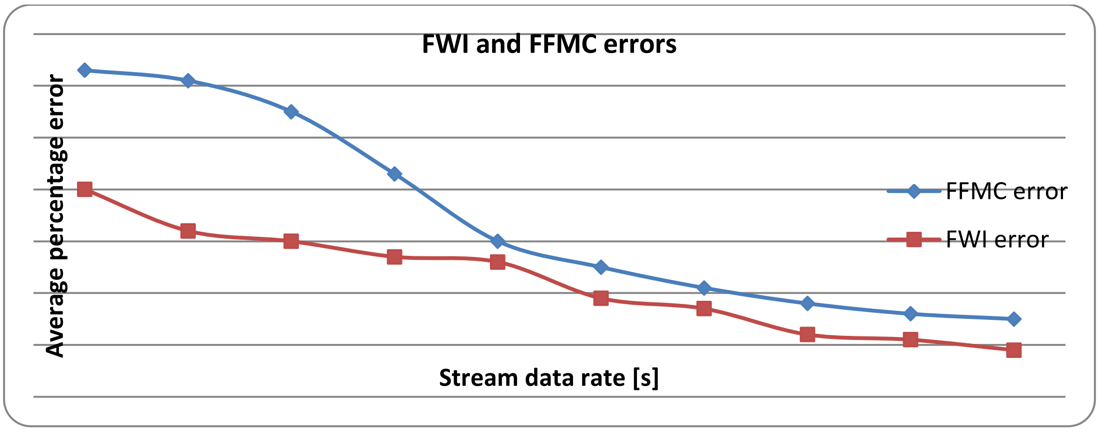

Figure 6: Average FWI error

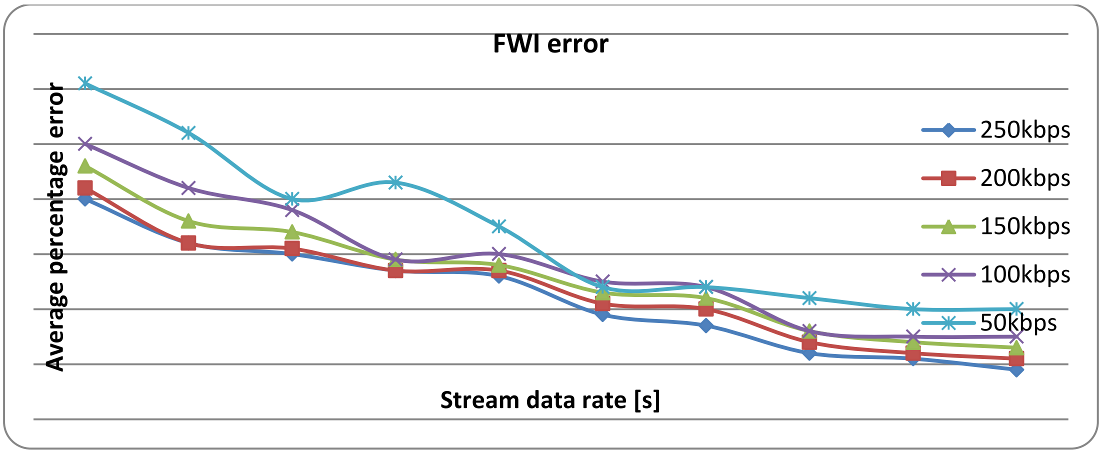

Figure 7: Average FWI error for different network data rates

Discussions and conclusions

A distributed weather data stream mining model for bushfire hazard prediction application of wireless sensor network is proposed. The model makes use of the individual wireless sensor node's computation capability coordinated through wireless network architecture to compute bushfire hazard prediction indices as given in the FWI system. TrueTime network modelling and simulation tool is used for modelling the proposed system. Real weather data streams containing the weather parameters required for the computation of FWI system indices is used to validate the model capability.

Simulation results show that the model is able to handle weather data streams acquired at 1 second intervals with reasonable errors. For the simulation settings as shown in table 3, the resulting FWI system indices error is bound to less than 7%. The worst case error bounds observed through simulations based on the real weather data sets indicate that the algorithm provides high performance for the conditions of the simulation. The average errors for the various simulations also shows that network data rate have significant consequences on model performance as shown in figure 7.

The weather stream data sets used are tuples generated at hour time intervals and transformed to shorter intervals. This may have an effect on the model performance. Further work has to validate the model on continuously generated streams. Effects of other network parameters and resource consumption is yet to be investigated.

References

[1] I. F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *Communications Magazine, IEEE,* vol. 40, pp. 102-114, 2002.

[2] A. Ameer Ahmed and Y. Mohamed, "A survey on clustering algorithms for wireless sensor networks," *Comput. Commun.,* vol. 30, pp. 2826-2841, 2007.

[3] Z. Mingze, C. Mun Choon, and A. L. Ananda, "Location-Aided Topology Discovery for Wireless Sensor Networks," in *Communications, 2008. ICC '08. IEEE International Conference on*, 2008, pp. 2717-2722.

[4] Y. J. Pan and H. T. Nian, "The development of microsystems device based on Wireless Sensor Network," in *Computer Communication Control and Automation (3CA), 2010 International Symposium on*, pp. 419-422.

[5] Lukasz G., Tamer M., and zsu, (2003) Issues in data stream management. *SIGMOD Rec.,* **32**, 5-14.

[6] Mohamed, H., and Bagheri, M., 2009 Forest Fire Modeling and Early Detection using Wireless Sensor Networks, *Ad Hoc & Sensor Wireless Networks*, 7(3-4), pp.169--224, April 2009.

[7] http://cwfis.cfs.nrcan.gc.ca/en_CA/background/dsm/fwi

[8] Sabit, H., Al-Anbuky, A., & Gholam-Hosseini, H. (2009),"Distributed WSN Data Stream Mining Based on Fuzzy Clustering," in *Ubiquitous, Autonomic and Trusted Computing, 2009. UIC-ATC '09. Symposia and Workshops on*, 2009, pp. 395-400.

[9] Diallo, C., Marot, M., & Becker, M. (2010), "Single-node cluster reduction in WSN and energy-efficiency during cluster formation," in *Ad Hoc Networking Workshop (Med-Hoc-Net), 2010 The 9th IFIP Annual Mediterranean*, pp. 1-10.

[10] Liliana MCA, & Nidal N, (2006), "Comparison of Clustering Algorithms and Protocols for Wireless Sensor Networks," in *Electrical and Computer Engineering, 2006. CCECE '06. Canadian Conference on*, 2006, pp. 1787-1792.

Micro-scale Forest Fire Weather Index and Sensor Network

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Abstract

Micro-scale fire weather index (FWI) system locates impending bushfires to their exact locations well before their occurrence and remotely alerts the authorities with detailed fire management information. It enables high temporal and spatial resolution of information on bushfire activity. This is considered ideal for early warning system of bushfire-prone regions. A large number of low-cost, intelligent and wireless sensors are deployed within the area of interest with the sensors located at short distances apart. These sensors intimately interact with the physical environment of the bush/forest floor and gather the necessary information which is shared among the neighbouring sensors wirelessly. The information is fed to the hazard prediction algorithm embedded into each sensor unit to generate an alarm for any fire hazard and for data management. The system could be organized to alert the fire management authority timely via the available backbone communication (GSM, Internet or satellite) link.

Keywords: Wireless sensor network, Micro-scale, Bushfire hazard, Fire Weather Index

Introduction

The existing standard Fire Weather Index (FWI) system acquire current weather parameters, elevation and produces the sub-indexes of the FWI system daily at noon local time. The FWI indexes are indicators of daily potential and behaviour of bushfires. The FWI system relies on sparsely distributed meteorological stations as its current weather parameter data sources. Data from the meteorological stations are transferred to a central processing and repository centre via satellite communication. At the central processing and repository centre, weather parameter grids for the entire national area will be produced. Geographic Information Systems (GIS) software is used to interpolate the weather data between stations taking into account elevation data to produce gridded weather maps. The FWI system components are then calculated on a cell-by-cell basis according to the equations in [1] to produce the FWI maps. While the existing FWI system does a great job in producing daily bushfire hazard maps, it lacks several desirable capabilities which are very important from fire management and control point of view.

Limitations of the existing FWI system

In the existing FWI system, weather data grids between stations are obtained by interpolating data from outlying stations. Therefore, the hazard prediction spatial resolution is estimate rather than actual. Consequently, the hazard maps for locations further away from the stations are estimates and potentially of low accuracy. In cases of a station failure, the region around the station is cut-off and the data grids' values between stations will degrade in accuracy. Further, the standard FWI system produces fire hazard ratings on daily (24 hour time resolution) basis and hence is unable to capture fire potential and behaviour fluctuations at higher time resolution, information which enables fire managers to understand and control fire dynamics at higher time resolutions. The system as is does not allow real-time querying of specific forest domain at specific times for hazard rating. This may be necessary when there are specific domains of the forest that require special attention such as urban-rural-interface, national parks, and nuclear facility. A new station start-up and integration also involves high cost, labour and long time.

Micro-scale FWI system is an attempt to implement scaled-down version of the Canadian FWI system for fire danger monitoring of a relatively smaller geographic area. It considers an area as small as few square meters or as large as many square kilometres. It is specifically important for local forest zones where the nature of the vegetation and topography largely differs from the surrounding forest area. It is based on deployment of large number of low-cost, low-power, and small-size weather sensor nodes linked by low-power wireless communication network –Wireless Sensor Network (WSN).

The weather sensor nodes as the basic building blocks of the micro-scale FWI system are capable of individually probing their surroundings and acquiring weather parameters such as temperature, relative humidity, wind speed, and rainfall. They are also capable of minor data processing and short range wireless communication with other nearby nodes.

In order to monitor a specific forest zone using the micro-scale FWI system, the forest zone is divided into grids of small square cells (e.g. 20m x 20m) and a weather sensor node is placed in each cell. Since the size of the square cells can be as small as possible, high spatial resolution weather parameter measurements can be made by taking multiple measurement points in the region. The fire danger rating values' accuracy is robust to a single or a few sensor failures due to the dense measurement points. The size of the forest zone that can be monitored using micro-scale FWI system is determined by the WSN which usually employs numerous low cost nodes communicating over multiple hops to cover a large geographical area.

The micro-scale FWI system also provides high temporal resolution fire danger rating as the system can make low-power frequent measurements and transmit (e.g. hourly) to base station. The system can also operate in event detection mode in which, the individual sensor nodes instantaneously send information to the base station upon detection of predetermined danger rating threshold.

The micro-scale FWI system allows intermittent interaction to the normal (e.g. hourly) operation for querying specific region's situation. Such queries can be generated and injected into the network at the base station.

The data sources and FWI system components are carefully analysed and calculations are transposed to suite relatively smaller area fire danger rating system.

Related work

A wildfire is any uncontrolled fire in combustible vegetation that occurs in the countryside or a wilderness area [2]. Other names such as bush fire, bushfire, forest fire, grass fire, wild land fire may be used to describe the same phenomenon depending on the type of vegetation being burned [3]. Wildfire differs from other fires by its extensive size, the speed at which it can spread out from its original source, its potential to change direction unexpectedly, and its ability to jump gaps such as roads, rivers and fire breaks [4].

Wildfires may be ignited by a number of natural causes such as lightning, volcanic eruption, sparks from rockfalls and spontaneous combustion [5, 6]. However, the most common causes of wildfires varies throughout the world, and includes human sources such as arson, discarded cigarettes, sparks from equipment, and power line arcs [7, 8]. These ignition sources have to be brought into contact with combustible material such as vegetation for the fire to occur. Weather and climatic conditions play major roles in drying the vegetation to ignition point. Hence weather and climatic conditions are the major parameters in wildfire potential and spread modelling.

An adequate fire-intelligence system is the cornerstone for effective management of wild land fire. A major component of any fire-intelligence system is a fire-danger rating system. The purpose of fire-danger rating systems is that where the fire environment (i.e. weather, fuels, and topography) varies in space and time, and where fire-management resources are costly and limited, a means is needed to allocate the available resources across a region or country from day to day or place to place, on the basis of fire danger. The process of systematically evaluating and integrating the individual and combined effects of the factors influencing fire potential is referred to as fire-danger rating. Fire-danger rating systems provide for one or more qualitative and/or numerical indices of ignition potential and probable fire behaviour [9].

One of the most comprehensive forest fire danger rating system in North America is the FWI system developed by the Canadian Forest Service (CFS) [10]. The Canadian FWI System is based on several decades of forestry research [11] and will be used for the purpose of this work.

FWI System

The FWI was originally proposed by Van Wagner [1] for the wildfire prevention in Canadian forests [12]; it is calculated from a set of weather parameters and described the evolution of the current moisture content of different fuel layers of the forest system, together with the influence of wind in fire propagation. It is widely used by many fire prevention systems in the world [13]. The FWI system models the complex relationships between the forest weather variables, the forest floor moisture profiles, and the Fire Behaviour Indices [1,14]. The FWI system consists of six components that account for the effects of different forest weather variables on likelihood and behaviour of forest fires; the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC), the Initial Spread Index (ISI), The Build Up Index (BUI), and the FWI. The general structure of the FWI system with modifications for Micro-scale FWI is shown in figure 1 below.

Fine Fuel Moisture Code (FFMC)

The FFMC model requires the current moisture condition m of the fuel, which is determined by the combined effect of rainfall and absorption/desorption of atmospheric moisture. Given as

$$FFMC = 59.5\frac{250-m}{147.2+m} \qquad (1)$$

Duff Moisture Code (DMC)

The duff moisture code (DMC) is a combined effect of rainfall modified duff moisture code DMC_r and evaporation from the duff layer DMC_d which are functions of temperature (T), relative humidity (RH) and effective day length (L_{eff}).

$$DMC = DMC_r + DMC_d \qquad (2)$$

where $DMC_r = 244.72 - 43.43\ln(m_r - 20)$ and $DMC_d = 1.894(T+1.1)(100-RH)L_{eff}10^{-4}$.

Drought Code (DC)

The drought code (DC) is determined by estimating the change in a moisture equivalent scale caused by a source term and loss term. Given as:

$$DC = DC_r + DC_d \qquad (3)$$

where $DC_r = 400\ln(800/Q_r)$ and $DC_d = 0.5(0.36(T+2.8)+L_f)$,

DC_r is the rainfall modified drought code, Q_r is rain modified moisture equivalent scale. DC_d is moisture loss from duff layer, T is temperature, and L_f is seasonal day length adjustment.

Initial Spread Index (ISI)

The initial spread index (ISI) is related to FFMC and wind speed, v, limited to a maximum of 100 km h^{-1}. It has the wind speed component, FW and the FFMC component, FF, related through the current moisture condition m.

$$ISI = 0.208(FW)(FF) \qquad (4)$$

where $FW = e^{0.5039v}$ and $FF = 91.9e^{-0.1386m}\left(1+\frac{m^{5.31}}{4.93\cdot 10^{7}}\right)$.

Build Up Index (BUI)

The build up index (BUI) is calculated by combining DMC and DC. A form of the harmonic mean of the DMC and the DC is used to calculate the BUI [11], to ensure that changes about smaller values of either the DMC or the DC will receive a greater weight.

$$BUI = \begin{cases} \dfrac{0.8DMC\cdot DC}{DMC+0.4DC} & DMC \le 0.4DC \\ DMC-\left(1-\dfrac{0.8DC}{DMC+0.4DC}\right)\left[0.92+(0.0114DMC)^{1.7}\right] & DMC > 0.4DC \end{cases} \qquad (5)$$

Fire Weather Index (FWI)

The fire weather index (FWI) is a function of both the BUI and the ISI and is given as;

$$FWI = \begin{cases} B & B<1 \\ e^{2.72(0.434\ln B)^{0.647}} & B \ge 1 \end{cases} \qquad (6)$$

Where, $B = 0.1(FD)(ISI)$ and $FD = \begin{cases} 0.626BUI^{0.809}+2 & BUI \le 80 \\ \dfrac{1000}{25+108.64e^{-0.023BUI}} & BUI > 80 \end{cases}$

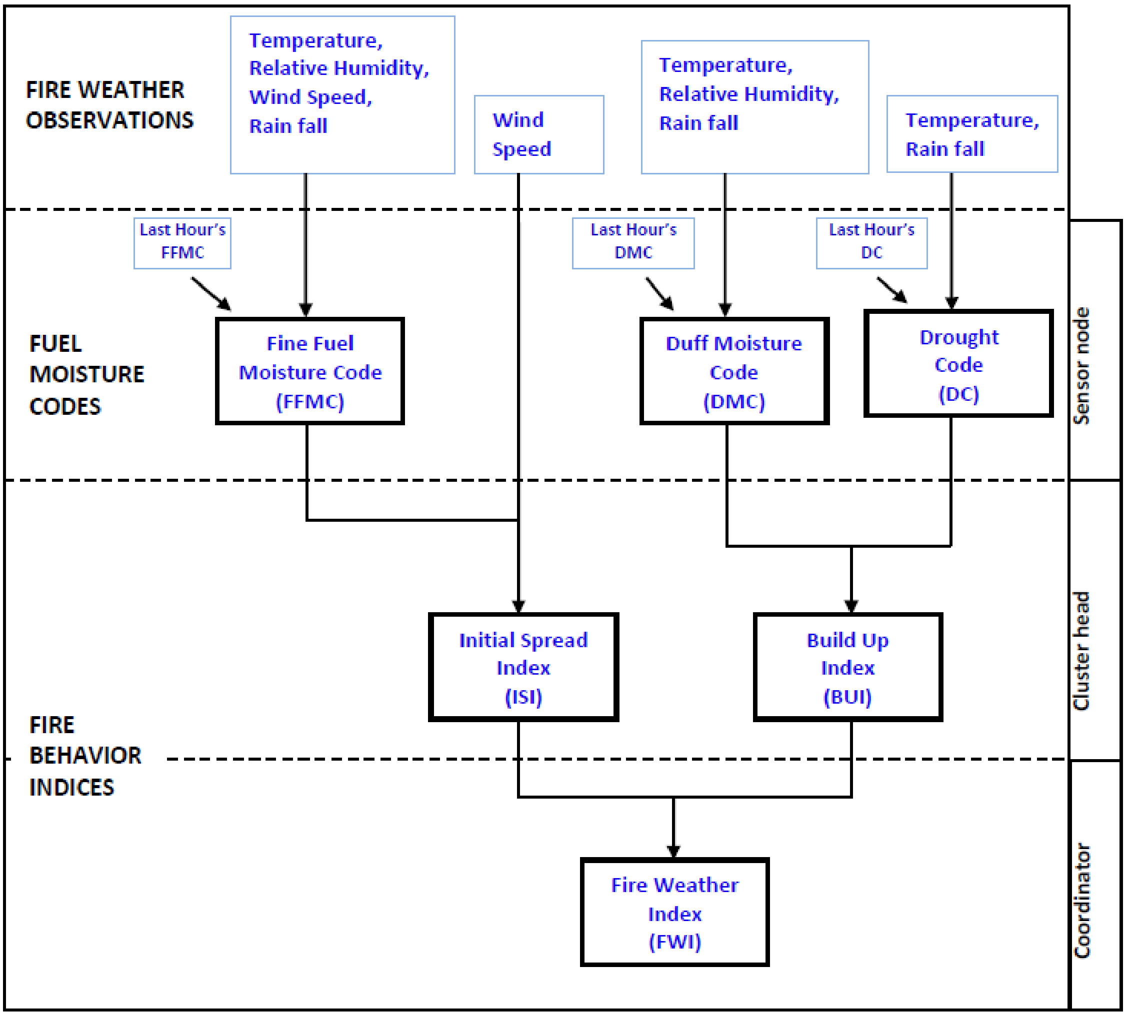


Figure 1: The general structure of the FWI system with modifications for Micro-scale FWI

WSN architecture

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to *monitor* physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and to cooperatively pass their data through the network to a main location [15]. However, wireless sensor nodes are resources constrained devices; energy, computational power, and bandwidth are typically limited. Sensing, data processing and communication tasks are the major consumers of the nodes' resources. WSN design requires efficient implementation of these tasks so that un-tethered WSN operational life is long enough for the specific application.

The design of WSN for Micro-scale FWI system considers cluster topology where sensor nodes are grouped into clusters based on their physical location. Each cluster is managed by a more capable node called cluster head (CH). Data routing within each cluster forms star topology. However, the CHs are mesh linked to a network coordinator (NC) so as to extend the network coverage beyond a single hop range. The mesh link also allows for robust data routing by avoiding faulty path to the NC.

The network coordinator is connected to a base station node which is gateway to remote manager node via general public network (GSM, Internet). Remote manager node is a point of fire management decision and fire hazard dispatch for general public user nodes. The architecture of the system is shown in figure 2.

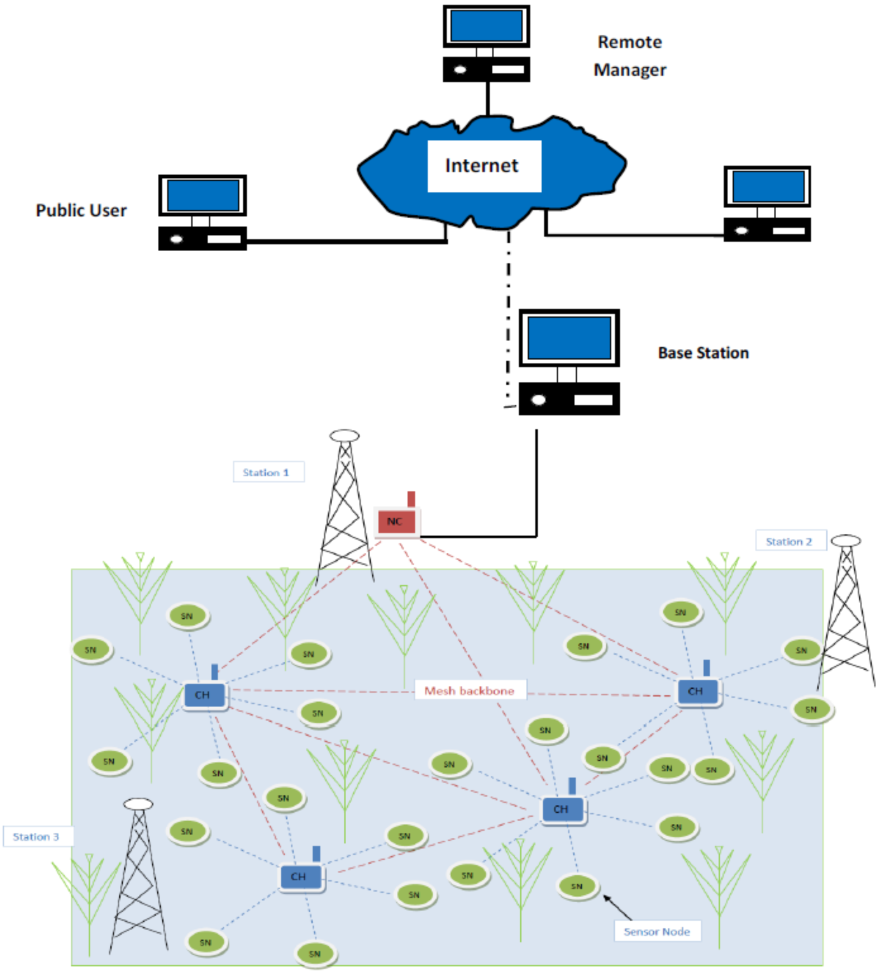


Figure 2: The Micro-scale FWI system WSN architecture

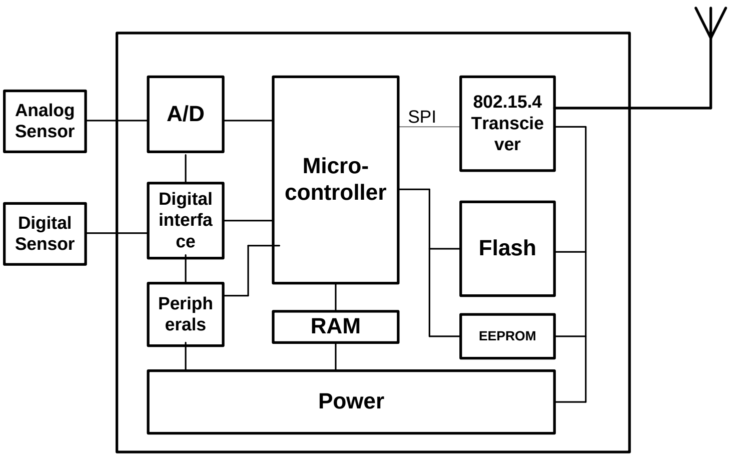
Micro-scale FWI

The Micro-scale FWI system addresses the limitations of the existing FWI system by modelling the FWI system as a distributed wireless sensor network application. Unlike the standard FWI System developed for a macro scale area (e.g. a country or a continent), Micro-scale FWI system does not depend on few large weather stations located tens of kilometres apart for current weather data sources. Current Weather data sources in Micro-scale FWI System are the tiny wireless sensor nodes equipped with various weather sensors and deployed on a given area short distances apart. Due to the short distances between the weather data sources, micro scale FWI does not need elevation information of a given area and hence simplifies FWI system implementation. The Micro-scale FWI system uses wireless capable sensor nodes as weather data sources to form a fire weather network based on wireless sensor network. Distributed in-network data clustering algorithm is used to efficiently compute the FWI indices locally in real-time utilizing a specific WSN architecture (figure 2). Basic components of the Micro-scale FWI system are described below.

Data sources:

The Input to the Micro-scale FWI system is current weather data. Atmospheric temperature, relative humidity, wind speed, and precipitation or rain fall are the weather parameters of interest. Micro-scale FWI acquires these weather parameter data from individual wireless sensor nodes also known as motes. A typical wireless sensor node, an entity of a wireless sensor network, is capable of performing some processing, gathering sensory information, and communication with other nodes in the network [15]. See figure 3 for typical architecture of sensor network nodes.

The main components of a wireless sensor node are a microcontroller, transceiver, memory, power source, and sensors. Power source for the nodes are often batteries. The sheer number of sensor nodes required for most application makes battery replacement expensive [16]. Therefore, using dynamic power management schemes and using batteries rechargeable through solar cells are often recommended. Sensors are used by the node as its means of interacting with the physical world. The continual analogue signal produced by the sensors is digitized by the analogue-to-digital converter (ADC) unit of the microcontroller and is passed on to the application for further processing. As wireless sensor nodes are typically very small electronic devices, they can only be equipped with a limited power source. Hence, sensors have to have extremely low energy requirement in probing the environment.



‘**Figure 3:** Wireless sensor node architecture

Fire weather Network

Micro-scale FWI system acquires current weather parameters data simultaneously from a large number of sources (sensor nodes) densely distributed on a given micro area. The weather data sources are linked via wireless communication to form a structured fire weather network. The weather data acquired by large sensor nodes at different locations in the area monitored need to be transmitted to a base station to be processed and provide fire potential, prediction, and behaviour information to fire managers. The fire weather network structure consists of sensor nodes as data sources, cluster heads as point of data aggregation and false alarm filtering, and a network coordinator as a gateway to the base station.

The fire weather network uses industrial, scientific, and medical (ISM) band radio spectrum in the license-free communication frequencies 433 MHz, 868 MHz, 915 MHz, and 2.4 GHz. A standard IEEE 802.15.4 based ZigBee wireless protocol stack is used for the purpose of evaluating this study. The IEEE 802.15.4/ZigBee protocol enables every node 250 Kbps (kilobits per second) data rate at a very low power of 1 mW (mili watt) for an average transmission range of 100m. ZigBee enables virtually unlimited number of nodes per network.

Data processing

Micro-scale FWI involves distributed computing of the FWI indices. The different nodes of the fire weather network (sensor nodes, cluster heads, and coordinator) are assigned tasks of computing some part of the FWI indices. The WSN architecture (figure 2) coordinates the individual nodes tasks so that the complex computation of the FWI indices can be achieved through minor local computations working together as a whole. The distributed computation method enables fast near real-time fire indices production. The Micro-scale FWI system further embeds incremental distributed FWI information clustering algorithm-SUBFCM [17] throughout the network in order to efficiently utilize the nodes energy and network bandwidth resources and consequently extend the network lifetime.

The sensor nodes are assigned the task of periodically computing local fuel moisture codes (equations 1, 2 and 3) and transmit to their Cluster Head (CH). The CHs are assigned the task of computing fire behaviour indices (equations 4 and 5). Besides the fire behaviour indices, the CHs execute the indices clustering algorithm locally and transmit to the network coordinator. The network coordinator is assigned the task of computing the final FWI index based on the indices received from all CHs. The network coordinator produces global clusters of indices.

The Base station assisted by the coordinator produces periodic virtual clusters. The virtual clusters are clusters of fire hazard rating or intensity mapped onto the exact physical node locations as shown in figure 4. The virtual clusters provide spatial map of the hazard distribution as an overlay to the physical node clusters. The virtual clusters mapped onto the physical nodes' locations map provide geographic distribution of the hazard situation. The virtual cluster could be viewed periodically and could provide dynamic information of the fire hazard situation such as speed and direction of hazard movements. The virtual cluster information can further be utilized to reconfigure the physical cluster for better and efficient WSN resources utilization.

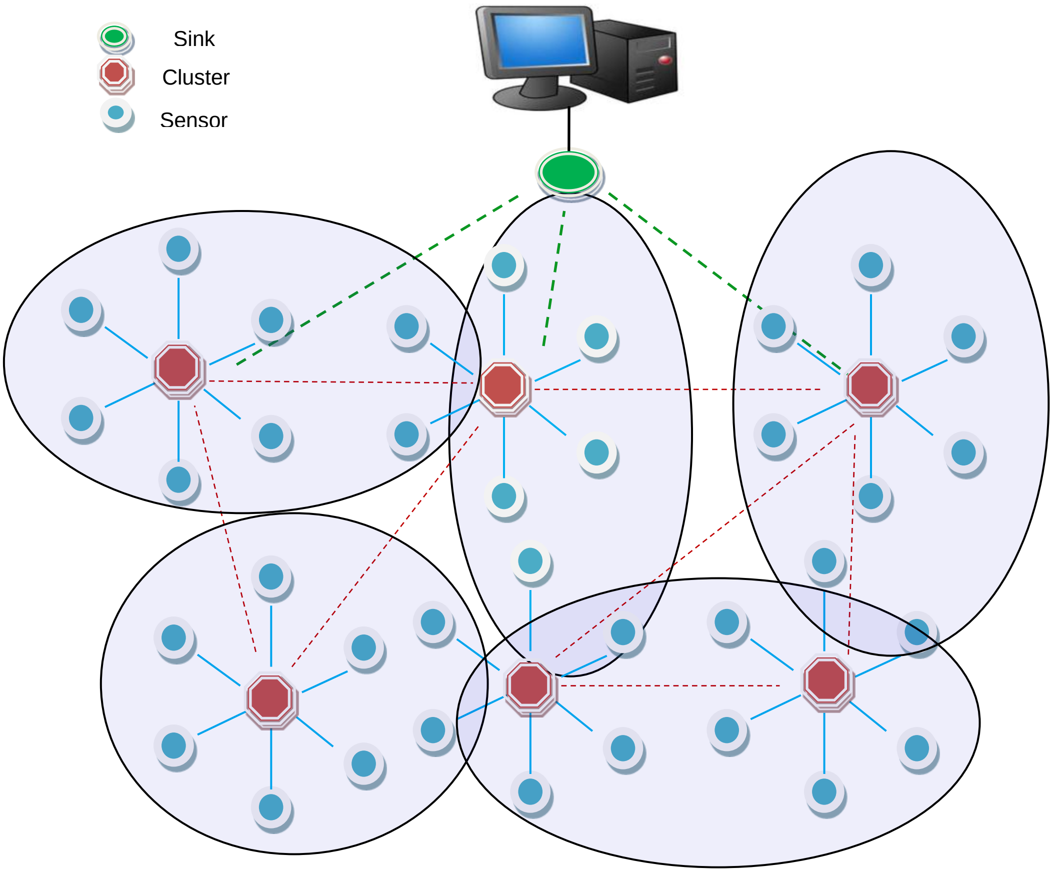


Figure 4: Virtual cluster overlay to the physical cluster

Results presentation

Hourly maps of temperature, relative humidity, wind speed and precipitation have to be computed for each pixel of the grid. For small areas between the sensor nodes, values are computed by interpolating values from their nearest neighbour nodes to produce continuous weather maps. Inverse distance weighted (IDW) interpolation is employed to produce grids of weather values to feed into the FWI maps.

The Micro-scale FWI system Model

The Micro-scale FWI model consists of the weather sensor models linked through TrueTime ZigBee wireless network. The weather sensor nodes cluster organization, data transmit period for each node, FWI processing algorithms and processing time delays are configured through Matlab scripts which are attached to the model through an interface dialog. The model takes the path-loss of the radio signals into account by taking the x and y coordinates of every node as inputs.

The Micro-scale FWI system modelling is done in MATLAB environment utilizing the TrueTime network simulation toolbox. The Model consists of weather sensor nodes sub-models linked through the TrueTime's ZigBee wireless network sub-model.

The weather sensor nodes sub-models consist of functional modules that represent a Kernel, Sensors interface, radio transceiver, localization, and power source. The parameters of these functional modules are set to represent the Texas Instruments MSP430F2274+CC2530 low power ZigBee module powered from two AAA size batteries of each 1.5V, 1200 mAh rating. The sensor module settings are that of Sensirion's SHT15 digital temperature and relative humidity sensor. Some modules include Sparkfun's SEN-08942 weather meter.

The ZigBee wireless network sub-model consist of functional modules to handle radio signal characteristics, network topology, data routing, FWI indices processing algorithm tasks, data processing and transmission delays, and localization.

Simulations and Results

Real weather data sets recorded at several meteorology stations in South Island, New Zealand and obtained from National Institute of Water and Atmospheric Research (NIWA). These data sets are used as benchmarks to validate the system performance and consist of weather parameters (temperature, relative humidity, rainfall and wind speed) along with their corresponding Canadian FWI indices (FFMC, DMC, DC, ISI, BUI, and FWI) collected hourly for the years 1994 to 2004.

The Micro-scale FWI system model described above is set up for simulation. The initial simulation configuration consisted of 16 weather sensor nodes self-organizing themselves autonomously into two clusters; each of these clusters is managed by a cluster head. Once the organization of the wireless network is achieved, the weather sensor nodes acquire weather data from an input file, compute part of the FWI indices, and send to their respective cluster heads every 30 seconds. The cluster head nodes, upon receiving the partial indices from all of their member nodes, enhance the partial FWI indices and transmit them to the sink for further processing. The initial simulation configuration consisted of 16 weather sensor nodes for the sake of fire hazard prediction model sanity check. However, the rest of the simulation consisted of up to 200 weather sensor nodes and 25 cluster head nodes within an area of 1.72 square Km to mimic a naturally dense WSN. In order to investigate the effect of the number of sensor nodes on prediction results, the number of weather sensor nodes involved varied from 16 to 200 during simulations.

A small scale Micro-scale FWI system model is simulated on real datasets for the purpose of model sanity check. A total of 16 closely located weather sensor nodes were assumed to represent 16 sparsely located real weather stations. Weather parameter datasets obtained hourly at 16 stations and were fed to the corresponding weather sensor nodes every 30 seconds. The FWI index computed by each sensor node was logged at the gateway and compared to the actual FWI index from the conventional FWI system. Sample FWI index logged for a single sensor node was compared to the corresponding station for 100 datasets as shown in figure 5.

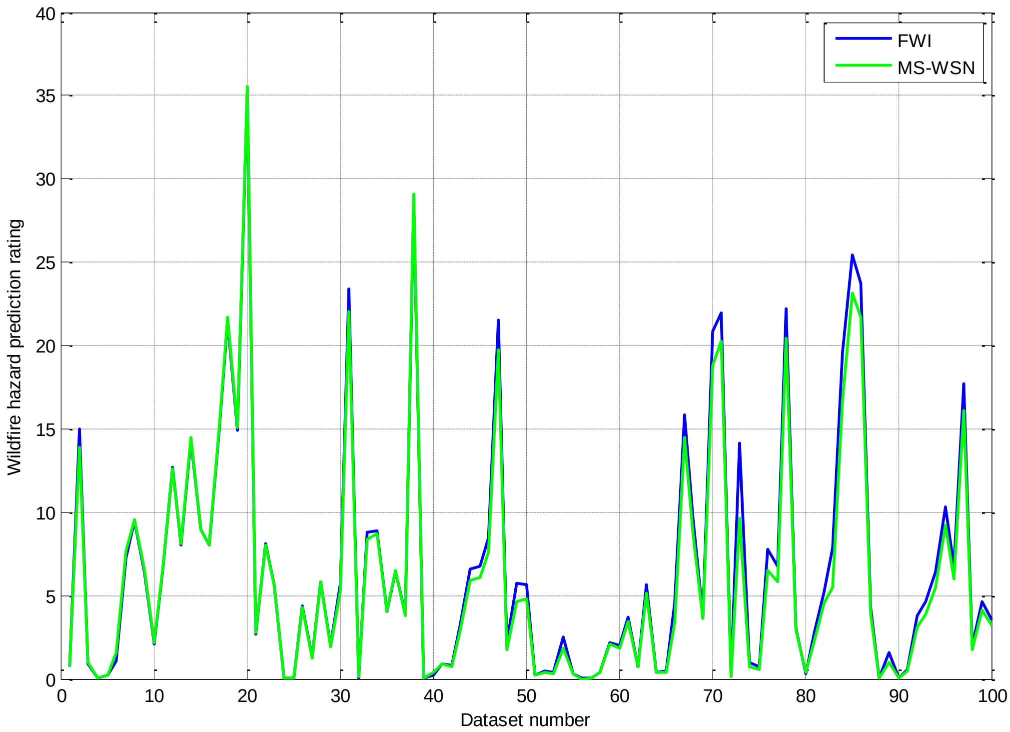


Figure 5: Comparison of Micro-scale FWI and FWI systems FWI index

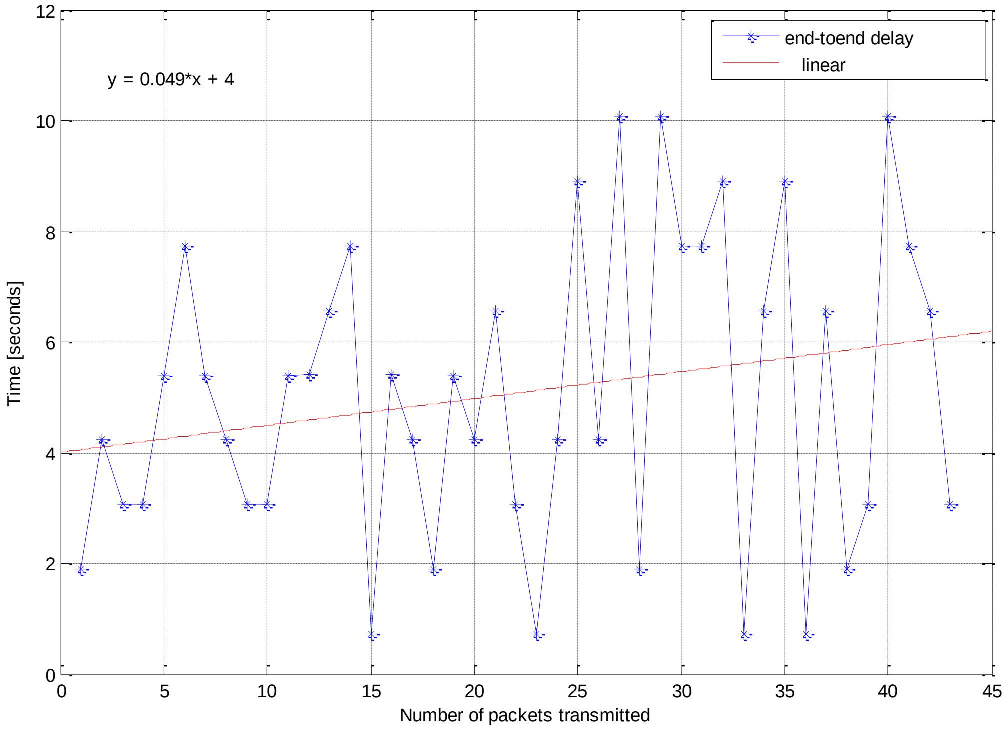


Figure 6: Average end-to-end delay

The average end-to-end delay of the Micro-scale FWI system model is shown in figure 6. Up to 54 weather sensor nodes and 6 cluster heads were competing for the wireless channel; the maximum delay observed was 10 seconds, with an average of 5.0747 seconds.

The Micro-scale FWI system model was evaluated for the amount of data packets lost under different data transmit periods. The results in figure 7 show that the number of packet loss decreases exponentially as sensors transmit data packets less frequently.

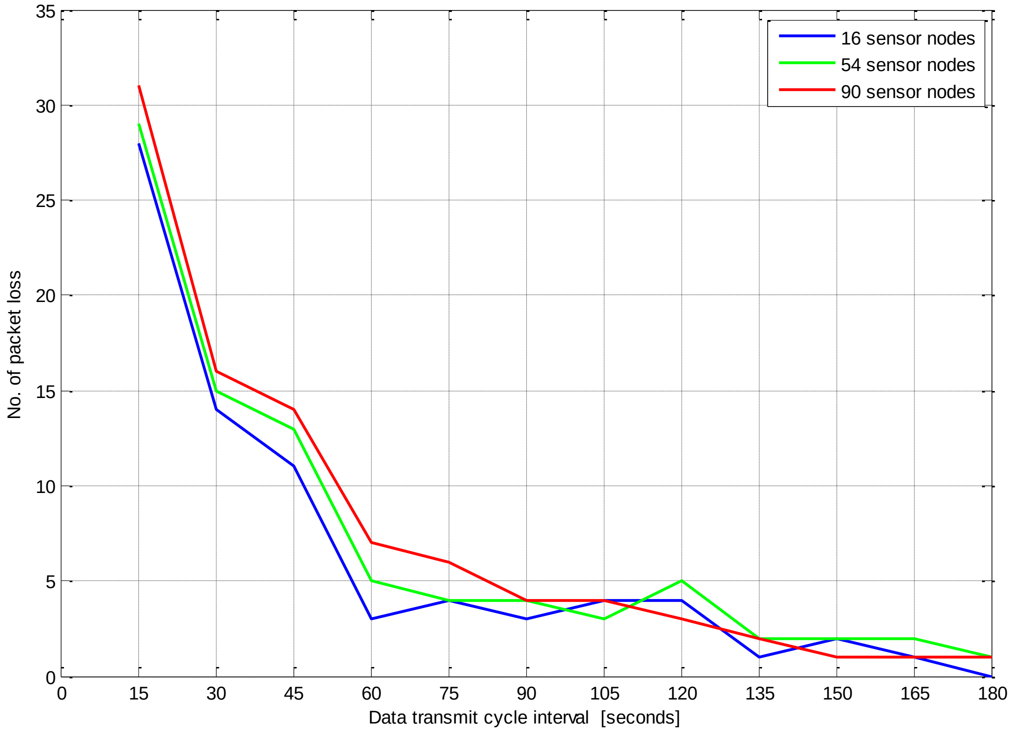


Figure 7: The Micro-scale FWI system Packet loss performance

The model's energy consumption is analysed based on the TrueTime battery model. The battery model computed energy consumption due to kernel data processing, packet transmission/reception, and idle waiting. Two AAA size batteries performance on the Micro-scale FWI system model is shown in figure 8.

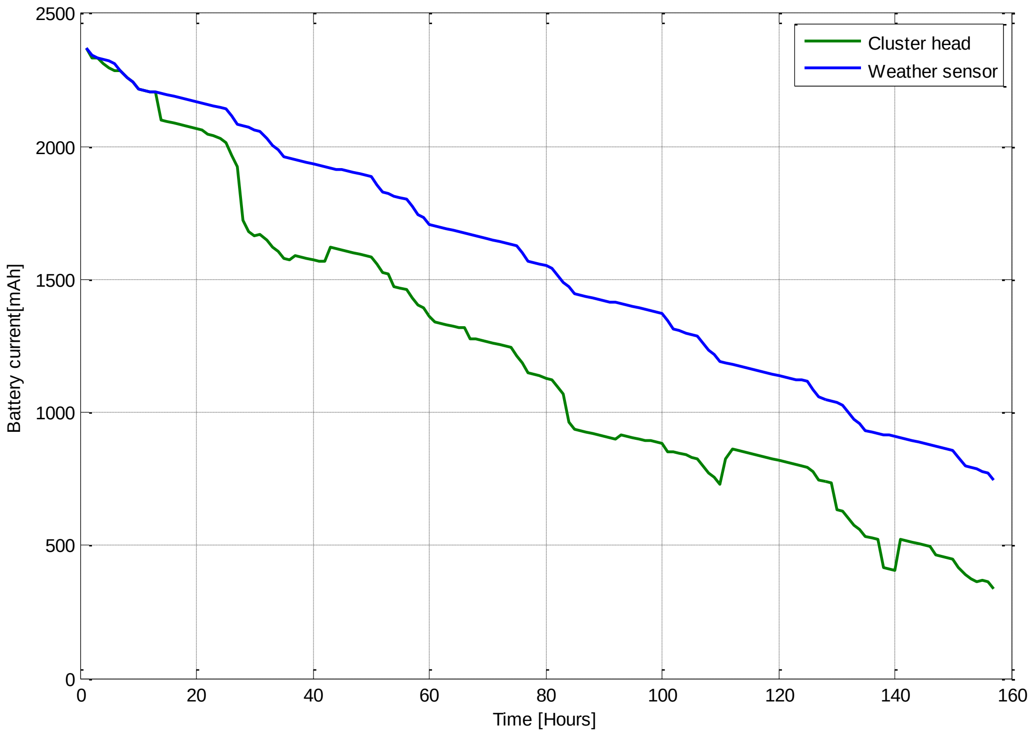


Figure 8: The Micro-scale FWI system nodes energy consumption performance

Discussion and Conclusion

The paper has presented wireless sensor network based Micro-scale FWI system. This is based on TrueTime modelling and simulation software. The MS-WSN model sanity has been verified through real weather datasets. Distributed in-network processing of wildfire hazard prediction based on WSN has several advantages while producing similar results to satellite communication based FWI system. The end-to-end delay, packet loss and energy consumption performance of WSN model have been observed through simulations. The simulation results indicate that for two-tiered WSN architecture, the influence of end-to-end delay, energy consumption and pack loss on the FWI indices results are insignificant. This system offers high spatial and temporal resolution wildfire hazard prediction system which is cost-effective, energy efficient, and easily deployable for emergency situations.

References

[1] Van Wagner, C. E. “Development and structure of the Canadian forest fire weather index,” Tech. Rep. 35, Canadian Forest Service, Ottawa, Canada, 1987.

[2] Cambridge Advanced Learner's Dictionary, Third Edition. Cambridge University Press; 2008. ISBN 9780521858045.

[3] Wikipedia article on Wildfire, http://en.wikipedia.org/wiki/Wildfire, [cited 2010-07-06].

[4] National Interagency Fire Center. The Science of Wildland fire [cited 2008-11-21].

[5] National Wildfire Coordinating Group. Wildfire Prevention Strategies; March 1998 [cited 2008-12-03]; p. 17.

[6] Scott, A. The Pre-Quaternary history of fire. Palaeogeography Palaeoclimatology Palaeoecology. 2000;164:281. doi:10.1016/S0031-0182(00)00192-9.

[7] Pyne, Stephen J.; Andrews, Patricia L.; Laven, Richard D. *Introduction to wildland fire*. 2nd ed. John Wiley and Sons; 1996 [cited 26 January 2010]. p. 65.

[8] Utility Consumers' Action Network (UCAN) News. News 8 Investigation: SDG&E Could Be Liable For Power Line Wildfires; 2007-11-05 [cited 2009-07-20].

[9] Stocks, B. J., Lawson, B. D., Alexande, M. E., Wagner, C. E. V., McAlpine, R. S., Lynham, T. J., et al. (1988, 11-12 July 1988). *The Canadian System of Forest Fire Danger rating.* Paper presented at the Bushfire Modelling and Fire Danger Rating Systems, Canberra. From

[10] Canadian Forest Service (CFS)Web Page. http://www.nrcan.gc.ca/cfs.

[11] J. San-Miguel-Ayanz, J.D. Carlson, M. Alexander, K. Tolhurst, G. Morgan and R. Sneeuwjagt. Chapter 2: Current methods to assess fire danger potential. In *Wildland Fire Danger Estimation and Mapping—The Role of Remote Sensing Data*. World Scientific Publishing Co. Pte. Ltd, 2003.

[12] The Canadian forest Service (CFS), Canadian Forest Fire Weather Index (FWI) System, 2009-12-22, http://cwfis.cfs.nrcan.gc.ca/en_CA/background/dsm/fwi#ref

[13] Mohamed, H., and Bagheri, M., 2009 Forest Fire Modeling and Early Detection using Wireless Sensor Networks, *Ad Hoc & Sensor Wireless Networks*, 7(3-4), pp.169--224, April 2009.

[14] Dowdy, Andrew J. & Centre for Australian Weather and Climate Research. & Australia. Bureau of Meteorology. & CSIRO. 2009 *Australian fire weather as represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index / Andrew J. Dowdy ... [et al.]* Centre for Australian Weather and Climate Research, Melbourne : http://www.cawcr.gov.au

[15] Wikipedia article on senor node, http://en.wikipedia.org/wiki/Sensor_node, [cited 2011-08-22].

[16] Qi, H., Kuruganti, P., & Xu, Y. (2002). The Development of Localized Algorithms in Wireless Sensor Networks. *Sensors, 2*(7), 286-293.

[17] Sabit, H., Al-Anbuky, A., & Gholam-Hosseini, H. (2009),"Distributed WSN Data Stream Mining Based on Fuzzy Clustering," in *Ubiquitous, Autonomic and Trusted Computing, 2009. UIC-ATC '09. Symposia and Workshops on*, 2009, pp. 395-400.

Atypical bushfire spread driven by the interaction of terrain and extreme fire weather

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Abstract

Under conditions of extreme fire weather, the interaction of wind, terrain and bushfire can result in atypical modes of fire spread. These events can result in the rapid escalation of bushfires to their most catastrophic state, thereby subjecting communities and their associated assets to the highest levels of bushfire risk. This paper discusses research aimed at providing a more formal understanding of these interactions, their effects on fire propagation and the overall level of risk posed by bushfires. The research methods and key findings will be presented and discussed along with some examples of the implications of the atypical spread taken from the 2003 Canberra fires and the 2009 Victorian fires.

Keywords: *Dynamic fire spread, wind-terrain interaction, atypical fire spread, bushfire, fire channelling*

1. INTRODUCTION

Over the last decade south-eastern Australia has experienced a number of catastrophic bushfires that burnt under extreme fire weather conditions. These include the January 2003 Alpine Fires (Nairn 2003), the 2006/07 Great Divide Fires (Smith 2007) and the 2009 Victorian Fires (Teague et al. 2010). These fires caused widespread destruction of assets (both natural and anthropogenic) and multiple fatalities. Most notably, the 'Black Saturday' fires, which burnt on 7 February 2009, resulted in the death of 173 people, the destruction of 2200 dwellings, 400,000 ha burnt and an overall cost of more than a billion dollars (Teague et al. 2010; Insurance Council of Australia 2010). In terms of lives lost, they currently stand as the nation's worst natural disaster.

While such fires are undoubtedly tragic, they do offer rare opportunities to better understand extreme fire dynamics. Where possible, and when doing so doesn't detract from implementing fire suppression and public safety measures, enhanced observation of extreme bushfires can reveal a tremendous amount of information, which can be used to better inform preparation and response strategies into the future – the 2003 Canberra fires serve as a good case in point. The fires that burnt on the afternoon of 18 January 2003 to the west of Canberra were some of the best documented fires in Australia's history, with remote sensing platforms, land-based video and aerial photography all capturing various aspects of the fire development. In particular, an airborne mutispectral line-scanning device captured data that revealed a number of instances of atypical fire propagation, and these data were complemented by a number of photographs taken by a NSW Rural Fire Service air observer.

Based on analyses of the multispectral line-scan data, McRae (2004) noted the presence of atypical patterns of fire spread. When considered in combination with data in other formats these data further indicated an atypical mode of fire propagation that did not seem to have been documented in the existing wildfire literature. The atypical fire spread was characterised by relatively rapid lateral fire propagation (in a direction transverse to the synoptic wind direction) across steep, lee-facing slopes; multiple spot fire development; and the production of expansive flaming zones (Sharples et al. 2011). Initially this type of fire spread was thought to be driven by winds that were dynamically channelled by the complex topography (Whiteman 2000; Kossmann et al. 2001) and so was dubbed 'fire channelling'. Subsequent research, however, revealed that the presence of dynamically channelled winds were not necessary for the atypical spread to occur and so the term 'fire channelling' may not be entirely etymologically correct. Indeed, McRae (2004) postulated that the atypical spread was caused by what he termed *lee-slope channelling*. Paraphrasing McRae (2004), lee-slope channelling involves recirculation of a significant quantity of embers within a lee rotor, which results in burn-out of the lee slope. The recurrent part of the eddy also sheds some embers into the synoptic flow, and causes rapid and intense progression of the fire immediately downwind. McRae (2004) did not postulate a cause for the lateral component of the fire progression during an instance of lee-slope channelling. It is clear however, that lee-slope channelling involves interaction with a fire and as such shouldn't be included as a form of dynamic channelling, which only involves interaction between wind and terrain. Noting the

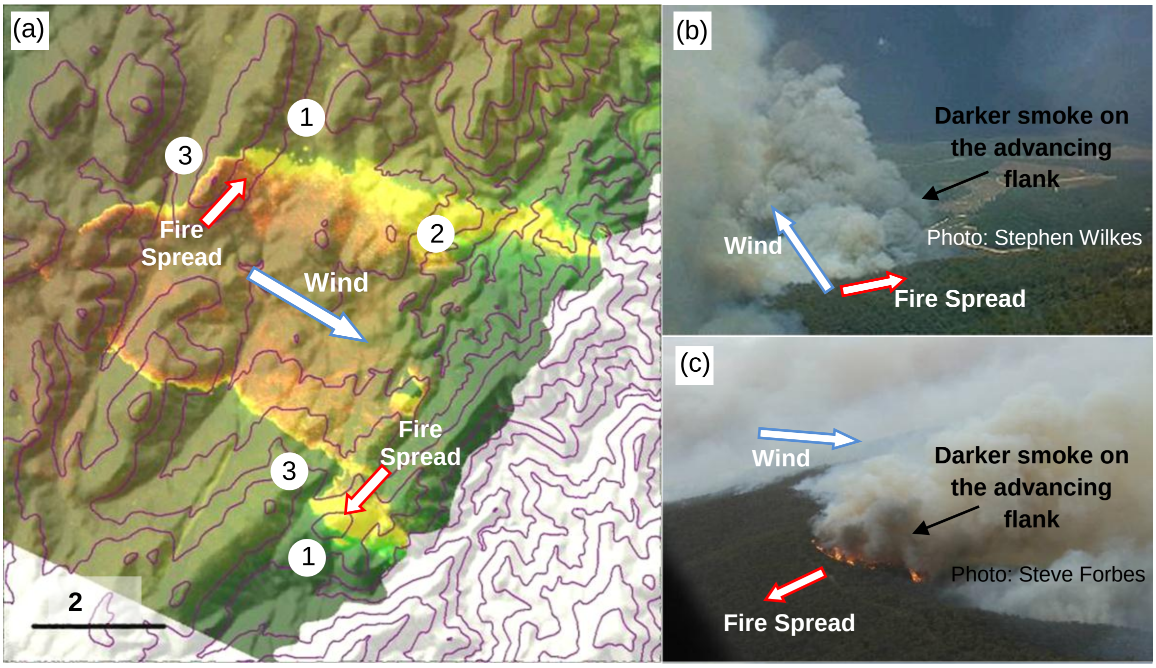

Figure 1. (a) Multispectral line-scan data overlayed on DEM data (100m contours) showing atypical lateral spread during the Broken Cart fire to the south-west of Canberra, 18 January 2003, (b) Photograph of a fire channelling event near the Blue Range west of Canberra, January 2003, (c) Photograph of a fire channelling event during the Tinderry fires south-east of the ACT, January 2010.

possible etymological inaccuracies, in the present paper the term 'fire channelling' will be used to refer to the phenomenon nonetheless[2].

The aim of the present paper is to provide a less-technical overview of the fire channelling phenomenon (compared to that provided by Sharples et al. (2011)). This includes a summary of the research that established its existence as a bona fide fire spread mechanism, the key characteristics of the phenomenon, its dependence on landform and environmental conditions and its implications for bushfire risk. Some recent experimental advances will also be summarised and some future research directions will be discussed. Based on the limited evidence available, we also speculate about the possible involvement of fire channelling during the Black Saturday fires, with particular reference to the Kilmore East and Yea-Murrundindi fires.

2. CHARACTERISTICS OF THE ATYPICAL SPREAD

As mentioned above, the atypical spread was first noted by McRae (2004) after analysing multispectral line-scan data collected by an airborne platform during the Canberra fires of January 2003. The multispectral line-scanning device collects surface irradiance in a number of discrete spectral bands covering the visual and infra-red parts of the electromagnetic spectrum. After rectifying the data with respect to an underlying digital elevation model, and correcting for perturbations in the flight path of the aircraft carrying the device, various spectral bands can be combined using the standard Red-Green-Blue coordinate system to produce spatially coherent patterns of irradiance (Cook et al. 2009). Based on the assigned

[2] The authors would be interested to hear any other suggestions readers might have regarding the naming of the phenomenon!

colourings and with the input of advice from remote sensing experts (Cook et al. 2009; Sharples et al. 2011), these processed line-scan images enable discrimination between active flaming and smouldering combustion, as well as providing a snapshot of the spatial development of a fire. Combined with the assumption of an approximately constant burn-out time over regions of similar fuel loading and type, the processed line-scan imagery provides information on the relative rates of spread of different parts of the fire. Thus, with reference to Figure 1a, the distinguishing features of a fire channelling event are revealed:

- Rapid lateral propagation of the flank (i.e. in a direction transverse to the synoptic winds) along a lee slope, including instances of lateral spot fire development (points 1 in Figure 1a),
- Downwind extension of the flaming zone with uniform spectral signature indicating active flaming for 2-5 km (point 2 in Figure 1a),
- The upwind edge of the flaming zone constrained by a major break in topographic slope (points 3 in Figure 1a).

Aerial photography has also revealed some additional features of fire channelling events:

- Darker smoke on the advancing flank (see Figure 1b and 1c),
- Vigorous convection above the advancing flank (see Figure 1b and 1c).

The darker smoke visible on the advancing flank in Figures 1b and 1c indicates incomplete combustion, presumably due to the higher rates of spread and/or a reduced oxygen environment. The vigorous convection column also indicates a fire of significant intensity. Invoking Byram's fireline intensity formula (Byram 1959) thus provides further indirect support for rapid rates of spread.

The locations of fire channelling events indicated a distinct preference for steep, lee-facing parts of the landscape. To better quantify this relationship, Sharples et al. (2011) developed a simple wind-terrain model that identified parts of the landscape with topographic slope greater than a threshold slope angle and with topographic aspect within a specified range centred on the synoptic wind direction. By tuning the model parameters (i.e. the threshold slope angle and the topographic aspect range) Sharples et al. (2011) demonstrated that, in addition to the strong winds present during the observed fire channelling events, topographic slopes greater than approximately 25° and topographic aspects within about 40° of the direction the wind is heading were also necessary conditions for fire channelling occurrence. Figure 2 shows the relationship between fire channelling locations (as identified in the line-scan imagery) and parts of the landscape identified by the calibrated wind-terrain model. Note that Figure 2 also portrays parts of the landscape that were not formally associated with fire channelling occurrence. This means that in general the environmental conditions embodied in the model output are necessary, but not sufficient to cause fire channelling. However, it should be noted that there is strong evidence that some areas not formally identified as fire channelling locations in Figure 2 did in fact experience fire channelling events. The east-facing slopes of the Tidbinbilla Range (circled in red in Figure 2) serve as an example in this regard: the damage to the vegetation on these lee-slopes was consistent with that observed in connection with other fire channelling events, yet there was no line-scan coverage or photographic evidence available to formally confirm a fire channelling occurrence. It should also be noted that some of the regions identified in Figure 2 were not affected by fire or had already been burnt in the preceding days, and thus had no opportunity to exhibit fire channelling occurrence.

3. WIND-TERRAIN-FIRE INTERACTIONS

There are a number of mechanisms that could possibly account for the atypical lateral spread. These include:

- Forced channelling: where synoptic winds are diverted along valleys due to terrain forcing,
- Pressure driven channelling: where valley winds flow in response to the component of the synoptic pressure gradient that aligns with the valley axis,
- Downward momentum transport: where winds at altitude moving in a different direction to surface winds are mixed down to the surface by the fire plume,
- Thermal winds: where winds in valleys arise due to differential heating of various parts of a valley or slope,
- Spatial changes in fuel,
- Indrafts into nearby fire plumes,
- Wind-terrain-fire interactions: complex interactions whose exact nature and dynamics may not be fully understood.

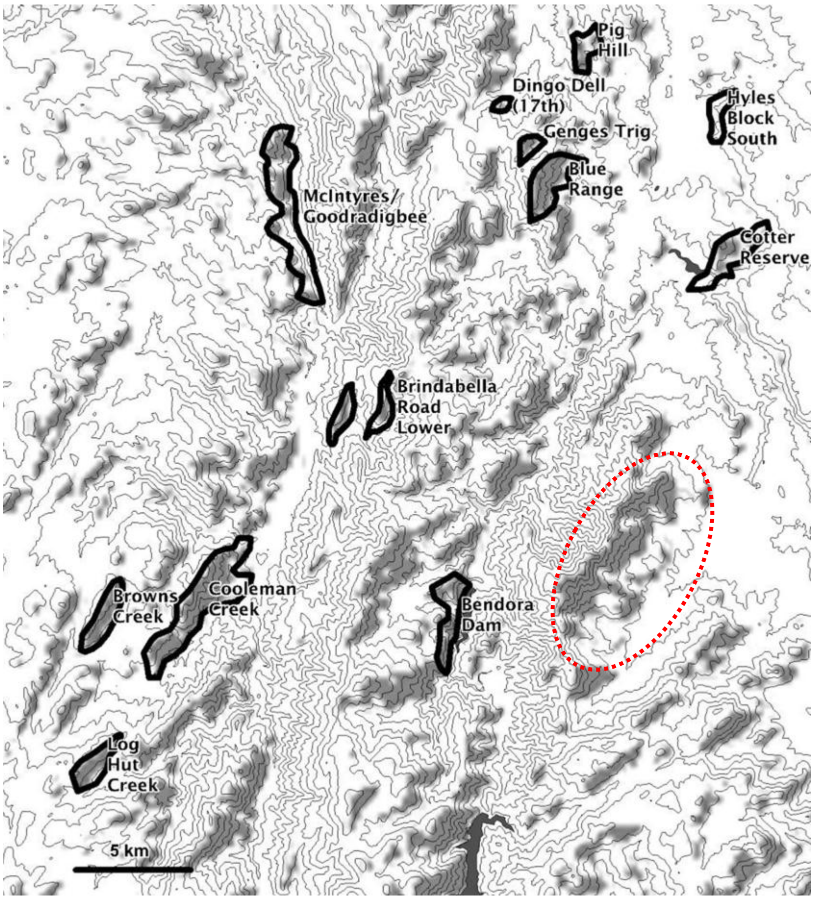

Figure 2. Fire channelling events, 18 January 2003. Thin black curves are 100m topographic contours, while the thick black curves enclose regions where fire channelling was observed. Grey shading indicates parts of the landscape identified by the wind-terrain model. The model was applied assuming a WNW wind direction and identified slopes greater than about 25° and aspects within 40° lee.

For example, Figure 3 illustrates the way in which winds at altitude can be mixed down to the surface by the fire's plume. If the winds at altitude are moving in a different direction to the near-surface winds, then conservation of momentum means that the air at the surface will inherit some of this direction, and this can affect the direction of spread of the fire. However, if downward transport of momentum was responsible for the atypical lateral spread then it should only occur in one direction, namely the direction of the upper winds. This does not fit

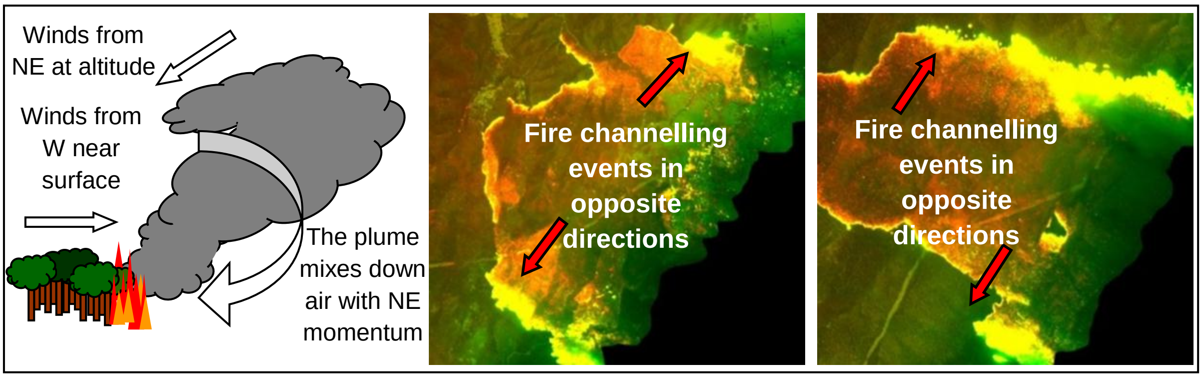

Figure 3. Schematic illustrating how a fire plume mixes down air with momentum travelling in a different direction to surface winds (left) and two line-scan images showing fire channelling events propagating in opposite directions (centre and right).

with the observations, as can be seen in the line-scan imagery in Figure 3 where fire channelling events are occurring simultaneously in opposite directions. Downward momentum of transport can therefore be ruled out as the main mechanism driving the atypical spread.

Similarly, pressure-driven channelling can also be ruled out as the main governing mechanism since it too would only induce fire spread in a single direction. It is also unlikely that forced channelling is the main driving process. Based on the results of the wind-terrain modelling discussed in the previous section, the necessary terrain feature for fire channelling to occur was a steep, lee-facing slope, and in some instances fire channelling was observed to occur in the absence of a definite valley with a windward-facing sidewall. Since forced channelling requires a windward-facing valley sidewall to divert the winds, if it was driving the atypical spread then there is no prima facie reason why only lee-facing slopes should be identified.

Thermal winds, spatial changes in fuel and indrafts into nearby fire plumes can also be discounted as the main processes driving the atypical spread. The strong winds accompanying all known instances of fire channelling would overwhelm any thermal effects; in the majority of observed fire channelling events there were no significant changes in vegetation and certainly none that would cause such a significant change in the direction of fire spread; and in many cases there were simply no nearby fire plumes in locations that would cause the fire to propagate in directions that it was observed to.

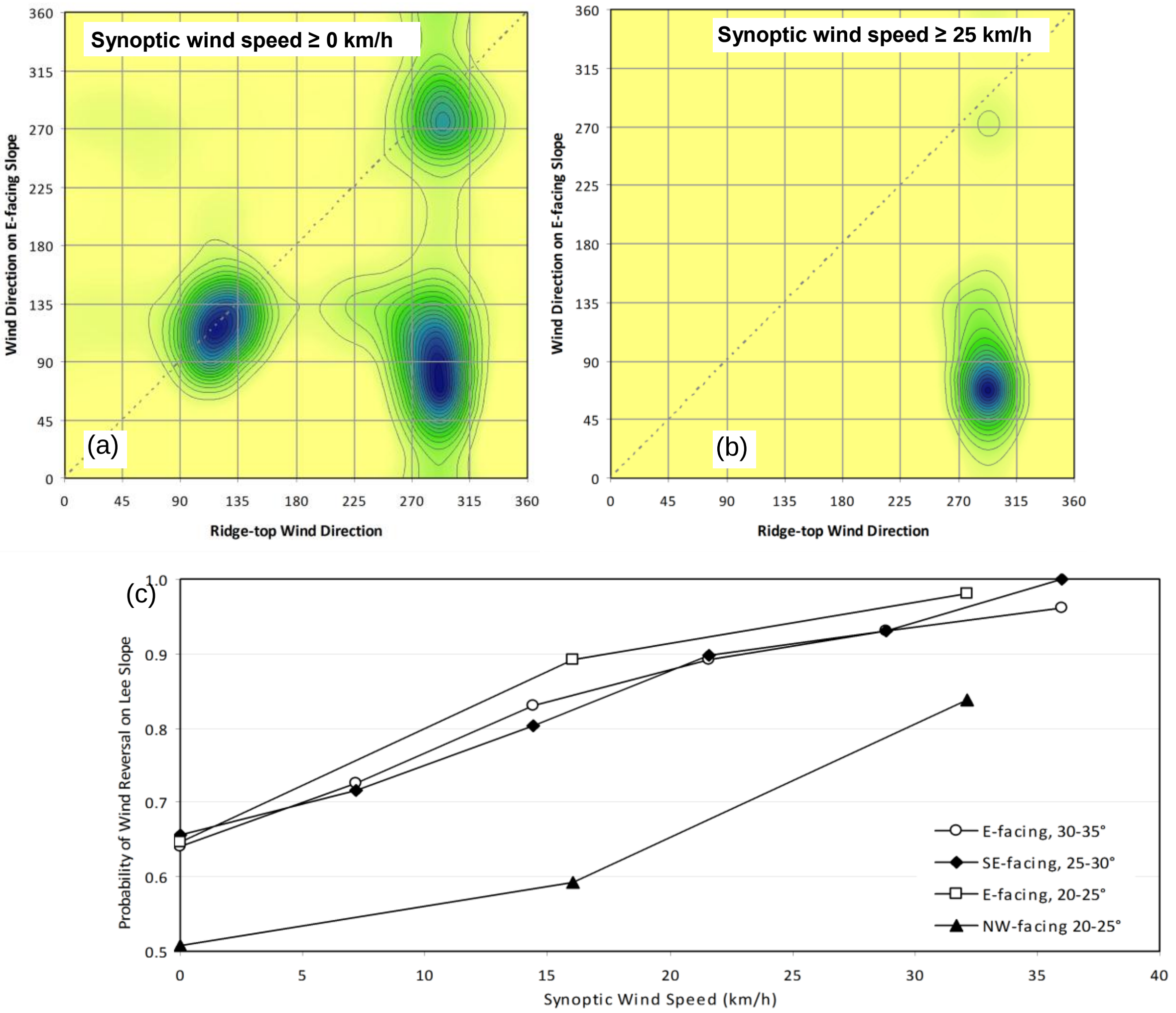

Figure 4. (a) Surface representing the frequency of various wind direction pairings for all synoptic wind speeds. Blue is most frequent, yellow indicates no occurrence. The green-blue region in the bottom right of the plot indicates the relatively frequent occurrence of a wind reversal on the E-facing slope (i.e. westerly winds over the ridge and easterly winds over the slope), (b) Same as (a) but only considering synoptic winds greater than 25 km h^{-1}, (c) Probability of a wind reversal plotted against synoptic wind speed for various slopes to the west of Canberra.

Based on the above arguments, Sharples et al. (2011) concluded that the most likely process driving the atypical spread was an interaction between the wind, the terrain and the fire. This conclusion was further supported by the analyses of Sharples et al. (2010a), which considered wind direction responses over steep slopes. In this study reference anemometers were placed on ridges to record data representative of the synoptic winds, while other anemometers were placed on slopes and in valleys to record data representative of the way that the winds respond to terrain-forcing in the various locations.

Of particular note in the context of fire channelling considerations, were the results of Sharples et al. (2010a) concerning wind-reversals over steep lee-facing slopes. It was found that as the synoptic wind speed increased beyond about 20 km h^{-1} the possibility of the wind blowing up a steep lee-facing slope (in a direction approximately opposite to the synoptic wind direction) became a near certainty. Figure 4 illustrates the results: the surface plots in Figures 4a and 4b indicate the effects of synoptic wind speed on the modal (probabilistic) response of the wind-terrain system, while the plot in Figure 4c depicts how the probability of a wind-reversal on lee-facing slopes (with different aspects and gradients) varies with synoptic wind speed. Analysis of the timing and duration of the wind-reversals indicated that when winds were strong the upslope winds were due to the presence of a lee rotor, or separation eddy (Sharples et al. 2010a).

It is significant that the topographic characteristics of the steep, lee-facing slopes identified by Sharples et al. (2010a) as being prone to eddy-driven wind-reversals accord very well with those parts of the landscape identified by Sharples et al. (2011), using the wind-terrain model, as being prone to the fire channelling phenomenon. This provides a strong indication that horizontal-axis lee rotors are a key component of the interaction driving the atypical fire spread. Indeed, Sharples et al. (2011) proposed the *fire channelling hypothesis*: the atypical lateral spread results from the interaction between an active fire and a lee rotor, with the mass ignition of regions downwind resulting from embers generated within the rotor being incorporated into the synoptic flow at the top of the rotor. Sharples et al. (2011) also conjectured that the lateral component of the spread was driven by thermal expansion within

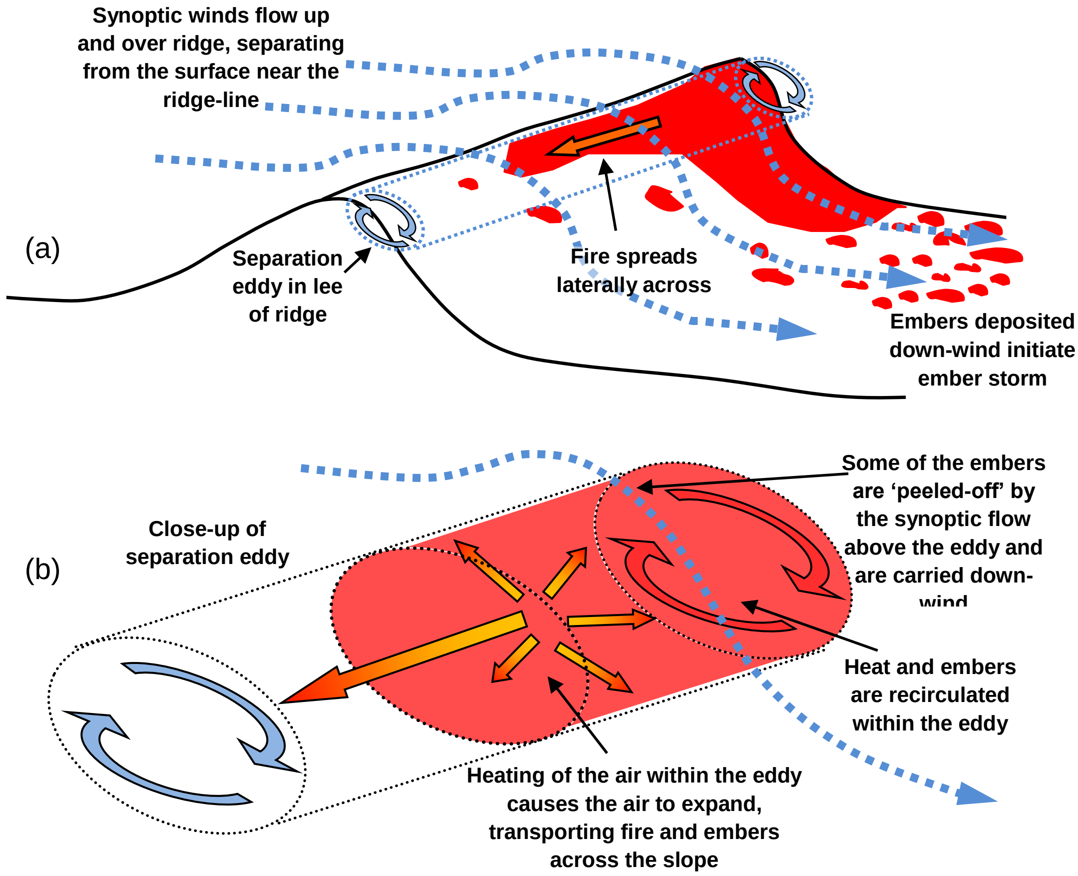

Figure 5. Schematic diagram illustrating the fire channelling hypothesis. (a) Diagram showing the rotor (separation eddy) in the lee of the ridge, the fire spreading across the slope and the mass spotting downwind. (b) Close up of the separation eddy illustrating how the recirculated heat and embers cause expansion of the air, which transports heat and embers across the slope.

the rotor – heat from the fire is recirculated within the rotor and causes the quasi-isolated air within the rotor to expand. The strong wind shear at the top of the rotor means that the path of least resistance for the expansion-driven air to flow is across-slope within the rotor. This across-slope flow carries flames and embers which cause the fire to spread in that direction (see Figure 5).

4. COMBUSTION TUNNEL EXPERIMENTS

In August 2010 the first author travelled to Portugal under the auspices of an Australian Academy of Science grant to collaborate with researchers from the Center for the Study of Forest Fires at the University of Coimbra. Part of this collaboration focused on testing the fire channelling hypothesis using a small-scale, triangular ridge apparatus in a combustion tunnel.

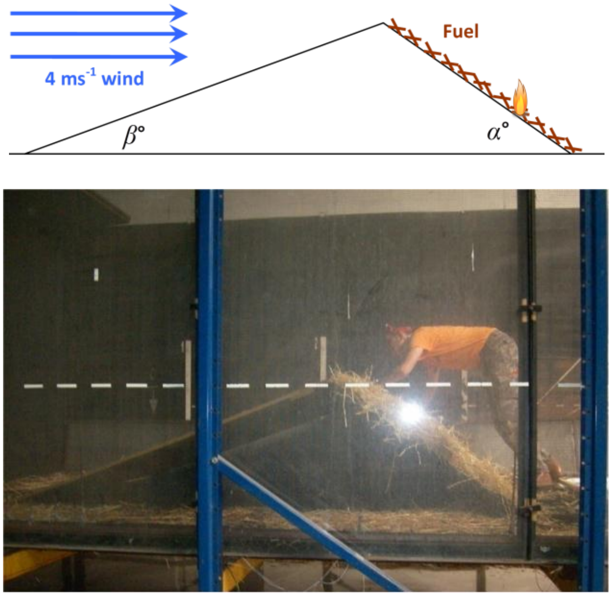

Figure 6. Schematic cross-section of the experimental ridge configuration and the approximate ignition point (top), and the actual combustion tunnel set-up (bottom).

Sharples et al. (2010b) reported on the results of some preliminary combustion tunnel experiments, which demonstrated the existence of the fire channelling phenomenon at the laboratory scale. The experimental set-up is illustrated in Figure 6. The fuel covered slope consisted of a 1m × 2m metal sheet with wire mesh and contained straw fuel at a load of 0.6 kg m^{-2}. The ridge line was aligned perpendicular to the combustion tunnel wind direction. In these initial experiments the slope angles α and β were taken to be 35° and 20°, respectively. Experiments were conducted in the absence of any wind and in the presence of a 4 ms^{-1} (~15 km h^{-1}) wind − the maximum wind speed possible in the combustion tunnel. Ignitions were made on the right side of the slope, the left side of the slope and in the centre of the slope.

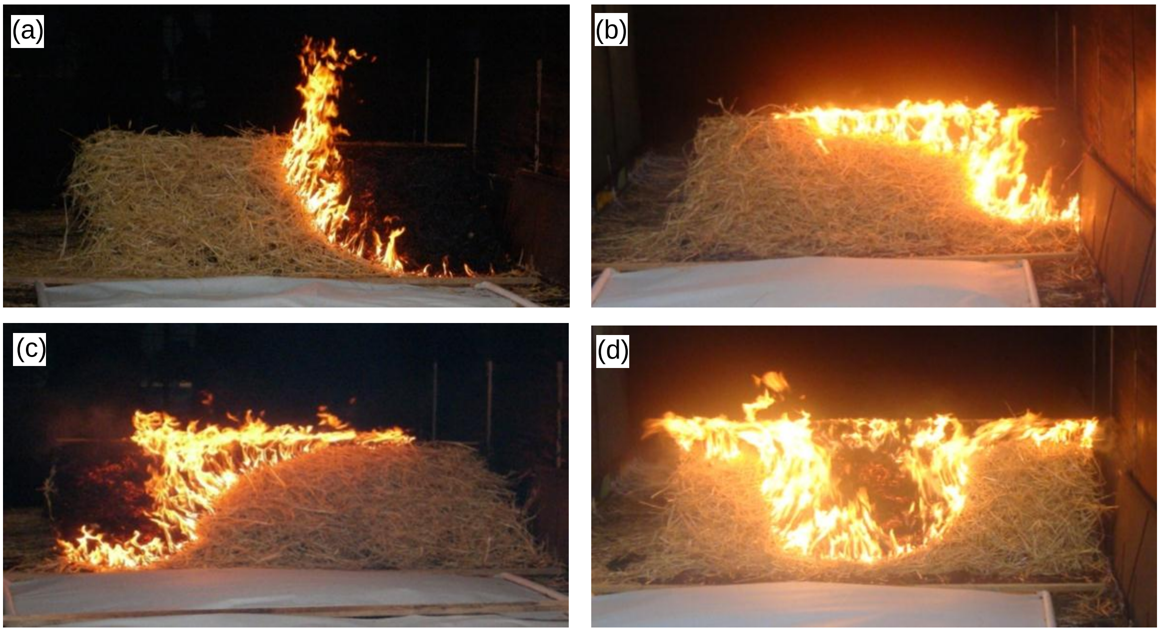

Figure 7. Experimental fires burning across the lee slope. (a) right side ignition, no wind; (b) right side ignition with 4 ms^{-1} wind; (c) left side ignition with 4 ms^{-1} wind; (d) central ignition with 4 ms^{-1} wind.

The observed fire spread across the slope was distinctly different in the presence of the 4 ms^{-1} wind, when compared to the no wind cases. In the presence of wind, the fire consistently exhibited rapid unsteady spread across the top of the ridge in the form of a 'finger' of turbulent flame. Figures 7a and 7b illustrate the difference in lateral spread characteristics for the 'wind' and 'no wind' cases when the point ignition was made on the right hand side of the lee slope. Figures 7c and 7d demonstrate that similar atypical spread occurred when the ignition was made on the left side and centre of the slope. As can be seen, for the central ignition the rapid lateral spread was observed to occur in both directions along the top of the slope. While deflection of winds off the combustion tunnel wall, which is visible on the right of Figure 7b, did have a small effect on the pattern of fire spread, Figures 7c and 7d indicate that this was by no means the main factor driving the lateral spread. The dark smoke on the advancing flank associated with fire channelling occurrence was also

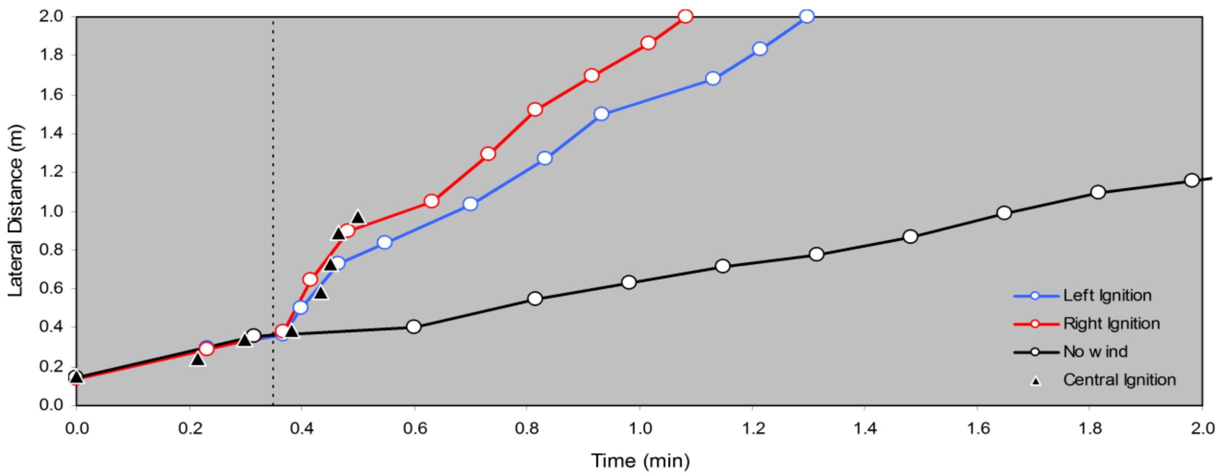

Figure 8. Comparison of maximum lateral distance travelled versus time since ignition for the different ignition locations and the wind and no wind cases. The dashed vertical line marks the time when the fire reached the top of the slope.

observed in the laboratory experiments.

Figure 8 illustrates the differences in the lateral rates of spread (as determined from lateral spread distances and time intervals) across the lee slope for the wind and no wind cases. The figure also illustrates the qualitative similarities in the maximum lateral rates of spread for the different ignition locations. In fact, the results indicate that the rate of lateral spread associated with fire channelling is independent of the ignition location. These results also confirm that any effects on the pattern of fire spread caused by winds deflecting off the combustion tunnel wall were not significant.

Collaborative work between the authors and the Centre for the Study of Forest Fires is ongoing and will address the effects of changing the combustion tunnel wind speed, the fuel load and the orientation of the ridge. There is also further potential to investigate wind-topography interactions (with and without fire) using coloured smoke bombs, or similar, to visualise the air flow. This experimental work will be complemented by numerical simulations using a non-hydrostatic, three-dimensional numerical weather model to simulate the fire channelling phenomenon in an effort to better understand the physical mechanisms driving the lateral spread. This work will begin in late 2011 in a collaborative research effort between researchers at the UNSW Canberra and Kensington campuses and the ACT Emergency Services Agency. Further research into the phenomenon will also need to address the issue of scalability between fire channelling occurrence at the laboratory- and landscape-scale. It is worth noting in this context, that the 20 km h^{-1} wind speeds deemed necessary for fire channelling to occur in the landscape do not match with the ~15 km h^{-1} wind speeds employed in the laboratory experiments, and for which fire channelling was observed to readily occur. This issue will be addressed with reference to research into the problem of scalability of wind speeds and other factors involved in laboratory fire experiments through dimensional analyses (Pérez et al. 2006; 2010), and through careful parameterisation of the numerical simulations.

5. FIRE CHANNELLING AND BLACK SATURDAY

Given the extreme fire weather and the rugged terrain in which some of the fires burnt in Victoria on 7 February 2009 (Black Saturday), it is natural to wonder if the fire channelling phenomenon featured at all during the day. Unfortunately, only limited data is available to address this question. However, the data that is available does suggest the occurrence of fire channelling. The photographs in Figure 9a and 9b indicate that fires were burning across lee slopes, with the distinctive darker smoke and turbulent plume on the advancing flank consistent with fire channelling occurrence. Indeed, the dark smoke circled in Figure 9b appears to have formed in the lee of the ridge, at a significant lateral distance from the fire’s main flank. Figure 9c shows a visualisation of the digital elevation model (DEM) derived from the Shuttle Radar Topography Mission[3] (SRTM). The visualisation, which takes approximately the same view as that seen in Figure 9a, clearly shows the series of three ridges aligned almost perpendicular to the synoptic wind direction, upon which the fires are burning. Moreover, Figure 9d shows the output of the wind-terrain model, which identifies fire channelling prone parts of the landscape as brown grid cells, overlayed with 10m

[3] http://www2.jpl.nasa.gov/srtm/

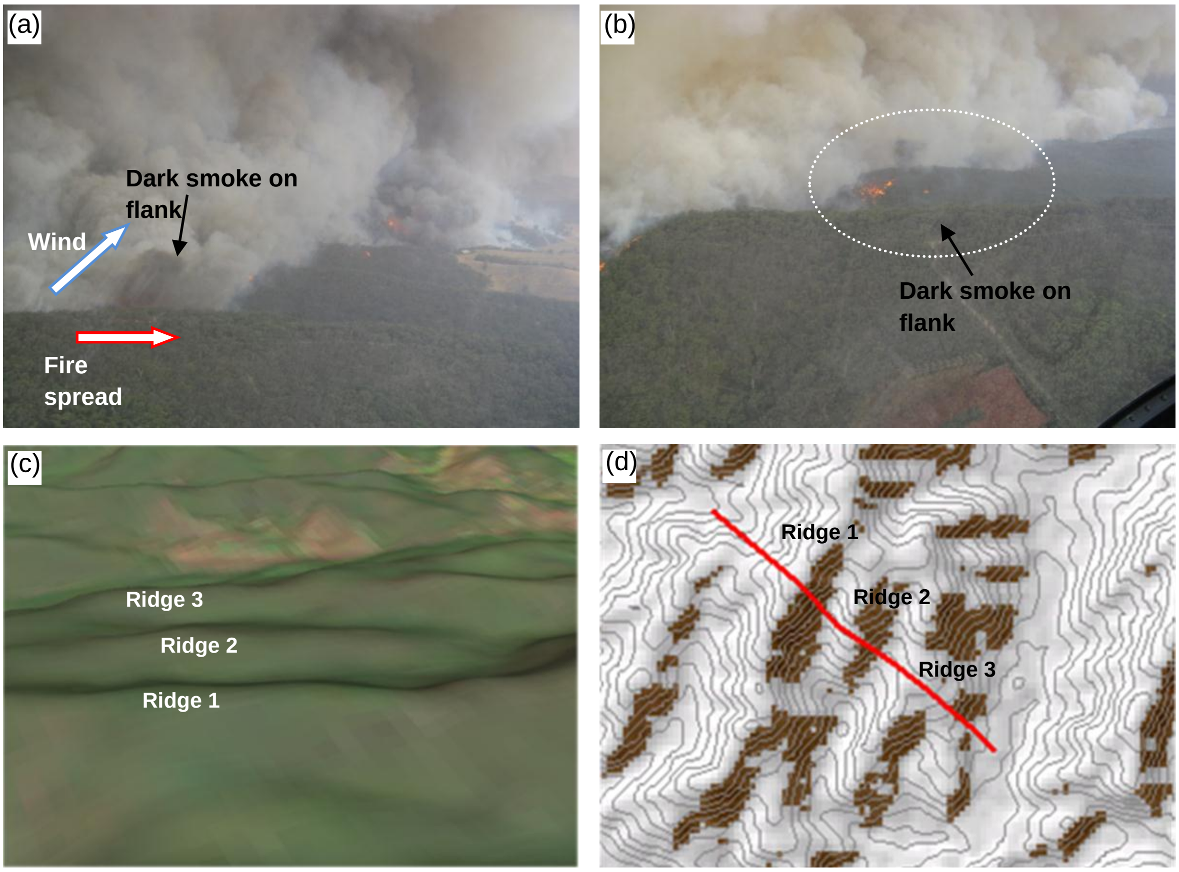

Figure 9. Panels (a) and (b) show photographs of the Kilmore East fire burning in rugged terrain 7 February 2009, showing patterns of fire behaviour consistent with fire channelling. The white oval in panel (b) highlights dark smoke that has formed well across from the fire's flank in the lee of the ridge in the foreground. Panel (c) provides a visualisation of the SRTM DEM data showing approximately the same view as that seen in panel (a). Panel (d) shows 10m DEM contours and output from the wind-terrain model with a wind direction of ~320° (brown grid cells). The red line indicates the approximate line of view, looking from the northwest to southeast, in panels (a) and (c).
(Photos: Richard Alder, DSE).

topographic contours. The wind-terrain model has been applied assuming the same values for the threshold slope angle and topographic aspect range as determined by Sharples et al. (2011), but with a wind direction of approximately 320° to match the pre-change conditions on 7 February 2011. As was seen in the 2003 Canberra fires, there is again a strong association with parts of the landscape identified by the wind-terrain model in Figure 9a and the location of the apparent lateral fire propagation in the photographs (cf. Figure 2).

Moreover, it is interesting to speculate about the role fire channelling may have played in the destruction of the township of Marysville (99 km northeast of Melbourne). Figure 10 shows the wind-terrain model output in the vicinity of Marysville and indicates that, based on the synoptic wind direction before the wind change occurred, the conditions necessary for fire channelling occurrence were met immediately upwind of Marysville. The Yea- Murrundindi fire had reached the southern part of the region indicated in Figure 10 prior to the wind change and so it is possible that the northerly progression of the fire towards Marysville might have initially been fire channelling driven. This possibility might also explain the apparently erratic and confounding directions of fire spread reported (Bushfire CRC 2009).

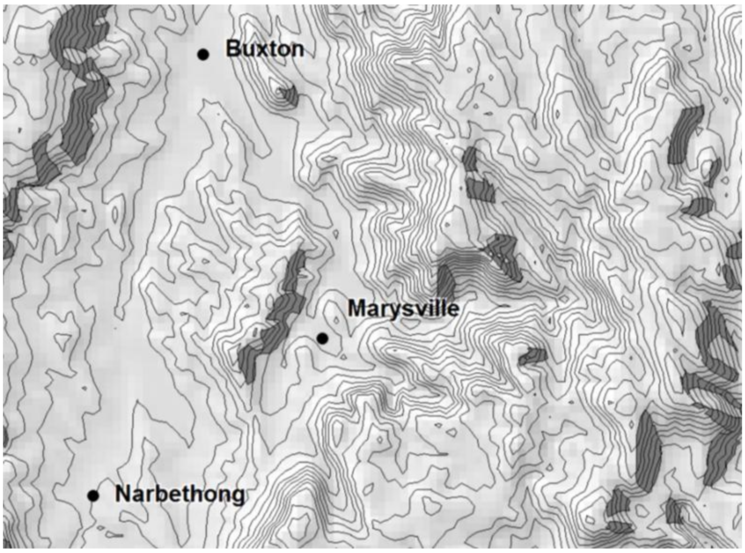

Figure 10. Output of the wind-terrain model overlayed on 10m DEM contours. The model indicates a significant fire channelling-prone landform immediately to the west of Marysville.

Bradstock and Price (2009) analysed fire severity data from the Black Saturday fires and found, contrary to intuition, that the most severely burnt parts of the landscape were associated with lee aspects, both prior to and after the wind change. While such a finding may be counter-intuitive in the context of the traditional conception of fire spread on slopes, the findings are entirely consistent with fire channelling occurrence. In fact Bradstock and Price (2009) themselves speculate on the involvement of lee-slope vortices that act on the fire in a way that is synergistic with the effects of slope on fire intensity.

6. CONCLUSIONS

The atypical bushfire spread associated with fire channelling occurrence has a number of significant implications for bushfire risk management. Fire channelling can cause a relatively small fire to develop rapidly in size and intensity, spawning extensive regions of active flame through the ignition and coalescence of numerous spot fires. The pattern of fire spread associated with a fire channelling event also raises some interesting questions about the standard assumptions that are made about the spatial distribution of spotting downwind from a fire plume. The fact that fire channelling causes the fire to spread laterally with simultaneous shedding of embers downwind means that spot fires will be distributed in more of a rectangular shape downwind of the event rather than the triangular shape that is often assumed (Tolhurst and Chong 2010).

The mass ignition of fire through spotting can have a dramatic effect on the evolution of a fire. Given favourable upper atmospheric conditions, the rapid release of large quantities of heat and moisture from extensive regions of active flaming can cause a fire plume to develop into a thunderhead (pyro-cumulonimbus). At this stage of fire development, the fire can involve tens of thousands of cubic kilometres of atmosphere, and consequently can produce fire behaviour whose predictability lies well beyond current fire modelling capability. In this context it is worth noting that the pyro-cumulonimbus that formed over the McIntyres

Hut fire on the afternoon of 18 January 2003 has been directly linked to a fire channelling occurrence along the Goodradigbee River corridor (Sharples et al. 2011).

Fire channelling occurrence also has some significant implications for fire crew safety. The rapid lateral advance of the fire could pose a significant danger to fire crews involved in flank attack in rugged terrain. Indeed, the authors are aware of a number of instances of unexpected fire propagation that have put fire crews in danger. In one instance members of an ACT Rural Fire Service Remote Area Fire-fighting crew, working on the Tinderry fires (see Figure 1c), were impacted by smoke and embers moving across a lee slope. In fact in this case one of the crew's back-packs was set alight by a firebrand (K. Chambers, 2011 pers. comm.). In another more notable case, a NSW Rural Fire Service Group Captain involved in the suppression activities during the 1983 Grays Point fire (Cheney et al. 2001) witnessed fire behaviour "*exactly like that seen in the video*" (footage of the combustion tunnel experiments) that may have played a part in the multiple fatalities on the afternoon of 9 January 1983 (L.W. Carter 2011, pers. comm.). Indeed, the occurrence of fire channelling provides an alternate explanation for the unexpected appearance of fire to the northeast of the main fire flank, immediately upwind of where the crew were burnt-over (the fire was burning under the influence of northwesterly winds (Cheney et al. 2001)). Personal accounts of fire behaviour consistent with fire channelling have also been noted in Portugal and Sardinia – these cases will be investigated in ongoing work.

The possible role that fire channelling events may have played during the Black Saturday bushfires is also worthy of further investigation. This avenue of inquiry will be pursued in collaboration with the Black Saturday fire reconstruction team and researchers that specialise in violent pyro-convection. In particular, the above speculations about the role of fire channelling during the Black Saturday fires should be explored in combination with the concurrent work of Gellie et al. (2011). This further work will involve analyses of the wind-terrain model output as a predictor of fire severity and the spatial association between fire channelling prone landforms and locations of intense pyro-convective cells.

ACKNOWLEDGMENTS

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REFERENCES

Bradstock, R., Price, O. (2009) *Fire Severity Patterns in the Victorian Fires of February 7th 2009: influences of weather, terrain and land use history.* Report to the 2009 Victorian Bushfires Royal Commission. Available from: www.royalcommission.vic.gov.au

Bushfire CRC (2009) *Victorian 2009 Bushfire Research Response Final Report*. October 2009, Bushfire CRC ISBN 978-0-9806759-8-6

Byram, G. M. (1959) Combustion of forest fuels. In: K.P. Davis (ed.) *Forest Fire: Control and Use*. New York: McGraw Hill.

Cheney, N.P., Gould, J.S., McCaw, L. (2001) The Dead-Man Zone - A neglected area of firefighter safety. *Australian Forestry*, **64**, 45-50.

Cook, R., Walker, A., Wilkes, S. (2009) Airborne fire intelligence. In: *Innovations in Remote Sensing and Photogrammetry*. (Eds S Jones, K. Reinke) pp. 239-254 (Springer: Heidelberg)

Gellie, N., Gibos, K., Potter, B., Bannister, T. (2011) Extreme fire processes of the February 2009 Victorian Fires. In R. Thornton (ed.) *Proceedings of the 2011 Australasian Fire and Emergency Services Authorities Council and Bushfire Cooperative Research Centre Annual Conference*, August 2011, Sydney, Australia.

Insurance Council of Australia (2010) *Insurance Council of Australia: Year in Review 2009*. Insurance Council of Australia, Sydney.

Kossmann, R., Sturman, A., Zawar-Reza, P. (2001) Atmospheric influences on bush fire propagation and smoke dispersion over complex terrain. In: *Proceedings, 2001 Australasian Bushfire Conference*, Christchurch NZ.

McRae, R.H.D. (2004) Breath of the dragon – observations of the January 2003 ACT Bushfires. In: Proceedings of 2004 Australasian Bushfire Research Conference, May 2004, Adelaide.

Nairn, G. (2003) *A Nation Charred: Inquiry into the Recent Australian Bushfires*. The Parliament of the Commonwealth of Australia, Canberra.

Pérez, Y., Àgueda, A., Pastor, E., Planas, E. (2006) Study of the effect of changing scale in forest fires experimentation by means of dimensional analysis. In: D.X. Viegas (ed.) *Proceedings of the 5th International Conference on Forest Fire Research*. November 2006, Figueira da Foz, Portugal.

Pérez, Y., Pastor, E., Àgueda, A., Planas, E. (2010) Effect of wind and slope when scaling the forest fires rate of spread of laboratory experiments. *Fire Technology*, **47**, 475-489.

Sharples, J.J., McRae, R.H.D., Weber, R.O. (2010a) Wind characteristics over complex terrain with implications for bushfire risk management. *Environmental Modelling and Software*, **25**, 1099-1120.

Sharples, J.J.**,** Viegas, D.X., Rossa, C.G., McRae, R.H.D. (2010b) Small-scale observations of atypical fire spread caused by the interaction of wind, terrain and fire. In: D.X. Viegas (ed.) *Proceedings of the VI International Conference on Forest Fire Research*, November 2010, Coimbra, Portugal.

Sharples, J.J., McRae, R.H.D., Wilkes, S.R. (2011) Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channelling. International Journal of Wildland Fire. In press, accepted for publication 25 May 2011.

Smith, R. (2007) Report of the Key Issues Identified from Operational Reviews of Major Fires in Victoria 2006/07. Melbourne: Department of Sustainability and Environment.

Teague, B., McLeod, R., Pascoe, S. (2010) 2009 Victorian Bushfires Royal Commission Final Report, State of Victoria, Melbourne, Victoria.

Tolhurst, K.G., Chong, D.M.O. (2010) The importance of mass-ignition by spotting on wildfire behaviour – examples from the 2009 Black Saturday bushfires in Victoria Australia. In: D.X. Viegas (ed.) Proceedings of the VI International Conference on Forest Fire Research, November 2010, Coimbra, Portugal.

Whiteman, C.D. (2000) Mountain Meteorology: Fundamentals and Applications. Oxford University Press.

Assessing Potential House Losses Using PHOENIX RapidFire

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Abstract

There has been a considerable body of work identifying the characteristics of houses and their surroundings that contribute to house loss in bushfires (Wilson & Ferguson 1986, Ramsey et al. 1987, Cohen 1995, Blanchi et al. 2006, Blanchi et al. 2010, Mell et al. 2010) . However, the characteristics of a bushfire, such as flame length, intensity, size, and spotting characteristics are also important. PHOENIX RapidFire characterizes fire in a spatially and temporally explicit way. One logical use of a simulation model such as PHOENIX RapidFire is to estimate the number of houses that might be lost when they are impacted by a bushfire. The recent Black Saturday fires in Victoria, have provided an opportunity to evaluate the utility of PHOENIX RapidFire to assess potential for house losses under Black Saturday conditions) nt conditions associated with about 2000 house losses. This dataset has provided an opportunity to develop a potentially better predictive model of house loss for use by emergency response agencies during a bushfire event as well as provide criteria to evaluate the potential benefits of a range of planning and land management activities on reducing the impact of bushfires on houses.

This paper presents the results from this analysis and the algorithms developed for predicting house loss based on modelled fire behaviour characteristics from PHOENIX RapidFire.

Introduction

Barrow (1945) was the first person in Australia to record the fact that house loss in bushfires is not a random event. He identified that embers were a major house ignition source, and that building details rather than building materials were important to house survival, in the 1944 fire in Beaumaris, then on the outskirts of Melbourne. Since then, research by Wilson and Ferguson (1985), Ramsey *et al.* (1987), Leonard and Blanchi (2005), Blanchi *et al.* (2006) and others have increased our understanding of the mechanisms by which houses are ignited in bushfires and other factors leading to their destruction. These studies have identified that factors related to fire characteristics such as fireline intensity, flame height, and ember production are important to the probability of house loss. They have also shown the importance of building design, construction materials, degree of maintenance and siting were also important. And an additional factor of high importance is whether or not someone was actively defending the home by extinguishing ignitions while they were in their early stages of development.

This study investigates the feasibility of using PHOENIX RapidFire (Tolhurst *et al.* 2008), a fire characterization simulator, to adequately spatially and temporally describe some key fire characteristics, to find a statistically significant connection between these modelled fire characteristics and the known pattern of house loss from the 2009 Black Saturday bushfires in Victoria.

Methods

An extensive survey of houses, both damaged and undamaged, in the areas affected by the Black Saturday fires in Victoria was coordinated by the Bushfire CRC. This provided an unusually large dataset for model evaluation. Records from 5024 houses surveyed were used in this analysis. The dataset used was supplied by Geoscience Australia. The dataset comprised houses that were affected by the Churchill, Murrindindi and Kilmore East Fires. Of the sample 2640 houses were either damaged or destroyed by the fires and 2381 survived. The Black Saturday fires were large (about 300,000 ha burnt in the first day) and intense and occurred in largely dissected mountainous terrain with pronounced spotting being a major feature of the fire behaviour. A further 58 houses were included in the sample from the Deep Lead fire, near Stawell, from 2005, 13 of which were destroyed. The Deep Lead fire burnt in mixed agricultural and remnant bushland in gently undulating terrain and was primarily a wind-driven grass fire with minimal spotting contributing to the overall fire behaviour, providing a contrasting set of conditions to the Black Saturday fires. All houses surveyed that had been damaged or destroyed were classified as "Lost" in this analysis and all others were classified as "Survived".

PHOENIX RapidFire is a spatio-temporal fire characterization model (Tolhurst *et al.* 2008) that estimates fire behaviour characteristics as it burns through a landscape. Fire spread is calculated as a series of continuous variables across the landscape, but the fire characteristics are only recorded within a fixed square grid, the cell-size of which can be selected by the user, but in this analysis, a 180 x 180 m cell size was used. This grid size

(3.24 ha) provided sufficient detail to see the fire pattern across the landscape without unnecessarily consuming computer time on details that make little difference to the fire pattern. In each cell, 10 input variables related to fuel, terrain, and access are recorded and 14 output variables related to fire characteristics and modified winds are recorded. The fire characteristics are: the time a cell is burnt since ignition, its average rate of spread and associated fireline intensity (Byram 1959), the time when the first embers arrived since ignition, the maximum distance embers have travelled to reach this cell, cumulative ember density landing in a cell until it ignited, the time from ignition when fire was suppressed, the time from ignition when fire self-extinguished, the average flame height when fire first entered cell, the flame depth when fire first entered cell (assuming a 10 second residence time in grassland and 80 seconds in shrubland and forests), maximum relative convective updraught strength[4] in cell, fine fuel moisture content, local wind speed as affected by terrain, and local wind direction as affected by terrain. In the analysis here, two additional fire variables were derived from the basic 14, these being flame cross-sectional area (FlameXS) which assumed the flame was a triangle with a base length (L) equal to the flame depth and the triangle height (H) being equal to the flame height (Fig. 1). The second derived variable was "convection density" where the local convective strength was averaged across an area with a 2000 m radius and recorded with 100 m resolution using a kernel density routine in ESRI ArcGIS. The house locations were intersected with the fire characteristics in ArcGIS to produce a dataset that connected the house location with the simulated fire characteristics. It was this dataset that was used in the analysis report here.

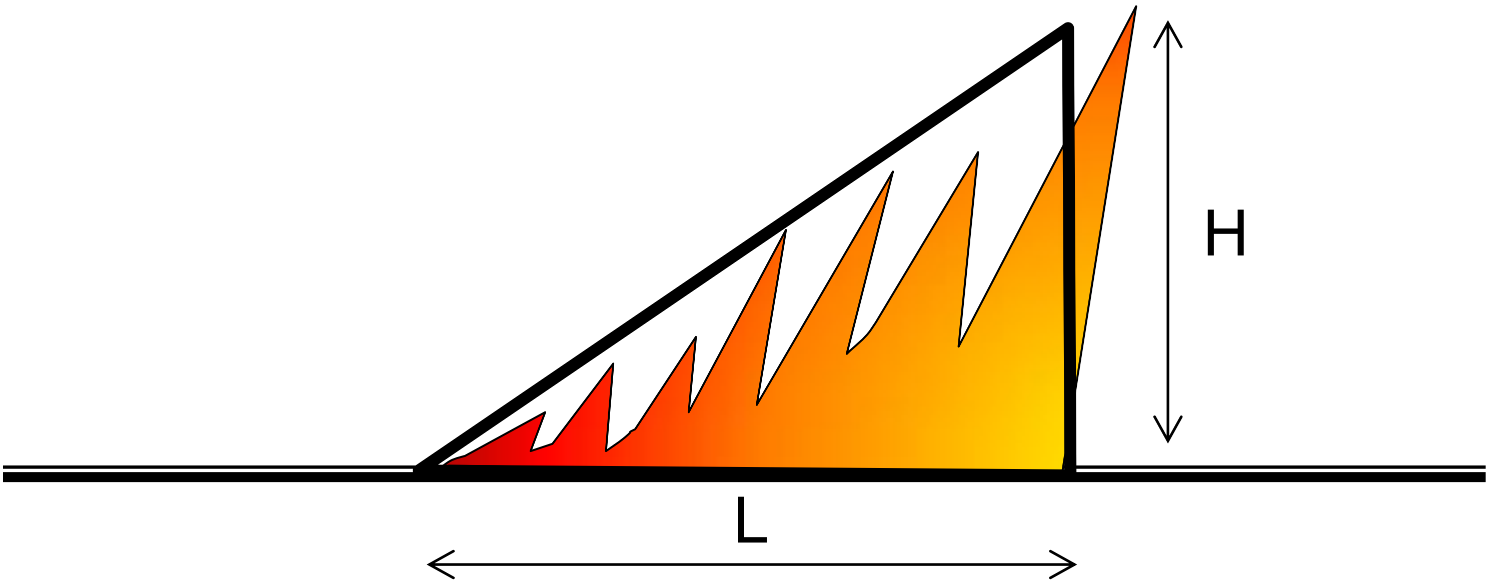

Figure 1. Diagramatic representation of how the flame cross-sectional area is calculated. H is the flame height and L is the flame base length.

Both univariate and multivariate statistical analyses were used. Univariate analyses were primarily non-linear regression analyses. Before the regression analysis, output variables

[4] Relative Convective Strength was calculated as the total energy output (MW) of a segment of the fire perimeter which was assessed to be drawn into a common convection centre, at each timestep of the modelling process.

were grouped into classes and the probability of loss for each class was based on the number of houses "Lost" as a proportion of the total number of houses in each class. These data were graphed for each of variables and regression analysis was made to find the best regression model to describe the relationship between the probability of house loss and the variable of interest. Multivariate analysis consisted of a Principal Component Analysis and Logistic regression using Minitab version 16 (Minitab Inc., 2010).

Results

The multivariate analysis (Principle Component Analysis) showed that there was a strong correlation between the local convection strength ("Convect") and the generalized convection density ("ConvectDens") (Fig. 2). Similarly, there was a strong correlation between flame height ("FlameHt"), flame depth ("FlameDpth") and fireline intensity ("Intensity"). Flame cross-sectional area was correlated to the other flame dimensions, but showed some independence. Modelled ember density ("Embers") was independent of all other fire variables, but explained a smaller proportion of the variation in the data than the other variables. This analysis shows that there are three relatively independent factors describing the simulated fire characteristics associated with house loss on Black Saturday - "Ember Density", Flame Height/Flame Depth/Flame Cross-sectional area/Fireline Intensity, and Convective Strength/Convective Strength Density.

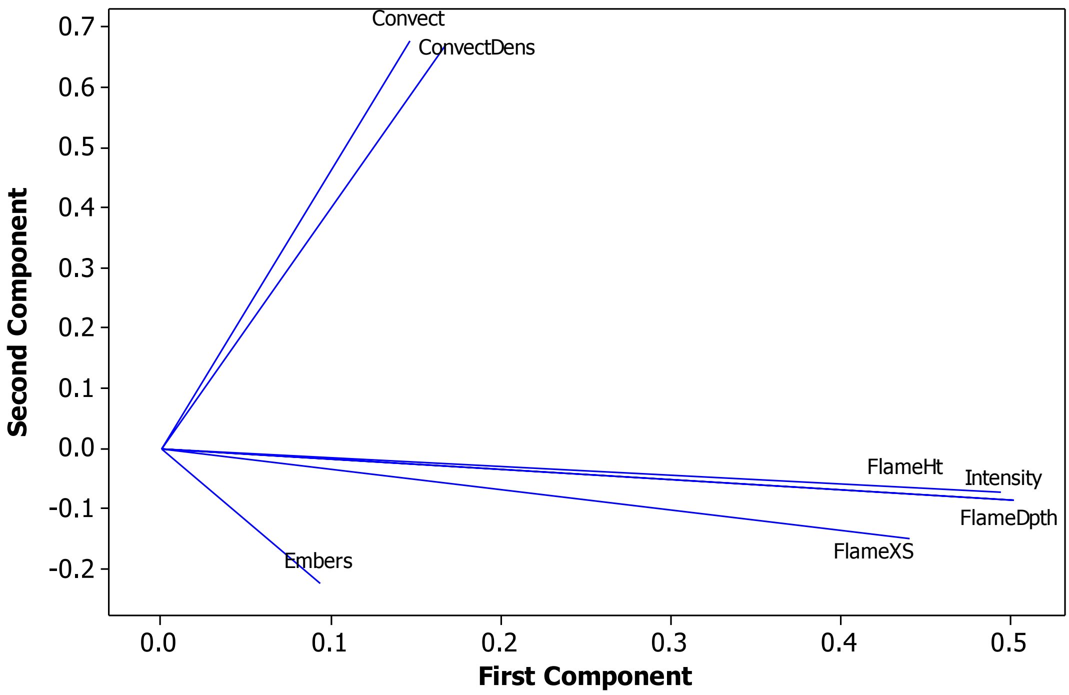

Figure 2. Principle Component Analysis of predicted fire variables for houses destroyed in the Kilmore East, Murrindindi and Churchill fires on Black Saturday 2009.

Analysis of individual fire characteristics showed significant trends between the magnitude of each factor and the probability of house loss (Figures 3 to 8). The line of best fit for each factor is given in Table 1.

Table 1. Line of best fit regressions for a number of modelled fire parameters and the probability of house loss.

Fire Parameter	**Model**	**R value**
Flame height (m)	Pr(Loss) = 0.8348/(1+1.10667*EXP(-0.05726*FlameHt))	0.896
Flame cross-sectional area (m^2)	Pr(Loss) = 0.40935*FlameXS^0.0793	0.935
Ember density (No./m^2)	Pr(Loss) = 0.5715*(1.1747-EXP(-0.9513*Ember))	0.907
Fireline Intensity (kW/m)	Pr(Loss) = 1/(4.5278-1.7366*Intensity^0.05456)	0.952
Convection	Pr(Loss) = 0.2543*(Convect+5.6966)^0.104	0.981
Convection Density	Pr(Loss) = 0.9303-0.7554*EXP(-0.0000926*ConvectDens^0.7085)	0.989

If instead of predicting a probability of house loss, each house was assessed on the basis of a binary classification of "Lost" or "Survived", then the threshold values of each fire parameter that would be define the 50/50 chance of loss or survival are listed in Table 2. This analysis does not consider the interaction of variables, e.g. the enhancing of house ignition by embers when there is also a significant radiation heat load, which would be confounded in these thresholds. For example, it is likely that a house might be subjected to both radiation and ember attack, but these factors cannot be separated in this analysis.

Table 2. 50% survival/loss threshold value for each fire parameter based on the line-of-best-fit regression lines in Table 1.

Fire Parameter	**50/50 Survival Threshold Value**
Flame height (m)	9 m
Flame cross-sectional area (m^2)	13 m^2
Ember density (#/m^2)	1.3 embers/m^2
Fireline Intensity (kW/m)	1,000 kW/m
Convection	700

Convection Density	220,000

Two binary logistic regressions were fitted to the house survival/loss data using Logit. A range of factor combinations were explored, but only two combinations were considered to be generally applicable. Three factors were used in each of the two models. Both included Flame Cross-sectional Area and Ember Density. The difference between the two regressions was the use of either Convective Strength or Convective Density. Both these regressions are statistically significant at the p=0.001 level and the ranked-based non-parametric statistic, Somers' D (Newson 2002), indicates that 51% of the variation in the probability of house loss is explained by equation 1 and 42% of the variation is explained by equation 2.

Logistic equation 1.

Pr(Loss)=1-EXP(0.63076-0.0000021*ConvectDens-0.0002662*FlameXS-0.01832*Embers)/(1+EXP(0.63076-0.0000021*ConvectDens-0.0002662*FlameXS-0.01832*Embers))

Somers' D = 0.51

Logistic equation 2.

Pr(Loss) =1-EXP(0.2894-0.000487*FlameXS-0.02003*Embers-0.0000157*Convect)/(1+EXP(0.2894-0.000487*FlameXS-0.02003*Embers-0.0000157*Convect))

Somers' D = 0.42

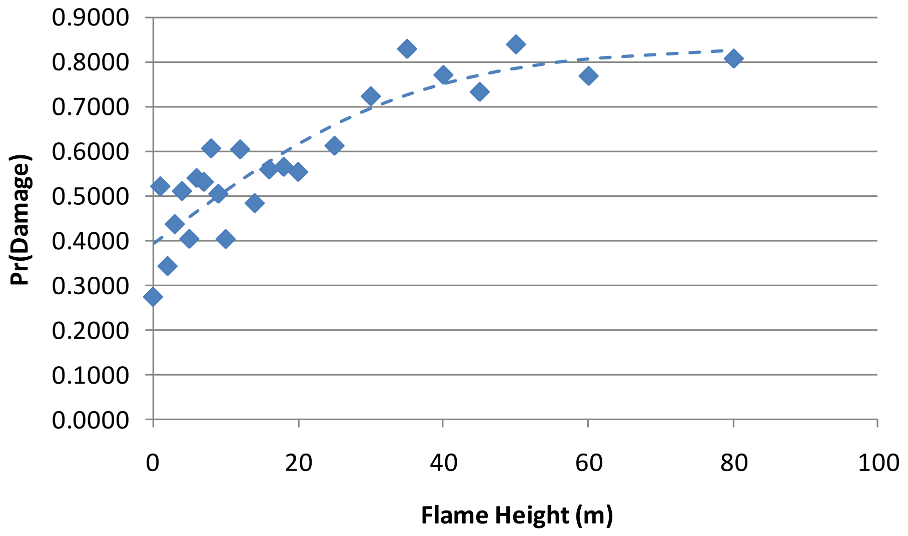

Figure 3. Probability of house loss when associated with predicted flame height.

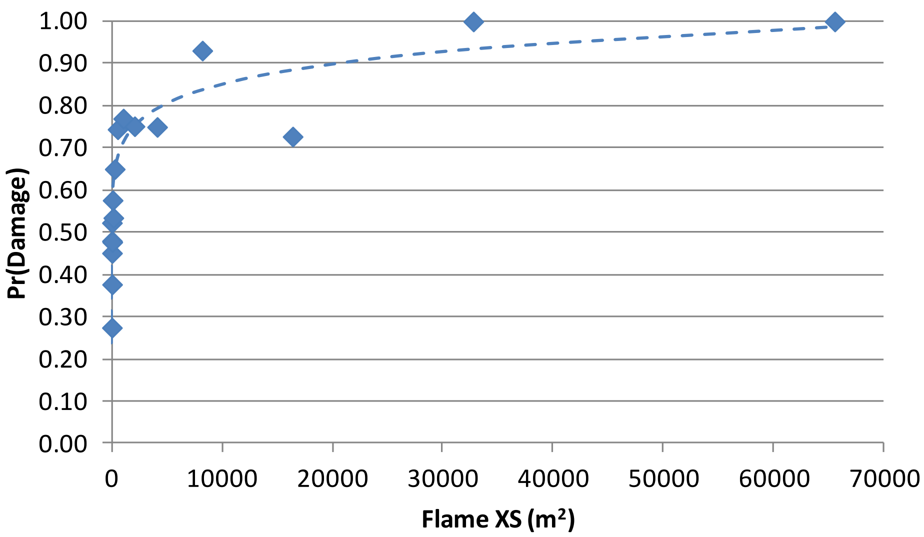

Figure 4. Probability of house loss associated with predicted flame cross-sectional area.

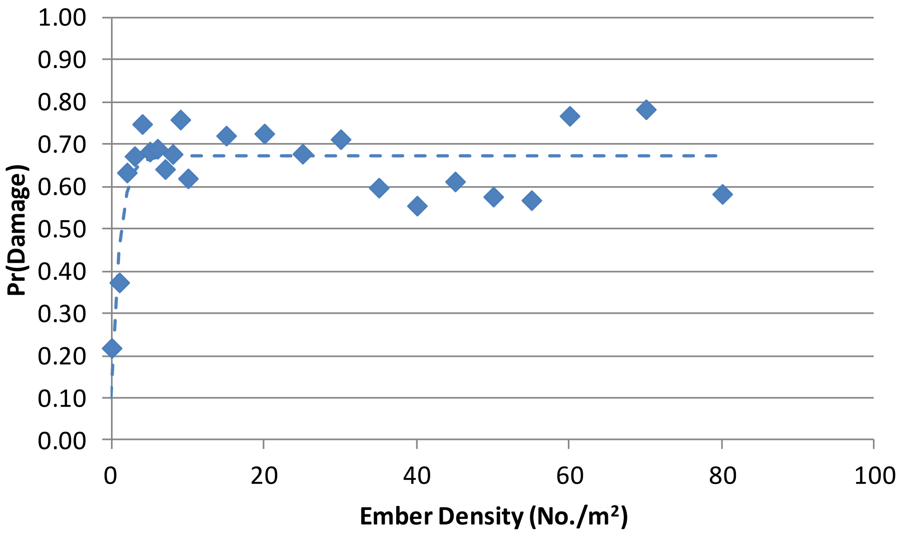

Figure 5. Probability of house loss associated with predicted ember density.

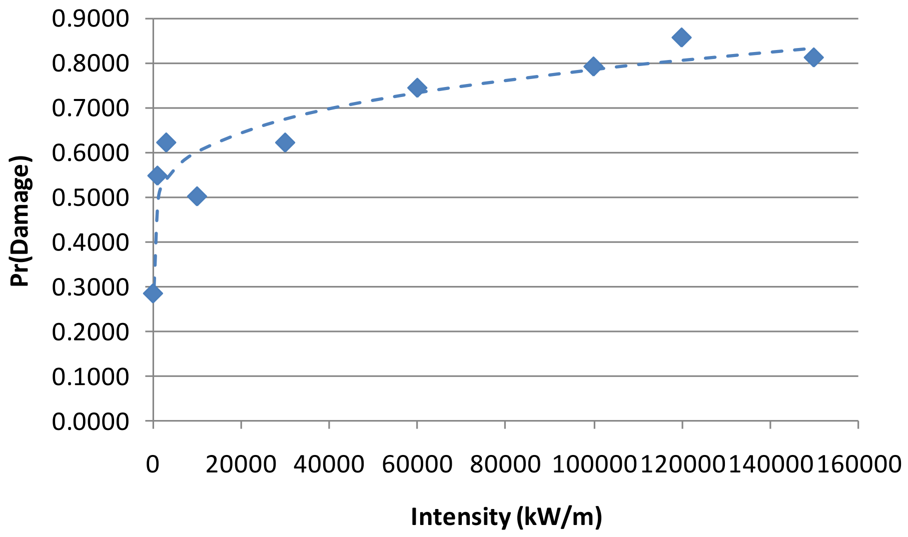

Figure 6. Probability of house loss associated with predicted fireline intensity.

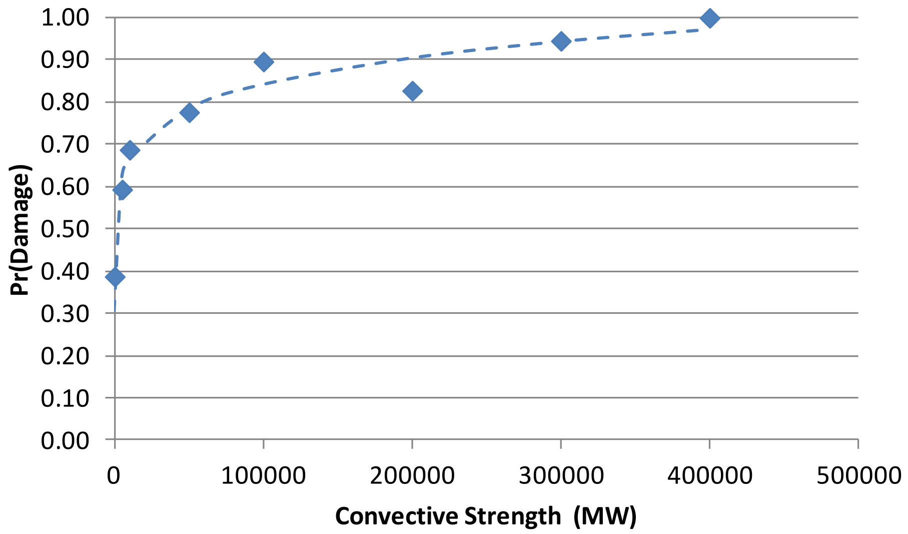

Figure 7. Probability of house loss associated with predicted convective strength.

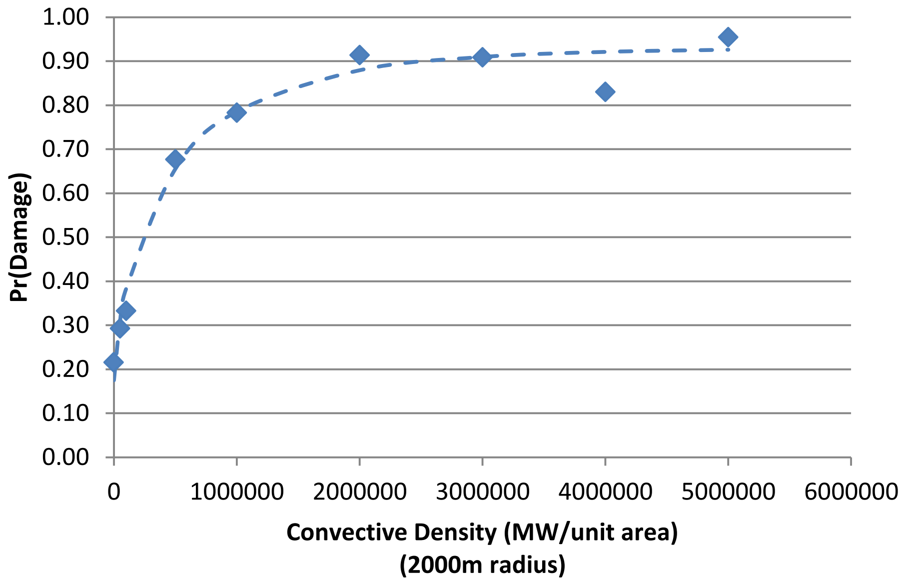

Figure 8. Probability of house loss associated with predicted convective strength smoothed over a 2000 m radius.

Table 2. Average probability of house loss predicted by each of the proposed models (Table 1 and Logistic equations) compared with the actual house status "Lost"/"Surv", subdivided by fire event. (Flame XS = flame cross-sectional area, EmberDens = ember density, Intensity = fireline intensity, Convection = convective strength, ConvectDens = convective strength density.)

	Logit1		Logit2		FlameXS		FlameHt		EmberDens		Intensity		Convection		ConvectDens	
FIRE	Lost	Surv	Lost	Surv	Lost	Surv	Lost	Surv	Lost	Surv	Lost	Surv	Lost	Surv	Lost	Surv
Churchill	0.59	0.46	0.58	0.50	0.52	0.35	0.53	0.48	0.61	0.34	0.58	0.47	0.50	0.39	0.52	0.35
Kilmore	0.61	0.45	0.58	0.49	0.53	0.41	0.58	0.49	0.53	0.37	0.57	0.48	0.49	0.38	0.52	0.35
Murrindindi	0.54	0.41	0.50	0.45	0.48	0.33	0.50	0.46	0.52	0.24	0.54	0.43	0.40	0.34	0.52	0.33
Stawell	0.36	0.37	0.43	0.44	0.51	0.47	0.44	0.44	0.13	0.15	0.60	0.57	0.33	0.38	0.25	0.27
Total	**0.59**	**0.44**	**0.56**	**0.48**	**0.52**	**0.40**	**0.55**	**0.48**	**0.53**	**0.34**	**0.56**	**0.47**	**0.47**	**0.38**	**0.52**	**0.34**

The average probabilities of house loss predicted by various models compared to the actual status of each house on an individual basis is not strongly differentiated, certainly not as strongly differentiated as might be expected from the consistency of the relationships shown in Figures 2 to 7. This is interpreted to suggest that the relationships between the fire characteristics predicted by PHOENIX RapidFire and the probability of house loss are not a very good basis for predicting the probability of loss of individual houses even though the predictions about the general house loss for groups of houses is quite strong. In all cases in Table 2, the averaged predicted probability of house loss is higher for the damaged and destroyed houses ("Lost") than for the houses that survived ("Surv"), so each of the models work on average

Table 2 shows an interesting distinction between the three fires analyzed from Black Saturday and the Stawell fire. With most of the models, the predicted probability of loss is less than 0.5 and distinctly less than the probabilities for the Black Saturday fires. The Stawell fire was a fast moving, wind-driven grassfire largely in grassland with only scattered areas of forest and woodland, quite different to the situation in the Kilmore East, Murrindindi and Churchill fires which were largely in mountainous forested country and developed very large convective plumes. Even though the "EmberDens", "ConvectDens" and "Logit1" models gave the best overall prediction of house loss, it was the model based on the Flame Cross-sectional Area ("FlameXS") which gave the most consistent prediction regardless of whether the fire was in grassland or forest.

In all cases, except one, the average probability of house loss predicted for surviving houses was less than 0.5. The sole exception was for the houses surviving the Stawell fire when using the predictive model based on Fireline Intensity. The intensity of the Stawell fire was dominated by the rapid rate of spread rather than the effect of fuels and topography, as would be expected in a grassland-dominated fire.

Discussion

House loss in bushfires results from the combination of many interacting factors including characteristics of the house construction, the presence or not of fire suppression efforts during the fire event, the level of garden (fuel) and house maintenance, the proximity of flammable objects to the house, the nature of the bushfire itself, the position of the house in the terrain and an element of chance (Wilson & Ferguson 1986, Blanchi *et al.* 2006). Previous attempts to predict bushfire threat in terms of potential house loss using a static view of geospatial data such as vegetation, slope, aspect and potential fire intensity, had limited success in identifying houses most at risk (Lowell *et al.* 2009). It is not surprising that it is difficult to accurately predict which specific houses will survive and which will be lost when it is not possible to accurately quantify all the interacting factors during a fire event. However, there are some factors which can be adequately quantified and have a significant bearing on the probability of a house surviving or being destroyed during a bushfire. These probability ratings can give a reasonable prediction of the likely number of houses that will be lost in a neighborhood, without being certain about specific houses and this has been demonstrated in this study. A dynamic view of fire behaviour as provided by a simulator such as PHOENIX RapidFire is likely to result in better predictive ability than a bushfire threat model based on a static view of fire.

Detailed analysis of the circumstances associated with house loss in bushfires has identified the critical factors. Some of these factors are related to the nature of fire and it is these that have been used here. Flame characteristics such as flame height and flame cross-sectional area affect the radiative heat load on a house and the likelihood of flame contact, so it was not surprising to find a strong association between the flame characteristics predicted by PHOENIX RapidFire and the known level of house loss. Fireline intensity was also identified by Wilson and Ferguson (1986) as being strongly associated with house loss and again, there was a strong relationship between the modelled fire intensity and the probability of house loss. Embers have been associated with about 90% of all house losses as either the primary ignition source or an ignition source in combination with other factors (Leonard and Blanchi 2005). In the analysis here, the probability of house loss increases rapidly with ember density and then seems to "saturate" at relatively low levels. The addition of further embers does not change the probability of house loss, and the probability of house loss with embers alone does not exceed about 70%. A unique aspect of using PHOENIX RapidFire to assess the nature of the fire is the ability to calculate the local convective strength. Strong convective influences only occur in large intense fires where the weather, fuel and topography combine to create suitable convective development. Convective strength has not been a factor specifically included in house loss studies because of the difficulty in determining it. Computer modelling makes this possible, even if the method used to calculate convection in PHOENIX RapidFire is not a 3-dimensional fluid-dynamic model it provide sufficient convective characteristics to correlate local fire behaviour with potential house loss. In this study, the convective strength (and convective density) was strongly correlated with the house loss in the fires of Black Saturday in Victoria, but was not as important in the Stawell fire in 2005 where grass fuels dominated and the topography was flat to undulating.

The most robust model for predicting the probability of house loss is the logistical model that combines the effects of flame cross-sectional area, ember density and convective strength density. These three variables represent the three main components of the data shown in Fig.1. This model incorporates the main factors, related to the fire itself, that are known to be associated with house loss. However, the model using just flame cross-sectional area would give a more consistent prediction of house loss across contrasting fire types - flat grassland fires compared with fires in forested hills and mountains. Flame characteristics explain the greatest amount of variation in the house loss data (Fig.1). Given the history of greater house loss in forested hills and mountains, it would seem prudent to use the logistical model as the first choice in complex landscapes.

Conclusions

PHOENIX RapidFire provides an adequate spatial and temporal characterization of bushfires to be able to estimate the probability of house loss at a neighborhood scale. Although the fire characterization by PHOENIX RapidFire has not been, nor is ever likely to be validated at a scale similar to that used here (3.24 ha) it does provide a realistic range of fire behaviour characteristics and spread that can be used for analyses such as this. A logistic model incorporating flame cross-sectional area, ember density, and convective strength density produced the most robust model overall. A non-linear regression model using just flame cross-sectional area gave more reliable results in grassland dominated landscapes.

House design and level of preparation and maintenance were not considered in this modelling process, nor was the level of active defense during the passage of the fire. These are known to also be important contributing factors to the probability of house survival, but could not be included in this analysis due to lack of adequate data.

The predicted level of house loss using simulated fire characteristics, provides a useful basis for assessing the relative threat of fire in a range of circumstances. It is therefore expected that this modelling approach could be used to evaluate the relative benefits of different fire mitigation options such as broadscale planned burning and fuel modification in and around townships and small communities.

References

Ahern, A. and Chladil, M. (1999). How far do bushfires penetrate urban areas?. Australian Bushfire Conference, Albury, July 1999. 12 pp. http://www.csu.edu.au/special/bushfire99/papers/ahern.

Blanchi, R., Leonard, J.E., and Leicester, R.H. (2006). Lessons learnt from post-bushfire surveys at the urban interface in Australia. Proceedings of V International Conference on Forest Fire Research, Portugal, D.X. Viegas (ed). 12 pp.

Blanchi, R., Lucas, C., Leonard, J. and Finkele, K. (2010). Meteorological conditions and wildfire-related house loss in Australia. *International Journal of Wildland Fire*, **19**(7), 914-926.

Byram, G. (1959). 'Combustion of forest fuels' in K.P.Davis, G.M.Byram and W.R.Krumm (eds.), *Forest Fire - Control and Use*, McGraw-Hill Book Co., New York. Chapter 3.

Chen, K. and McAneney, J. (2010). Bushfire penetration into urban areas in Australia: a spatial analysis. Bushfire CRC submission to 2009 Victorian Bushfires Royal Commission, Document ID: CRC.304.001.0001. http://www.royalcommission.vic.gov.au/Documents/Document-files/Exhibits/CRC-304-001-0001.pdf

Cohen, J.D. (1995). Structure Ignition Assessment Model (SIAM). In "*The Biswell Symposium: Fire Issues and Solutions in Urban Interface and Wildland Ecosystems*", 15-17 February 1994, Walnut Creek, California. USDA Forest Service, General Technical Report PSW-GTR-158, pp. 85-92.

Leonard, J. and Blanchi, R. (2005). Investigation of bushfire attack mechanisms involved in house loss in the ACT Bushfire 2003. CSIRO Manufacturing & Infrastructure Technology, Highett, Victoria. Bushfire CRC report. 61pp.

Lowell, K., Shamir, R., Siqueira, A., White, J., O'Connor, A., Butcher, G., Garvey, M. and Niven, M. (2009). Assessing the capabilities of geospatial data to map built structures and evaluate their bushfire threat. *International Journal of Wildland Fire*, **18**, 1010-1020.

Massada, A.B., Volker, C.R. and Stewart, S.I. (2011). Allocating fuel breaks to optimally protect structures in the wildland-urban interface. *International Journal of Wildland Fire*, **20**, 59-68.

Mell, W.E., Manzello, S.L., Maranghides, A., Butry, D. and Rehm, R.G. (2010). The wildland-urban interface fire problem - current approaches and research needs. *International Journal of Wildland Fire*, **19**, 238-251.

Newson, R. (2002). Parameters behind "nonparametric" statistics: Kendall's tau, Somers' D and median differences. *The Stata Journal*, **2**(1), 45-64.

Ramsay, G.C., McArthur, N.A., and Dowling, V.P. (1987). Preliminary results from an examination of house survival in the 16 February 1983 bushfires in Australia. *Fire and Materials*, **11**(1), 49-51.

Tolhurst, K.G., Shields, B.J. and Chong, D.M. (2008) PHOENIX: development and application of a bushfire risk management tool. *Australian Journal of Emergency Management*, **23**(4), 47-54.

Wilson, A.A.G. and Ferguson, I.S. (1986). Predicting the probability of house survival during bushfires. *Journal of Environmental Management*, **23**, 259-270.

Rethinking the fuel – fire relationship

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Abstract.

Recent advances in the understanding of fire behaviour and the effectiveness of fire management techniques present a number of major new challenges for fire and incident management. The Forest Flammability Model addresses these challenges by characterising fuels with physical measurements of plants rather than indices or approximations. Fuel is described as a discontinuous array of fuel elements with spaces that must be crossed by fire for new fuels to become available. The implications of this are that fire behaviour can change very rapidly with even minor changes in factors such as slope or wind speed, and that vegetation can also act to slow fire spread by reducing wind speed or maintaining more moist fuels. The Forest Flammability Model quantifies these effects, providing improved accuracy in fire behaviour forecasts and identifying new options for fuel management that take into account the effect of forest structure and seral stages on fire spread and intensity.

Additional keywords: Fire behaviour, fuel management, prescribed burning, fire ecology, Forest Flammability Model, climate change

Introduction

Recent work quantifying the effectiveness of fuel treatments for reducing the impact of fire in the landscape has identified the need to re-examine our understandings of the fire-fuel relationship. Loehle (2004) quantified the assumed effectiveness of prescribed burning via the modelling of 'leverage' - the relative reduction in wildfire area for each unit area of prescribed burning. Assuming that fuel reduced areas would not re-burn; each treated cell was found to protect an area in its 'shadow', so that strategically placed prescribed burns produced a leverage of 11 cells protected for each cell treated - a leverage factor of 11. In this sense, prescribed burning could be described as burning a small area to protect a large area and therefore clearly an effective tool for risk management. When the assumed effectiveness of such burns was compared to actual measurements however, the reality was sobering. In the largest such study to date, Boer *et al* (2009) found that the leverage for a prescription burnt area of SW Western Australia was only 0.25. Although the fuel treatments did have an effect on the size of bushfires, Loehle's assumed efficacy of prescribed burning was up to 44 times greater than the measured reality. Very slightly stronger leverage values have been found for forest in the Sydney sandstone (Price and Bradstock 2010), but no study has yet identified a forest community where the introduction of prescribed fire has not increased the total area burnt each year. This has significant implications for landscape values such as catchment management, carbon accounting, smoke production and biodiversity, as well as for the protection of built structures. Leverage does not account for reductions in fire severity or intensity, but as the leverage was measured from a site where active fire suppression also took place, this value of 0.25 indicates that on average, unplanned fires were of sufficient intensity that suppression efforts were unable to contain them over three quarters of any prescription-burnt area.

Although leverage studies do provide an objective measure of prescribed burn efficacy, the practice of contrasting 'young', recently burnt fuels with 'old' long unburnt fuels is fundamentally flawed. The premise for this is the fuel-age paradigm (Zedler and Sieger 2000) - an assumption that forest flammability increases with age. In their examination of prescribed burn efficacy, Fernandes and Botelho (2003) found that "…post-treatment recovery can be so fast that fuel management may be futile or even counter-productive in some fuel types" and that it "leads to the conclusion that the fuel/age paradigm is a simplification, and that the hazard reduction effectiveness of prescription burning will vary by ecosystem (or fuel type) and according to the relative impacts of fuels and weather on fire behaviour." If this is the case, it becomes clear that the leverage when measured across a landscape is likely to be an average of areas where prescribed burns were more effective along with other areas where burns were less effective or counter-productive. If the efficacy of prescribed burning can be identified for specific forest communities then, it may be possible to improve fuel management in general by utilising prescribed fire where it is most effective, and by using other approaches where it is ineffective or counter-productive.

Fundamental to achieving this is the way that the relationship between fine fuels and fire behaviour is understood. McArthur (1967) asserted that fuel load and rate of spread were directly related, so that halving the fuel load would result in a halving of fire spread rate. This concept that the weight of fuels determines the flammability of a forest remains a dominant view across Australia, repeatedly reaffirmed in popular literature (e.g. McCaw *et al* 2008, Attiwill *et al* 2009) and providing theoretical justification to the fuel age paradigm. The reality is however that successive peer-reviewed studies since the 1940's have consistently demonstrated that no such relationship exists (Fons 1946, Fang and Steward 1969, Wolff *et al* 1991, McAlpine 1995, Burrows 1999), that is, that fuel load and head fire rate of spread are unrelated or have such a weak relationship as to be unworthy of consideration in fire behaviour modelling. As surface fine fuels typically increase following the same negative exponential pattern regardless of forest type (e.g. Hamilton 1964, McColl 1966, Ashton 1975, Hutchings and Oswald 1975, Raison *et al* 1986, Burrows & McCaw 1990, McCaw 1997, Gould *et al* 2007), any attempt to reduce flammability premised on the goal of reducing the fuel load therefore imposes an identical view of flammability dynamics across all forests; a view which runs counter to the empirical evidence and has been demonstrated to be significantly less effective than expected. If fuel management is to be made more effective then, it is critical that an evidence-based understanding of the fuel-flammability relationship is adopted so that the different dynamics between ecosystems can be identified and quantified. Effective fuel management requires that we no longer see Australian forests as just “the bush” with one management tool to fit all. This is consistent with Australia’s history of Indigenous fire management, which was characterised by specific approaches in different environments (Zylstra 2006*a*, 2011*a*).

The Forest Flammability Model

The Forest Flammability Model (FFM, Zylstra 2011*a*) was developed in response to this need as part of the Bushfire CRC fuel and risk management studies (Zylstra 2009). The FFM adopts a semi-physical approach to modelling fire behaviour that examines the interactions between fire and all potential fuels in the array using a dynamic, complex systems approach based primarily on convective heat transfer in the context of forest geometry and the principles of flammability (Gill and Zylstra 2005). Surface fuels are treated as the baseline stratum for fire spread, providing a ‘pilot flame’ which is modelled using Burrows (1999) empirical surface spread model. The trajectory for the convective plume is based on flame length and wind speed (Van Wagner 1973), with limits imposed by geometrically calculated blocking effects on air entrainment due to slope. Potential fuels in the higher strata are exposed to a temperature which decreases along the plume according to Weber *et al* (1995), based on distances defined by the geometry of the plants. Ignition of new fuels occurs if the ignition delay time (Anderson 1970) of the leaves is exceeded by the flame duration, where ignition delay time was modelled (R^2 = 0.90) across multiple species based on temperature, leaf thickness and moisture content using the experimental procedure of Gill and Moore (1996). Flame duration for surface fuels was based on Burrows (2001), and modelled across species for foliage (R^2 = 0.74) based on leaf moisture and cross-section area. The depth of ignition into the exposed foliage was determined iteratively for a one-second time step, then the new flame length calculated from the existing flame minus any expired flame and with new burning leaves added. The length of flame from burning leaves was modelled (R^2=0.83) across species based on leaf surface area, and the methods for this and flame duration experiments are described in Zylstra (2006*b*). Flames burning in close proximity were merged to produce a longer flame due to blocked air entrainment and heat feedback (Thomas, 1963, Thomas *et al* 1965, Huffman *et* al 1967, Steward 1970, Chigier and Apak 1975, Tewarson 1980, Gill 1990, Heskestad 1998, Weng *et al* 2004, Liu *et al* 2009). The increased flame length was modelled due to lateral effects using Gill (1990), and due to longitudinal effects using Mitler and Steckler (1995).

This approach has the advantage of being grounded in observable, physically explicable phenomena, and demonstrates that the characteristics of fire behaviour are determined as much by the spaces between fuels as they are by the quantity of fuels. Although the forest from floor to canopy may contain an enormous quantity of potential fuel, if fire is unable to bridge gaps between strata, then the higher fuels are unavailable. Significantly however, unavailable fuels still affect fire behaviour by determining the 'fuel environment'. Foliage in higher strata directly affects the probability of fire occurrence and the behaviour of fire in dead surface fuels by shading those fuels and thereby affecting the temperature, moisture content and drying rates (e.g. Van Wagner 1969, Viney 1991, and Matthews 2006). Even more significantly, the density and height of foliage in these strata directly reduces the wind speed at lower levels (McArthur 1962, 1966, Cionco *et al* 1963, 1972, 1978, Albini 1981) so that flames in the lower strata are more upright and convective heat is directed upward rather than forward, slowing fire spread. Rather than subjectively applying wind reduction factors as per McArthur (1962, 1966), the 'canopy flow index' in the model of Cionco *et al* (1963) was developed, extending work by Greene and Johnson (1996) and Wang and Cionco (2007) so that the speed of wind can be calculated for any point in the vertical profile of a fuel array based upon the dimensions and leaf area index of fuels above that point.

The FFM has received some validation to date (Zylstra 2011*a*), demonstrating lower mean absolute errors than earlier empirical models for both rates of spread and flame heights (table 1). Although this has provided statistically significant improvement in some cases, further validation is ongoing to identify specific strengths and weaknesses.

Implications for fuel and risk management

The implications of the FFM for fuel management are primarily that the focus is shifted from reducing fuel quantity to managing the fuel structure and environment. Because fire is a complex system, finding widespread rules to achieve these goals is not simple as changes in one area may produce positive or negative feedbacks to other areas. For example, a sensitivity analysis of the model (Zylstra 2011*b*) which considered both mature and regrowth Alpine Snowgum (*Eucalyptus niphophila*, figures 1 & 2) found that elevated levels of dead material in the shrub strata increased the mean rate of spread in the mature forest, but slowed fire spread in the regrowth forest. Dead material is generally drier than live material and therefore burns more readily producing greater flame lengths and consequently more upright flames. In mature forest this increased the incidence of active crown fires, where loss of crown foliage facilitated access of wind to the lower strata. In regrowth forest however, the absence of a tree canopy removed this influence, so that the more upright flame simply reduced the forward transfer of convective heat.

Table 1. Mean absolute error for the FFM in comparison with three empirical models (from Zylstra 2011*a*). Models were tested against eight fires ranging from low to extreme intensity to assess rates of spread, and against 10 fires of low to extreme intensity to assess flame heights. Significance was assessed using a paired *t*-test to determine whether the error margin in the model was higher than that of the FFM.

	RATE OF SPREAD		**FLAME HEIGHT**	
MODEL	**Mean error**	**Significance**	**Mean error**	**Significance**
McArthur (1962)	287%	N.S.	111%	N.S.
McArthur (1967)	843%	95.0%	528%	95.0%
Gould *et al* (2007)	349%	90.0%	106%	N.S.

FFM	69%	46%

Figure 1. Six year-old regrowth Snowgum forest

Figure 2. Long unburnt (50 year-old) Snowgum forest

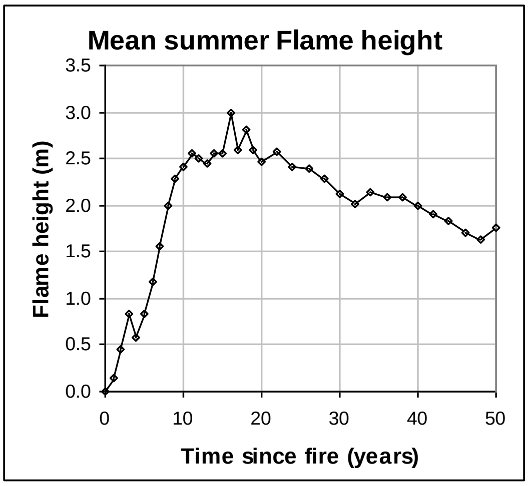

Figure 3. Mean summer flame height modelled for one summer in Snowgum forest on a 17 degree slope. Source: (Zylstra 2011*a*)

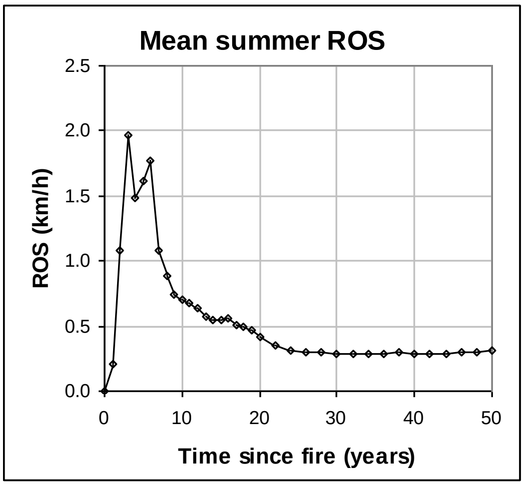

Figure 4. Mean summer rate of spread modelled for one summer in Snowgum forest on a 17 degree slope. Source: Zylstra (2011*a*)

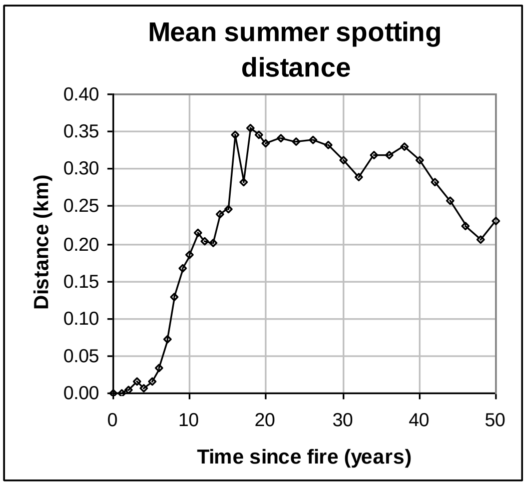

Figure 5. Mean summer spotting distance modelled for one summer in Snowgum forest on a 17 degree slope. Source: (Zylstra 2011*a*)

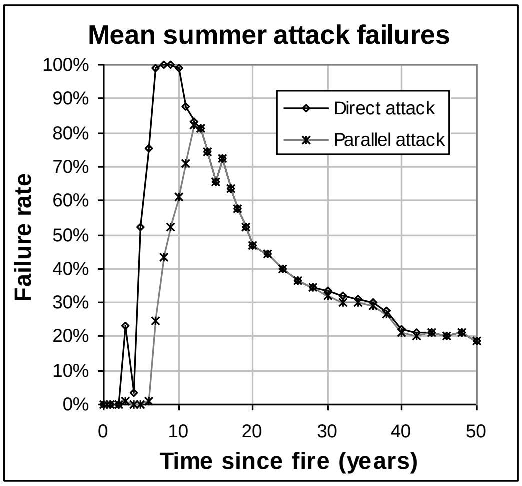

Figure 6. Percentage of a summer where direct and parallel attack methods are expected to fail, modelled for one summer in Snowgum forest on a 17 degree slope. Source: Zylstra (2011*a*)

In order to overcome such complexities, the FFM can be used to develop age-flammability profiles which examine typical weather conditions for a site, considering the changes that are expected based on the known post-fire succession of the community. Such an analysis of the Snowgum community (Zylstra 2011*a*) identified three stages in the regrowth of the forest – young fuels with low rates of spread and flame heights for the first few years following the fire, a regrowth phase of heightened flammability and a long lasting mature phase where rates of spread and frequency of attack failure rapidly decreased to very low levels but mean flame heights and spotting distances declined more gradually (figures 3 to 6). This pattern was similar to that observed in the Dee Vee study as part of the Project Vesta experiments (Gould *et al* 2007, McCaw *et al* 2008), but was more pronounced and determined primarily by the proximity of the regenerating canopy to the lower fuels and its capacity to remain unburnt and thereby reduce wind speeds at the lower fuels. The sensitivity analysis (Zylstra 2011*b*) found that across six different communities, the capacity for midstorey and canopy foliage to slow wind speeds at lower levels was by far the most influential factor determining the flammability of a forest.

The differences in these responses highlight three important points:

If fuel structure and environment are considered, the fuel-age paradigm does not necessarily hold true; that is, flammability may actually decrease with time since fire in some circumstances. Effective fuel management should focus primarily on the way that treatments influence fuel structure and environment over time.

Different aspects of fire behaviour do not necessarily correlate with each other. Effective fire management should identify the specific fire behaviour outcome desired (e.g. reduced flame height or increased direct attack success) and target management to the fuel age that will best achieve this.

Effective fuel management needs to be decisive. Either very frequent fire or active fire exclusion would have achieved similar outcomes for rates of spread for example, but a compromise frequency (e.g. every ten years) would only serve to maintain the forest at its most flammable stage. It should be noted that very frequent fire may have other effects that are not captured here; for example whether planned or unplanned, fire promotes topsoil loss (Smith and Dragovich 2008) which can result in a shift from grasses toward shrubs in this environment (Wimbush and Costin 1979, Williams 1992), which will in turn affect the flammability. Such decisions need to be grounded in quantitative risk assessment so that the actual costs and benefits are compared objectively.

By including multiple aspects of plant and forest structure and physiology, the FFM provides a mechanism by which the effects of external environmental influences on bushfire risk can also be better quantified. The moisture content of some plant species for example is heavily influenced by temperatures averaged over the preceding week, while other species respond primarily to soil moisture (Zylstra 2011*a*). The influence of a hot day following a protracted heatwave compared to that of an isolated event can therefore be compared directly, or contrasted with the effects that drought has on fire behaviour through the drying of different plant species. Changes in temperature and atmospheric CO_2 levels also affect features such as leaf dimensions and the capacity of some plants to grow in shaded areas (Ashton 1975, Ashton and Turner 1979), and the occurrence of heavy frosts imposes limits to the distribution of some species (Newman 1954, Moore and Williams 1976). These factors are observably changing as a result of anthropogenic global warming (Rosenzweig *et al* 2007) and the FFM provides a tool by which the impact of such changes can be modelled. Increased temperature for example may result in the earlier seasonal growth of large leaves in some species (Ashton 1975). This may in turn increase the flammability of a forest as longer leaves produce larger flames (Zylstra 2006*b*, 2011*a*), or may decrease flammability by providing more shade (Matthews 2006) and reduced wind speed in lower plant strata (Cionco 1972). As these factors are part of a complex system of feedbacks and interactions, it is impossible to predict the outcome without careful modelling and it certainly cannot be addressed with a simplistic attention to fuel load.

Existing responses

The over-simplification of the fuel load argument has been partly recognised through industry tools (Hines *et al* 2010), which consider some aspects of fuel structure such as shrub density and assign different weightings to fuels in different strata. Major structural and environmental feedbacks such as canopy density and separation from lower strata are not captured however, so the overall effect is still the consideration of fuel load, albeit weighted by its location in the array. While Hines *et al* (2010) does not provide a connection between fuels and fire behaviour, Gould *et al* (2007) used a similar approach to differentially weight fuels in three different strata using two fuel load parameters and two wholly structural parameters, and provide a fuel-fire connection. This has produced large improvements in predictive accuracy compared to McArthur (1967, Table 1). Canopy separation from lower strata is partially inferred by the inclusion of shrub height; however without consideration of other critical structural and environmental effects as outlined earlier the model is also unlikely to identify major discrepancies from the fuel-age paradigm.

In applied risk management applications, fuel load is still very frequently the sole determining factor. Under Australian Standard AS 3959_2009, specific issues of risk management around built structures are still assessed on fuel load alone, as are some other tools currently being developed to determine optimal placement and extent of prescribed burning in the landscape for likelihood assessments (e.g. Tolhurst *et al* 2009). Bushfire threat at the urban interface is currently being re-examined using the FFM (Zylstra 2011*c*) as part of the Bushfire CRC Fire Impact and Risk Evaluation Decision Support Tool (F.I.R.E_D.S.T) with the intention of both improving accuracy of assessments and of informing more effective fuel management. Fuel management in the landscape however continues to be informed by tools that do not incorporate the major factors of fuel structure and environment such as canopy density and the continuity of fuels to the canopy. Consequently, those areas where the introduction of fire may be “futile or even counter-productive” (Fernandes and Botleho 2003) cannot yet be effectively identified, rendering prescribed burning programs less effective than they could be.

Model implementation

The main obstacle to implementation at this stage is the fact that the FFM utilises many more fuel inputs than other Australian fire models. This however can be overcome by a shift in thinking. The FFM identifies that many factors in the structure and physiology of plants and forests work together to affect their flammability, so what is needed is not more intensive fuel measurement but better measurement of forests in general. Because the fuel parameters are direct measurements rather than subjective scores or visual estimates, all parameters are either measurable from herbarium specimens or via remote sensing methods (Zylstra 2011*b*). Using a combination of these methods to produce a central database of static species-specific traits such as leaf dimensions along with remotely sensed imagery from either satellite sensors such as

QuickBird or airborne sensors such as LiDAR or ADS40 imagery, it may become possible to move from a culture of subjective point measurements obtained by labour-intensive field survey toward objective landscape-scale measurement. The mean sensitivity of the parameters was also very low (0.18, Zylstra 2011*b*) compared to 1.00 for the McArthur meter, allowing for considerable error in measurements.

Natural variability in forest structure produces variability in fire behaviour, so collection of the variability in parameters will allow ensemble modelling of behaviour with statistically defined limits. This produces a trade-off between mapping resolution and predictive precision, so that finer mapping scales will produce a narrower range of potential outcomes. In this way, the desired level of accuracy can be used to determine the mapping resolution needed for an area.

Conclusions

Although tools such as the Overall Fuel Hazard Assessment Guide (Hines *et al* 2010) are beginning to increase the focus on fuel structure to some extent, fuel environment and many structural elements are not yet considered and the resulting management remains underpinned by the fuel-age paradigm. Popular thinking still describes the objective of fuel management as fuel reduction rather than optimisation of fuel structure and environment (e.g. Adams & Attiwill 2011), and tools used for risk assessment such as the AS 3959_2009 and others currently being developed to determine optimal placement and extent of prescribed burning (e.g. Tolhurst *et al* 2009) remain constrained by McArthur's modelling of fuel load effects on fire behaviour. Because this underlying paradigm persists despite the weight of evidence, fuel management programs have very little capacity to identify the forest communities where prescribed burns will be effective and where they will not, so that empirical analysis of the effectiveness of these programs has demonstrated disappointing results when compared with theoretical expectations. More effective fuel management may be achieved by rejecting the assumption that 'young' fuels are automatically less flammable and instead using an evidence-based approach to identify and manage for an ideal age range. As different measures of fire behaviour or risk do not necessarily correlate, the priority measures should be identified based upon specific objectives for the location and the target age range planned to minimise these.

To this end, the FFM provides a peer-reviewed and scientifically credible tool for understanding and quantifying the complexities involved. By utilising physical measurements of plants, the FFM also provides a means to move away from labour-intensive and subjective point-based generalisations around fuels so that landscape-scale tools such as remote sensing can be adopted. More complex changes to the risk environment such as through climate change can also be treated with the necessary detail and adequately quantified.

References

Adams MA, Attiwill PM (2011) Burning issues – sustainability and management of Australia's southern forests. CSIRO Publishing: Vic

Albini FA (1981) A phenomenological model for wind speed and shear stress profiles in vegetation cover layers. *Journal of Applied Meteorology* **20**(11), 1325-1335

Ashton DH (1975) The seasonal growth of *E. regnans* F. muell. *Australian Journal of Botany* **23**, 239-252

Ashton DH, Turner JS (1979) Studies on the light compensation point of *Eucalyptus regnans* F. Muell. *Australian Journal of Botany* **27**, 589-607

Attiwill P, Packham D, Barker T, Hamilton I (2009) 'The people's review of bushfires, 2002 – 2007, in Victoria.' www.landsalliance.org/download/25

Boer MM, Sadler RJ, Wittkuhn RS, McCaw L, Grierson PF (2009) Long-term impacts of prescribed burning on regional extent and incidence of wildfires – Evidence from 50 years of active fire management in SW Australian forests. *Forest Ecology and Management* **259**, 132-142

Burrows ND (1999) Fire behaviour in jarrah forest fuels. *CALMScience* **3**(1), 31-84

Burrows ND (2001) Flame residence times and rates of weight loss of eucalypt forest fuel particles. *International Journal of Wildland Fire* **10**, 137-143

Burrows ND, McCaw WL (1990) Fuel characteristics and bushfire control in *Banksia* low woodlands in Western Australia. *Journal of Environmental Management* **31**, 229-236

Chigier NA, Apak G (1975) Interaction of multiple turbulent diffusion flames. *Combustion Science and Technology* **10**(5-6) 219-231

Cionco RM (1972) A wind-profile index for canopy flow. *Boundary-layer Meteorology* **3**, 255-263

Cionco RM (1978) Analysis of canopy index values for various canopy densities. *Boundary-layer meteorology* **15**, 81-93

Cionco RM, Ohmsteade WD, Appleby JF (1963) A model for airflow in an idealized vegetative canopy. USAERDAA, Fort Huachuca Meteorology Research Notes 5. (Arizona: USA)

Fang JB, Steward FR (1969) Flame spread through randomly packed particles. *Combustion and flame* **13**, 392-398

Fernandes PM, Botelho HS (2003) A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* **12**, 117-128

Fons WL (1946) Analysis of fire spread in light forest fuels. *Journal of Agriculture* **27**(3), 93-121

Gill AM (1990) Fire behaviour in discontinuous fuels: a contract report to the New South Wales National Parks and Wildlife Service. CSIRO Plant Industry: Canberra

Gill AM, Moore PHR (1996) Ignitability of leaves of Australian plants. Contract report to the Australian flora foundation. CSIRO: Canberra

Gill AM, Zylstra P (2005) Flammability of Australian forests. *Australian forestry* **68**(2), 87-93

Gould JS, McCaw WL, Cheney NP, Ellis PF, Knight IK, Sullivan AL (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

Greene DF, Johnson EA (1996) Wind dispersal of seeds from a forest into a clearing. *Ecology* **77**(2), 595-609

Hamilton CD (1964) The effect of Monterey Pine (*Pinus radiate* D. Don) on properties of natural *Eucalyptus* forest and woodland soils. M.Sc Thesis, Australian National University, Canberra, ACT

Heskestad G (1998) Dynamics of the fire plume. *Philosophical Transactions, Royal Society of London* **356**, 2815-2833

Hines F, Tolhurst KG, Wilson AG, McCarthy GJ (2010) Overall fuel hazard assessment guide, 4th Edn. Fire and Adaptive Management , Report No. 82. Dept. Sustainability and Environment: Vic

Huffman KG, Welker JR, Sliepcevich CM (1967) *Wind and interaction effects on freeburning fires*. Technical Report, Defense Technical Information Centre: USA

Hutchings PT, Oswald KM (1975) Litter fall and litter accumulation in eucalypt forests of the Australian Capital Territory. In 'Proceedings of the 3rd Australian Specialist Conference in Soil Biology'. (Adelaide: SA)

Liu N, Liu Q, Lozano JS, Shu L, Zhang L, Zhu J, Deng Z, Satoh K (2009) Global burning rate of square fire arrays: experimental correlation and interpretation. *Proceedings of the Combustion Institute,* **32**(2), 2519-2526

Loehle C (2004) Applying landscape principles to fire hazard reduction. *Forest Ecology and Management*, **198**, 261-267

Matthews S (2006) A process-based model of fine fuel moisture. *International Journal of Wildland Fire* **15**, 155-168

McAlpine RS (1995) Testing the effect of fuel consumption on fire spread rate. *International Journal of Wildland Fire* **5**(3), 143-152

McArthur AG (1962) 'Control burning in eucalypt forests.' Commonwealth Australia Forestry Timber Bureau Leaflet 80, Canberra

McArthur AG (1966) 'Notes on fire behaviour in eucalypt forests.' Commonwealth Australia Forestry Timber Bureau Report produced for NSW NPWS, Canberra

McArthur AG (1967) Fire behaviour in Eucalypt forests. Forestry and Timber Bureau Leaflet 107, 9th Commonwealth Forestry Conference¸ India

McCaw LM (1997) Predicting fire spread in Western Australian mallee-heath shrubland . PhD thesis, University of New South Wales, Canberra

McCaw WL, Gould JS, Cheney NP (2008) Quantifying the effectiveness of fuel management in modifying wildfire behaviour. Proceedings 'Fire Environment and Society'15th AFAC Conference". (Adelaide,SA)

McColl JG (1966) Accession and decomposition of litter in spotted gum forests. *Australian Forestry* **30**, 191-198

Mitler HE, Steckler KD (1995) Spread – a model of flame spread on vertical surfaces. NISTIR 5619. Building and Fire Research Laboratory, U.S. Department of Commerce, Gaithersburg: MD

Moore RM, Williams JD (1976) A study of a subalpine woodland-grassland boundary. *Australian Journal of Ecology* **1**, 143-153

Newman JC (1954) Burning on subalpine pastures. *Journal of Soil Conservation Service NSW*. **10**, 135-40

Price O, Bradstock RA (2010) The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia. *International Journal of Wildland Fire* **19**: 35-45

Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P (2007) Assessment of observed changes and responses in natural and managed systems. Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson), pp. 79-131. Cambridge University Press, Cambridge

Smith, H.G., Dragovich, D. (2008) Post-fire hillslope erosion response in a sub-alpine environment, south-eastern Australia. *Catena,* **73**(3), 274-285

Steward FR (1970) Prediction of the height of turbulent diffusion buoyant flames. *Combustion Science and Technology* **2**(4), 203-212

Tewarson A (1980) Heat release rate in fires. *Fire and materials* **4**, 185-191

Thomas PH (1963) The size of flames from natural fires. ‘Ninth symposium (International) on combustion’. pp 844-859. (Academic: NY)

Thomas PH, Baldwin R, Heselden AJM (1965) Buoyant diffusion flames: some measurements of air entrainment, heat transfer and flame merging. ‘Tenth symposium (International) on combustion’. pp 983-996. The combustion institute

Tolhurst KG, Chong DM, Ackland A (2009) Assessing and evaluating bushfire management options in the rural-urban interface using PHOENIX-RapidFire. http://knowledgeweb.afac.com.au/research/fire_management/documents/Program_A_-_Kevin_Tolhurst.pdf

Van Wagner CE (1969) Combined effect of sun and wind on surface temperature of litter. Canadian Forest Service Information Report PS-X-10. Petawawa Forest Experimental Station, (Chalk River, Ontario)

Van Wagner CE (1973) Height of crown scorch in forest fires. *Canadian Journal of Forest Research* **3**: 373-378

Viney NR (1991) A review of fine fuel moisture modelling. *International Journal of Wildland Fire* **1**(4), 215-234

Wang Y, Cionco R (2007) ‘Wind profiles in gentle terrains and vegetative canopies for a three-dimensional wind field (3DWF) model.’ Army Research Laboratory, Report ARL-TR-4178. Adelphi: Maryland

Weber RO, Gill AM, Lyons RRA, Moore PHR, Bradstock RA, Mercer GN (1995) Modelling wildland fire temperatures. *CALM Science Supplement* **4**, 23-26

Weng W, Kamikawa D, Fukuda Y, Hasemi Y, Kagiya K (2004) Study on flame height of merged flame from multiple fire sources. *Combustion Science and Technology* **176**(14), 2105-2123

Williams RJ (1992) Gap dynamics in subalpine heathland and grassland vegetation in south-eastern Australia. *Journal of Ecology* **80**, 343-352

Wimbush DJ, Costin AB (1979) Trends in vegetation at Kosciuszko. I. Grazing trials in the subalpine zone, 1957 – 1971. *Australian Journal of Botany* **27**, 741-787

Wolff MF, Carrier GF, Fendell FE (1991) Wind aided fire spread across discrete fuel arrays, 2. Experiments. *Combustion Science and Technology* **77**, 261-289

Zedler PH, Seiger LA (2000) Age mosaics and fire size in chaparral: a simulation study. In '2nd interface between ecology and land development in California'. (Eds JE Keeley, M Baer-Keeley and CJ Fotheringham), pp. 9-18, US Geological Survey Open-File Report 00-62

Zylstra P (2006*a*) 'Fire History of the Australian Alps'. (AALC: Canberra)

Zylstra P (2006*b*) Physical properties determining flammability in sclerophyllous leaves and flame propagation within shrubs and trees in the Australian Alps. *Forest Ecology and Management* **234S**, S81

Zylstra P (2009) How fire works and what it means for fuel control. Bushfire CRC Firenote Issue 49. http://bushfirecrc.com/publications/downloads/0912_firenote_49_lowres.pdf

Zylstra P (2011*a*) Forest flammability: modelling and managing a complex system. PhD Thesis, UNSW: Canberra

Zylstra P (2011*b*) Development of rapid fuel assessment techniques for the Forest Flammability Model. NSW Office of Environment and Heritage Report to Geoscience Australia for the Fire Impact and Risk Evaluation Decision Support Tool Project – Bushfire CRC. OEH 2011/0584

Zylstra P (2011*c*) Defining plan structure and its obscuration profile for use in interface scene assessment. NSW Office of Environment and Heritage Report to Geoscience Australia for the Fire Impact and Risk Evaluation Decision Support Tool Project – Bushfire CRC. OEH 2011/0810

Developing an operational grassland curing system

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Abstract

The extent of grassland curing, the percentage of cured or dead material in a grassland fuel mixture, has a major effect on the Fire Danger Rating system used in Victoria.

The Grassland Curing and Fire Danger Rating (GCFDR) project was created after the 2009 Victorian Bushfires Royal Commission to obtain more accurate grassland curing information for increased accuracy of fire danger ratings. Fire danger ratings are no longer only a tool for fire managers to predict fire behaviour, but also a fire threat prediction tool for preparing the community. Obtaining accurate information about grassland conditions across Victoria is complex and difficult. Using the latest research, the project aims to achieve best practice in collecting, analysing and representing data from variable sources such as visual observations, remote sensing techniques and geo-referenced photos. Grassland observational data will be combined with the latest spatial techniques and satellite data to develop a prototype system tested and implemented over the next three years. The system will eventually be automated and will represent current and accurate data at a detailed scale for the advancement of fire danger forecasting and for information to fire agencies and the community.

Background

Current Victorian System

The fire danger rating (FDR) system is a prediction of fire behaviour which includes how hard it would be to put out a fire once it starts (Cheney and Sullivan, 2008). The degree of grassland curing is used as an input into the grassland fire danger index (GFDI) and fire spread prediction component of the FDR system. Currently the Country Fire Authority (CFA) of Victoria is heavily reliant on the grassland curing observation network to provide curing information across the state. Each Sunday in the fire danger period, the ground observers in the observation network report to CFA headquarters on the state of grassland condition in their area. Headquarters staff then collate this data and validate it with district operational staff. The curing data is used to produce a statewide map which is distributed to the Bureau of Meteorology (BoM) for use as a data layer to produce a spatial map of grassland fire danger across the state. The BoM uses a combination of the grassland fire danger ratings, the forest fire danger ratings and weather predictions to issue fire weather warnings to the general public and for the Victorian fire agencies to determine the need for “Total Fire Bans”.

CFA commenced monitoring grassland pasture and crop dryness via remote sensing from the 1987-1988 fire season (Garvey, 1988), utilising the United States National Oceanic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite data to produce colour graduated maps that show the stages of grassland curing (Barber, 1990). However, there are issues with accuracy and cloud interference and, over time, the satellite data product was replaced by ground-based human assessments alone. The satellite data map continues to be produced, and is displayed on the BoM’s registered users website, but is not used in any public warnings or operational decision making.

The current ground observation data collection process is very time consuming and labour intensive to produce a state wide map of grassland curing condition. The objective of the GCFDR project is to create an automated grassland curing estimation system for improved fire weather forecasting and FDRs. The system will produce a map of grassland curing and later include other aspects of grassland condition such as fuel continuity and fuel load.

Methodology

Visual observations

The accuracy of grassland curing data in Victoria is limited, as it is currently based solely on visual observations. Problems with visual observations include: the geographic coverage, the sparsity of the observation network, experience and/or training of observers and the subjectiveness of visual observations in general (Andrews et al, 2006). Recent studies show that visual observations are more subjective and more variable than any other technique, in the order of +/-25% (Newnham et al, 2011). However, Cheney and Sullivan (2008) argue that with practice, it is possible to make a reasonable visual estimate of curing on a local scale.

CFA acknowledges that there are other techniques for measuring curing, such as the modified levy rod and weighted plate; however one significant limitation is that these techniques are time consuming. CFA needs to be very conscious of the expectations placed on its volunteer ground observers. The project has determined that, for the initial project phases, the time taken versus the benefit of the various techniques means that visual observations are the preferred option. Comparison of the ground observation results with ongoing field validation from destructive sampling will provide more data on the accuracy and appropriateness of this method.

The project will also conduct a statistical analysis on the distribution and optimal number of observations needed to produce acceptable results. More observers will be recruited and inducted into the network. Trained observers will also be able to assist the CFA with additional information on grassland condition by assisting in measuring other aspects, such as identifying species composition, taking destructive sampling to authenticate results and determining fuel condition and distribution. The additional grassland curing information is an important consideration when looking at fire behaviour, and cannot be collected solely via remote sensing techniques.

Destructive sampling techniques

Destructive sampling is where grass is cut from the source, dried and weighed, to determine various measurements such as fuel moisture content and grassland curing percentage. It is widely known to be the most accurate way to determine grassland curing, however results cannot be determined for at least 24 hours making this method impractical operationally. During the development phase of the project, destructive sampling will be conducted to compare the accuracy of visual observations and satellite results.

Training

Prior to the GCFDR project, observers were provided with the Grassland Curing photo guide booklet (Garvey and Millie, 2000) but no further formal training. The project determined that more comprehensive training of observers was required, especially since a memorandum of understanding was signed with the BoM that fuel load data would be collected by observers in addition to observations on percentage of cured grasslands. During the 2010-2011 fire season a DVD titled “Visually Measuring Grassland Curing” (Country Fire Authority Grassland Curing and Fire Danger Rating Project, 2010) was produced to assist observers in determining curing. The DVD runs for about 6 minutes and is intended to increase accuracy and consistency in visual curing measurement, by distinguishing grass colour and seed head development in relation to percentage cured vegetation.

A CFA grassland observer competency training package is under development for rollout prior to the 2011-2012 fire season. Included in the competency is a new field card for collecting both visual curing and fuel load data. The competency will be used to train observers in using the field card to accurately measure these parameters in the field. Fuel load data requires height and percent cover of the grass to be measured, raising the number of field observation parameters collected from one to three. Observers will also be informed about the use of satellite data and taught to take consistent and repeatable measurements that can be used to directly compare the satellite and ground data.

Further guides or DVDs may also be developed to assist observers to make accurate measurements. Photo books showing grass at different stages of curing and fuel loads, or guides for using digital cameras or other field tools may also be developed. Data collection via the internet is being considered.

Satellite imagery and remote sensing techniques

Satellite imagery can provide a synoptic landscape scale analysis of the grassland curing state. MODerate resolution Imaging Spectroradiometer (MODIS) satellite data has been received and processed for many years in Australia yet has only recently been processed in real time by the BoM (Newnham et al, 2011). The MODIS satellite is similar in design to the AVHRR with many more spectral bands. The Bushfire CRC research project "Improved methods for assessment and prediction of grassland curing" (Newnham et al, 2011) looked into the technical aspects of MODIS and investigated four different models for determining curing in the Australian landscape. Over the 2009-2010 fire season, CFA and other fire agencies participated in a trial of these models to compare against current operational processes. The project recommended that fire agencies use MODIS satellite data to map curing due to the performance benefit of this method over field techniques (Newnham et al, 2011).

The results of the MODIS trial were very promising, and MODIS data will be a component of the overall grassland curing methodology in Victoria. The project also requires the collation of other grassland parameters which need to occur through an observation network, and these cannot be obtained through remote sensing methods. The project will develop a methodology to amalgamate these data sources.

Spatial representation and automation of system

The amalgamated data will be available as a spatial dataset which will be compatible with BoM forecasting tools and fire behaviour models. An interactive map is also planned to produce the data overlayed in Google Earth® with geo-referenced photos. In the future, ground observers may directly compare their observation data and photos with other observers' data state-wide via an online grassland curing website. The direct comparison method is intended to lead to greater observation accuracy and consistency.

The system will be automated by the end of the project. Automation will not directly improve the accuracy of the system, but it will dramatically reduce the amount of manpower required to collect and collate current data.

Results

The project has completed the first of four phases. During phase one, the project delivered the first instalment of training to volunteers, via DVD development. A new spatial product was also developed in 2010-2011 using GIS analysis, which is compatible with the BoM forecasting tools and fire behaviour models. In future, the project will commence integrating data sources and developing a prototype system which will be trialled and tested over the next three years. A curing competency will be created and delivered to ensure that all observers produce accurate and consistent results.

The current GFDI uses percent cured of grass and fuel quantity. The future fire danger index will use a combination of satellite and ground information to categorise potential fire behaviour and impact in landscape grassland fuels for the purpose of issuing warnings, determining suppression difficulty and potential fire damage. The work will result in developing scalable fire behaviour prediction systems, which categorise expected fire behaviour for major grassland fuel types.

The outputs from the improved grassland curing assessment system will be useful in the declaration of Total Fire Bans, determination of fire suppression difficulty, fire preparedness and community warning, and operational guidance on a district scale.

References:

Andrews, P. L., Anderson, S. A. J., Anderson W. R. (2006) Evaluation of a dynamic load transfer function using grassland curing data. USDA Forest Service Proceedings, 381-394

Barber, J. R. (1990) Monitoring the curing of grassland fire fuels in Victoria, Australia with sensors in satellites and aircraft. Country Fire Authority

Cheney, P. and Sullivan, A. (2008) Grassfires: Fuels, weather and fire behaviour. Second Edition. CSIRO Publishing

Country Fire Authority Grassland Curing and Fire Danger Rating Project (2010) Visually Measuring Grassland Curing DVD http://www.cfaconnect.net.au/news/new-grassland-curing-video.html

Garvey, M. (1988) Country Fire Authority and remote sensing. CFA internal report

Garvey, M. and Millie, S. (2000) Country Fire Authority Grassland Curing Guide http://www.cfa.vic.gov.au/documents/curingguide.pdf

Newnham, G. J., Grant, I. F., Martin, D. N. and Anderson, S. A. J. (2011) Improved methods for assessment and prediction of grassland curing: satellite based curing methods and mapping. Final Report. Bushfire CRC Project A1.4.

The effect of prescribed fire severity and burn patchiness on runoff and erosion

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Abstract

Fire severity and burn patchiness – potentially important factors influencing post-fire surface runoff and erosion – are controlled by fire managers to some extent during prescribed burning. A better understanding of this influence could improve burning practices to minimise water quality impacts. In this study 116 unbounded runoff samplers (opening 10 cm wide; ~ 100 m from catchment divide) were installed on six hillslopes beneath: (1) high fire severity (shrubs burnt; canopy scorched), (2) low fire severity (shrubs scorched or burnt; canopy intact), (3) unburnt, and low fire severity above (4) 1 m, (5) 5 m, and (6) 10 m wide unburnt patches. Runoff volume and sediment load were measured on 27 occasions over 16 months. The sediment loads on the burnt hillslopes were approximately four orders of magnitude larger than on the unburnt hillslope, while there was a 13% difference in sediment load between the high and low fire severities. Much larger loads for the burnt hillslopes could equate to large increases in the total suspended sediment load in streams if the entire catchment were burnt. However, prescribed burns are usually patchy. Measurements on patchily burnt hillslopes found that unburnt patches were highly effective at reducing runoff and sediment – for rainfall events with an average recurrence interval < 1 year sediment loads from low severity areas were reduced by 92%, 97% and 99% beneath 1 m, 5 m and 10 m wide unburnt patches, respectively. Thus, it seems that while there is little difference in sediment loads between the high and low fire severities, unburnt patches are important for reducing potential water quality impacts following prescribed burning. Fire managers should aim to maintain unburnt patches, especially towards the bottom of hillslopes.

Introduction

As governments set ambitious targets to increase prescribed burning (e.g. Parliament of Victoria 2010), it is important to understand and manage the potential effect on ecosystem services such as water supply. This paper considers the effects of prescribed burning on runoff and erosion. Runoff and erosion following fire can reduce water quality in streams and reservoirs (Smith *et al.* 2011), which is a problem for aquatic ecology (Minshall 2003) and human consumption (Smith *et al.* 2011). There is little research into the effects of prescribed burning on runoff and erosion in south-eastern Australia (e.g. Ronan 1986; Smith *et al.* 2010).

Forest fires increase runoff and erosion by removing vegetation, changing the soil's hydrologic properties, and providing a readily erodible layer of sediment and ash (see reviews by Certini 2005; Neary et al. 1999; Shakesby 2011; Shakesby and Doerr 2006; Shakesby et al. 2007; Wondzell and King 2003). The magnitude of post-fire runoff and erosion is determined by a combination of factors relating to the fire regime, post-fire rainfall and site characteristics (Figure 1). This study focuses on the effects of fire severity and burn patchiness – fire regime characteristics particularly relevant to prescribed burning.

Fire severity – a qualitative measure of the loss of organic matter caused by fire (Keeley 2009) – is considered one of the most important factors affecting post-fire runoff and erosion (Neary *et al.* 1999; Shakesby and Doerr 2006). The relationship between fire severity and post-fire runoff and erosion is thought to depend on the amount of soil heating during the burn (Doerr *et al.* 2006; Neary *et al.* 1999) and the loss of vegetative cover (Benavides-Solorio and MacDonald 2005). Overall, less runoff and erosion are reported for low fire severity areas than high severity areas (Benavides-Solorio and MacDonald 2005; Dragovich and Morris 2002; Robichaud 2000), or at least low severities are associated with soil properties less conducive to runoff and erosion (Doerr *et al.* 2006; Woods *et al.* 2007).

Patchiness influences the connectivity of runoff and erosion across a hillslope (Bracken and Croke 2007). Within a prescribed burn, different fire severities and unburnt areas create a mosaic of patches (Penman *et al.* 2007). Burnt patches are thought to act as sediment sources while unburnt patches act as sediment sinks. Several authors acknowledge the potential significance of burn patchiness to runoff and erosion (e.g. Benavides-Solorio and MacDonald 2005; Kutiel *et al.* 1995; Smith *et al.* 2010) and hydrologic modelling has demonstrated that some spatial arrangements of fire severities increase runoff connectivity (e.g. Moody *et al.* 2008; Robichaud and Monroe 1997).

A greater understanding of how fire severity and burn patchiness affects runoff and erosion could improve burning practices and reduce water quality impacts. This paper aims to assist fire managers by quantifying:

- the effect of prescribed fire severities on runoff and erosion, and
- the reduction in runoff and sediment caused by unburnt patches on burnt hillslopes.

Fire regime	+	**Rainfall properties**	+	**Site characteristics**	=	**Magnitude of post-fire runoff and erosion**
Fire severity Patchiness Fire frequency Fire season		Rainfall total Rainfall intensity Rainfall duration		Slope gradient Flow convergence Aspect Soil type and geology Vegetation type		

Figure 1 Factors that determine the magnitude of post-fire runoff and erosion

Methods

Site description

The study site was on the north-facing slopes of McMahons Creek and Smoko Creek catchments, tributaries to the Upper Yarra catchment in Victoria (37°43' S , 145°51' N). The vegetation was shrubby foothill forest according to the Victorian Government's Ecological Vegetation Classification (www.dse.vic.gov.au). The soils were shallow (70 cm), clay-loam soil over a sedimentary substrate. The site was burnt by prescribed fire in April 2009. Fire severity was mostly low, with some high severity patches on the northerly aspects and ridges and large unburnt areas on the southerly aspects and in the gullies (Figure 2).

Unburnt	**Low severity**	**High severity**
	(shrubs scorched or burnt; canopy intact)	(shrubs burnt; canopy scorched)

Figure 2: Unburnt, low severity and high severity on northerly aspects within the prescribed burn.

Field measurements

Unbounded samplers were used to measure the amount of surface runoff and sediment crossing a particular point on the hillslope from August 2009 (4-months post-burn) to December 2010 (20 months post-burn). Figure 3 illustrates the design of the samplers, which were installed in transects on planar hillslopes beneath six treatments: (1) high fire severity, (2) low fire severity, (3) unburnt, low fire severity above (4) 1 m, (5) 5 m and (6) 10 m wide unburnt patches (Figure 4 and 5). There were 20 samplers in each transect except for the 1 m unburnt patch treatment, which had 16 samplers. On 27 occasions runoff depth was measured in every sampler and sediment concentration in 50% of them if there was sufficient runoff. Rainfall was measured at 3-minute intervals with a weather station located within 2.5 km of the samplers.

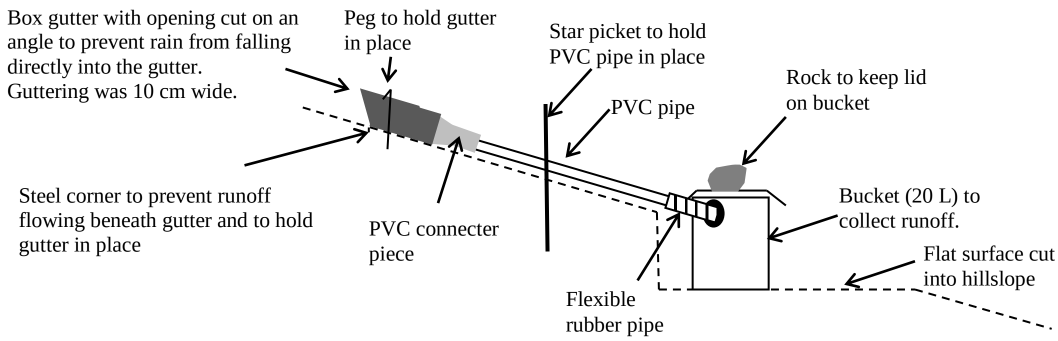

Figure 3: Design of the runoff samplers. Surface runoff and sediment were measured regularly following rainfall.

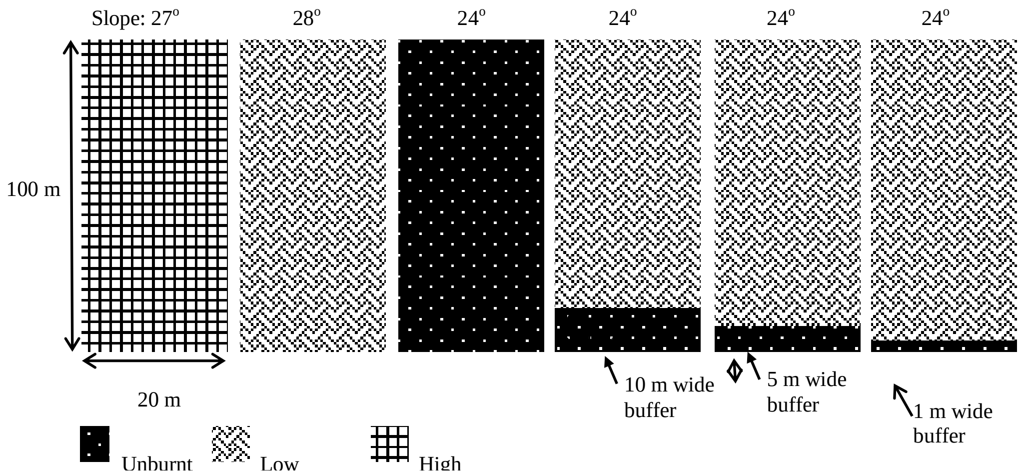

Figure 4: Patch arrangements above the runoff samplers. The low severity, 10 m buffered, 5 m buffered and unburnt transects were located side-by-side on the same hillslope. Slopes for each hillslope are shown above the diagram.

(a) High severity, August 2009 **(b) High severity, August 2010**

Figure 5: Transect of 20 runoff samplers on the high severity hillslope. Samplers were located 100 m from the ridge on planar hillslopes. The total length of the hillslopes was approximately 200-300 m.

Data analysis

Total runoff volume per metre width of hillslope was calculated for each treatment on each measurement date:

$$\text{Runoff total per metre width} = \frac{(\text{Sampler 1 vol.} + \text{Sampler 2 vol.} + \cdots + \text{Sampler } n \text{ vol.})}{(\text{no. samplers } \times 10 \text{ cm})} \times 100\ cm$$

If there were overflowing samplers (2.5% of the time) the total runoff volume was predicted from a linear regression between total runoff volume and the n^{th} percentile runoff volume for rainfall events when there were no overflowing tanks (Table 1). Runoff volumes were converted to runoff ratios by assuming a contributing hillslope length of 100 m – approximately the distance to the catchment divide from the samplers:

$$\text{Runoff ratio } \% = \frac{\text{runoff depth}}{\text{rainfall depth}} \times 100$$

Sediment load was calculated per metre width of hillslope for each treatment on each measurement date:

$$\text{Sediment load} = \text{Runoff total } \times \text{ mean sediment concentration}$$

For the hillslopes with 1 m, 5 m and 10 m unburnt patches (located below the low fire severity burns) the sediment trapping efficiency of the unburnt patch was calculated on each measurement date:

$$\% \text{ reduction in sediment} = \frac{\text{sediment load beneath unburnt patch}}{\text{sediment load from low severity hillslope}} \times 100$$

Means and standard deviations were calculated for runoff volume, sediment concentration and sediment load. T-tests (two-tailed, unequal variances) were used to test the significance of differences between the means for each treatment. A function was found to describe the relationship between the width of the unburnt patch and its sediment trapping efficiency using Lab Fit Curve Fitting Software.

Table 1: Regression equations used to calculate the runoff total when there were overflowing tanks; y = the runoff total and x = the nth percentile runoff volume

Treatment	Regression equation	X	R^2
High severity	y = 23.304 x + 5.4279	60th percentile	0.7561
Low severity	y = 44.832 x + 8.1642	40th percentile	0.8235
1 m buffer	y = 42.442 x + 0.8621	60th percentile	0.8157
5 m buffer	y = 17.167 x + 0.7692	80th percentile	0.7337
10 m buffer	y = 13.45 x + 0.7868	80th percentile	0.8744
Unburnt	Not required – no overflowing tanks		

Results

The volume of runoff was approximately two orders of magnitude greater on the burnt hillslopes compared with the unburnt hillslope (44-45 L m-1 compared to 0.5 L m-1) while the annual sediment load was approximately four orders of magnitude greater on the burnt hillslope (1.3-1.5 kg m-1 compared to 8 x 10-4 kg m-1) (Figure 6 and

Table 2). In comparison, differences in runoff between the high and low fire severity hillslopes were small (44 L m^{-1} compared to 45 L m^{-1}). A slight difference in the mean sediment concentration between the fire severities (0.9 g L^{-1} compared to 0.6 g L^{-1}) resulted in cumulative sediment loads that were 13% larger on the high fire severity hillslope. Standard deviations were large, probably reflecting large differences in the rainfall events. T-tests showed significant differences between burnt and unburnt hillslopes but not between high and low fire severity hillslopes for runoff volume and sediment concentration. There were no significant differences between the sediment loads.

For most rainfall events (i.e. those with average recurrence intervals (ARI) < 1 year), there were distinct differences in sediment load between the uniformly burnt hillslopes and those with unburnt patches (Figure 6). The percentage reduction in sediment ranged from 92% to 99% depending on patch width, with higher percent reductions beneath wider unburnt patches. For an intense storm on the 27th November 2009 (I_{30} = 44 mm h^{-1}; ARI of 10 years) the 5 m and 10 m unburnt patches continued to be effective at reducing the sediment load, but the 1 m unburnt patch was ineffective yielding more sediment than the low severity hillslope. This rainfall event was highly influential overall in terms of the annual sediment loads for each hillslope treatment (Figure 6). The functions fitted in Figure 7 illustrate the effect of patch width on sediment load and the influence of rainfall properties.

Table 2: Summary statistics for the entire measurement period. Standard deviations are in brackets. Letters denote the outcome of statistical testing between treatments (i.e. values on the same line). Values which are not significantly difference share the same letter (t-tests; $p < 0.05$).

	Hillslope treatment					
	High severity	Low severity	Unburnt	1 m patch	5 m patch	10 m patch
Mean runoff volume ($L\ m^{-1}$)	44 (50)a	45 (64)a	0.5 (0.7)b	23 (94)abc	6 (21)bc	2 (2.1)c
Mean runoff ratio (%)	0.86 (0.7)a	0.84 (1.0)a	0.01 (0.01)b	0.36 (1.5)abc	0.10 (0.3)bc	0.04 (0.1)c
Mean sediment concentration ($g\ L^{-1}$)	0.9 (1.5)a	0.6 (0.9)a	0.04 (0.1)bc	0.3 (0.7)ab	0.09 (0.1)bc	0.04 (0.1)c
Mean sediment load ($g\ m^{-1}$)	86 (295)a	70 (257)a	0.06 (0.3)a	69 (329)a	2 (9.4)a	0.2 (0.37)a
Total sediment load ($g\ m^{-1}$)	2058	1671	1	1646	57	4
Mean annual sediment load ($kg\ m^{-1}\ y^{-1}$)	1.5	1.3	8×10^{-4}	1.2	0.04	3×10^{-3}
Mean annual sediment load ($kg\ ha^{-1}\ y^{-1}$)	154	125	0.08	123	4.3	0.3

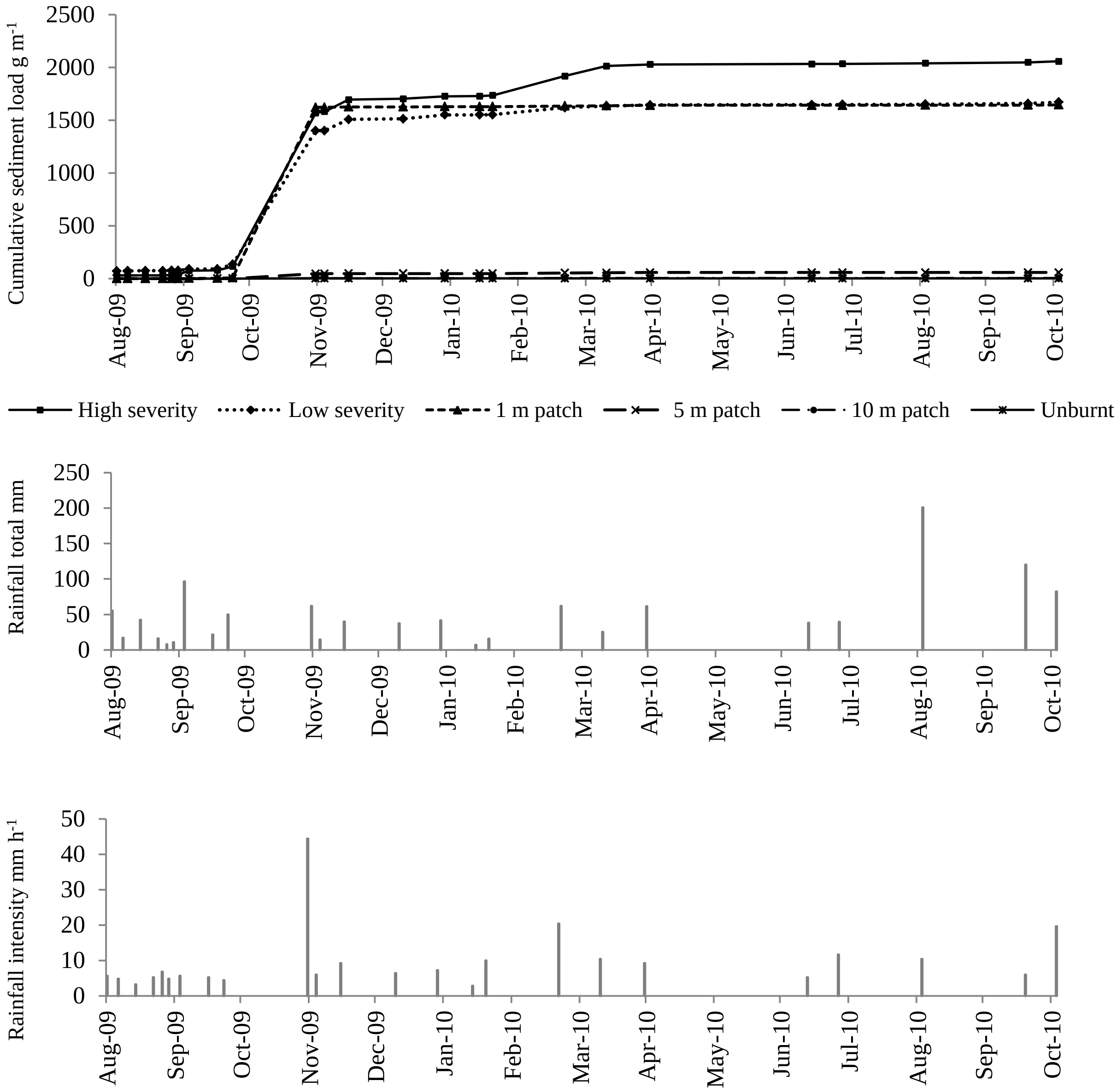

Figure 6: Time series charts showing (a) the cumulative sediment load; (b) the rainfall total contributing to each measurement date; and (c) the 30-minute maximum (I_{30}) rainfall intensity contributing to each measurement date.

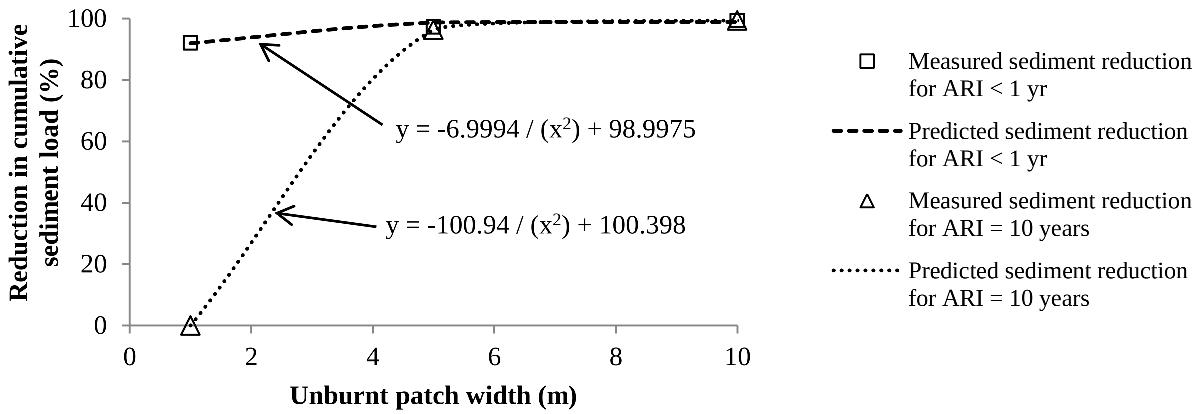

Figure 7: Relationship between unburnt patch width and percent reduction in sediment load relative to the low fire severity hillslope. Fitted curves are for the function $y = a/(x^2) + b$.

Discussion

The effects of fire severity on runoff and erosion

Runoff and erosion rates were minimal from the unburnt planar hillslope; the mean runoff ratio was 0.01% and the sediment load was 0.08 kg ha^{-1} y^{-1}. Other studies also report low runoff and erosion rates from unburnt eucalypt forests. Bren and Turner (1979) measured hillslope runoff ratios of < 0.5% in mixed-species eucalypt forest in north-eastern Victoria. Ronan (1986) measured mean runoff ratios of 0.5-1.3% and mean sediment loads of 0.12 - 0.19 t ha^{-1} y^{-1} for plots (20 x 20 m) in a mixed-species eucalypt forest in the Central Highlands of Victoria. Prosser and Williams (1998) measured hillslope sediment yields of 0.02 kg m^{-1} y^{-1} in a mixed-species eucalypt forest in the Blue Mountains, New South Wales. Given such low rates of hillslope runoff and erosion in unburnt forest, the catchment-scale contribution of runoff to instream suspended sediment loads (TSS) is likely to be low. Few studies report catchment-scale TSS loads for undisturbed eucalypt forests (Table 3). Of the catchments listed in Table 3, the Ella Creek catchment (Bren and Hopmans 2007), with its mixed-species eucalypt forest, probably most resembles the Upper Yarra study site. Assuming the TSS load at the Upper Yarra site were similar to that of Ella Creek (i.e. 0.007 t ha^{-1} y^{-1}), then the hillslope contribution to the TSS load (i.e. 0.08 kg ha^{-1} y^{-1}) would be approximately 1%. This suggests that hillslope runoff is unimportant to TSS loads in undisturbed forest catchments.

Table 3: Total suspended sediment loads (t ha-1 y-1) for undisturbed forest catchments in Victoria

Location	Dominant vegetation type	Sediment load (t ha^{-1} y^{-1})	Author
Upper section of the Tyers River catchment (13,451 ha) on the southern face of Mt Baw Baw in the Victorian Central Highlands.	Ash eucalypt forest (wet)	0.085 Sampling over one year	Sheridan and Noske (2007)
Ella Creek catchment (113 ha), a tributary to the Buffalo river in north-eastern Victoria.	Mixed-species eucalypt forest (dry)	0.0074 Sampling over six years	Bren and Hopmans (2007)
Stony Creek (75 ha), a tributary to the Latrobe River in the Victorian Central Highlands	Ash eucalypt forest (wet)	0.024 Sampling over five months	Lane and Sheridan (2002)
Sub-catchment (25 ha) of Myrtle Creek in the Maroondah catchment area of the Victorian Central Highlands	Ash eucalypt forest (wet)	0.076 Sampling over 10 years	Grayson *et al.* (1993)

Differences in hillslope runoff and erosion between burnt and unburnt areas were substantial. Annual sediment loads on the burnt hillslopes (125-154 kg $ha^{-1}y^{-1}$) were approximately three orders of magnitude larger than on the unburnt hillslope (0.08 kg $ha^{-1}y^{-1}$). Other studies also report large increases in runoff and erosion in burnt areas (as reviewed by Certini 2005; Shakesby and Doerr 2006; Smith *et al.* 2011). For mixed-species eucalypt forest, Prosser and Williams (1998) found that sediment yields increased by approximately one order of magnitude following burning, while Ronan (1986) found that they increased by approximately two orders of magnitude. The significance of those increases at the catchment scale depends on the relative contribution of hillslope runoff and erosion to instream TSS loads. By using the Ella Creek catchment (Bren, 2007) as an example, the effect of burning on catchment-scale TSS loads can be estimated. If burning within the Ella catchment resulted in similar amounts of surface runoff and erosion to burning in the Upper Yarra catchment (i.e. an erosion rate of 125-154 $kg^{-1}ha^{-1}y^{-1}$), then burning the entire catchment could increase the instream TSS load by approximately two orders of magnitude (from 0.007 t ha^{-1} y^{-1} to approximately 0.132-0.161 t ha^{-1} y^{-1}). Such large increases could have water quality implications.

The sediment concentration from the high fire severity hillslope was larger than from the low fire severity hillslope, resulting in different sediment loads (154 kg m^{-1} y^{-1} compared to 125 kg m^{-1} y^{-1}). However, those differences in concentration and load were not statistically significant. Other studies also report higher sediment loads for high fire severity areas (e.g. Benavides-Solorio and MacDonald 2005; Dragovich and Morris 2002; Inbar *et al.* 1998). Benavides-Solorio and Macdonald (2005) reported hillslope sediment loads that were 40-200 times larger for high compared to low fire severity in the Colorado Front Range, USA. Inbar *et al.* (1998) reported hillslope sediment loads that were 156 times larger for high compared to low fire severity at Mt Carmel in Israel. Dragovich and Morris (2002) reported hillslope sediment loads were two times greater for high compared to moderate fire severity hillslopes. The differences reported in the literature between fire severities are generally much larger than those measured in this study, which suggests that the hydrologic properties of the fire severities in this study were similar. Also, the hillslopes in this study were planar, which may have reduced the relative difference in erosion rates between the fire severities.

The effect of unburnt patches on runoff and erosion connectivity on a burnt hillslope

Unburnt patches were extremely effective at reducing runoff and erosion from burnt hillslopes – for rainfall events with an ARI < 1 year the sediment loads from the unburnt patches were 92%, 97% and 99% smaller than from the low severity hillslope for the 1 m, 5 m and 10 m patches, respectively. There was a clear relationship between patch width and the percentage reduction in sediment load. For higher rainfall intensities, the 1 m patch was less effective at reducing the sediment load – i.e. for the 27th November 2009 rainfall event (ARI = 10 years) there was no reduction in the sediment load. Other studies also report reductions in sediment loads beneath vegetated patches (Cerdà 1997; Dosskey 2001; Helmers *et al.* 2005; Mayor *et al.* 2009), though there are no similar studies in burnt environments. In a semi-arid environment Bartley *et al.* (2006) reported a hillslope runoff ratio of 71% when there was a large bare patch near the base of the hillslope, compared with a runoff ratio of 8% for a hillslope with uniformly distributed bare and vegetated patches. In modelling simulations, Reaney (2003) predicted that no runoff would reach the bottom of a hillslope if there was a five metre vegetated strip at its base during 75 mm h^{-1} rainfall lasting for five minutes. In tree belts across pastoral land Leguédois *et al.*(2008) reported that sediment loads were reduced by 90% below the tree belts.

The results of this study suggest that unburnt patches play an important role in reducing connectivity between burnt patches and streams, thus ultimately reducing water quality impacts following prescribed burning. The simplified diagram in Figure 8 demonstrates this by depicting the potential influence of different unburnt patch arrangements on runoff and erosion connectivity for planar hillslopes. For each scenario 80% of the hillslope is burnt and 20% is unburnt. The unburnt patches are wide enough to reduce sediment transport from the burnt areas above by 100%. The percentage values are the potential burnt area connected to the stream – note that the actual burnt area contributing runoff and erosion to the stream is likely to be less than the potential area due to interception by obstacles or deposition when the sediment weight exceeds the energy of the overland flow. This connected area varies as a function of rainfall intensity. The diagram shows that while unburnt patches anywhere on the hillslope reduce the amount of burnt area potentially connecting to the stream, those patches near the bottom of the hillslope are likely to have the greatest effect. Prescribed burns often have unburnt patches, especially in riparian zones (Penman *et al.* 2007). This may explain why large increases in TSS loads are rarely reported following prescribed burning. This research demonstrates the importance of maintaining a mosaic of unburnt patches throughout a prescribed burn, particularly at the bottom of the hillslope, to reduce water quality impacts.

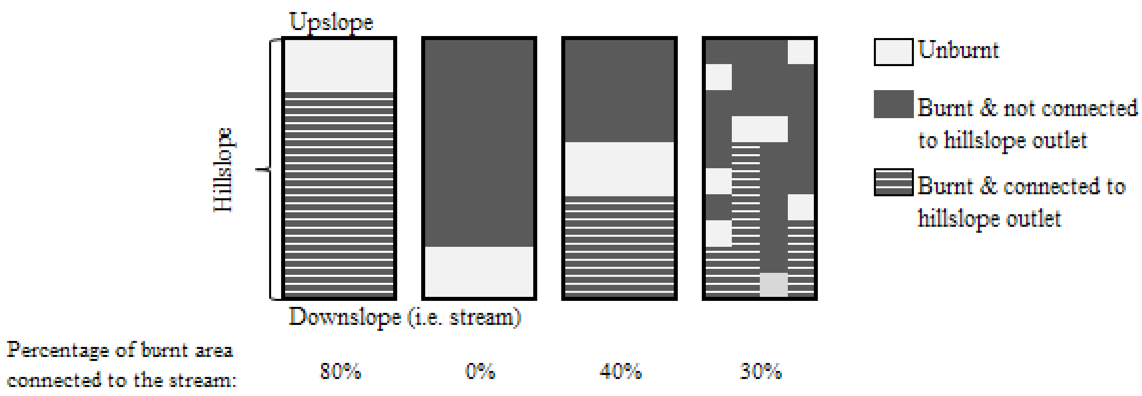

Figure 8: Percentage of burnt area potentially connected to a stream for different unburnt patch arrangements on planar hillslopes. For each hillslope 80% is burnt and 20% is unburnt. Unburnt patches reduce runoff and erosion from above by 100%.

Conclusion

Prescribed burning increased the annual hillslope sediment load by approximately four orders magnitude from 8×10^{-4} kg ha^{-1} to 1.3-1.5 kg ha^{-1}, but the relative difference in sediment loads between the high and low fire severity hillslopes was only 13%. The implications for water quality are potentially very large – e.g. burning could cause a 100-fold increase in annual instream TSS if the entire catchment were burnt. However, in reality prescribed burns are often patchy. Unburnt patches on a burnt hillslope are highly effective at reducing runoff and sediment from burnt areas above –for rainfall events with an ARI < 1 year, sediment loads were reduced by 92-99% when there were unburnt patches beneath a burnt hillslope compared to hillslopes with no unburnt patches. Thus the potential for water quality impacts from prescribed burning is greatly reduced by the presence of unburnt patches, particularly near the bottom of the hillslope.

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References

Bartley R, Roth CH, Ludwig J, McJannet D, Liedloff A, Corfield J, Hawdon A, Abbott B (2006) Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales. *Hydrological Processes* **20**, 3317-3333.

Benavides-Solorio JdD, MacDonald LH (2005) Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* **14**, 457-474.

Bracken LJ, Croke J (2007) The concept of hydrological connectivity and it contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* **21**, 1749-1763.

Bren L, Hopmans P (2007) Paried catchments observations on the water yield of mature eucalypt and immature radiata pine planations in Victoria, Australia. *Journal of Hydrology* **226**, 416-429.

Bren LJ, Turner AK (1979) Overland flow on a steep, forested infiltrating slope. *Australian Journal of Soil Research* **30**, 43-52.

Cerdà A (1997) The effect of patchy distribution of *Stipa tenacissima* L. on runoff and erosion. *Journal of Arid Environments* **36**, 37-51.

Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia* **143**, 1-10.

Doerr SH, Shakesby RA, Blake WH, Chafer CJ, Humphreys GS, Wallbrink PJ (2006) Effects of differing wildfire severities on soil wettability and implications for hydrological response. *Journal of Hydrology* **319**, 295-311.

Dosskey MG (2001) Toward quantifying water pollution abatement in response to installing buffers on crop land. *Environmental Management* **28**, 577-598.

Dragovich D, Morris R (2002) Fire intensity, slopewash and bio-transfer of sediment in eucalypt forest, Australia. *Earth surface processes and landforms* **27**, 1309-1319.

Grayson RB, Haydon SR, Jayasuriya MDA, Finlayson BL (1993) Water quality in mountain ash forests - separating the impacts of roads from those of logging operations. *Journal of Hydrology* **150**, 459-480.

Helmers MJ, Eisenhauer DE, Dosskey MG, Franti TG, Brothers JM, McCullough MC (2005) Flow pathways and sediment trapping in a field-scale vegetative buffer. *Transactions of the American Society of Agricultural Engineers* **48**, 955-968.

Inbar M, Tamir M, Wittenberg L (1998) Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Gemorphology* **24**, 17-33.

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116-126.

Kutiel P, Lavee H, Segev M, Benyamini Y (1995) The effect of fire-induced surface heterogeneity on rainfall-runoff-erosion relationships in an eastern Mediterranean ecosystem, Israel *Catena*, 77-87.

Lane PNJ, Sheridan GJ (2002) Impact of an unsealed forest road stream crossing: water quality and sediment sources. *Hydrological Processes* **16**, 2599-2612.

Leguédois S, Ellis TW, Hairsine PB, Tongway DJ (2008) Sediment trapping by a tree belt: processes and consequences for sediment delivery. *Hydrological Processes* **22**, 3523-3534.

Mayor AG, Bautista S, Bellot J (2009) Factors and interactions controlling infiltration, runoff, and soil loss at the microscale in a patchy Mediterranean semiarid landscape. *Earth surface processes and landforms* **34**, 1702-1711.

Minshall GW (2003) Responses of stream benthic macroinvertebrates to fire. *Forest Ecology and Management* **178**, 155-161.

Moody JA, Martin DA, Haire SL, Kinner DA (2008) Linking runoff response to burn severity after a wildfire. *Hydrological Processes* **22**, 2063-2074.

Neary DG, Klopatek CC, DeBano LF, Ffolliott P, F. (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51-71.

Parliament of Victoria (2010) 'Victorian Bushfires Royal Commission. Final Report.' Melbourne.

Penman TD, Kavanagh RP, Binns DL, Melick DR (2007) Patchiness of prescribed burns in dry sclerophyll eucalypt forests in south-eastern Australia. *Forest Ecology and Management* **252**, 24-32.

Prosser IP, Williams L (1998) The effect of wildfire on runoff and erosion in native *Eucalyptus* forest. *Hydrological Processes* **12**, 251-265.

Reaney SM (2003) Modelling runoff generation and connectivity for sem-arid hillslopes and small catchments (PhD thesis). University of Leeds.

Robichaud PR (2000) Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology* **231-232**, 220-229.

Robichaud PR, Monroe TM (1997) Spatially-varied erosion modeling using WEPP for timber harvested and burned hillslopes. In 'ASAE Annual International Meeting'. (American Society of Agricultural Engineers: Minneapolis, MN)

Ronan NM (1986) 'The hydrological effects of fuel reduction burning and wildfire at Wallaby Creek.' Melbourne and Metropolitan Board of Works, MMBW-W-0015.

Shakesby RA (2011) Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth Science Reviews* **105**, 71-100.

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. *Earth science reviews*, 269-307.

Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, Blake WH, Tomkins KM (2007) Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management* **238**, 347-364.

Sheridan GJ, Noske PJ (2007) Catchment-scale contribution of forest roads to stream exports of sediment, phophorus and nitrogen. *Hydrological Processes* **21**, 3107-3122.

Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S (2011) Wildfire effects on water quality in forest catchments: a review with implications for water supply. *Journal of Hydrology* **396**, 170-192.

Smith HG, Sheridan GJ, Lane PNJ, Sherwin CB (2010) Paired *Eucalyptus* forest catchment study of prescribed fire effects on suspended sediment and nutrient exports in south-eastern Australia. *International Journal of Wildland Fire* **19**, 624-636.

Wondzell SM, King JG (2003) Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* **178**, 75-87.

Woods SW, Birkas A, Ahl R (2007) Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado. *Geomorphology* **86**, 465-479.

The development of an automated algorithm to map fire severity from satellite imagery: tropical savannas northern Australia.

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Abstract
Fire severity is the post-fire effect of fire on the vegetation. The fire severity mapping algorithm developed in this study correlated helicopter-based spectra collected over a site using a hand held spectrometer and ground data describing the fire severity within the spectrometer field of view. The differenced Normalized Burn Ratio (ΔNBR) quite clearly distinguished between severe and not-severe fires (r^2 = 0.94). However, further discrimination into three or more classes required the development of other indices incorporating the region of the spectrum represented by MODIS band 6 (1628-1652 nm). This poses problems operationally as band 6 on Aqua is dysfunctional thus halving the available data.

Keywords: Fire severity mapping, normalised burn ratio, operational application.

INTRODUCTION

Fire severity is the post-fire effect of fire on the vegetation (Lentile*, et al.*, 2006; Keeley, 2009). Current landscape wide mapping does not describe the effect of fire. It describes its spatial and temporal occurrence, providing land managers with information regarding the habitat affected and the seasonality of occurrence. Russell-Smith and Edwards (2006) demonstrated there was valuable information to derive from fire seasonality. They determined the probability of occurrence of categories of fire severity within various habitats in the tropical savannas of northern Australia. However the data do not provide intra-seasonal descriptions of the effects of management imposed fire, applied regularly, and essential to reduce the high probability of wildfire across an extremely fire-prone landscape (Yates*, et al.*, 2008).

A field guide illustrating fire severity categories for the dominant savanna woodland matrix, describes simple metrics for characterising fire severity (Edwards, 2009). It uses the scorch height (i.e. the height to non-pyrolised fire affected foliage (Williams*, et al.*, 1998) and the proportion of ground patchiness. The categorisation is understood by users, as the input was derived from researchers and land managers in the tropical savanna region, Figure 1. Five categories were determined for use: 1. Patchy - small trees and shrubs scorched to 2m, < 80% burnt ground layer patchiness; 2. Low - small trees and shrubs scorched to 2m, ≥ 80% burnt ground layer patchiness; 3. Moderate - scorched leaves through the mid-storey (> 2 and ≤ 8 m) perhaps into the lower parts of the upper canopy; 4. High - complete canopy scorch and; 5. Extreme - all foliage removed or charred.

It is estimated that global combustion of vegetation is around 9,200 Tg (± 50%) on average, each year (Scholes and Archer, 1997). The tropical savannas are the largest single source of GHG and particulate emissions in Australia (Meyer*, et al.*, 2008) emitting 2% of Australia's annual GHG emissions in 2005. Savanna burning accounted for 39% of the Northern Territory's emissions from 1990-2005 (Tropical Savannas, 2004). Much of the north Australian landscape is rural and sparsely populated, containing a matrix of savanna grassland, woodland and open forest. The fuel from this biomass accumulates over time. The amount of fuel consumed by a fire determines the GHG emissions (Russell-Smith*, et al.*, 2009). Landscape analysis for strategic planning and greenhouse gas emissions calculations presumes that the proportion of biomass fuels is reset to zero post-fire (Meyer*, et al.*, 2008). Fuel accumulation relationships are derived on this basis. However, the level of effect of fire determines the proportion of fuel not consumed in one year. Fire history information incorporating fire severity will improve the fuel accumulation relationships. It will assist the strategic planning undertaken by land managers in their attempt to mitigate the occurrence of wildfire. The availability of landscape wide accurate fire severity mapping will provide vast improvements to fire management planning and calculations of GHG emissions.

Satellite derived fire information has been available to land managers in the tropical savannas of northern Australia through the North Australia Fire Information web site (www.firenorth.org.au) since 2005. A cost saving of > $10.5 million was estimated in the first 3 years of operation to conservation land management agencies alone (TSMCRC, 2005). Similar cost savings should be expected with the addition of fire severity mapping. It will inform land managers of the efficacy of their burning activities, i.e. was a fire, light to provide a break, of sufficient severity to mitigate a wildfire?

A near-ground top-down/bottom-up approach was adopted to derive data for the calibration of satellite based optical imagery. Such coupled approaches have been previously undertaken. Most notably, classification of the differenced Normalised Burn Ratio (ΔNBR) through calibration of field data using the Composite Burn Index (Key and Benson, 2006), or similarly, using ΔNBR with customised field data describing fire severity (Hammill and Bradstock, 2006; Smith*, et al.*, 2007; Allen and Sorbel, 2008; Chafer, 2008; French*, et al.*, 2008). In these instances calibration data are collected specifically for classification of a single image or small set of images. In this approach satellite imagery is replaced with near-ground helicopter-based reflectance data and detailed ground measurements.

There are three main improvements required in the development of an algorithm to map fire severity to meet the needs of fire managers in the tropical savannas of northern Australia. Firstly, automation due to high fire recurrence and the extent and continuity of fire in the landscapes. Secondly, the near-ground collection of reflectance spectra markedly decreasing geolocation error. Lastly, collaboration with researchers and land managers across the breadth of the region. This last requirement is the most significant as it will improve the calibration data for the models, it will assist in providing a geographically extensive validation dataset, and it will provide a sense of ownership and extended usage of the fire severity map product.

METHODS

Study area

The tropical savannas cover approximately 1.9 million km^2 of the northern tropical portion of the Australian continent, Figure 1. Rainfall is strongly seasonal, over 90% falling in the summer months, creating a distinct fire season. The assessment region is in the high end of the rainfall gradient. It extends across the Top End of the Northern Territory, lying between the city of Darwin, across the World Heritage Listed Kakadu National Park into the west of the Arnhem Land Aboriginal Land Trust, approximately 300 km east to west, Figure 1.

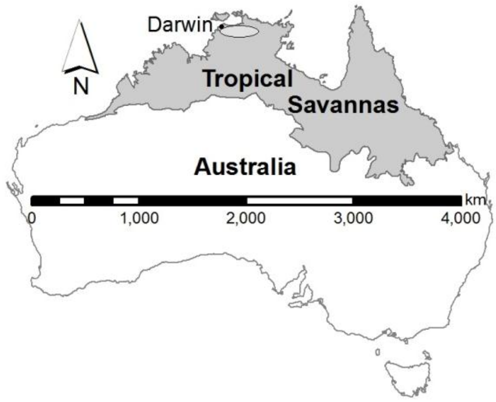

Figure 1. Location of the study region in the tropical savannas of northern Australia.

Data collection

Reflectance data collection occurred the morning after a fire event between 10:00 and 11:00 hours. Using a hand held ASD field spectrometer (Taylor, 2004) sensing 400 to 2500 nm at 1 nm intervals. Reflectance spectra were collected from a helicopter at a height of 100 m above ground. The helicopter was landed in the sampling region and the altimeter reset to zero prior to data collection. Site selection was random and stratified within burnt areas. The end of the optic fibre of the field spectrometer was suspended ~1 m horizontally from the side of the helicopter. Above the end of the supporting rod was a bubble level to ensure the sensor was pointing downward during measurement. Reflectance readings were averaged 250 times at each site. The proximity of the sensor to the ground, and GPS location averaging, greatly reduced geolocation error to ensure ground and reflectance data location correlated as accurately as possible.

Ground data collection occurred at sites in the 48 hours subsequent to the fire event. Detailed 50 m transects were laid out, north to south, centred on the average of the GPS locations. Measurements of the percentage occurrence of the ground variables in each of four strata were taken (Table 1).

Table 1. Ground data collection: variables measured for each of 4 strata: PV = photosynthetic vegetation. NPV = non-photosynthetic vegetation. Sc = scorched foliage, fire affected but not pyrolised. Char = partly pyrolised PV or NPV. Ash = completely pyrolised PV and NPV.

	Strata			
Variable	**Upper >5m**	**Mid 2to5m**	**Lower 0.5to<2m**	**Ground ≤0.5m**
%PV	x	x	x	x
%NPV	x	x	x	x
%Sc	x	x	x	x
%Char	x	x	x	x
%Ash				x
%Dry Grass				x
%Bare Soil				x

Table 2. Ground data collection: Floristic and structural data collected from all plant stems $\geq$ 5 cm diameter at breast height (DBH, measured at 1.3 m above the base of the stem).

Structural Measurement	**Variable**	**Derived Parameter**
Plant Position	*x, y*	*stem density (ha^{-1})*
Basal area	*BA (m^2)*	*total basal area ($m^2 ha^{-1}$)*
Species ID	*Genus species*	*floristic class*
Total Height	*z (m)*	*structural class*
Canopy Radii	r_1, r_2, r_3, r_4 *(m)*	*canopy area (m^2)*
Canopy Height	h_c *(m)*	*canopy volume (m^3)*

Estimation of the fire severity category was recorded for the whole site as given in the field guide. A continuous fire severity parameter, FSIv, was calculated, as a measure of the scorch height (SH) weighted by ground patchiness, for correlative analyses. Measurements of scorch height and char height were averaged at 5m intervals for each plant 10m either side of the transect. Ground patchiness was derived from a point-line intercept at 1m intervals along the 50 m transect. Floristic and structural information was collected in a 50 x 5 m swath on the eastern side of the transect for all plants > 5 cm diameter at breast height (DBH), Table 2.

Data analysis

FSIv was calculated from:

$$FSIv = (100 - (\%PV_G + \%NPV_G)) / 100 * SH \qquad (1)$$

where $\%PV_G$ = the proportion of photosynthetic vegetation in the ground stratum and $\%NPV_G$ = the proportion of non-photosynthetic vegetation in the ground stratum.

A cluster analysis of FSIv produced FSIc. An accuracy assessment of FSI versus FSIc was then undertaken to determine the suitability of the metrics from the field guide. FSIv was correlated with the summed proportions of each of the normalised ground variables to determine the main drivers of the effects of fire on the savanna vegetation. FSIv was correlated with normalised averages of discrete spectra representing the MODIS channels, and derived spectral indices, the normalised differenced vegetation index (NDVI) and NBR. A candidate set of ground and reflectance models was assessed using Akaike's Information Criteria analysis, for a small number of variables (AICc), for suitability to map fire severity.

The models selected from AICc analysis were applied to a time series of MODIS imagery for the study region (Figure 1) in the fire season of 2009. A burnt area algorithm was previously applied to mask the imagery, so that fire severity classification occurred only in known burnt areas. The threshold values between fire severity categories in the experimental dataset were calculated for the models and applied to classify the image data for each fire event as determined from the burnt area mapping. An extensive validation dataset, collected aerially using the methods as outlined by Edwards *et al.* (2001) was used for accuracy assessment.

RESULTS

The overall accuracy in the comparison of FSI and FSIc was 76%. However, when the comparison was severe (high fire severity) versus not-severe (low and moderate fire severity pooled) the accuracy increased to 92%. The normalised summed percentage of PV (%PV) explained 72% of the variability in fire severity. %PV, in combination with other significant ground variables, %NPV and %Scorch Leaves (%Sc), provided a candidate set of models for AICc analysis. The "best" model was determined to be %PV + %NPV + %Sc.

The linear transformed reflectance channels representing the short wave infra-red region (MODIS bands 6 (SWIR1) and 7 (SWIR2)) were significant when correlated with FSIv, explaining the greatest variation, 67% and 52 % respectively. The NBR and NDVI indices were significant and explained 39% and 41% respectively. Whilst in the near infra-red, MODIS band 5 (NIR2) explained only 38%, but was significantly correlated. The significant variables and combinations of the variables were selected for the candidate set for AICc analysis.

In a visual assessment of the mean values for each fire severity category ∆NBR best discriminated severe from not-severe fire events. Although not the best model, parsimony and simplicity for further data manipulation of large satellite image datasets, suggested ∆SWIR1 for discriminating low from moderate fire severity. Unfortunately from an operational perspective the dysfunction of the SWIR2 (band 6) of the MODIS sensor on the Aqua satellite excludes its application. SWIR2 was removed from the candidate set of models. AICc analysis revealed the product of NIR1, NIR2 and SWIR2 (NIR1*NIR2*SWIR2) explained 60% of the variation.

The nested algorithm was developed by first applying ∆NBR to discriminate severe from not-severe fire severity. Then by applying the product of NIR1, NIR2 and SWIR2 to discriminate low from moderate fire severity within the previously classified not-severe class. The accuracy assessment of the ∆NBR classification resulted in an overall accuracy of 94%. The result for NIR1*NIR2*SWIR2 was 60%.

DISCUSSION

The results suggest that a binary fire severity map for the north Australian tropical savannas can be produced with a high degree of accuracy. However, the categories of low and moderate severity are not yet calibrated accurately to clearly differentiate them. Similar accuracies were reported in other biomes where canopy cover is < 50%, (Epting*, et al.*, 2005; Hammill and Bradstock, 2006; Kasischke*, et al.*, 2008). Change in the PV, NPV and bare soil matrix due to fire is possibly more complex than this simple categorisation can explain (Hutley and Beringer, 2010). It would seem prudent to develop a mapping legend based on a continuum, applying the continuous fire severity index. Thus indicating mixed types of disturbance rather than specifying specific thresholds of effect. A continuous variable is more pertinent for a range of applications. The continuous variable has improved benefit for burning efficiency assessment. Ground data sampling of the proportions of fuel types consumed for various habitats under various fire conditions include measurements of mean scorch height and ground patchiness (Russell-Smith*, et al.*, 2004). The scorch height weighted by the ground patchiness provides a continuous fire severity ground variable.

Therefore the data used to derive fuel accumulation relationships also equate to a continuum of fire severity.

The ground truth data, collected aerially, did not sufficiently indicate the severity class. To improve the classification they require modification and calibration from higher resolution ground based measurements.

CONCLUSION

Operationally the fire severity mapping can be incorporated into on-line resources currently available at the North Australia Fire Information web site (www.firenorth.org.au). This will allow intra-seasonal analysis of strategic burning efforts undertaken to mitigate wildfire through hazard reduction burning. Inter-seasonally the data indicate a relative proportion of fuel consumed. This information can be applied to strategic planning for the coming fire season, and has major benefit to conservation management planning when used as a measure of habitat affect.

Fire seasonality currently defines the proportion of biomass consumed by fire for GHG emissions calculations, as the date of fire occurrence is available from fire mapping. The fire severity of a habitat relates directly to the proportion of biomass consumed. A spatially explicit layer of fire severity will provide improved, landscape wide, accuracy to GHG emissions calculations.

The categories of fire severity as outlined in the field guide developed for tropical savanna land managers (Edwards, 2009) provide a quick and simple method of data collection. A much larger set of calibration/validation data will rely upon the input from a collaboration of many researchers and land managers. Coupled with a simplified assessment undertaken throughout the whole fire season, will allow for discrimination within the not-severe categories.

REFERENCES

J. L. Allen and B. Sorbel, "*Assessing the differenced Normalized Burn Ratio's ability to map burn severity in the boreal forest and tundra ecosystems of Alaska's national parks*," International Journal of Wildland Fire, vol 17. p.p. 463-475, 2008.

C. J. Chafer, "*A comparison of fire severity measures: An Australian example and implications for predicting major areas of soil erosion*," CATENA, vol 74. p.p. 235-245, 2008.

A. C. Edwards, "*Fire Severity Categories for the Tropical Savanna Woodlands of northern Australia*," Bushfire Cooperative Research Centre, Darwin, Northern Territory, Australia, 2009.

J. Epting, D. Verbyla and B. Sorbel, "*Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+*," Remote Sensing of Environment, vol 96. p.p. 328-339, 2005.

N. H. F. French, E. S. Kasischke, R. J. Hall, K. A. Murphy, D. L. Verbyla, E. E. Hoy and J. L. Allen, "*Using Landsat data to assess fire and burn severity in the North American boreal forest region: an overview and summary of results*," International Journal of Wildland Fire, vol 17. p.p. 443-462, 2008.

K. A. Hammill and R. A. Bradstock, "*Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity*," International Journal of Wildland Fire, vol 15. p.p. 213-226, 2006.

L. B. Hutley and J. Beringer, "*Disturbance and climatic drivers of carbon dynamics of a north Australian tropical savanna*," in "Ecosystem Function in Savannas: Measurement and Modeling at Landscape to Global Scales," p.p. 57-75, CRC Press, Boca Raton, 2010.

E. S. Kasischke, M. R. Turetsky, R. D. Ottmar, N. H. F. French, E. E. Hoy and E. S. Kane, "*Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests*," International Journal of Wildland Fire, vol 17. p.p. 515-526, 2008.

J. E. Keeley, "*Fire intensity, fire severity and burn severity: a brief review and suggested usage*," International Journal of Wildland Fire, vol 18. p.p. 116-126, 2009.

C. H. Key and N. C. Benson, "*Landscape Assessment: Ground measure of severity, the Composite Burn Index; and Remote sensing of severity, the Normalized Burn Ratio.*," In: FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT., (Ed.s D. C. Lutes, R. E. Keane, J. F. Caratti, C. H. Key, N. C. Benson, S. Sutherland and L. J. Gangi), Gen. Tech. Rep. RMRS-GTR-164-CD: LA 1-51. 2006.

L. B. Lentile, Z. A. Holden, A. M. S. Smith, M. J. Falkowski, A. T. Hudak, P. Morgan, S. A. Lewis, P. E. Gessler and N. C. Benson, "*Remote sensing techniques to assess active fire characteristics and post-fire effects*," International Journal of Wildland Fire, vol 15. p.p. 319-345, 2006.

M. C. P. Meyer, J. Russell-Smith, B. Murphy, G. D. Cook, A. Edwards, C. Yates, J. Schatz, P. Brocklehurst, A. Luhar, R. Mitchell and D. Parry, "*Accounting and verification of greenhouse gas emissions from fire management programs in northern Australia*," International Bushfire Research Conference 2008 - incorporating The 15th annual AFAC Conference, vol p.p. 2008.

J. Russell-Smith, A. Edwards, G. D. Cook, P. Brocklehurst and J. Schatz, "*Improving greenhouse emissions estimates associated with savanna burning northern Australia: Phase 1, Final Report to the Australian Greenhouse Office, June 2004*," In: (Ed.s 2004.

J. Russell-Smith, B. P. Murphy, C. P. Meyer, G. D. Cook, S. Maier, A. C. Edwards, J. Schatz and P. Brocklehurst, "*Improving estimates of savanna burning emissions for greenhouse accounting in northern Australia: limitations, challenges, applications*," International Journal of Wildland Fire, vol 18. p.p. 1-18, 2009.

R. J. Scholes and S. R. Archer, "*Tree-grass interactions in savannas*," Annual Review of Ecology and Systematics, vol 28. p.p. 517-544., 1997.

A. M. S. Smith, L. B. Lentile, A. T. Hudak and P. Morgan, "*Evaluation of linear spectral unmixing and ?NBR for predicting post-fire recovery in a North American ponderosa pine forest*," International Journal of Remote Sensing, vol 28. p.p. 5159-5166, 2007.

F. Taylor, "*Field guide for the ASD FieldSpec Pro - White Reference Mode*," vol p.p. 2004.

C. R. C. Tropical Savannas, "*Improving greenhouse emissions estimates associated with savanna burning in northern Australia: Phase 1*," Australian Greenhouse Office, Canberra, Australia., 2004.

TSMCRC, "*Fireplan: benefit cost evaluation*," In: Evaluation of the CRC for Tropical Savannas: Looking Back, (Ed.s C. f. I. Economics), 2005.

R. J. Williams, A. M. Gill and P. H. R. Moore, "*Seasonal changes in fire behaviour in a tropical savanna in northern Australia*," International Journal of Wildland Fire, vol 8. p.p. 227-239., 1998.

C. P. Yates, A. C. Edwards and J. Russell-Smith, "*Big fires and their ecological impacts in Australian savannas: size and frequency matters*," International Journal of Wildland Fire, vol 17. p.p. 768-781, 2008.

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Human fire maintains a balance of nature.

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Abstract

A perception of conflict between conservation of biodiversity and burning for socioeconomic protection persists in Australia. Numerous studies of ‘impacts of burning’ have concluded that burning depletes nutrients, simplifies vegetation structure by reducing woody vegetation and fallen timber, and threatens biodiversity. However ecological history shows that burning can maintain a dynamic balance in eucalypt ecosystems whereas nutrients, woody vegetation and fallen timber accumulate in the absence of fire, impairing their health, resilience, diversity and safety. Some recent studies of fire and nutrient cycling have elucidated the underlying processes and provided insights into the intervals between fires that can maintain health, resilience and diversity. Human fire is part of the ‘balance of nature’ in eucalypt ecosystems.

Introduction

Human fires have had a pivotal role in Australia's ecological history (e.g. Pyne 1991; Bowman 2003; Gammage 2011; Jurskis 2011). About the time Aboriginal people occupied Australia, climate was relatively stable but there was a peak in charcoal production and mesic vegetation retreated whilst eucalypts and grasses became dominant indicating that human fires were primarily driving vegetation change (Kershaw *et al.* 2002). Consequently browsing megafauna with specialized diets gave way to less specialized grazers (Miller *et al.* 2005; Prideaux *et al.* 2007). Subsequently charcoal production or biomass burning declined and then remained at relatively low levels for about 20 ka until the time of European settlement (Mooney *et al.* 2010). Woody thickening, loss of ground layers and associated fauna, pest outbreaks, eucalypt decline and extensive conflagrations occurred when Aboriginal fire management was displaced by European settlers (Mitchell 1848; Curr 1883; Howitt 1891). Charcoal production peaked once more, then declined from the mid 20th Century as broadscale prescribed burning including aerial ignition reduced the frequency and extent of wildfires (Jurskis *et al.* 2003; Boer *et al.* 2009; Mooney *et al.* 2010). There has been a resurgence in eucalypt decline, extensive wildfires and loss of species over recent decades with expansion of unmanaged conservation reserves and reduced prescribed burning (Jurskis 2005, 2011; Adams and Attiwill 2011).

The proposition that prescribed burning threatens biodiversity in Australia (e.g. Morrison *et al*. 1996; Bradstock *et al*. 1998; Henderson and Keith 2002) ignores this ecological history and views burning as a disturbance that impacts our environment rather than an essential part of the natural balance (Jurskis *et al*. 2003; Attiwill and Adams 2008; Adams and Attiwill 2011; Jurskis 2011; Jurskis *et al*. 2011). The scene was set in 1976 when the international Scientific Committee on Problems of the Environment initiated a project on 'The Effects of Fire on Ecological Systems'. Under this project Gill (1981) popularised the notion in Australia that the response of non-sprouting plant species to fire was either reproduction from seed or local extinction. Since then we have seen thirty years of ecological research focused on life cycle analyses of obligate seeders in an effort to identify critical thresholds for prescribed fire intervals to maintain biodiversity (e.g. Keith *et al*. 2002). This work has been based on assumptions that prescribed fires kill most/all obligate seeders within their boundaries, that fire sensitive plants grow naturally on fire prone sites and that sites which have had little recent human activity reflect natural (pre-European) conditions (e.g. Morrison *et al*. 1996; Bradstock *et al*. 1998; Henderson and Keith 2002).

The first assumption has been based largely on observations of plants' responses to wildfire and has been contradicted by studies of prescribed burning (e.g. Jurskis *et al.* 2003; Penman *et al*. 2008). The second and third assumptions fail to recognize that fire sensitive plants were mostly confined to refugia such as rock outcrops, swamps and deep, dark gullies by Aboriginal burning and increased greatly in number and extent after Aboriginal burning was disrupted (e.g. Pyne 1991; Jurskis 2002, 2009, 2011; Jurskis *et al*. 2003; Gammage 2011). For example, Morrison *et al*. (1996) compared floristic composition against fire intervals in woodlands and shrublands near Sydney that had been burnt by a megafire and several other wildfires and prescribed fires during a quarter of a century. They assumed that European settlement did not change the fire regimes and implicitly, the vegetation.

However the historical record (e.g. Mitchell 1839, 1848) shows that European settlement had profound impacts on fire regimes and vegetation in this area and the floristic homogeneity across vegetation formations (Morrison *et al*. 1996) is a consequence of post - European disruption of Aboriginal burning and imposition of a regime of less frequent and more severe fires (Jurskis *et al*. 2003; Gammage 2011; Jurskis 2011). Morrison *et al*. (1996) found that short (< 7 years) intervals between fires reduced the abundance of five very common shrubs that currently dominate vegetation on Hawkesbury sandstone and increased the abundance of two less common shrubs. The very common shrubs were more abundant on sites with short fire intervals than were the uncommon shrubs on sites with long fire intervals and one of the uncommon shrubs was absent from sites with long fire intervals (Morrison *et al*. 1996 Table 2). Thus Morrison's *et al*. (1996) conclusion that biodiversity will be lost if there are short intervals between prescribed fires is at odds with their data.

Studies of frequent prescribed burning in New South Wales State Forests have confirmed that most obligate seeders are promoted by burning whilst a few common shrubs are disadvantaged (Jurskis *et al*. 2003; Penman *et al*. 2008). Species richness starts to decline within a short time after fire while shrubs are increasing in numbers and density (Penman *et al*. 2008, 2009). This points to competition rather than burning as the cause of species loss and several studies have shown that a few common 'fire sensitive' shrubs proliferate at the expense of many smaller species in the absence of fire and/or grazing (e.g. Jurskis *et al*. 2003; Penman *et al.* 2008, 2009; Price and Morgan 2009; Jurskis 2011). This contributes to chronic tree decline, fire hazard problems and loss of rare biota (Jurskis 2011). Instead of basing prescribed fire intervals on disproven theories we should be looking at the timing of the processes of competition, nutrient cycling and fuel accumulation that cause these problems.

Ecological processes

In dry forests at Eden, groundcover species richness declined within 3 or 4 years of fire (Penman *et al*. 2008 Fig. 4c; Penman *et al*. 2009 Fig. 1a) and continued to decline by 6 species over 20 years (Penman *et al*. 2009 Fig. 1a). Shrub species richness increased by 2 species over 15 years after fire (Penman *et al*. 2009 Fig. 1a), whilst shrub density increased by 1500 stems per hectare over 20 years after fire (Penman *et al*. 2009 Fig. 2). In the same forests, substantial accumulation of soil N occurs after 10 years without fire and C:N is reduced causing increasing acidity and nutrient imbalances that are harmful to eucalypts (Turner *et al*. 2008). These changes are exacerbated by microclimatic changes associated with shrub development such as increased shading and topsoil moisture (Jurskis *et al*. 2011) and by proliferation of N-fixing shrubs such as acacias and casuarinas (Turner *et al*. 2008). Fire ecologists typically report that burning depletes soil N (e.g. Christie and York 2009) because they compare levels in frequently burnt areas against long unburnt 'controls' where N has accumulated over several decades (Turner *et al*. 2008; Jurskis *et al*. 2011). Based on rates of N accumulation in the absence of fire and N removal by prescribed burning, Turner *et al*. (2008) suggested that an interval of about 5 years between fires would maintain dynamically stable nutrient cycling processes. This is similar to the interval that would maintain competitive interactions supporting maximum plant diversity and minimum shrub cover according to the data of Penman *et al*. (2008, 2009).

In the study reported by Penman *et al*. (2008) frequent burning was ineffective after 1994, cumulatively affecting only 30% of the treatment area compared to 130% in the period to 1994 (Penman *et al*. 2007 Fig. 2(b)). Species richness declined at a rate inversely proportional to the area burnt (Penman *et al*. 2008 Fig 4(c)) indicating that the declines were occurring in unburnt areas (Fig. 1). Declining health of eucalypts as indicated by rates of infection by mistletoes (Jurskis 2005) showed a similar pattern. Between 1990 and 2004 mistletoes doubled in the frequent burning treatment while they quadrupled in the other treatments (Jurskis *et al*. 2005) suggesting that eucalypt health declined in the frequent burning treatment after 1994 when burning was ineffective. Assuming that mistletoe numbers were stable when frequent burning was applied effectively, they increased at a similar rate in all treatments after 1994 (Fig. 2).

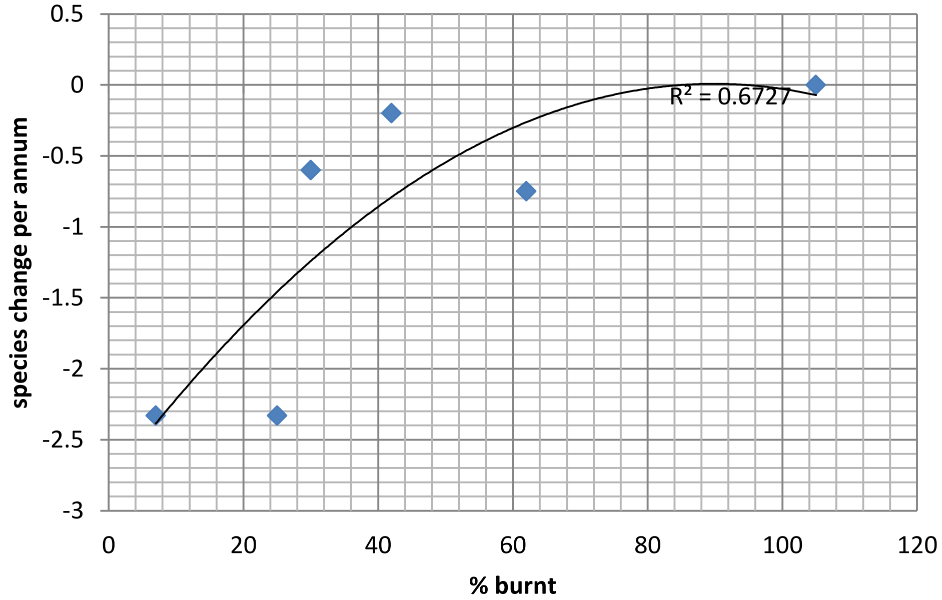

Figure 1 Rate of species loss according to area burnt during the corresponding period

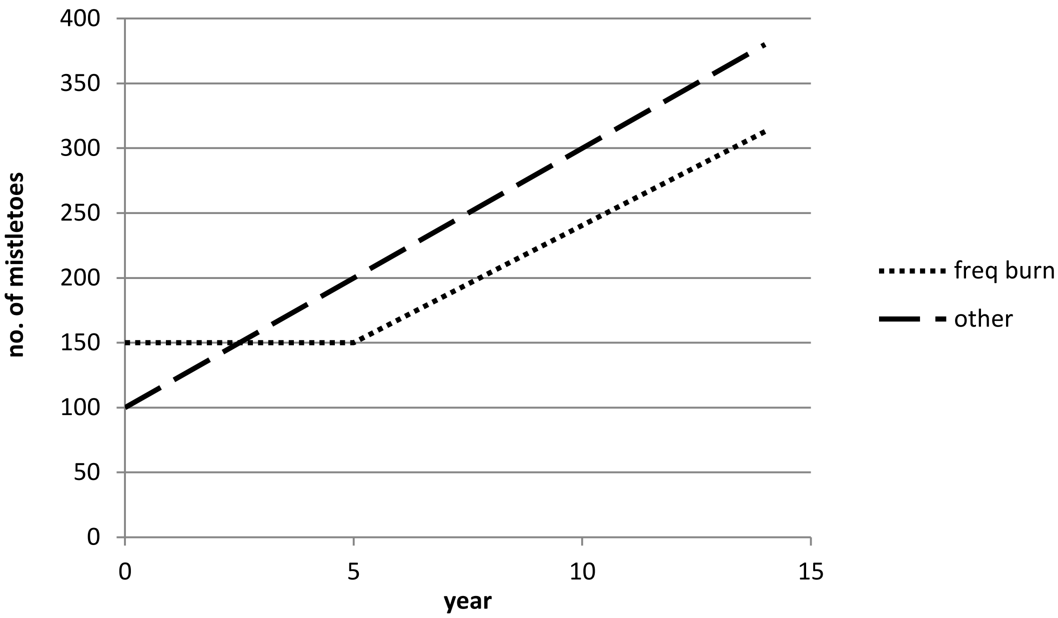

Figure 2 Increasing mean count of mistletoes by treatment between 1990 and 2004. Count for year 5, frequent burn treatment is a dummy variable.

Irruptions of bellbirds are another indicator of declining health in eucalypts because they follow irruptions of psyllids stimulated by enhanced nutrient value of leaves on declining eucalypts (Jurskis 2005). Increasing populations of bellbirds were closely correlated with lack of fire in the Eden burning study (Fig.3).

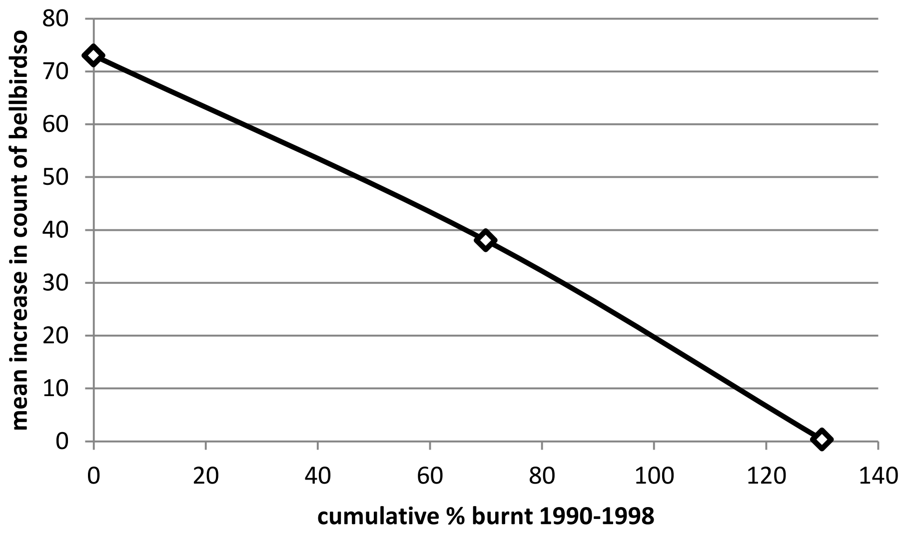

Fig. 3 Increase in bellbirds according to cumulative percent of area burnt 1990 – 1998.

Accumulation of litter, fallen timber, shrubs and fibrous bark on eucalypts reduces fire safety by increasing the quantity and three-dimensional continuity of fuels. Shading, reduced air circulation and increased topsoil moisture exacerbate the problems because the accumulating fuels are not flammable in temperate conditions but explosively flammable in severe conditions (Jurskis *et al*. 2003). However burning studies often measure a relatively small proportion of the fuels available to high intensity fires in severe conditions. For example, Birk and Bridges (1989) measured fuels up to 25 mm diameter and up to 0.9 m above the mineral soil, described as fine fuels, in dry blackbutt (*Eucalyptus pilularis*) forest on New South Wales' north coast. These fuels accumulated to pre-burn levels within 4 years. However Birk and Bridges (1989) noted that fire hazard was reduced because frequent burning restored a grassy understorey at the expense of woody shrubs such as Lantana or Allocasuarina and that this was not well reflected in the fine fuel measurements. In contrast, Penman and York (2010) did not recognize that much fuel was not measured (i.e. fuel > 25mm diameter, fuel > 0.9 m above the mineral soil, fibrous bark on trees such as blackbutt) and thus concluded that burning did not reduce medium term fuel loads. They also did not recognize the natural diversity of groundlayers in dry and moist eucalypt forests (> 70% of total species richness, Penman *et al*. 2008 Figs. 2, 4) and suggested that frequent burning would be environmentally harmful by 'reducing', i.e. controlling, shrubs (Jurskis *et al*. 2011).

The efficacy and longevity of fuel reduction by burning has been demonstrated empirically in the dry eucalypt forests of southwestern Australia. Boer *et al*. (2009) found that burning reduced the extent and incidence of wildfires over half a century and that the effect lasted for 6 years after burning. Since the three aspects of competition, vegetation/fuel mass/structure and nutrient cycling are inextricably linked, it is not surprising that they point to similar fire intervals (3-6 years) to maintain biodiversity, health and fire safety of dry eucalypt forests. This is consistent with estimates of pre-European fire regimes derived from a combination of dendrochronology, sedimentary charcoal, grasstree records and historical accounts (e.g. Mitchell 1848; Curr 1883; Howitt 1891; Burrows *et al*. 1995; Ward *et al*. 2001; Abbott 2003; Hassell and Dodson 2003).

In contrast 'acceptable' fire intervals according to theoretical life cycle analyses are from 7 to 30 years and there are calls for more detailed study of the requirements of species associated with long unburnt areas (e.g. Penman *et al*. 2009). Thus there is a failure to recognize that fire sensitive plants are naturally associated with physically protected habitats and that this protection is reinforced by frequent low intensity burning in the landscape (e.g. Bowman 2003; Jurskis *et al*. 2003; Burrows 2005). In the absence of frequent burning, the majority of fire refugia throughout whole regions can be reset to a young fire age by megafires as happened in wet sclerophyll ash forests in Victoria following megafires in 1939 and on three occasions between 2002 and 2009 (Adams and Attiwill 2011). Similarly all the granite outcrops formerly providing fire refuge to rare species in southwestern Australia were burnt throughout 18,000 hectares by a single high intensity fire in 2003 after 20 years of exclusion of fire from a National Park (Burrows 2005).

Conclusion

Eucalypt forests are fire dependent ecosystems that were shaped by human burning over about 50 ka (Pyne 1991; Bowman 2003). Loss of species (e.g. Bowman 2003; Penman *et al*. 2008; Jurskis 2011), chronic decline of eucalypts (Jurskis 2005; Close *et al*. 2009, 2011; Jurskis *et al*. 2011) and megafires (Jurskis *et al*. 2003; Adams and Attiwill 2011) can occur with environmental changes in the absence of frequent burning. Human fire is essential to maintain diversity, resilience and fire safety in these forests.

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References

Abbott I (2003) Aboriginal fire regimes in south-west Western Australia: evidence from historical documents. In ‘Fire in ecosystems of south-west Western Australia: impacts and management.’ (Eds I Abbott and N Burrows) pp 119-46 (Backhuys Publishers: Leiden)

Adams M, Attiwill P (2011) ‘Burning issues. Sustainability and management of Australia’s southern forests.’ (CSIRO Publishing: Collingwood)

Attiwill PM, Adams MA (2008) Harnessing forest ecological sciences in the service of stewardship and sustainability. A perspective from ‘down-under’. *Forest Ecology and Management* **256**, 1636–1645.

Birk EM, Bridges RG (1989) Recurrent fires and fuel accumulation in even-aged blackbutt (Eucalyptus pilularis) forests. *Forest Ecology and Management* **29**, 59–79.

Boer MM, Sadler RJ, Wittkuhn RS, McCaw L, Grierson PF (2009) Long-term impacts of prescribed burning on regional extent and incidence of wildfires – Evidence from 50 years of active fire management in SW Australian forests. *Forest Ecology and Management* **259**, 132–142.

Bowman DMJS (2003) Australian landscape burning: a continental and evolutionary perspective. In ‘Fire in Ecosystems of South-West Western Australia: Impacts and Management’. (Eds I Abbott, N Burrows) pp. 107–118. (Backhuys: Leiden, the Netherlands)

Bradstock RA, Bedward M, Kenny BJ, Scott J (1998) Spatially explicit simulation of the effect of prescribed burning on fire regimes and plant extinctions in shrublands typical of southeastern Australia. *Biological Conservation* **86**, 83 – 95.

Burrows N (2005) Burning rocks *Landscope* **20**, 55-61.

Burrows ND, Ward B, Robinson AD (1995) Jarrah forest fire history from stem analysis and anthropological evidence. *Australian Forestry* **58**, 7 – 16.

Christie FJ, York A (2009) No detectable impacts of frequent burning on foliar C and N or insect herbivory in an Australian eucalypt forest. *Applied Vegetation Science* **12,** 376 - 384.

Close DC, Davidson NJ, Johnson DW, Abrams MD, Hart SC, Lunt ID, Archibald RD, Horton B, Adams MA (2009) Premature decline of *Eucalyptus* and altered ecosystem processes in the absence of fire in some Australian forests. *Botanical Review* **75**, 191-202.

Close DC, Davidson NJ, Swanborough PW (2011) Fire history and understorey vegetation: water and nutrient relations of *Eucalyptus gomphocephala* and *E. delegatensis* overstorey trees. *Forest Ecology and Management* **262**, 208-14.

Curr EM (1883) Recollections of Squatting in Victoria, Then Called the Port Phillip District, from 1841 to 1851, Facsimile Edition 1968. (George Robertson/Libraries Board of South Australia: Melbourne/Adelaide)

Gammage B (2011) *The biggest estate on earth: how Aborigines made Australia*. Allen & Unwin, Sydney.

Gill AM (1981) Adaptive responses of Australian vascular plant species to fire. In 'Fire and the Australian biota.' (Eds AM Gill, RH Groves, IR Noble) pp. 243-272. (Australian Academy of Science: Canberra)

Hassell CW, Dodson JR (2003) The fire history of south-west Western Australia prior to European settlement in 1826-1829. In 'Fire in Ecosystems of South-West Western Australia: Impacts and Management'. (Eds I Abbott, N Burrows) pp. 71–86. (Backhuys: Leiden, the Netherlands)

Henderson M K & Keith DA (2002) Correlation of burning and grazing indicators with composition of woody understorey flora of dells in a temperate eucalypt forest. *Austral Ecology* .**27** , 121–31.

Howitt AW (1891) The eucalypts of Gippsland. *Transactions of the Royal Society of Victoria* **II**, 81–120.

Jurskis V (2002) Short note: Restoring the prepastoral condition. *Austral Ecology* **27**, 689 – 690.

Jurskis V (2005) Eucalypt decline in Australia, and a general concept of tree decline and dieback. *Forest Ecology and Management* **215**, 1–20.

Jurskis, V (2009) River red gum and white cypress forests in south-western New South Wales, Australia: ecological history and implications for conservation of grassy woodlands. *Forest Ecology and Management* **258**, 2593–2601.

Jurskis V (2011) Benchmarks of fallen timber and man's role in nature: some evidence from temperate eucalypt woodlands in southeastern Australia. *Forest Ecology and Management* **261**, 2149-2156.

Jurskis V, Bridges B de Mar P (2003) Fire management in Australia: the lessons of 200 years. In '*Joint Australia and New Zealand Institute of Forestry Conference Proceedings 27 April – 1 May 2003'* (eds EG Mason CJ Perley) pp. 353-368. (Ministry of Agriculture and Forestry: Wellington)

Jurskis V, Turner RJ, Jurskis D, (2005) Mistletoes increasing in 'undisturbed' forest: a symptom of forest decline caused by unnatural exclusion of fire? *Australian Forestry* **68**, 221–226.

Jurskis V, Turner J, Lambert M, Bi H (2011) Fire and N cycling: getting the perspective right. *Applied Vegetation Science* doi: 10.1111/j.1654-109X.2011.01130.x

Keith DA, Williams JE, Woinarski JCZ (2002) Fire management and biodiversity conservation: key approaches and principles. In 'Flammable Australia: the Fire Regimes and Biodiversity of a Continent'. (Eds RA Bradstock, JE Williams, AM Gill) pp. 401-428. (Cambridge University Press: Cambridge, UK)

Kershaw AP, Clark JS, Gill AM, D'Costa DM (2002). A history of fire in Australia. In 'Flammable Australia: the Fire Regimes and Biodiversity of a Continent'. (Eds RA Bradstock, JEWilliams,AM Gill) pp. 3-25. (Cambridge University Press: Cambridge, UK)

Miller GH Fogel ML Magee JW Gagan MK Clarke SJ Johnson BJ (2005) Ecosystem collapse in Pleistocene Australia and a human role in megafaunal extinction. Science **309**, 287–90.

Mitchell TL (1839) *Three Expeditions into the Interior of Eastern Australia; With Descriptions of the Recently Explored Region of Australia Felix and of the Present Colony of New South Wales,* Second ed., vol. 2. Rediscovery Books, Uckfield, Facsimile Edition 2006, 770 pp.

Mitchell TL (1848) Journal of an Expedition into the Interior of Tropical Australia in Search of a Route from Sydney to the Gulf of Carpentaria. (Longman, Brown, Green and Longmans: London, Facsimile Edition 2007: Archive CD Books Australia)

Mooney SD, Harrison SP, Bartlein PJ, Daniau A-L, Stevenson J, Brownlie KC, Buckman S, Cupper M, Luly J, Black M, Colhoun E, D'Costa D, Dodson J, Haberle S, Hope GS, Kershaw P, Kenyon C, McKenzie M, Williams N (2010) Late quaternary fire regimes of Australia. *Quaternary Science Review* doi:10.1016/j.quascirev.2010.10.010.

Morrison DA, Buckney RT, Bewick BJ Cary GJ (1996) Conservation conflicts over burning bush in south-eastern Australia. *Biological Conservation* **76**, 167-175.

Penman TD, Binns DL, Brassil TE, Shiels RJ, Allen RM (2009) Long-term changes in understorey vegetation in the absence of wildfire in south-east dry sclerophyll forests. *Australian Journal of Botany* **57**, 533-540.

Penman TD, Binns DL, Shiels RJ, Allen RM, Kavanagh RP (2008) Changes in understorey plant species richness following logging and prescribed burning in shrubby dry sclerophyll forests of south-eastern Australia. *Austral Ecology* **33**, 197–210

Penman TD, Kavanagh RP, Binns DL, Melick DR (2007) Patchiness of prescribed burns in dry sclerophyll eucalypt forests in south-eastern Australia. *Forest Ecology and Management* **252**, 24–32

Price JN, Morgan JW (2009) Multi-decadal increases in shrub abundance in nonriverine red gum (Eucalyptus camaldulensis) woodlands occur during a period of complex land-use history. Australian Journal of Botany **57**, 163–170.

Prideaux GJ, Roberts RG, Megirian D, Westaway KE, Hellstrom JC, Olley JM (2007) Mammalian responses to Pleistocene climate change in southeastern Australia. *Geology* **35**, 33–36.

Pyne SJ (1991) Burning bush. A fire history of Australia. (University of Washington Press: Seattle)

Turner J, Lambert M, Jurskis V, Bi H (2008) Long term accumulation of nitrogen in soils of dry mixed eucalypt forest in the absence of fire. *Forest Ecology and Management* **256**, 1133–42.

Ward DJ, Lamont BB, Burrows CL 2001. Grasstrees reveal contrasting fire regimes in eucalypt forest before and after European settlement of southwestern Australia. *Forest Ecology and Management* **150**, 323 – 329.

Integrated decision support model for fuel management and suppression preparedness planning

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Abstract

Bushfire management involves a complex mix of interrelated components including fuel management, fire prevention, fire detection and suppression preparedness planning. Previous wildfire optimisation models have tended to consider these components in isolation from one another. Such models fail to capture the interdependency of system elements and can lead to myopic decision making. We propose an approach that considers both fuel management and suppression preparedness planning within a single optimisation model. The model's effectiveness is tested using a series of hypothetical landscapes, with results indicating that an integrated approach to fuel management and suppression preparedness planning can lead to improved coverage outcomes. Model benefits, potential applications, future testing and possible model extensions are also discussed.

Introduction

Bushfire management involves a complex mix of interrelated components and processes including: fuel management, fire detection, fire weather forecasting, identification of vulnerable areas, inter-agency coordination, fire suppression and knowledge of fire behaviour (Bonazountas et al. 2007). Operations Research (OR) is a discipline that can assist managers operating in this challenging environment. OR is the use of analytical techniques such as mathematical modelling to analyse complex interactions between people, resources and the environment to aid decision-making and the design and operation of systems (Altay and Green 2006).

Fire managers are faced with complex problems consisting of a large number of inter-related decisions together with resourcing and other operational constraints. Optimisation is a field of OR that is suited to such problems. Optimisation is concerned with optimising the use of limited resources to achieve an objective. In an optimisation model this objective is defined as a mathematical function of the decision variables in the form of an ‘objective function’ and is optimised subject to a series of related constraints. Optimisation models have been applied to a range of wildfire management problems including: fuel management, fire prevention, fire detection, deployment of suppression resources to bases and dispatch of suppression resources to fires. Details of the use of optimisation methods in wildfire management from 1961-1981 can be found in Martell’s (1982) comprehensive review of wildfire OR work, elements of this review were subsequently updated in 1998 (Martell et al. 1998). Minas et al. (paper in press) provide a detailed account of post-1998 wildfire optimisation work.

Fuel reduction burning is a bushfire management mechanism aimed at minimising risk to human assets and life. Fire agencies undertake fuel reduction burning with a view to reducing fuel loads in strategic areas and thus reducing the intensity and rate of spread of future bushfires (Penman et al. 2011). A number of optimisation models have been developed for spatial allocation of fuel treatment across a landscape. Hof and Omi (2003) developed a model to determine optimal spatial application of fuel reduction treatments so as to mitigate the effects of a particular “target fire” with a known origin and spread behaviour. Wei et al. (2008) formulated a model for optimal allocation of fuel treatment across a landscape based on spatially explicit ignition risk, fire spread probability, fire intensity levels and values-at-risk. Konoshima et al. (2008; 2010) used optimisation methods to explore optimal fuel treatment spatial patterns across a hypothetical landscape subject to fire risk.

Bushfire agencies establish fire suppression systems that seek to control and extinguish destructive fires. Limits to suppression system capacity are reached when: there are too many fires to attend at once, the fire perimeter grows more quickly than it can be put out, parts of the fire perimeter are too intense to control, or there are too many point assets such as houses to protect (Gill 2005). Fire managers make strategic preparedness decisions about where to base suppression resources in an attempt to maximise fire suppression system effectiveness. Optimisation methods have been applied to the problem of home-basing and deployment of suppression resources. The maximal covering location model (MCLM) (Church and ReVelle 1974) is a classic optimisation model that has been used extensively in emergency service deployment. Dimopoulou and Giannikos (2001; 2004) used a variant of the MCLM model for suppression resource deployment as part of a larger wildfire decision support system. Kirsch and Rideout (2005) developed an optimisation model for initial attack preparedness planning. Their model deployed initial attack resources across a user-defined set of fires with the objective being to maximise the weighted area protected for a given level of budget funding, with weights assigned based on protection priorities. Haight and Fried (2007) formulated a scenario-optimisation model for suppression resource deployment that included a binary “standard response” variable as a proxy for fire-line construction. Their model’s objective was to minimise the number of fires not receiving a “standard response” across a defined set of scenarios.

The optimisation models discussed above consider the fuel treatment and suppression preparedness components of bushfire management in isolation from one another. However, these components are interrelated in that fuel treatment positively affects suppression efforts by reducing fire spread rates and fire intensity (Rideout et al. 2008). This altered fire behaviour has implications for suppression resource requirements and in turn suppression preparedness planning. This interrelation suggests a need for integrated approaches to fuel treatment and suppression preparedness planning. In this paper we present an optimisation model that incorporates both fuel management and suppression preparedness decisions. The model is presented in a general form and demonstrates how these interrelated fire management elements can be integrated into a single optimisation model. As such the model represents an important first step in the development of operational optimisation models that capture dependencies amongst fuel management and suppression preparedness actions. The remainder of the paper is structured as follows. The mathematical formulation of our model is presented and explained. The effectiveness of the model is then tested using a series of hypothetical landscapes with test results discussed. We then conclude by discussing future testing and possible model extensions and enhancements.

Model Formulation

We present an optimisation model that considers fuel management and suppression preparedness planning within an integrated framework. The model has been designed for seasonal (year-ahead) planning at either the state-wide or district scale. The mathematical formulation of the model is as follows.

Sets	
I:	Set of cells (candidate locations for fuel treatment and demand points), indexed i.
J:	Set of bases where suppression resources can be deployed, indexed j.
$NOTREAT$:	Set of cells where no fuel treatment is permitted, indexed i.
Variables	
$COVER_{ij}$:	$=1$, if cell i is covered by resources deployed at base j $=0$, otherwise
$TREAT_i$:	$=1$, if cell i is treated $=0$, otherwise
$PROX_{ij}$:	$=1$, if $TTIME_{ij}$ is less than the time taken for a fire in cell i to spread to 5Ha in size $=0$, otherwise
$SUFF_{ij}$:	$=1$, if resources deployed at base j are sufficient to cover a fire in cell i $=0$, otherwise
$DEPLOY_j$:	Number of suppression resources (e.g. crews) deployed to base j.
Parameters	
$VALUES_i$:	Values threatened by an uncontained fire originating in cell i.
ROS_i:	Time taken (mins) for an uncontained fire in cell i to grows to a size of 5Ha.
$PTROS_i$:	Time taken (mins) for an uncontained fire in cell i to spread to a size of 5Ha, if cell i is treated.
$TTIME_{ij}$:	Time taken (mins) for suppression resources to travel from base j to cell i.
HFI_i:	Head fire intensity (kW/m) of a fire in cell i.
$PTHFI_i$:	Head fire intensity (kW/m) of a fire in cell I, if cell i is treated.
f :	Conversion factor for relating suppression resource requirements in terms of HFI.
$MAXDEPLOY_j$:	Maximum number of suppression resources that can be deployed to base j.
$TBUDGET$:	Fuel treatment budget (\$).
$TCOST_i$:	Cost (\$) of treating cell i.
$DBUDGET$:	Suppression resource deployment budget (\$).
$DCOST_j$:	Cost (\$) of deploying a suppression resource to base j.

$$\text{MAX} \quad \sum_{i \in I} \sum_{j \in J} COVER_{ij} * \sum_{i \in I} VALUES_i \tag{1}$$

Subject to:

$$\forall i \in I \quad \forall j \in J \qquad PROX_{ij} + SUFF_{ij} \geq 2 * COVER_{ij} \tag{2}$$

$$\forall i \in I \quad \forall j \in J \qquad (1 - TREAT_i) * ROS_i + TREAT_i * PTROS_i \geq TTIME_{ij} * PROX_{ij} \tag{3}$$

$$\forall i \in I \quad \forall j \in J \qquad SUFF_{ij} * [(1 - TREAT_i) * HFI_i + TREAT_i * PTHFI_i] \leq DEPLOY_j * f \tag{4}$$

$$\forall i \in I \qquad \sum_{j \in J} COVER_{ij} \leq 1 \tag{5}$$

$$\forall i \in NOTREAT \qquad TREAT_i = 0 \tag{6}$$

$$\forall j \in J \qquad DEPLOY_j \leq MAXDEPLOY_j \tag{7}$$

$$\sum_{i \in I} TREAT_i * TCOST_i \leq TBUDGET \tag{8}$$

$$\sum_{j \in J} DEPLOY_j * DCOST_j \leq DBUDGET \tag{9}$$

$$\forall i \in I \quad \forall j \in J \qquad COVER_{ij} \text{ is binary} \tag{10}$$

$$\forall i \in I \quad \forall j \in J \qquad PROX_{ij} \text{ is binary} \tag{11}$$

$$\forall i \in I \quad \forall j \in J \qquad SUFF_{ij} \text{ is binary} \tag{12}$$

$$\forall i \in I \qquad TREAT_i \text{ is binary} \tag{13}$$

$$\forall j \in J \qquad DEPLOY_j \text{ is integer} \tag{14}$$

The objective function (1) maximises the weighted number of cells covered, with each cell's weighting based on the values threatened if a fire originating in that cell is not contained. Constraint (2) defines coverage, such that cell *i* is covered if there is a base *j* within close enough proximity with sufficient resources deployed there. Constraint (3) defines base *j* as within close enough proximity to cover cell *i* if the travel time between them is less than the anticipated time for a fire in cell *i* to spread to 5Ha in size. Constraint (4) defines whether or not there are sufficient resources at base *j* to cover cell *i* given the anticipated head fire intensity (HFI) in cell *i.* Constraint (5) ensures that each cell can only be covered once. Such a constraint is required in instances when there are insufficient resources available to cover all cells in the landscape. Constraint (6) identifies cells where treatment is not permitted. In practice treatment restrictions may apply for a number of reasons such biodiversity considerations or smoke hazard. Constraint (7) defines location specific deployment restrictions. In practice such restrictions would relate to a bases size or capacity. Constraint (8) imposes a budget on fuel treatment expenditure that cannot be exceeded. Constraint (9) imposes a budget on suppression resource deployment expenditure that cannot be exceeded. Constraints (10-13) restrict several variables to binary (zero or one) values. This means a cell is either covered or it is not, a cell is treated or it is not and so forth. Constraints (14) restricts the number of resources deployed to a base to integer (whole number) values.

These binary and integer constraints lead to a more computationally complex model, making it is more difficult to solve. However they capture key of elements of the problem at hand such as the indivisibility of resource types such as tankers, and the requirement to select a certain number of cells for treatment rather than allowing “partial” treatment of the entire landscape.

A key and novel feature of the formulation is the inclusion of both fuel treatment and suppression deployment decision variables within a single model. Constraints (3 and 4) capture the interrelation between these variables, in that fuel treatment changes a cell’s fire behaviour properties which in turn effects the proximity and number of suppression resources required to cover the cell in question. In Constraint (3) application of fuel treatment reduces a cell’s rate of spread meaning suppression resources based further away can now cover the cell. In Constraint (4) fuel treatment lowers a fire’s head fire intensity meaning less suppression resources are required to cover the cell.

The model structure allows for the use of spatially-explicit data such as: fuel type, fuel load, likely fire behaviour, fuel treatment costs and restrictions, suppression resource deployment costs and restrictions, fuel treatment effectiveness, travel times and values-at-risk. Fire behaviour dependent model parameters such as pre and post treatment rate-of-spread (ROS) and head fire intensity (HFI) can be either estimated or obtained using fire behaviour models. Since these parameters will be fire-weather dependent, in practice it would be prudent to run the model for a range of fire-weather scenarios. Climatology models could potentially be used to help in the selection of these scenarios.

Application of the model requires the landscape to be divided into a number of cells that need not be uniform in shape or size. Rather this partitioning would be done based on what for practical purposes constitutes the fuel treatment units specific to the given landscape that is being modelled.

The values threatened by an uncontained fire in a given cell are used in the model’s objective function to weight or prioritise the coverage of cells. Estimation of this parameter requires an understanding of fire behaviour and the use of spatially explicit values-at-risk data. The model in its present form could consider a single value, such as the number of households threatened, or a number of different values provided they can be aggregated using a common currency such as monetary value. Consideration of multiple values that are not readily expressed in a common currency would require the model to be reformulated in multi-objective form. If spatially explicit values-at-risk data is not readily available the value term can be removed from the model, this is equivalent to giving all cells an equal weighting.

The model is presented here in a fairly general form, there are a number of simple extensions that could be added to the model without significantly changing the model’s structure or the solution approach. Such extensions could include the consideration of several different suppression resource and fuel treatment types with varying costs and levels of effectiveness. Another straightforward extension would be the addition of a discretionary budget component that could be spent on either fuel treatment or suppression resource deployment, this could be used to assist with strategic budget allocation decisions.

Model Testing and Results

The model was tested using 50 hypothetical sixteen-cell landscapes with parameter values defined in Table 1 below. A landscape size of sixteen cells was chosen so as to generate sufficiently complex non-trivial test cases that are small enough that for demonstration purposes one can intuitively see how the model is working.

Parameters	
$VALUES_i$:	random value 0-9
ROS_i :	random value 0-200
$PTROS_i$:	200
$TTIME_{ij}$:	Within cell =20 One cell away = 150 Two cells away = 200 Three cells away = 300
HFI_i :	random value 0-8000
$PTHFI_i$:	800
f :	1000
$MAXDEPLOY_j$:	12
$TBUDGET$:	3
$TCOST_i$:	1
$DBUDGET$:	12
$DCOST_j$:	1

Table 1: Parameter values for model testing

The 50 hypothetical landscapes are composed of a mixture of randomly generated and arbitrarily chosen constant parameter values. Three parameters values were randomly generated: rate-of-spread (ROS_i), head fire intensity (HFI_i) and values threatened ($VALUES_i$). For simplicity post-treatment rate-of-spread ($PTROS_i$) and post-treatment head fire intensity ($PTHFI_i$) were set as constants for all cells, meaning all treated cells exhibited the same post-treatment fire behaviour irrespective of their pre-treatment states. Bases for suppression resource deployment were able to be established in each of the sixteen cells, with no restrictions on the number of resources permitted at each base. Similarly there was no fuel treatment restrictions, with treatment permitted in all 16 cells. A matrix of travel times was constructed based on relative position of cells in the landscape. The conversion factor *f* was set at 1000 meaning one suppression resource was required to contain fire of HFI 1000 kW/m, two resources for a fire of 2000 kW/m and so forth. For simplicity, deployment and treatment costs for all cells were set at a constant value of one. With a deployment budget of twelve and a treatment budget of three, the problem became selecting which three cells to treat and deciding how to deploy the twelve available suppression resources. The integrated model was solved on a regular PC (Intel 2Duo 2.10 GHz processor and 2.00 GB RAM) using the CPLEX 12.2 off-the shelf solver with standard settings. Solution time for each instance varied between 6 seconds and 14 minutes.

In order to assess the integrated model's performance we compared it with two alternate optimisation approaches. In the first "no treatment" approach, suppression resource deployment was optimised with no fuel treatment permitted. In the second "sequential" approach, fuel treatment was optimised first, with cells selected for treatment based on a function of values threatened and fire behaviour parameters. Treatments were then applied to selected cells, with suppression deployment then optimised based on this post-treatment landscape. The three approaches were applied to each of the 50 test landscapes. A summary of results is presented in Table 2 below, with results presented in terms of both percentage of landscape values covered and number of cells covered.

	No Treatment Approach	Sequential approach	Integrated Approach
Average % of values covered	51.2%	74.2%	79.5%
Average number of cells covered	6.1	8.9	9.4

Table 2: Summary of model testing results (50 test landscapes)

The "no treatment" approach provides a baseline measure of the level of coverage suppression resources are able to provide in the absence of fuel treatment. When we allow fuel treatment to three of the sixteen cells (i.e. 18.8% of the landscape) in the "sequential" approach it is not surprising that we see a marked improvement in the level of coverage that suppression resources are now able to provide.

The integrated model outperforms the "sequential" approach by 7.8% on average, despite the fact that in both approaches we have the same number of fuel treatment and deployment resources at our disposal. Table 3 below provides a summary of the distribution of difference in coverage achieved across the 50 test landscapes for the two approaches.

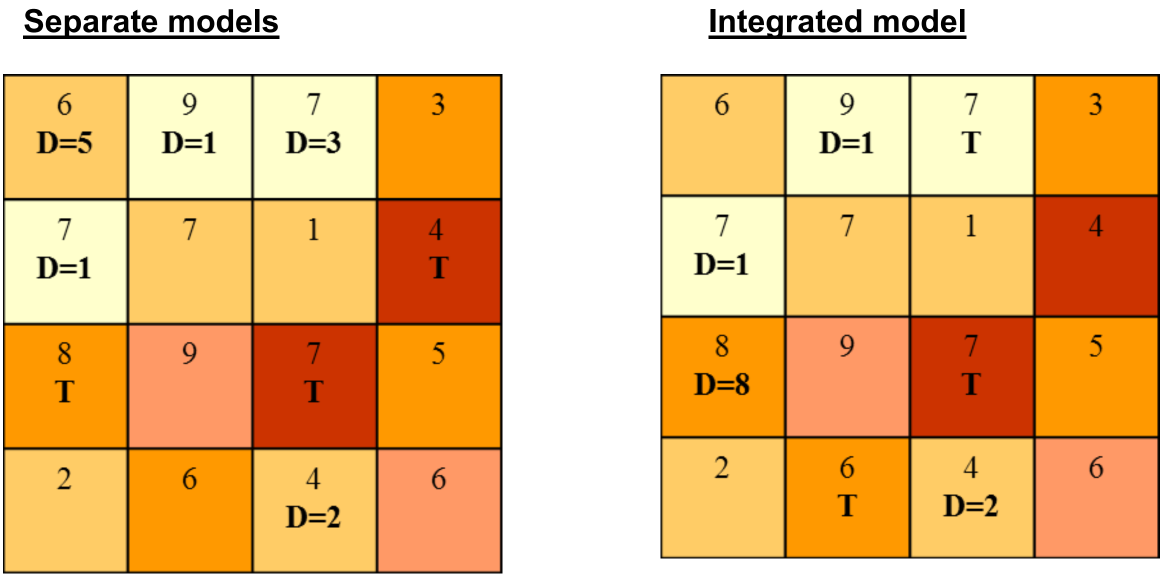
Values covered % difference between integrated and sequential approaches	Number of test landscapes
0 %	11
1-5 %	9
5 – 10%	12
10-15 %	11
15-20%	5
>20%	2

Table 3: Distribution of difference in coverage (integrated and sequential approaches)

The results in Table 3 show that whilst in eleven instances the two approaches performed equally, the results obtained using the integrated model were never bettered by the sequential approach. In many cases the integrated model performed substantially better, with greater than a 10% difference seen in eighteen of the 50 test instances. To replicate conditions where resources are more highly constrained, the 50 test instances were re-run with the deployment budget reset to five, with all other parameter values remaining unchanged. In this more constrained setting the integrated model did even better outperforming the sequential approach by 14.5%. Whilst further testing is required on larger and more realistic landscapes, the results of this initial testing seem to suggest that an integrated approach to fuel management and suppression preparedness planning can lead to improved coverage outcomes.

An illustrative example was selected from amongst the 50 test instances to demonstrate how the integrated model outperforms the “sequential” approach. In Figure 1 cells are colour-coded on an increasing scale from pale yellow up to red based on rate-of-spread and head fire intensity. Numerical values in each cell indicate values threatened if a fire originating in that cell is not contained. It can be seen in Figures 1 and 2 below that the combination of treatment and deployment decisions employed by the integrated model leads to a higher of coverage than the use of separate models in sequence.

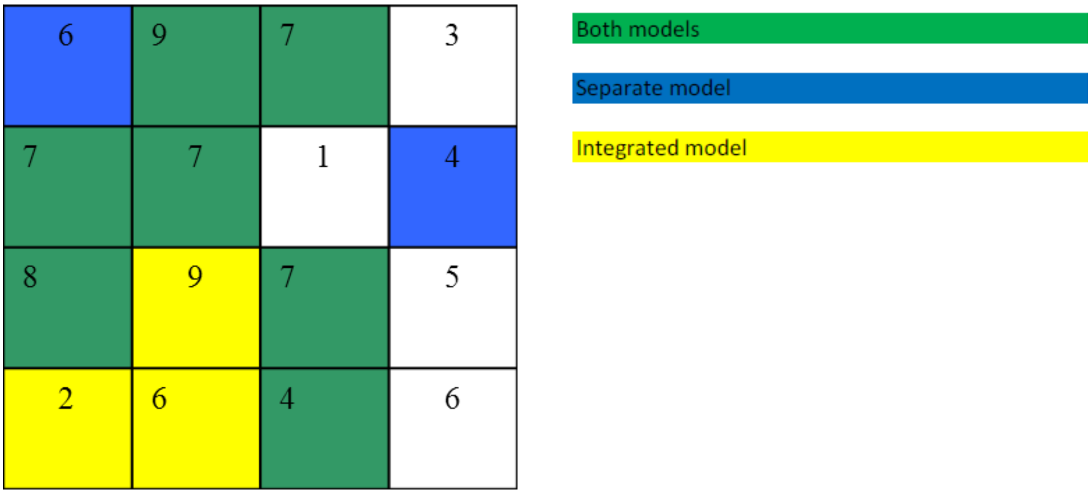
Figure 1: Treatment selection and suppression resource deployment (example test instance)



Proportion of values covered = 64.8%
Number of cells covered = 9

Proportion of values covered = 72.5%
Number of cells covered = 10

Figure 2: Coverage comparison (example test instance)



Discussion

Fire managers are faced with large and complex problems featuring a variety of interrelated decisions and operational constraints. In this context optimisation modelling can be a useful tool for systemically exploring the decision space and seeking good solutions from the many alternatives. The optimisation model presented in this paper provides an integrated spatially-explicit framework for fuel management and suppression preparedness planning. The model has been designed to incorporate inputs from a range of sources including geospatial databases, as well as fire behaviour, fuel and climatology models. The model provides a framework to assist fire mangers in using this information to guide fuel management and suppression preparedness decision making. The model captures the interaction between these two fire management elements, so it is not surprising that it appears to outperform approaches that treat these elements separately. The integrated modelling approach supports transparent, defensible decision making and allows for comparative cost-effectiveness analysis for strategic budget allocation decisions. An integrated model such as this could be employed to assist with determining spatial locations and extents of fuel treatment whilst concurrently considering suppression resource deployment locations. In its present form the model could be applied to year-ahead planning at a district scale.

The next stage of the model’s development will be the undertaking of rigorous testing using both real data and a series of larger hypothetical landscapes with a range spatial attributes. Testing using real data will provide insights into the operational time required for application of the model in real life scenarios. This would include the time needed to source and format the requisite input data, as well as optimisation model solution times. This further testing will also incorporate the simple model extensions discussed earlier including: consideration of different suppression resource and fuel treatment types, and the addition of a discretionary budget component available for either fuel treatment or suppression resource spending.

There are a number of possible extensions that could be made to the model to expand the scope of analysis a few of these extensions are discussed briefly here. A multi-objective (MO) formulation could be employed to allow for the explicit consideration of conflicting objectives including the protection of various market and non-market values threatened by fire. An MO model would allow decision-makers to examine trade-offs amongst the various objectives and support transparent and defensible decision making. Another possible extension is the use of a multi-period formulation in order to consider fuel treatment over a number of years rather than just one year ahead. Such a model could incorporate “diminishing returns” on fuel treatment effect over time due to vegetation regrowth. A multi-year model could also include ecological considerations relating to burn frequency and spatio-temporal landscape composition. The problem could also be formulated as a two-stage stochastic programming model with recourse, with fuel treatment decisions made in the first stage and suppression deployment decisions made in the second stage.

References

Altay N, Green WG (2006) OR/MS research in disaster operations management. *European Journal of Operational Research* **175**(1), 475-493

Bonazountas M, Kallidromitou D, Kassomenos P, Passas N (2007) A decision support system for managing forest fire casualties. *Journal of Environmental Management* **84**(4), 412-418.

Church R, ReVelle C (1974) The maximal covering location problem. *Papers in regional science* **32**(1), 101-118.

Dimopoulou M, Giannikos I (2001) Spatial optimization of resources deployment for forest-fire management. *International Transactions in Operational Research* **8**(5), 523-534.

Dimopoulou M, Giannikos I (2004) Towards an integrated framework for forest fire control. *European Journal of Operational Research* **152**(2), 476-486.

Konoshima M, Albers H, Montgomery C, Arthur J (2010) Optimal spatial patterns of fuel management and timber harvest with fire risk. *Canadian Journal of Forest Research* **40**(1), 95-108.

Konoshima M, Montgomery C, Albers H, Arthur J (2008) Spatial-Endogenous Fire Risk and Efficient Fuel Management and Timber Harvest. *Land Economics* **84**(3), 449.

Gill M (2005) Landscape fires as social disasters: An overview of the bushfire problem. *Environmental Hazards* **6**(2), 65-80.

Haight RG, Fried JS (2007) Deploying wildland fire suppression resources with a scenario-based standard response model. *INFOR* **45**(1), 31-39.

Hof J, Omi P (2003). Scheduling removals for fuels management. RMRS USDA Forest Service. Fire, fuel treatments, and ecological restoration: Conference proceedings RMRS-P 29, pp.367–378 (Fort Collins, CO).

Kirsch A, Rideout D (2005). Optimizing initial attack effectiveness by using performance measures. PNRS USDA Forest Service. System analysis in forest resources: Proceedings of the 2003 symposium. General Technical Report PNW-GTR-656, pp.183-188 (Portland, OR).

Martell DL (1982) A review of operational research studies in forest fire management. *Canadian Journal of Forest Research* **12**(2), 119-140.

Martell DL, Gunn EA, Weintraub A (1998) Forest management challenges for operational researchers. *European Journal of Operational Research* **104**(1), 1-17.

Minas J, Hearne J, Handmer J A review of operations research (OR) methods applicable to wildfire management. *International Journal of Wildland Fire* **Paper in press**.

Penman, T. D., Christie, F. J., Andersen, A. N., Bradstock, R. A., Cary, G. J., Henderson, M. K., et al. (2011). Prescribed burning: how can it work to conserve the things we value? *International Journal of Wildland Fire, 20*(6), 721-733.

Rideout D, Wei Y, Kirsch A, Botti S (2008) Toward a unified economic theory of fire program analysis with strategies for empirical modelling. In 'The economics of forest disturbances: Wildfires, storms and invasive species.' (Eds T Holmes, J Prestemon and K Abt) pp. 361-380. (Springer: New York).

Wei Y, Rideout D, Kirsch A (2008) An optimization model for locating fuel treatments across a landscape to reduce expected fire losses. *Canadian Journal of Forest Research* **38**(4), 868-877.

The dirt on assessing post-fire erosion in the Mount Lofty Ranges: comparing methods

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Abstract

Land managers are required to assess a range of environmental attributes prior to and after prescribed burning. Current environmental assessments vary depending on the organisation involved and the existing information about localised soil erosion. Auditing successful environmental assessments requires ongoing field monitoring to evaluate whether the magnitude and extent of predicted post-fire impacts are comparable. The impacts of post-fire erosion were assessed by the authors using the techniques of water sampling, sediment traps, erosion pins, laser scanning, photogrammetry and visual field assessment. Each data collecting method varies in its spatial and temporal reach in terms of monitoring landscape changes in a post-fire environment. The methods also vary in cost, time and technical complexity.

This paper uses a case study of the Mount Lofty Ranges, South Australia to apply and assess post-fire erosion field techniques in relation to a wildfire at Mount Bold, a Holocene paleofire located at Cleland and ten prescribed burns conducted within the Mount Lofty Ranges. The techniques are assessed for their merits in the context of simplicity for land management staff to use and associated costs. They are further examined in light of their application to different timeframes, spatial scales, magnitude and frequency. Our investigation leads to the recommendation of a simple framework for quick and relatively easy assessment, which is cost effective and can be carried out by both researchers and land management agencies.

Additional keywords: spatial scale, soil loss, laser scanning, prescribed burning, wildfire, environmental assessment

Introduction

Managing erosion in a fire prone landscape requires an appreciation of the diverse processes that influence the movement of sediment. The accurate prediction of post-fire erosion still remains an unresolved problem (Moody and Martin 2009). Moderate- to high-magnitude erosion events have received considerable attention (Certini 2005; Shakesby 2010; Shakesby and Doerr 2006; Shakesby *et al.* 2007) due to the significant difference between post-fire sediment movement and natural denudation rates (Lane *et al.* 2006; Tomkins *et al.* 2007); and the detrimental impact on water supply catchments (Moody and Martin 2004; Smith *et al.* 2011; White *et al.* 2006) and human infrastructure (Nyman *et al.* 2011). In contrast there is a paucity of research (Cerda and Lasanta 2005; Coelho *et al.* 2004; Moffet *et al.* 2007; Smith *et al.* 2010) into low-magnitude erosion events that typically follow prescribed burning.

Over the past ten years there has been a shift towards increasing prescribed burning in South Australia in part due to the Bushfire Summit held in 2003 (Richards 2006). This trend has continued in Victoria with the 2009 Victorian Bushfire Royal Commission (Teague *et al.* 2010) recommending that the state implement a long-term prescribed burning program based on an annual rolling target of 5 per cent minimum of public land. This shift towards increased prescribed burning increases the importance of monitoring in post-fire landscapes. Managers require evidence-based management strategies that address landscape characteristics of the burnt site, the timing of the burn in relation to known rainfall patterns and what ignition patterns are used to modify the fire severity. In South Australia, consideration of potential soil erosion is a legislative requirement (Department for Environment and Heritage 2009) prior to approval of prescribed burning, and an affordable simple technique is needed for land managers to audit this process post-fire.

Considerable technological developments have occurred since Loughran (1989) reviewed the measurement of soil erosion. New technologies such as digital close-range photogrammetry (Heng *et al.* 2010) and laser scanning (Heritage and Hetherington 2007) have enhanced our ability to measure erosion. However, these technologies currently require specialised technical skills to undertake the surveys and process the data so they currently have limited practical application to post-fire landscapes, particularly in remote areas. There is a need to review, assess and compare a variety of post-fire erosion field techniques for both research and land management purposes.

This paper discusses the merits of applying and assessing various post-fire erosion field techniques used in the Mount Lofty Ranges in the context of simple operational use, associated costs, application to different timeframes, spatial scales, magnitude and frequency of erosion events. The comparison includes a simple rapid visual post-fire erosion assessment framework, developed for auditing the accuracy of prescribed fire environmental assessments of post-fire erosion.

Study site

Field-based assessment of post-fire erosion was conducted in the Mount Lofty Ranges (Fig. 1) and focuses on an area to the east of Adelaide where the elevation reaches 727 m at Mount Lofty (34º58’36”S, 138º42’ 35”E). The slope is often greater than 18 degrees and is dissected by small tributaries that feed into the Gawler, Torrens and Onkaparinga Rivers.

Precambrian and Cambrian basement rocks are mantled by shallow to moderately deep acidic soils with high erosion potential (Soil and Land Program 2007). The area lies in a temperate climate zone with warm, dry summers and cool, wet winters. Mean annual rainfall at Mount Barker is 764 mm (Bureau of Meteorology 2010). Native vegetation predominantly consists of dry eucalypt forests and woodlands with either grassy or shrubby understoreys.

The study area has not experienced a major wildfire since Ash Wednesday in 1983 (Department of Environment and Natural Resources GIS fire history). Every year numerous fires are ignited but they rarely reach a sufficient size, such as 1000 ha, to result in major erosion events. In 2007 substantial sediment movement was recorded after a wildfire that burnt 1700 ha at Mount Bold (Morris *et al.* 2008a). The Mount Bold wildfire, ten prescribed burns and paleofire records from Wilson Bog in Cleland are used as case studies for this paper (Fig.1). All sites are located east of Adelaide in the Mount Lofty Ranges. The prescribed burns were conducted between 2007 and 2009 with an average area of 14 ha.

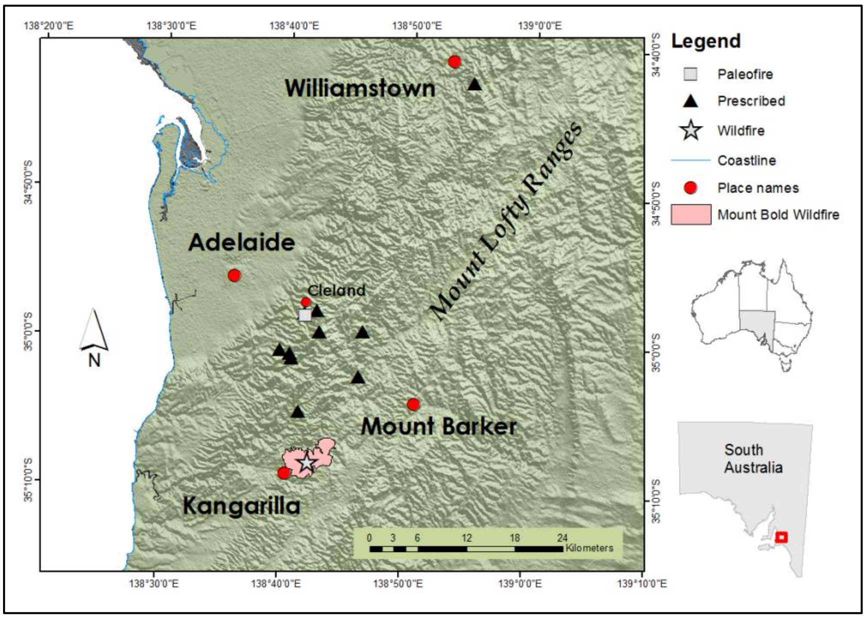

Fig. 1. Location map of the paleofire, wildfire and prescribed fires assessed in the Mount Lofty Ranges, South Australia. (DEM sourced from Shuttle Radar Topography Mission data)

Post-fire erosion assessment in the Mount Lofty Ranges

Selection of the most appropriate method to assess post-fire erosion depends on the temporal scale at which the threat is assessed, the spatial scale of operations, the likely event magnitude and the land management priorities. In the Mount Lofty Ranges various methods were applied by the authors in the post-fire landscape, including water sampling, sediment traps, stratigraphic analysis, erosion pins, terrestrial laser scanning, close-range photogrammetry and rapid visual assessment. Each method has differing temporal and spatial limitations that affect its suitability for assessing the severity and extent of post-fire erosion.

Water sampling in reservoirs

Analysis of water samples provides data on sediment loads and the differences in certain chemical characteristics between pre and post-fire conditions. Parameters that indicate erosion from within the catchment include suspended solids, total dissolved solids and turbidity. Extensive research into sediment loads following wildfire has been undertaken in water reservoir catchments (Lane *et al.* 2006; Moody and Martin 2001; Smith *et al.* 2011; White *et al.* 2006; Wilkinson *et al.* 2007) and to a lesser extent following prescribed fire (Smith *et al.* 2010) where pre-fire baseline data exists. The accuracy of data derived from water samples relies on the rigorous experimental design and sampling regimes implemented. Water samples do not allow temporal comparisons to be made unless regular and repeated sampling is undertaken. In their review of wildfire effects on water quality in forest catchments Smith *et al*. (2011) provided a comprehensive summary of the potential impact on water supply following wildfire and the directions for future research.

Water samples were collected and analysed for suspended sediment and turbidity from the water reservoir following the Mount Bold wildfire (Fig. 2a and Table 1). Additional sampling sites were added after the fire to assess the sediment load reaching the reservoir. Many of these sites did not have regular pre-fire data. The few sites with reliable pre-fire data indicated minimal disturbance by the wildfire even though substantial sediment movement was measured within the burnt catchment (Morris *et al.* 2008a). These results can be attributed to the already high background levels of turbidity and the limited replication of additional sites within the reservoir. Most of the prescribed burns conducted in the Mount Lofty Ranges are not within catchments with sufficient instrumentation to compare pre-and post-fire sediment loads.

Sediment traps

Sediment traps are designed to capture any sediment passing a given line. Fire researchers have used many different types of traps to measure post-fire erosion such as silt fences (Robichaud 2005; Robichaud and Brown 2002), gerlach troughs (Keizer *et al.* 2005) and concrete aprons with overflowing tanks (Blong *et al.* 1982; Dragovich and Morris 2002; Prosser and Williams 1998) or V-notch weirs (Lane *et al.* 2004). To mitigate post-fire erosion, land managers have installed hay bale traps also known as straw bales (Morris *et al.* 2008a; Robichaud *et al.* 2008), log contour traps (Robichaud *et al.* 2008) and silt fences (Dunkerley *et al.* 2009; Robichaud 2005). All traps are designed to capture sediment whose volume can be measured.

At Mount Bold over 50 traps (Fig. 2b and Table 1) were installed to minimise sediment transfer into the water reservoir (Morris *et al.* 2008a). Trap designs included three varieties made from hay, coir and silt fencing. Sediment volumes were measured using tape measures and shovels. Sediment samples from behind six traps were collected then analysed in the laboratory to determine nutrient content and leaching potential. Many of the traps were insufficient in size and strength to capture all the passing sediment. In hindsight rock gabions may have been a better material to use to prevent trap failure. Limitations of using sediment traps include inadequate design to capture all passing sediment, the expense of installing the number of traps required to undertake adequate statistical analysis, extensive maintenance, interference with the natural processes, and the amount of time taken to install and monitor the traps. The strength of sediment traps are that hydrological properties can be studied simultaneously and that the sediment can be collected and further analysed for chemical content and physical attributes.

Table 1. Equipment, associated cost, weight and field personnel involved in the Mount Lofty Ranges Case study. Cost expressed in Australian dollars (2008).

Technique	**Equipment**	**Estimated average cost**	**Approx.** Field Weight	**Field time to sample (does not include travel time)**	**Field personnel involved**
Reservoir water sampling	boat, jars, laboratory, chemicals	$10 - $300 per sample for lab analysis	500g per sample	5 min*	4
Sediment trapping-hay bales	hay bales, star pickets, jute matting, hammers, shovels	$170 per average sized trap	50kg per trap	30 min	28
Stratigraphy	sample bags, shovel, ruler	$20 for all sites	5kg plus sediment samples	30 min for one small trench	4
OSL dating	sample tubes, sample bags, dating machines, scintillation counter	$1000-$1500 per sample for lab analysis	15kg plus sediment samples	30 min*	2
Radiocarbon dating	sample bags, dating machine	$500-$700 per sample for lab analysis	5kg plus sediment samples	10 min*	2
Erosion pins	metal pins, hammers, rulers	$4 per pin	70g per pin	20 min	2
Terrestrial laser scanner	laser scanner, GPS	$240 000 for scanner, computer and software	20kg	20 min*	3
Close-range photogrammetry	field tripods, cameras, survey equipment, numerous personnel	$25 000 for cameras, tripod, survey equipment computer and software	20kg	60 min*	4
Visual assessment	GPS, clipboard, clinometer, water dropper	$60 for clinometer, water dropper, clipboard and bag	500g	5 min	1

* Although field time may appear minimal there is substantial time spent either in the laboratory or processing computer data.

Fig. 2. Field set-ups and associated equipment for assessing onsite natural post-fire soil erosion.

A) *Water sampling* B) *Sediment traps* C) *Stratigraphy* D) *Dating: OSL dating* E) *Erosion pins* F) *Terrestrial laser scanning* G) *Close-range photogrammetry* H) *Visual assessment*

Stratigraphic analysis

Stratigraphy involves the observation and interpretation of fire-related layers within soil or sedimentary profiles. Charcoal-rich sediment provides evidence of past fires. In the Australasian region Mooney *et al*. (2011) compiled 223 sedimentary charcoal records to examine the temporal and spatial variability of fire regimes during the Late Quaternary. Condera *et al.* (2009) highlighted a lack of agreement in defining fire-derived materials, choosing the best extraction procedures, and recognising of the processes involved in their formation and deposition.

In the Mount Lofty Ranges post-fire soil profiles in depositional environments (Fig. 2c and Table 1) were compared to the paleofire sedimentation processes inferred from the exposed peat bog at Cleland (Fig. 2d and Table 1) (Buckman *et al.* 2009). Eroded sites were devoid of charcoal-rich sediment and ash after the wildfire. Radiocarbon and OSL (optically stimulated luminescence) dating (Fig. 2d, Table 1) at the Cleland stratigraphic section has enabled the sedimentary sequences to be interpreted in relation to depositional environments. Over a period of approximately 6000 years there were at least fifteen separate fire events that caused post-fire deposition (Buckman *et al*. 2009). Soil profiles exposed from digging trenches after the 2007 Mount Bold wildfire also provided clear evidence of a charcoal-rich layer of sediment being deposited over the pre-fire soil profile and sediments. Stratigraphy therefore has potential for assessing both the short and long term effects of conducting frequent burns.

Erosion pins

Erosion pins provide a fixed position from which differences in ground surface change can be measured. A metal rod is hammered vertically into the ground, then either rulers or calipers are used to measure the distance between the top of the pin to the mineral earth surface. Erosion pins are generally installed in a grid pattern or along transect lines. A temporal comparison is possible as the pins remain relatively fixed at a given point within the landscape. In the post-fire landscape erosion pins have been used to monitor hillslope erosion in temperate forests (Mackay *et al.* 1984) and alpine areas in NSW, Australia (Smith and Dragovich 2008), monsoonal savannah woodlands in NT, Australia (Russell-Smith *et al.* 2006), moorlands in Yorkshire, UK (Imeson 1971) and pine forest in Mexico (White and Wells 1979).

In the Mount Lofty Ranges erosion pins (Fig. 2e and Table 1) were used to monitor surface level changes at two prescribed fires and the Mount Bold wildfire. At the prescribed fire locations a Before–After–Control–Impact (BACI) experimental design was implemented. A BACI design is not possible at the wildfire site due to pins not being installed prior to the fire. Limitations of using erosion pins included surface disturbance, trapping of sediment by the pin and limited spatial coverage due to the time-consuming nature of both installing and measuring each individual pin. Other sources of erosion pin data contamination are discussed by Haigh (1977). Erosion pins do not provide details on the hydrological processes associated with sediment movement or on sediment transfer beyond the pin grid. The strength of the erosion pin data in the Mount Lofty Ranges is the monitoring of a relatively fixed point location over a 2 to 3 year timeframe with potential for future readings if the pins remain installed.

Laser scanning

Terrestrial laser scanners (TLS) use laser beams to survey topography. Data generated by the survey can be collected over repeated timeframes allowing for comparisons of digital elevation data. Erosion and deposition have been quantified by using digital elevation models (Hancock *et al.* 2008; O'Neal and Pizzuto 2011). In the post-fire environment Martin *et al.*(2008) used terrestrial laser scanning to represent depression storage of sediment and Canfield *et al.* (2005) used aerial laser scanning to validate erosion models.

After the wildfire at Mount Bold, TLS was successfully trialled over two different dates to create a digital elevation model of surface elevation change. The survey was conducted using a Maptek I-Site 4400LR terrestrial laser scanner (Fig. 2f and Table 1). This TLS is a time of flight pulsed rangefinder. It has a range of up to 700 m depending on reflectivity with a typical range accuracy of 50 mm under general scanning conditions from 5 to 700 m. The scanner measures 4400 points per second. Scanning was conducted at numerous locations to reduce shadow effects by maximising scan angle across surfaces and to create scan overlap. At Mount Bold the TLS enabled measurement of surface elevation changes to be made on slopes that were previously inaccessible due to steep (greater than 45 degrees) unstable slopes.

Limitations with the TLS included the inability to measure through dense vegetation regrowth that occurred after 6 months and the technical knowledge required to operate the scanner and process the data. Operators need to be aware of the field operation of the equipment, terrain characteristics and instrument specifications to ensure accurate data is obtained (Heritage and Hetherington 2007). The strength of TLS as applied by the authors is its spatial coverage, ability to measure surface changes exceeding ±50 mm (magnitude), rapid data collection and a scanner that does not interfere with the hydrology or geomorphology at the measured site.

Digital close-range photogrammetry

Photogrammetry measures changes in the surface elevation by capturing overlapping images and applying morphometric survey techniques. Recent technological advances have made the use of digital close-range photogrammetry a viable option for measuring post-fire erosion. In laboratory and field conditions the use of this method is proving to be highly valuable (Gessesse *et al.* 2010; Rieke-Zapp and Nearing 2005). To date digital close-range photogrammetry has not been used in the post-fire environment to measure surface change.

Digital close-range photogrammetry was trialled at the Cleland prescribed burn in the Mount Lofty Ranges (Fig. 2g and Table 1) to measure the subtle changes in surface elevation between rainfall events following prescribed fire (Morris *et al.* 2008b). Success was limited at Cleland due to the developmental stage of the technique in the field (±6mm vertical scale accuracy compared with the capability of ±1mm). Limitations of close-range photogrammetry for operational management include a minimum of two personnel to carry and erect the equipment, the technical knowledge required to process the captured images and the early development stage of the technique. Spatial coverage and replication is limited by the time it takes both to carry and set-up the equipment. Close-range photogrammetry warrants further investigation due to the potential information it can provide on the movement of soil involved in micro-topography such as litter dams and micro-terraces, which retain soil and prevent potential excessive loss of sediment.

Visual assessment

Visual assessment involves describing and/or measuring the geomorphological features associated with sediment movement. Shakesby *et al.* (2003) described and measured ground surface changes including rock cover, newly deposited sediment, faunal activity, litter dam heights, soil pedastools and exposed roots after the Sydney 2001 wildfires. Ruiz-Gallardo *et al.*(2004) applied field erosion assessment to test the reliability of their forest intervention priority map and Berg and Azuma (2010) quantified observations of bare ground and rills to examine erosion recovery following fire. To date there has been no consistent framework for rapid and relatively easy assessment that can be carried out by both researchers and land management agencies.

A descriptive framework (Fig 3) was applied in the Mount Lofty Ranges to assess post-fire sediment movement based on the morphological runoff zones identified by Bracken and Kirkby (2005). This framework is designed to rapidly assess post-fire sediment movement so that researchers can obtain large representative sample numbers and land management field staff can readily and economically assess post-fire erosion. Sampling designs can incorporate the heterogeneous nature of the landscape due to the limited field time required. The framework incorporates ground surface features including splash pedestals, litter dams, small deposit features and debris flows recorded in other post-fire erosion studies (Nyman *et al.* 2011; Shakesby *et al.* 2003).

In the Mount Lofty Ranges case study 505 sites were assessed using the framework in relation to the 10 prescribed burns (Fig. 2h and Table 1). Control sites were included by applying the framework in adjoining unburnt areas. Field assessment was conducted using transects lines that ran both parallel and perpendicular to the contour for eight of the prescribed burn locations. Rapid assessment allowed a relatively unbiased assessment on whether the prescribed burning resulted in minimal sediment movement. Quantifiable results were included by measuring the depth of ground surface features. Differing magnitudes of erosion events were easily recorded and described. The framework enabled large areas to be assessed with adequate replication and spatial representation due to the freedom of not carrying heavy, expensive and bulky equipment as required in many of the methods (Fig 2, Table 1). Land management agencies can easily apply this framework in the field after minimal training.

Timeframes, spatial scales, magnitude and frequency

Selection of the appropriate method to assess post-fire erosion requires a combination of the land management priorities underlying the work, the spatial scale at which land management operations are conducted and the temporal scale at which the threat is assessed. Erosion in the post-fire landscape varies in scale and magnitude. To provide a framework for interpreting disturbance regimes such as erosion, Miller *et al*. (2003) and Benda and Dunne (1997a; 1997b) discuss three concepts including a spatial template, stochastic temporal driver and an antecedent sequence of events. After prescribed burning the magnitude of erosion tends to be low to moderate (Coelho *et al.* 2004) and the fire perimeter is within a known spatial scale. After wildfires the magnitude is highly variable depending on antecedent conditions (Pierson *et al.* 2002), fire severity (Chafer 2008; Godson and Stednick 2010; Prosser and Williams 1998; Shakesby 2010), timeframe (Tomkins *et al.* 2007) and the intensity of subsequent rainfall (Tomkins *et al.* 2008). In Table 2 the effectiveness of post-fire erosion assessment methods used in the Mount Lofty Ranges are outlined in the context of timeframes, spatial scale, magnitude and frequency.

In the Mount Lofty Ranges no one method was able to successfully assess sediment movement for extended timeframes over large spatial scales, covering all event magnitudes (Table 2). In the case of prescribed burning, the timeframe for assessment is usually within the first year, over a scale varying from plot to catchment, with an event magnitude of low to high. If land managers wanted to assess low magnitude erosional events, then the ideal methods would be visual analysis, stratigraphy or close-range photogrammetry. If the event magnitude was greater than high it would be advisable to replace close-range photogrammetry with terrestrial laser scanning as it measures features greater than 50 mm. If the prescribed burn covered large areas such as hillslopes or entire catchments, the use of sediment traps or water sampling may also be appropriate.

Sediment Class	Types of Evidence	Examples
1	Surface crusting Armouring Splash pedestals * Small areas of wash deposits	
2	Depositional steps (<10 cm^2) (often behind vegetation) Litter dams and micro-terraces * Larger areas of wash deposits (<50 cm^2)	
3	Some concentrated flow Erosional steps/small headcuts Deposition >10 cm * Colluvial fans <1 m deep Drainage scouring >10 mm	
4	Concentrated rills (cross-sections >0.1m^2) * Colluvial fans ≥1 m deep Debris flows <1 m wide	
5	Gullies (>1 m deep) with own side slopes Colluvial fans >5 m deep Debris flows >1 m wide *	

Fig. 3. Rapid visual post-fire erosion assessment framework. Modified from Bracken and Kirkby (2005) and Kirkby *et al.* (2005). A sixth category could be included for major landslides, debris flows and/or multiple gully developments. For this study in the Mount Lofty Ranges a sixth class was not required. *Image located to the right.

Table 2. Summary of the effectiveness of post-fire erosion assessment methods used in the Mount Lofty Ranges in the context of timeframes, spatial scale, magnitude and frequency.

Method	Event timeframe				Event spatial scale					Event magnitude					Frequency
	Short (<1yr)	Medium (>1<10yrs)	Long (>10 <100yrs)	Historical (>100)	Point (mm)	Plot (m^2)	Hillslope (m^2 to km^2)	Catchment (km^2)	Landscape ($>km^2$)	Low	Moderate	High	Very High	Extreme	
Water samples	Y	Y	Y	N	Y	N^*	N^*	Y	N^L	N	N	N^*	Y	Y	Y
Sediment traps	Y	N^*	N	N	N	Y	Y	N^L	N	Y	Y	Y	N^*	N^*	N^*
Stratigraphy	Y	Y	Y	Y	Y	Y	N^L	N^L	N^L	Y	Y	Y	Y	Y	Y
Dating	N^*	N^*	Y	Y	Y	N^L	N^L	N^L	N^L	N^*	N^*	Y	Y	Y	Y
Erosion pins	Y	Y	N^*	N	Y	N^L	N^L	N^L	N	Y	Y	Y	N^*	N^*	N^*
Laser scanning	Y	N^*	N^*	N	Y	Y	Y	N^L	N^L	N^*	Y	Y	Y	Y	N^*
Close-range photogrammetry	Y	N	N	N	Y	Y	N^L	N	N	Y	Y	Y	N^*	N^*	N^*
Visual assessment	Y	Y	N^*	N	Y	Y	Y	N^*	N	Y	Y	Y	Y	Y	N

Y = Yes, method is suitable

N = No, method is not suitable

N^* = If the materials or experimental designs were modified it would be possible to use this method.

N^L = Point or small areas can be interpreted and extrapolated to larger areas.

Conclusion

In this case study of assessing post-fire erosion in the Mount Lofty Ranges, the authors applied and compared different techniques to assess erosion. It was found that for operational use a simple rapid visual assessment framework provides an affordable approach that is time efficient compared to other methods. With minimal training land management operational staff could audit environmental assessments in relation to erosion from prescribed burning. Researchers would also benefit from using this framework due to the minimal cost and field time. Spatial variability within the landscape could be incorporated into the research due to the large datasets that can be easily complied using the framework.

Selecting the appropriate erosion assessment methods depends on land management priorities and the capability of the assessment. Historical erosion is best recorded using stratigraphy and dating to measure sediment characteristics, depth and age. Stratigraphy also provides details about the frequency of deposition, allowing comparison between current burning regimes with those in the past. Morphometric methods, including terrestrial laser scanning and close-range photogrammetry, have improved our ability to measure sediment movement over a variety of scales. These results can then be interpreted to assist in understanding micro-topography, catchment and landscape scale processes. The ideal assessment of post-fire erosion would use a combination of monitoring methods to cover all timeframes, spatial scales, event magnitudes and frequency.

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References

Benda L, Dunne T (1997a) Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research* **33**, 2849-2863.

Benda L, Dunne T (1997b) Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**, 2865-2880.

Berg NH, Azuma DL (2010) Bare soil and rill formation following wildfires, fuel reduction treatments, and pine plantations in the southern Sierra Nevada, California, USA. *International Journal of Wildland Fire* **19**, 478-489.

Blong RJ, Riley SJ, Crozier PJ (1982) Sediment yield from runoff plots following bushfire near Narrabeen Lagoon, NSW. *Search* **13**, 36-38.

Bureau of Meteorology (2010) Australian Government Bureau of Meteorology. 'The Recent Climate - Reports and summaries, Annual Summary, South Australia' viewed 5 Nov 2010, http://www.bom.gov.au/climate/current/annual/sa/summary.shtml

Bracken LJ, Kirkby MJ (2005) Differences in hillslope runoff and sediment transport rates within two semi-arid catchments in southeast Spain. *Geomorphology* **68**, 183-200.

Buckman S, Brownlie KC, Bourman RP, Murray-Wallace CV, Morris RH, Lachlan TJ, Roberts RG, Arnold LJ, Cann JH (2009) Holocene palaeofire records in a high-level, proximal valley-fill (Wilson Bog), Mount Lofty Ranges, South Australia. *Holocene* **19**, 1017-1029.

Canfield HE, Wilson CJ, Lane LJ, Crowell KJ, Thomas WA (2005) Modelling scour and deposition in ephemeral channels after wildfire. *Catena* **61**, 273-291.

Cerda A, Lasanta T (2005) Long-term erosional responses after fire in the Central Spanish Pyrenees - 1. Water and sediment yield. *Catena* **60**, 59-80.

Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia* **143**, 1-10.

Chafer CJ (2008) A comparison of fire severity measures: an Australian example and implications for predicting major areas of soil erosion. *Catena* **74** 235-245.

Coelho C, Ferreira A, Boulet A-K, Keizer J (2004) Overland flow generation processes, erosion yields and solute loss following different intensity fires. *Quarterly Journal of Engineering Geology and Hydrogeology* **37**, 233-240.

Conedera M, Tinner W, Neff C, Meurer M, Dickens AF, Krebs P (2009) Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews* **28**, 555-576.

Department for Environment and Heritage (2009) ‘Fire Management Plan, Reserves of the Hills Face Zone, Mount Lofty Ranges, 2009-2019’. 89pp. (Government of South Australia, Adelaide)

Dragovich D, Morris R (2002) Fire intensity, run-off and sediment movement in eucalypt forest near Sydney, Australia. In 'Applied Geomorphology: theory and practice'. (Ed. RJ Allison) pp. 145-162. (John Wiley and Sons, West Sussex)

Dunkerley D, Martin N, Berg S, Ferguson R (2009) Fire, catchment runoff and erosion processes, and post-fire rehabilitation programs: recent Australian experience. In 'Fire effects on soils and restoration strategies'. (Eds A Cerda and PR Robichaud) pp. 467-509. (Science Publishers: Oxford)

Gessesse GD, Fuchs H, Mansberger R, Klik A, Rieke-Zapp DH (2010) Assessment of erosion, deposition and rill development on irregular soil surfaces using close range digital photogrammetry. *Photogrammetric Record* **25**, 299-318.

Godson E, Stednick J (2010) Modelling post-fire soil erosion. *Fire Management Today* **70**, 32-36.

Haigh MJ (1977) The use of erosion pins in the study of slope evolution. *British Geomorphological Research Group Technical Bulletin* **18**, 31-48.

Hancock GR, Crawter D, Fityus SG, Chandler J, Wells T (2008) The measurement and modelling of rill erosion at angle of repose slopes in mine spoil. *Earth Surface Processes and Landforms* **33**, 1006-1020.

Heng BCP, Chandler JH, Armstrong A (2010) Applying close range digital photogrammetry in soil erosion studies. *Photogrammetric Record* **25**, 240-265.

Heritage G, Hetherington D (2007) Towards a protocol for laser scanning in fluvial geomorphology. *Earth Surface Processes and Landforms* **32**, 66-74.

Imeson AC (1971) Heather burning and soil erosion on North Yorkshire Moors. *Journal of Applied Ecology* **8**, 537-542.

Keizer JJ, Coelho COA, Shakesby RA, Domingues CSP, Malvar MC, Perez IMB, Matias MJS, Ferreira AJD (2005) The role of soil water repellency in overland flow generation in pine and eucalypt forest stands in coastal Portugal. *Australian Journal of Soil Research* **43**, 337-349.

Kirkby MJ, Bracken LJ, Shannon J (2005) The influence of rainfall distribution and morphological factors on runoff delivery from dryland catchments in SE Spain. *Catena* **62**, 136-156.

Lane PNJ, Croke JC, Dignan P (2004) Runoff generation from logged and burnt convergent hillslopes: rainfall simulation and modelling. *Hydrological Processes* **18**, 879-892.

Lane PNJ, Sheridan GJ, Noske PJ (2006) Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia. *Journal of Hydrology* **331**, 495-510.

Loughran RJ (1989) The Measurement of Soil-Erosion. *Progress in Physical Geography* **13**, 216-233.

Mackay SM, Long AC, Chalmers RW (1984) Erosion pin estimates of soil movement after intensive logging and wildfire. In 'Drainage basin erosion and sedimentation: conference and review papers 2. University of Newcastle, Australia '. (Ed. RJ Loughran) pp. 15-22.

Martin Y, Valeo C, Tait M (2008) Centimetre-scale digital representations of terrain and impacts on depression storage and runoff. *Catena* **75**, 223-233.

Miller D, Luce C, Benda L (2003) Time, space, and episodicity of physical disturbance in streams. *Forest Ecology and Management* **178**, 121-140.

Moffet CA, Pierson FB, Spaeth KE (2007) Modeling erosion on steep sagebrush rangeland before and after prescribed fire. In 'Proceedings RMS-P-47: Shrubland Dynamics-Fire and Water', 10-12 August 2004, Lubbock, Texas.(Eds RE Sosebee, DB Wester, CM Britton, ED McArthur and SG Kitchen) pp. 79-84. (U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Texas)

Moody JA and Martin DA (2001) Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **26**, 1049-1070.

Moody JA, Martin DA (2004) Wildfire impacts on reservoir sedimentation in the western United States. In 'Proceedings of the Ninth International Symposium on River Sedimentation'. Yichang, China: Beijing. (Eds C-h Hu and Y Tan) pp. 1095-1102. (Tsinghua University Press, Beijing)

Moody JA, Martin DA (2009) Forest fire effects on geomorphic processes. In 'Fire effects on soils and restoration strategies'. (Eds A Cerda and PR Robichaud) pp. 41-79. (Science Publishers: Oxford)

Mooney SD, Harrison SP, Bartlein PJ, Daniau AL, Stevenson J, Brownlie KC, Buckman S, Cupper M, Luly J, Black M, Colhoun E, Costa D, Dodson J, Haberle S, Hope GS, Kershaw P, Kenyon C, McKenzie M and Williams N (2011) Late Quaternary fire regimes of Australasia. *Quaternary Science Reviews* **30**, 28-46.

Morris R, Calliss S, Frizenschaf J, Blason M, Dragovich D, Henderson M and Ostendorf B (2008) Controlling sediment movement following bushfire - a case study in managing water quality, Mount Bold, South Australia. In 'Proceedings, Water Down Under 2008 Conference, incorporating 31st Hydrology and Water Resources Symposium and 4th International Conference on Water Resources and Environment Research', 14-17 April 2008, Adelaide, Australia, pp. 1937-1947. (Engineers Australia, Modbury)

Morris R, Connelly P, Bradstock R, Dragovich D, Henderson M, Ostendorf B (2008b) Sediment movement following prescribed burning - A comparison of three techniques including visual observations, erosion pins and digital close range photogrammetry. In 'Proceedings, International Fire 2008 Conference'. 1-3 September 2008, Adelaide, Australia, pp. 293-300.

Nyman P, Sheridan GJ, Smith HG, Lane PNJ (2011) Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology* **125**, 383-401.

O'Neal MA, Pizzuto JE (2011) The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. *Earth Surface Processes and Landforms* **36**, 695-701.

Pierson FB, Carlson DH, Spaeth KE (2002) Impacts of wildfire on soil hydrological properties of steep sagebrush-steppe rangeland. *International Journal of Wildland Fire* **11**, 145-151.

Prosser IP, Williams L (1998) The effect of wildfire on runoff and erosion in native Eucalyptus forest. *Hydrological Processes* **12**, 251-265.

Richards NW (2006) Prescribed burning in the Southern Mt. Lofty Ranges: How and why is the decision to burn made? In 'Proceedings 10th Biennial Australasian Bushfire Conference, Bushfire2006: Life in a fire-prone environment: translating science into practice ' 6-9 June 2006, Brisbane, Australia, pp.1-6 (Griffith University, Brisbane)

Rieke-Zapp DH, Nearing MA (2005) Digital close range photogrammetry for measurement of soil erosion. *Photogrammetric Record* **20**, 69-87.

Robichaud PR (2005) Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery. *International Journal of Wildland Fire* **14**, 475-485.

Robichaud PR, Brown RE (2002) Silt fences: an economical technique for measuring hillslope soil erosion. United States Department of Agriculture Forest Service Rocky Mountain Research Station. General Technical Report RMRS-GTR-94.

Robichaud PR, Pierson FB, Brown RK, Wagenbrenner JW (2008) Measuring effectiveness of three postfire hillslope erosion barrier treatments, western Montana, USA. *Hydrological Processes* **22**, 159-170.

Ruiz-Gallardo JR, Castano S, Calera A (2004) Application of remote sensing and GIS to locate priority intervention areas after wildland fires in Mediterranean systems: a case study from south-eastern Spain. *International Journal of Wildland Fire* **13**, 241-252.

Russell-Smith J, Yates C, Lynch B (2006) Fire regimes and soil erosion in north Australian hilly savannas. *International Journal of Wildland Fire* **15**, 551-556.

Shakesby RA (2010) Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth-Science Reviews* **105**, 71-100.

Shakesby RA, Chafer CJ, Doerr SH, Blake WH, Wallbrink P, Humphreys GS, Harrington BA (2003) Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. *Australian Geographer* **34**, 147-175.

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* **74**, 269-307.

Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, Blake WH, Tomkins KM (2007) Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management* **238**, 347-364.

Smith HG, Dragovich D (2008) Post-fire hillslope erosion response in a sub-alpine environment, south-eastern Australia. *Catena* **73**, 274-285.

Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S (2011) Wildfire effects on water quality in forest catchments: a review with implications for water supply. *Journal of Hydrology* **396**, 170-192.

Smith HG, Sheridan GJ, Lane PNJ, Sherwin CB (2010) Paired Eucalyptus forest catchment study of prescribed fire effects on suspended sediment and nutrient exports in south-eastern Australia. *International Journal of Wildland Fire* **19**, 624-636.

Soil and Land Program (2007) Land and soil spatial data for southern South Australia – GIS format. ([CD-ROM]. Department of Water, Land and Biodiversity Conservation)

Teague B, McLeod R, Pascoe S (2010) 'Final Report Summary 2009 Victorian Bushfires Royal Commission.'

Tomkins KM, Humphreys GS, Gero AF, Shakesby RA, Doerr SH, Wallbrink PJ, Blake WH (2008) Postwildfire hydrological response in an El Nino-Southern Oscillation-dominated environment. *Journal of Geophysical Research-Earth Surface* **113**, 17.

Tomkins KM, Humphreys GS, Wilkinson MT, Fink D, Hesse PP, Doerr SH, Shakesby RA, Wallbrink PJ, Blake WH (2007) Contemporary versus long-term denudation along a passive plate margin: the role of extreme events. *Earth Surface Processes and Landforms* **32**, 1013-1031.

White I, Wade A, Worthy M, Mueller N, Trevor D, Wasson R (2006) The vulnerability of water supply catchments to bushfires: impacts of the January 2003 wildfires on the Australian Capital Territory. *Australian Journal of Water Resources* **10**, 170-193.

White WD and Wells SG (1979) Forest-fire devegetation and drainage basin adjustments in mountainous terrain. In 'Adjustments of the fluvial system', 21-22 September 1979, Binghamton, New York. (Eds DD Rhodes and GP Williams) pp.199-223. (Kendall/Hunt Publishing, Iowa)

Wilkinson S, Wallbrink P, Hancock G, Blake W, Shakesby R, Farwig V (2007) Impacts on water quality by sediments and nutrients released during extreme bushfires: Report 4: Impacts on Lake Burragorang. 18 pp. CSIRO Land and Water Science Report 6/07.

Erosion and risk to water resources in the context of fire and rainfall regimes

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Abstract
The potential impacts of post-fire erosion on water quality are well documented in the literature. To date, research in this area has focused primarily on post-fire erosion processes and water quality impacts in the context of fire severity and vulnerability of hydrological systems to fire impacts. Accordingly, model development has been driven by the need to predict post-fire erosion given the burn impact and different rainfall conditions. However, there are no tools available for land managers to predict frequency and magnitude of erosion events under variable fire and rainfall regimes. Over time, the fire regime represents an important variable that can lead to changes in risk, especially given the strong influence of anthropogenic activities and climate change on fire regimes. Across landscapes, the regional variability in both fire and rainfall regimes may result in different levels of risk depending on the likelihood of storms intersecting with burnt areas. Fire and storms represent stochastic processes in space and time, in contrast to the deterministic nature of geophysical post-fire erosion processes. In this paper we propose a new risk framework which incorporates regional fire and rainfall regimes as stochastic variables in a system where erosion processes and sensitivity to fire effects represent landscape vulnerability, which is site-specific and driven by deterministic processes.

Introduction

Forest and rangeland fires (both prescribed fire and wildfire) impact on a wide range of social, economic and environmental values and land managers face a complex task in balancing the costs and benefits of different approaches to fire management. Management strategies must consider both the first-order effect of fire (injury, loss of life, property and livestock and damage to infrastructure) and second order-effects such as air pollution, erosion and water quality impacts, post-fire hydrological hazards, and altered ecosystems. This presents a very complex decision making environment with short- and long-term considerations across a large number of stakeholders and agencies with ‘different goals and mandates’ (Rieman *et al.* 2003; Wilson *et al.* 2011). Furthermore, risk factors often operate at multiple spatiotemporal scales and are subject to uncertainties stemming from both natural variability (stochasticity) and incomplete understanding of the processes and components that constitute the overall risk (Thompson and Calkin 2011).

The risk associated with erosion and flash flooding from burnt landscapes represents a second-order impact of fire. The potential impacts from post-fire erosion on water quality, infrastructure and human life are well documented in the literature (eg. Emelko *et al.* 2011; Rieman *et al.* 2003; Smith *et al.* 2011). Both statistical and physical-based approaches have been used in predicting the erosion response of burned catchments in different contexts, e.g. water quality (Benavides-Solorio and MacDonald 2005; Larsen and MacDonald 2007; Robichaud *et al.* 2007) hydrological hazards (Cannon *et al.* 2010) and geomorphic processes (Moody *et al.* 2008b). However, there are currently no predictive tools available to land and fire managers to determine how erosion and the associated risk responds *over time* to landscape-scale fuel management strategies, changing fire regimes and changing weather patterns.

What is the effect of annual prescribed burning rates on the likelihood of large erosion events occurring across the landscape? What is the effect of regional variation in rainfall regimes on the likelihood of post-fire erosion impacting water quality? How will the frequency and magnitude of erosion events be affected by climate- induced changes to fire regimes?

These are questions that typically face land managers during strategic planning and policy development where both short and long term outcomes are considered across multiple values and stakeholders. It represents a different level of inquiry to the currently available post-fire erosion models (e.g. Robichaud *et al.* 2007) and post-fire assessments of hydrological risk (e.g. Sheridan *et al.* 2009).

In this paper we review the current state of knowledge in terms of predicting post-fire erosion. We then present a conceptual risk model which highlights the different role of landscape controls, fire regimes and rainfall as components of the overall risk picture. Finally we conclude with suggestions for a new modelling framework which incorporates fire and rainfall regimes as variables which influence the erosion hazard and the overall risk to water resources.

Fire in the landscape and water quality - what’s the problem?

As major disturbance events in forested landscapes, wildfires can have a large impact on hydrological processes and landscape vulnerability to erosion (Swanson 1981). Increased erosion and sediment export from burnt catchments has been documented in major fire prone regions of the world including southeast Australia, the western USA, South Africa and the Mediterranean (e.g. Lane *et al.* 2006; Moody and Martin 2009a; Scott 1993). Process based research on runoff and erosion processes and fire effect on soil properties show that this increase in erosion is primarily due to:

i. Increased surface runoff and peak flows (increased transport capacity) due to removal of vegetation, reduced hydraulic roughness, and the reduced infiltration rates of burnt soils (Cerda and Doerr 2005; Imeson *et al.* 1992; Martin and Moody 2001; Sheridan *et al.* 2007)
ii. Reduced resistance to erosion (increased sediment supply) due to addition of vegetative ash, removal of vegetation, and reduced soil cohesion due to heat impacts from the burning (Moody *et al.* 2005; Robichaud *et al.* 2010; Sheridan *et al.* 2007)

To date, research has mainly focused on how hydrological systems respond to fire; the impacts of fire on soil physical properties; the underlying runoff and erosion processes; and catchment scale geomorphic and hydrologic responses. Shakesby and Doerr (2006) provide a comprehensive review on fire as a hydrological and geomorphic agent, with several other reviews available for more site specific conditions (Ice *et al.* 2004; Neary *et al.* 2003; Shakesby 2011; Shakesby *et al.* 2007; Wondzell and King 2003). Figure 1 provides a broad overview of the trends in recent publications related to fire and erosion.

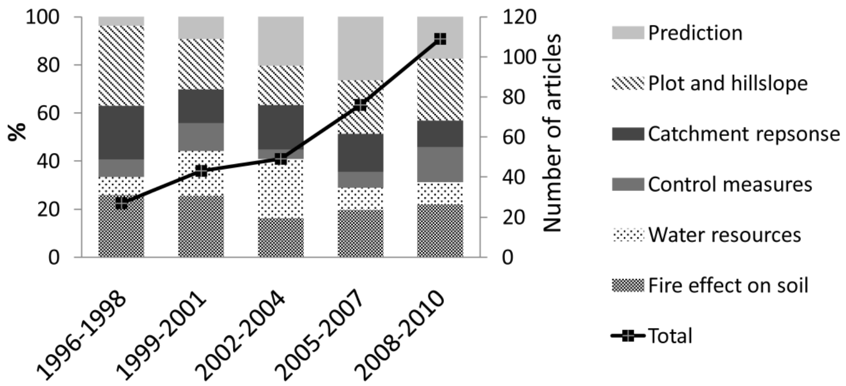

Figure 1. The figure is based on more than 400 results returned by ISI Web of Science using four search terms: 'fire and erosion', 'fire and runoff', 'fire and water quality' and 'fire and infiltration'.

Post-fire impacts on water quality occur mainly through the transfer of particulate and dissolved constituents from burnt hillslopes and ephemeral channels to permanent water bodies. Impacts have been documented in the form of increased turbidity, increased levels of nutrients (N,P), trace elements (Fe, Mn, As, Cr, Al, Ba & Pb) and solutes (Na^+, Cl^-, and SO_4^{2-}) (Smith *et al.* 2011). While the transfer of pollutants can occur through both surface and subsurface processes, the impact occurs largely through pulses of sediment and other pollutants from surface runoff and erosion during high intensity rainfall events in susceptible upland catchments (Bisson *et al.* 2003; Lane *et al.* 2006; Miller *et al.* 2003; Moody *et al.*

2008a; Nyman *et al.* 2011). The burned landscape is characterised by stores of available sediment with different residence times that are determined by the net flux of sediment between them (Figure 2). Transfer processes can be either purely gravity driven (dry ravel), surface hydrology driven (rill and channel erosion, runoff generated debris flows) or subsurface hydrology driven (mass wasting). Here we are concerned with transfer processes that are driven by surface hydrological processes.

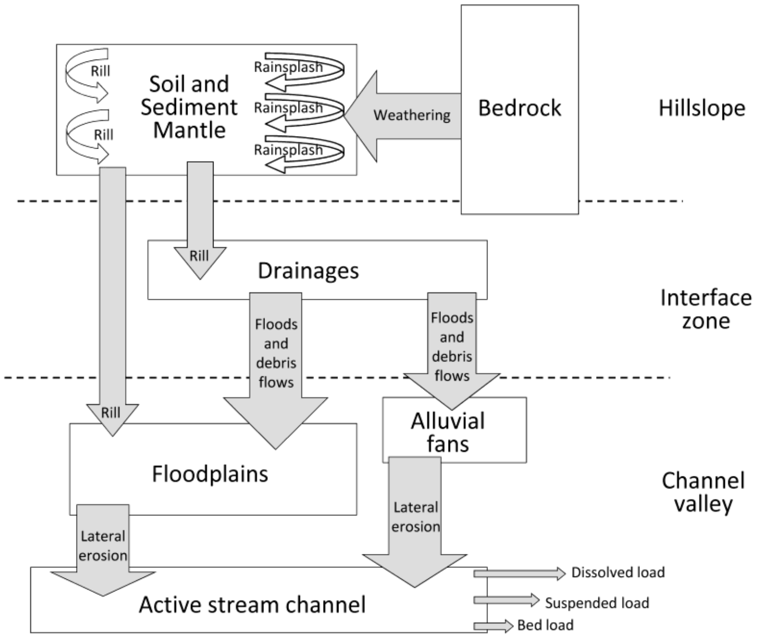

Figure 2. Components of a burned landscape. Sediment storage reservoirs are shown as rectangles and the transfer processes as gray arrows. The areas of the rectangles are roughly proportional to the residence times and the widths of the gray arrows are roughly proportional to the flux of sediment between storage reservoirs. The interface zone is the area between the channels and the hillslope, which can be described as unchannelised drainages (from Moody and Martin 2009b).

The intersection between rainfall events, burned areas and susceptible catchments occur episodically in patches and can therefore often be viewed as discrete events in space and time, in a similar manner to landslides (Istanbulluoglu *et al.* 2004; Nyman *et al.* 2011). These discrete events inject sediment and other potential pollutants into active stream channels where they are gradually transported downstream. While discrete post-fire erosion events in upland catchments may provide the main source of constituents, there are large spatial and temporal uncertainties associated with the transfer of sediment and other pollutants from source to a defined asset or point of impact (Gomi *et al.* 2002). In uplands catchments sediment transfer is driven by surface hydrological processes. At larger scales the sediment transfer is linked to geomorphic and hydrologic processes such as subsurface flow, flow routing and floodplain structure (Benda and Dunne 1997; Gomi *et al.* 2002; Lancaster and Casebeer 2007). In many cases, these processes can be considered to operate more or less independently of the fire disturbance This means that fire impacts on erosion are most pronounced at small scales where surface processes dominate and that the initial perturbation to water quality at any scale within a system is primarily linked to the supply of constituents from source areas in upland catchment. The majority of post-fire erosion research is therefore conducted at hillslope and small catchment scales.

How can risk be quantified in order to meet the demands of land managers?

Risk perspectives vary depending on management context and the spatial temporal scale at which risk is being assessed. In hydrology and geomorphology, the focus is on characterising and predicting hydrological events and the geophysical processes that drive the frequency and magnitude of post-fire erosion. The main task is not to quantify risk *per se*, but rather to provide the predictive tools required as inputs to risk assessment conducted by land and water management agencies. In a risk framework these predictive tools provide a measure of hazard. In a water supply system for instance, the hazard is the predicted frequency, magnitude and duration of post-fire water quality impact. These predictions in turn provide an input for quantifying the overall risk in the context of water quality thresholds, reservoir treatment capacity, alternative supply sources, etc. Here, the geophysical processes that lead to erosion events and that underlie the hazard are in themselves less relevant. The same principle applies to aquatic ecosystems where the risk is a function of ecosystem vulnerability and resilience given the hazard (predictions of post-fire water quality impacts). In this paper we refer to hazard as the frequency and magnitude if erosion events. The risk is the effect of erosion events on assets and is therefore a function of the hazard and the vulnerability.

The level at which the hazard is quantified must reflect the dominant processes that operate at the spatial or temporal scale at which events and management activities are defined. From an *operational* perspective for instance, management activities can influence risk through erosion mitigation works, the timing of prescribed fire and the pattern of prescribed burn in relation to drainages. The burn pattern applied during prescribed fire operations might influence the connectivity between hillslopes and drainages. At this scale of assessment, the hazard is a function of the hydrological connectivity and erosion processes occurring on hillslopes after fire. Here, models and hydrological research can address questions relating to the effectiveness of erosion control works (e.g. Robichaud *et al.* 2007) or the effect of burning patterns on connectivity between streams and drainages (e.g. Moody *et al.* 2008b) . At a *strategic* management level on the other hand, the risk is influenced by climate change, regional weather patterns, resources allocated towards fire suppression, annual prescribed fire targets, strategic fuel reduction burns and other regional fire management strategies. Here hydrologists can address questions relating to the change in hazard as a result of, for instance, increased wildfire occurrence or other changes to fire and rainfall regime parameters (e.g. Istanbulluoglu *et al.* 2004). In this case, predictions should be targeted toward detecting the change in the frequency and magnitude of erosion events (hazard) due to changing fire regimes and changing weather patterns.

A complete risk picture requires a risk analysis which involves i) identifying hazards or water resources at risk, ii) quantifying the degree of impact according to the frequency, extent and severity of fire, and iii) estimating the consequence for a range of potential impacts. The bow and tie diagram in Figure 3 is a simplified risk picture which links fire and rainfall regimes to the potential consequences to a water supply system due to post fire sediment delivery to the reservoir. The horizontal bars represent causes and consequence, vertical bars represents controls such as landscape vulnerability, treatment capacity or post-fire mitigation activities. The hazard is the measure of the potential impact given burn areas, rainfall, and landscape vulnerability and rehabilitation efforts. Quantifying the total risk to water supply is clearly a complicated task requiring information on i) the natural fire and rainfall regimes , ii) the susceptibility of landscapes to post-fire erosion, iii) spatiotemporal transfer processes and iv) the vulnerability of various assets to water quality impacts. Climate change, fire management and erosion mitigation strategies further complicate the risk picture.

Fire and erosion as geophysical processes are associated with large statistical uncertainties (stemming from natural variability and stochastic processes) and epistemic uncertainties (stemming from the lack of perfect knowledge) (Aven 2008; Helton *et al.* 2004). Statistical uncertainties are brought to the system through the random, spatial and temporal variability that is typically associated with climate and biophysical systems such as fire regimes and rainfall. These uncertainties reflect reality and can be incorporated into a modelling environment without loss of predictive power. Epistemic uncertainties however are more problematic in that they stem from the incomplete understanding and lack of data on how fire and rainfall processes translate into an undesirable outcome (i.e. water quality impact). In Figure 3, epistemic uncertainties are found across the entire risk picture, in the causes (fire and rainfall regimes), the vulnerability (landscape controls and transfer processes), rehabilitation (effectiveness) and water quality thresholds.

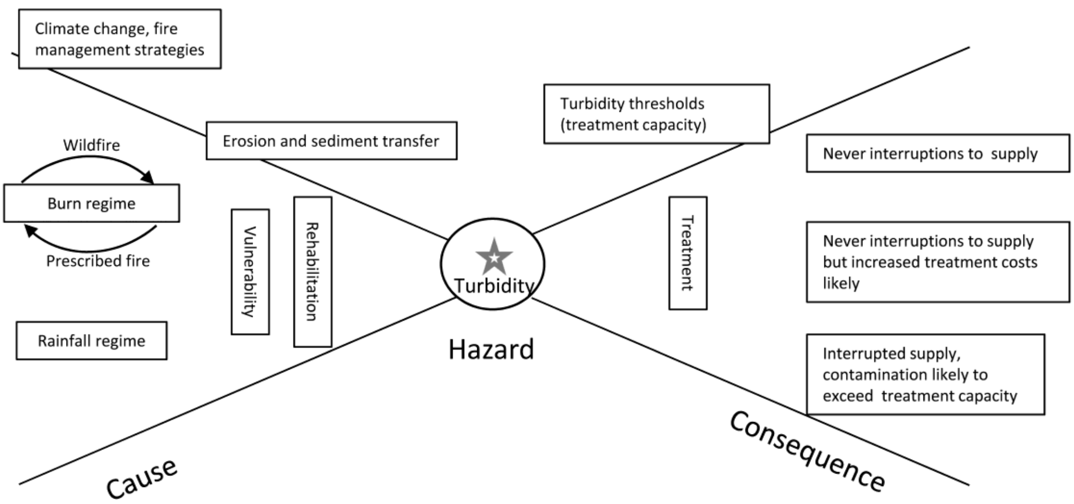

Figure 3. Bow and tie diagram outlining the risk picture for water supply catchments where the hazard is defined as the delivery of sediment to the reservoir. The horizontal bars represent causes and consequence, vertical bars represents controls such as the landscape vulnerability, treatment capacity or post-fire mitigation activities. Here the hazard is equal to the impact turbidity as indicated by the star.

Large epistemic uncertainties can obscure the signal from real effects in a model. In Figure 3 for instance, the hazard is equal to the impact and defined as the frequency and magnitude of sediment delivery event to the reservoir. Under this scenario, *what is the impact of* *changing fire regime on the hazard?* The large uncertainty associated with the controls (landscape vulnerability and rehabilitation) means that it is difficult to detect the effect of a changing fire regime on the hazard as it is defined here. The model would need to estimate the sediment delivery from the range of all possible (random) combinations of fire and rainfall events, an exercise requiring large number of parameters (=uncertainties) and modelling steps (=more uncertainties).

An alternative would be to view the hazard as the rate of intersection between rainfall events (storms) and burned areas (Figure 4). Here, the hazard translates into a consequence via landscape vulnerability, rehabilitation and treatment capacity. This means that a flat terrain with frequent fire and storms (e.g. savannah) can have a high hazard score but a very small likelihood of impact given the low vulnerability. The effect of fire regimes on the hazard is more likely to be detected in this conceptual risk model, given the reduced sources of uncertainty. If the landscape controls and hydrological transfer process are stationary, then any change in hazard would be proportional to the change in overall risk. With this definition, the risk model is more effective at quantifying changes in risk given variable climate, changing fire regimes and strategic fire management. However, if the interest is precise predictions of contamination following a wildfire or prescribed fire, then the hazard is better defined by some measure directly linked to hydrologic connectivity and sediment delivery to the reservoir (e.g. Figure 3).

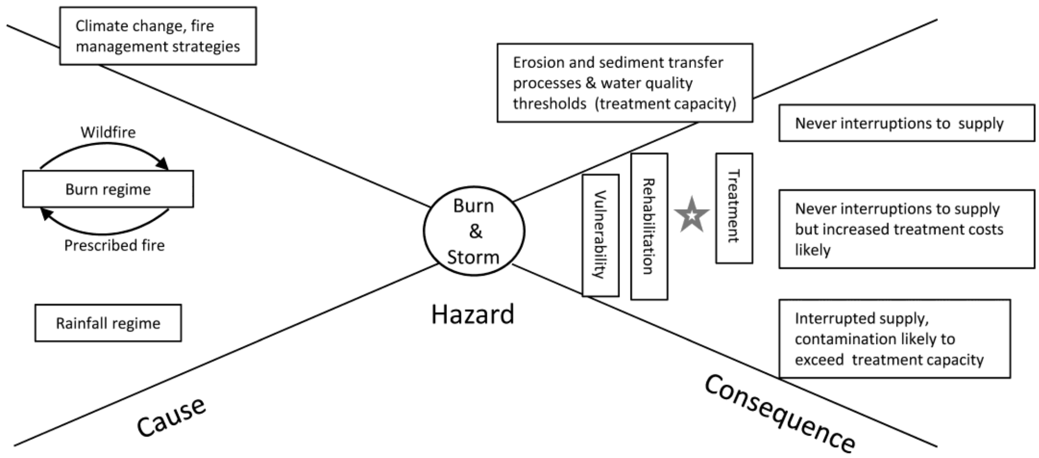

Figure 4. Bow and tie diagram outlining the risk picture for water supply catchments where the hazard is defined as the intersection of storms and burn areas within the catchment. Here the turbidity impact (star) occurs as a result of the hazard and the vulnerability.

Summary and future directions

The vulnerability of ecosystems and water supply systems to the impacts of post-fire erosion is often a function of critical thresholds. This means that the majority of the hazard is embedded in a relatively small number of high magnitude events that exceed critical thresholds. When contamination exceeds thresholds, the consequence is a function of the ability of the system to cope. In a water supply reservoir, the ability to of the system to cope is dependent on infrastructure such as treatment capacity, flexibility in off-take depth as well as alternative water supply sources. In aquatic ecosystems, the ability to cope is related to resilience or ability to bounce back from the disturbance

Common to all systems at risk from post-fire erosion is that the root cause of the hazard is linked to the intersecting burn (B) and rainfall (R) regimes (B∩R). Vulnerability (V) and post-fire rehabilitation (R) influence the way in which the cause translates to geomorphic/hydrological impact. The actual risk is in the end determined by the water quality thresholds (T) associated with the asset. Hence,

$$\text{Risk} = (B \cap R) * V * R * T$$

The hazard can be given different definitions depending on the level at which risk is being assessed. When the risk is assessed as function of erosion and sediment transfer processes *following* fire (connectivity, erodibility, burn patterns, etc...) then the hazard includes (B∩R, V and R. This is often the case in post-fire situations when priorities and management strategies are set based on the variability in erosion potential (hazard) across a burnt area. On the other hand, if risk is quantified *over time* as a function of climate change, burn regimes and rainfall regimes, then the hazard is better defined by fire and rainfall regimes (B∩R) alone. For instance, the difference in risk within a catchment due to different fire and rainfall regimes is independent of the landscape properties (V) or post-fire rehabilitation (R). This means that when the hazard is defined as B∩R, it is independent of site specific hydrological and geomorphic properties and processes. Excluding post-fire geophysical processes from the hazard term in turn means that the causes (rainfall and fire) can be linked to hazard with a higher degree of certainty.

The tendency is for research to focus on quantifying erosion and water quality impacts within burn areas following fire. Few attempts have been made to model post-fire erosion in the context of the causes - rainfall and fire. We propose that the aim should also be for research to characterise fire (the perturbation) and rainfall (the driver) as interacting spatial and temporal processes (e.g. Jones *et al.* submitted). This would allow for more robust analysis of the effects of prescribed fire and climate change on the risk to water resources. Both rainfall and fire represent complex landscape processes which vary across landscapes and over time.

In order to model these interactions more work is needed on questions relating to the effect of prescribed burning and climate change on the susceptibility of the landscape to post-fire erosion events. Prescribed fire means that perturbations appear more frequently in the landscape; however, they result in a reduction in extent and severity of wildfires. Modelling efforts should aim to incorporate the linkage between wildfire and prescribed fire and show how the risk to water resources responds to fire regimes given different fire management strategies. Fires represent hydrological perturbations which appear in the landscape and diminish as recovery progresses. As disturbance events prescribed fire and wildfire need to be treated differently both in terms of their hydrological impact and the way in which they appear in the landscape. Prescribed fire regimes are dominated by frequent, less extensive low severity fires compared as opposed to the less frequent, more extensive high severity wildfires. When applied across a landscape these different regimes result in variable rainfall thresholds for the initiation of high magnitude erosion events. As such, the different component of the fire regimes can be modelled as separate hydrological systems with different hydrological response potential. The concept of leverage or prescribed burn efficacy may can link the deterministic application of prescribed fire in the landscape to the extent and severity of (a stochastic process) (Bradstock and Williams 2009). The modelling approach aims to represent prescribed fire and wildfire as separate hydrological perturbations with different magnitudes. The aim is to address question relating to how the overall landscape is likely to respond under different climate change and fire management scenarios, when prescribed fire and wildfires are modelled simultaneously but as separate components of the overall fire regime. This approach is dependent on reliable data and simulated outputs from fire regime studies.

Another important avenue for future research would be to capture and quantify the landscape-scale variability in the sensitivity to the impacts of fire. This is a necessary step for linking a fire perturbation to erosion response potential. The effect of fire on hydrological processes depends on both the pre-fire vulnerability of the landscape to erosion and the sensitivity of the hydrological system to fire impacts. Fire regimes should be defined within eco-region (or functional response units) where fire effects can be directly linked to hydrological perturbations using a measure of sensitivity to fire impacts. Fire impacts and landscape susceptibility can then be combined to represent vulnerability.

Finally, we need more information on the frequency and magnitude of rainfall events that drive post-fire erosion events. A spatial temporal representation of rainfall requires information on the frequency of events, the intensity and duration of events and their spatial distribution. Both the measurement and modelling of these rainfall properties is a challenge. However, recent improvements in spatial information on rainfall (radar data) can provide important new sources of information.

It is clear that a landscape-scale approach to modelling fire impacts in erosion response can provide a useful tool for assessing at a strategic level, the impact of various fire management scenarios and climate change on future erosion. The data requirements can be large, and the model requires inputs from research activities across the fields of fire ecology, meteorology, climate change science in addition to hydrology and geomorphology which are at the core of post-fire erosion research. The reliability of the external inputs the model will essentially determine how the model can be applied and its capacity to deliver useful information to land managers. It is therefore important to work across agencies and collaborate to generate data and knowledge which can feed into the proposed erosion modelling framework.

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References

Aven T (2008) 'Risk analysis : assessing uncertainties beyond expected values and probabilities.' (Wiley: Chichester, England ; Hoboken, NJ) x, 194 p.

Benavides-Solorio JD, MacDonald LH (2005) Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* **14**(4), 457-474.

Benda L, Dunne T (1997) Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**(12), 2865-2880.

Bisson PA, Rieman BE, Luce C, Hessburg PF, Lee DC, Kershner JL, Reeves GH, Gresswell RE (2003) Fire and aquatic ecosystems of the western USA: current knowledge and key questions. *Forest Ecology and Management* **178**(1-2), 213-229.

Bradstock RA, Williams RJ (2009) Can Australian fire regimes be managed for carbon benefits? *New Phytologist* **183**(4), 931-934.

Cannon SH, Gartner JE, Rupert MG, Michael JA, Rea AH, Parrett C (2010) Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geological Society of America Bulletin* **122**(1-2), 127-144.

Cerda A, Doerr SH (2005) Influence of vegetation recovery on soil hydrology and erodibility following fire: an 11-year investigation. *International Journal of Wildland Fire* **14**(4), 423-437.

Emelko MB, Silins U, Bladon KD, Stone M (2011) Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies. *Water Research* **45**(2), 461-472. [In English]

Gomi T, Sidle RC, Richardson JS (2002) Understanding processes and downstream linkages of headwater systems. *Bioscience* **52**(10), 905-916.

Helton JC, Johnson JD, Oberkampf WL (2004) An exploration of alternative approaches to the representation of uncertainty in model predictions. *Reliability Engineering & System Safety* **85**(1-3), 39-71.

Ice GG, Neary DG, Adams PW (2004) Effects of wildfire on soils and watershed processes. *Journal of Forestry* **102**(6), 16-20.

Imeson AC, Verstraten JM, Vanmulligen EJ, Sevink J (1992) The effects of fires and water repellency on infiltration and runoff under Mediterranean type forest. *CATENA* **19**(3-4), 345-361.

Istanbulluoglu E, Tarboton DG, Pack RT, Luce CH (2004) Modeling of the interactions between forest vegetation, disturbances, and sediment yields. *Journal of Geophysical Research* **109**(F01009).

Jones O, Nyman P, SHeridan G A stochastic coverage model for erosion events caused by the intersection of burnt forests and convective storms. In 'MODSIM 2011 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand', submitted,

Lancaster ST, Casebeer NE (2007) Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. *Geology* **35**(11), 1027-1030.

Lane PNJ, Sheridan GJ, Noske PJ (2006) Changes in sediment loads and discharge from small mountain catchments following wildfire in south Eastern Australia. *Journal of Hydrology*(331), 495-510.

Larsen IJ, MacDonald LH (2007) Predicting postfire sediment yields at the hillslope scale: Testing RUSLE and Disturbed WEPP. *Water Resources Research* **43**(11), 18. [In English]

Martin DA, Moody JA (2001) Comparison of soil infiltration rates in burned and unburned mountainous watersheds. *Hydrological Processes* **15**(15), 2893-2903.

Miller D, Luce C, Benda L (2003) Time, space, and episodicity of physical disturbance in streams. *Forest Ecology and Management* **178**(1-2), 121-140.

Moody JA, Martin D (2009a) Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. *International Journal of Wildland Fire* **18**, 96-115.

Moody JA, Martin DA (2009b) Forest fire effects on geomorphic processes. In 'Fire effects on soils and restoration strategies.' (Eds A Cerda and PR Robichaud) pp. 41-79. (Science Publisher: Enfield, New Hampshire)

Moody JA, Martin DA, Cannon SH (2008a) Post-wildfire erosion response in two geologic terrains in the western USA. *Geomorphology* **95**(3-4), 103-118.

Moody JA, Martin DA, Haire SL, Kinner DA (2008b) Linking runoff response to burn severity after a wildfire. *Hydrological Processes* **22**(13), 2063-2074.

Moody JA, Smith JD, Ragan BW (2005) Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires. *Journal of Geophysical Research-Earth Surface* **110**(F1).

Neary DG, Gottfried GJ, DeBano LF, Tecle A (2003) Impacts of Fire on Watershed Resources. *Journal of the Arizona-Nevada Academy of Science* **35**(1), 23-41.

Nyman P, Sheridan GJ, Smith HG, Lane PNJ (2011) Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology* **125**(3), 383-401.

Rieman B, Lee D, Burns D, Gresswell R, Young M, Stowell R, Rinne J, Howell P (2003) Status of native fishes in the western United States and issues for fire and fuels management. *Forest Ecology and Management* **178**(1-2), 197-211.

Robichaud PR, Elliot WJ, Pierson FB, Hall DE, Moffet CA (2007) Predicting postfire erosion and mitigation effectiveness with a web-based probabilistic erosion model. *CATENA* **71**(2), 229-241.

Robichaud PR, Wagenbrenner JW, Brown RE (2010) Rill erosion in natural and disturbed forests: 1. Measurements. *Water Resour. Res.* **46**(10), W10506.

Scott DF (1993) Hydrological effects of fire in South-African mountain catchments. *Journal of Hydrology* **150**(4), 409-432.

Shakesby RA (2011) Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews* **105**(3-4), 71-100.

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* **74**(3-4), 269-307.

Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, Blake WH, Tomkins KM (2007) Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management* **238**(1-3), 347-364.

Sheridan G, Lane P, Smith H, Nyman P (2009) A rapid risk assessment procedure for post-fire hydrologic hazards: 2009/10 fire season. . Victorian Department of Sustainability and Environment (DSE), Report ISBN 9780734041470, Melbourne.

Sheridan GJ, Lane PNJ, Noske PJ (2007) Quantification of hillslope runoff and erosion processes before and after wildfire in a wet Eucalyptus forest. *Journal of Hydrology* **343**(1-2), 12-28.

Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S (2011) Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology* **396**(1-2), 170-192.

Swanson FJ Fires and geomorphic processes. In 'Proceedings, fire regimes and ecosystems conference', 1981, Honululu, pp. 401-420

Thompson MP, Calkin DE (2011) Uncertainty and risk in wildland fire management: A review. *Journal of Environmental Management* **In Press, Corrected Proof**.

Wilson RS, Winter PL, Maguire LA, Ascher T (2011) Managing Wildfire Events: Risk-Based Decision Making Among a Group of Federal Fire Managers. *Risk Analysis* **31**(5), 805-818.

Wondzell SM, King JG (2003) Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* **178**(1-2), 75-87.

Fire Regimes and Vegetation in the Greater Blue Mountains World Heritage Area

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Abstract

The Greater Blue Mountains World Heritage Area (GBMWHA) covers just over a million hectares, and comprises eight national parks. It is one of the most fire-prone regions on Earth, has extensive adjoining urban areas and contains internationally significant ecosystems and biodiversity. These features present significant management challenges, and increase the need for good science to underpin decision-making.

We carried out a synthesis of fire regime information for the GBMWHA, calculated fire frequencies for the four decades to 2010 and determined the status of area in relation to ‘fire-biodiversity thresholds’ that are suggested for the maintenance of plant species diversity. We found current fire frequencies across the GBMWHA are broadly appropriate, with approximately 76% of the landscape within threshold.

In addition, we generated fire severity maps for the GBMWHA for all five major bush fire seasons since 1990, using two different satellite image types (Landsat, SPOT) and two different approaches (pre/post-fire image differencing and single post-fire image analysis). Both image types and approaches produced useful fire severity maps, but image-differencing with Landsat produced the best cost-effective results. The resulting maps show the patterns of fire intensity for each of the bush fire seasons and provide new broad-scale information on this less-commonly documented component of fire regimes.

The comprehensive fire history now available for the GBMWHA is one of the most detailed in Australia, and is being used for fire planning and management, as a baseline against which to assess climate change impacts, and in further research.

Introduction

The Greater Blue Mountains World Heritage Area (GBMWHA) in eastern New South Wales covers an area of approximately 1.03 million hectares, and includes eight conservation reserves (Blue Mountains, Gardens of Stone, Kanangra-Boyd, Nattai, Thirlmere Lakes, Wollemi and Yengo national parks and Jenolan Karst Conservation Reserve). It stretches almost 250 kilometres from the southern edge of the Hunter Valley to the Southern Highlands of NSW. The Blue Mountains National Park (commonly thought of as "the Blue Mountains") makes up just 25% of the Greater Blue Mountains World Heritage Area.

The World Heritage Area is an ideal location to study bush fires for a number of reasons. The region is highly fire-prone, experiencing large bush fire seasons one to two times per decade: since 1970 there have been ten major bush fire seasons. There are also good basic fire history records available, because the New South Wales National Parks & Wildlife Service (NPWS) has kept perimeter maps of both bush fires and prescribed fires for most of the land now in the GBMWHA since 1970 (for some areas more recently gazetted as national parks, the fire history only goes back to their date of gazettal). The region has an extensive bushland-urban interface and substantial numbers of people and assets embedded within a rugged and highly flammable landscape. The area has suffered substantial losses of property in the past, such as in the 1957-58 fires (Cunningham 1984) and the 1993-94 fires. It also has very high conservation values (NPWS and Environment Australia 1998), being one of the three most diverse areas of sclerophyll vegetation on Earth, with 114 endemic species, approximately 100 species of eucalypts, 400+ species of vertebrates, and rare and ancient Gondwanan species of world significance, such as the Wollemi Pine (*Wollemia nobilis*) and Blue Mountains Pine (*Pherosphaera fitzgeraldii*).

Recent climate change modelling suggests that the region is likely to experience more high to extreme fire danger (FFDI > 40) days, an earlier start to the fire season, and potentially more frequent fires of high intensity in the future (Hennessy *et al*. 2006; Clarke *et al*. 2011). Extrapolation from these models (Bradstock *et al*. 2008) suggests that the area, intensity and frequency of bush fires may increase in the future. The forecasts from these studies add urgency to the need to better understand, predict and manage the impacts of fire regimes in the region.

In this paper we describe the enhancement of existing fire history information for the GBMWHA into a fire regime analysis of outstanding spatial and temporal coverage and resolution. Specifically, in this study we: (1) combined existing fire perimeter maps from various NPWS records and analysed the fire frequency patterns; (2) compiled a single seamless vegetation map from ten existing source maps to cover the entire GBMWHA; (3) combined the fire frequency and vegetation maps, and compared the output against suggested biodiversity fire thresholds for New South Wales vegetation; and (4) prepared fire severity maps for the five major bush fire seasons in the last 20 years for the region.

Fire Frequency Analysis

Maps of the occurrence and perimeter of all fires (including prescribed burns) in the GBMWHA were sourced from existing digital geographic information system layers held by the NPWS. These were available back to the 1960s for most of the GBMWHA, but only back to the 1980s for Gardens of Stone National Park— the most recently gazetted park. This provided a fire history analysis period of between 49 and 29 years to 2010, depending on the reserve (49 years for Blue Mountains, Kanangra-Boyd and Nattai national parks and Jenolan Karst Conservation Reserve; 43 years for Yengo National Park; 39 years for Wollemi National Park and 29 years for Gardens of Stone National Park). During the study period there have been a number of major fire seasons in the region (that is, years with multiple large fires requiring multi-agency fire-fighting), including 1977-78, 1979-80, 1980-82, 1982-83, 1984-85, 1993-94, 1997-98, 2001-02, 2002-03 and 2006-07. The large fires during these seasons have essentially determined the fire regimes of the region (Fig 1a). For example the 1993-94 and 2001-02 fires each burnt 25% of the GBMWHA and the 2002-03 fires burnt 19%.

Analysis of these fire maps revealed that the most common time-since-fire values in the GBMWHA (at 2010) were 9 years post-fire (23% last burnt in the 2001-02 fires), 8 years post-fire (19% last burnt in 2002-03), 4 years post-fire (10% last burnt in 2006-07) and 13 years post-fire (8%). More than half (58%) the GBMWHA is currently less than ten years post-fire age (Fig 2).

However, because successive big fire seasons have predominantly burnt different parts of the landscape, the majority of the GBMWHA has been burnt by just one (26%), two (29%) or three (20%) fires during the study period, with an additional 18% unburnt (Fig 1b). Less than 10% of the GBMWHA was burnt more often than this (four fires 5%, five fires 1%, six fires 1%, seven fires 1%). The areas of more frequent fire are concentrated in Yengo and (eastern) Wollemi national parks – which have lower average annual rainfall and higher temperatures than other parts of the GBMWHA – and in the Grose Valley in Blue Mountains National Park. Many parts of the cool and moist south-west of the GBMWHA (Kanangra-Boyd National Park and Jenolan Karst Conservation Reserve) have not been burnt since 1970. The major fires of the summer of 1957-58 affected some parts of Kanangra-Boyd, however reliable spatial information for these fires is not available.

Biodiversity Fire Threshold Analysis

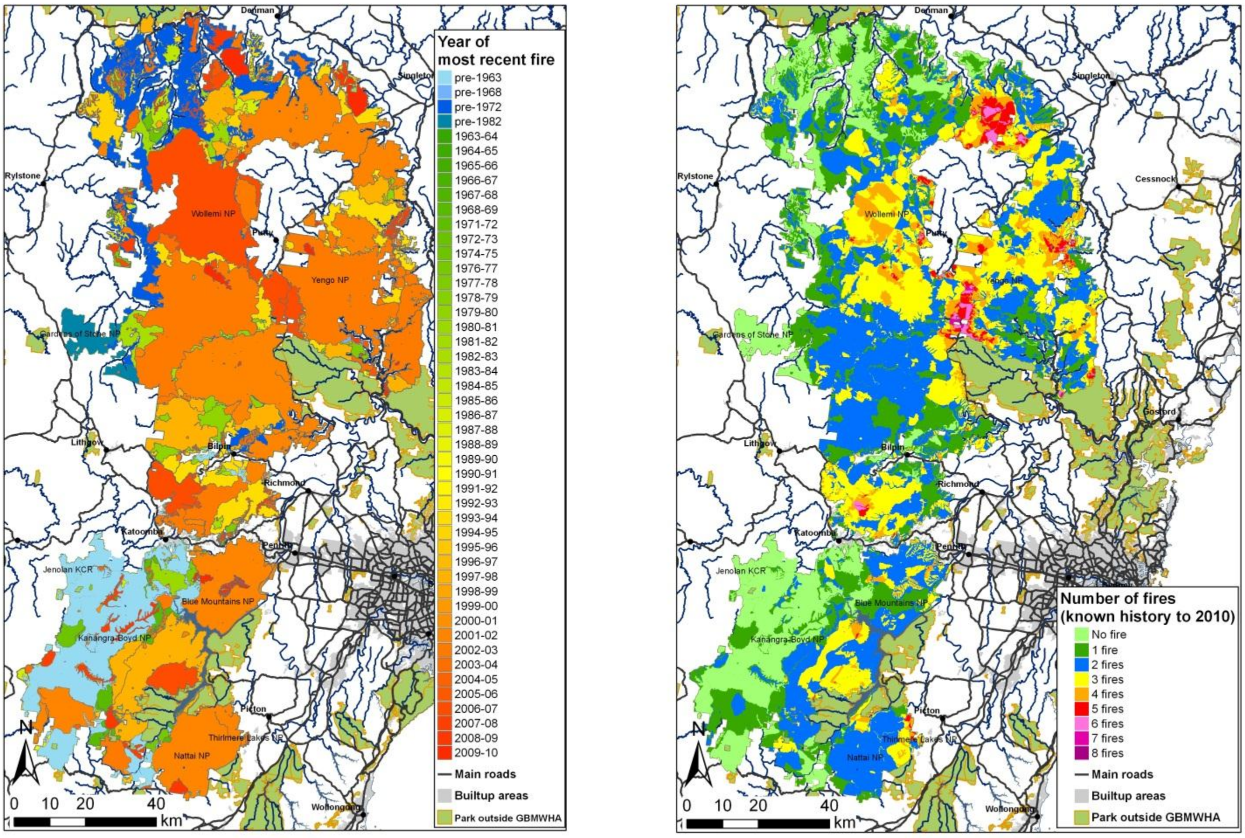
Broad-scale fire management for the conservation of native vegetation in New South Wales makes use of the concept of 'thresholds of potential concern' (*sensu* van Wilgen and Scott 2001). These are defined as the minimum and maximum intervals between fires predicted to maintain floristic diversity (Noble and Slatyer 1980; Kenny *et al.* 2004), and are based on known plant species responses to fire. Different intervals are defined for each of the twelve broad vegetation formations in New South Wales (Keith 2004), based on analysis of their component plant species, as recorded in the New South Wales Flora Fire Response Database (OEH 2010). The database currently includes information for 3088 species, including type of response to fire (e.g. seeder or resprouter), method of persistence at a site (e.g. soil seedbank), primary juvenile period (i.e. number of years from germination to first flowering), maximum lifespan (of individual plants) and longevity of the seed-bank.

The *minimum* interval threshold (for any given vegetation formation) is determined by the slowest-maturing species in that formation that is killed by fire and depends on seed to regenerate. This is the longest time to maturity of species sensitive to frequent fire. The *maximum* interval is determined by the shortest-lived of the species in that formation that needs fire to germinate, flower or release seed. This is the shortest time to extinction for species sensitive to infrequent fire.

These fire biodiversity guidelines are used in New South Wales for planning and management of all fire-prone national parks, as well as outside national parks in areas of native vegetation to which the Bush Fire Environmental Assessment Code (RFS 2006) applies, in accordance with the *Rural Fires Act 1997*.

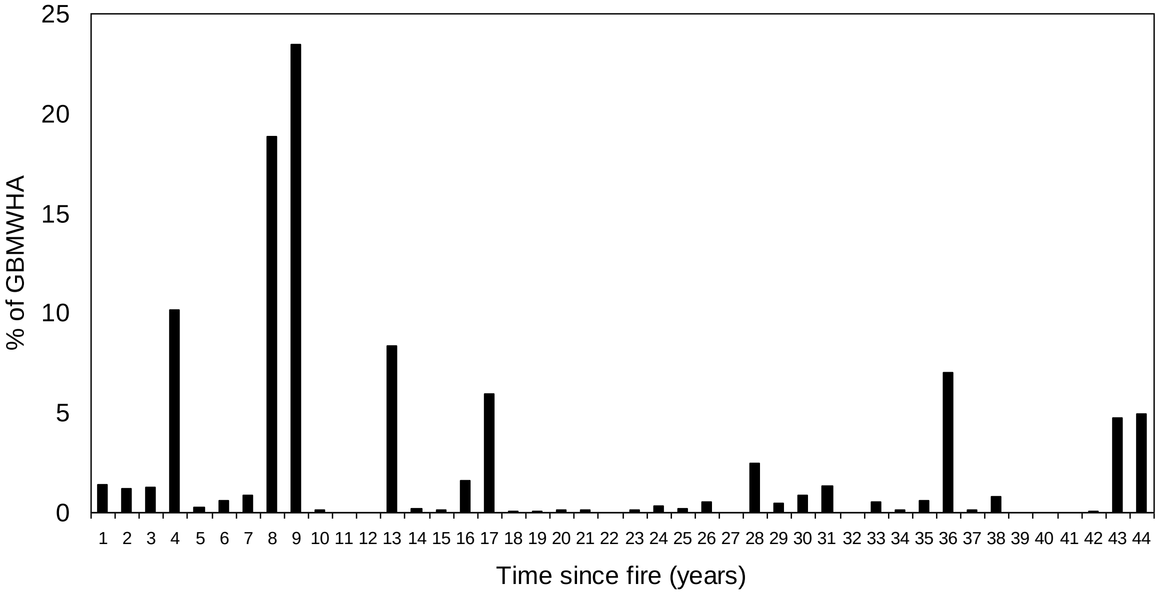
Fig 1: (a) Time of last fire, and (b) number of fires, for the Greater Blue Mountains World Heritage Area for the period of available fire history to 2010. Note that only fires within the GBMWHA reserves are shown and the length of fire history varies for the different

(a) (b)



reserves (see text).

Fig 2: Proportions of the Greater Blue Mountains World Heritage Area in each time–since–fire category, as at 2010.



To apply the thresholds, we used the following method. Fire perimeter maps were combined with a digital vegetation map using geographic information system software *ArcGIS* (v. 9.3, ©ESRI 2008). The fire maps were used to derive fire frequency and fire interval data and the vegetation map was re-classified at the broad level of formation (e.g. rainforest, heathland; Keith 2004). Combinations of fire and vegetation were analysed using a customised spatial analysis tool *Fire Tools* (OEH 2011) that runs within the ArcGIS platform. This compares the actual fire frequencies and sequences of inter-fire-intervals with the suggested minimum and maximum thresholds for each vegetation formation (Table 1), producing an output map with areas assigned to a series of fire-biodiversity frequency categories. These are: 'too frequently burnt' (inter-fire-intervals shorter than recommended), 'within threshold'; 'vulnerable to frequent fire' (areas that are 'within threshold' but recently burnt, and which if burnt again in the near future would become 'too frequently burnt'); 'long unburnt' (inter-fire-intervals longer than recommended); and 'unknown' (areas where there is insufficient fire history available to assess the status of the vegetation).

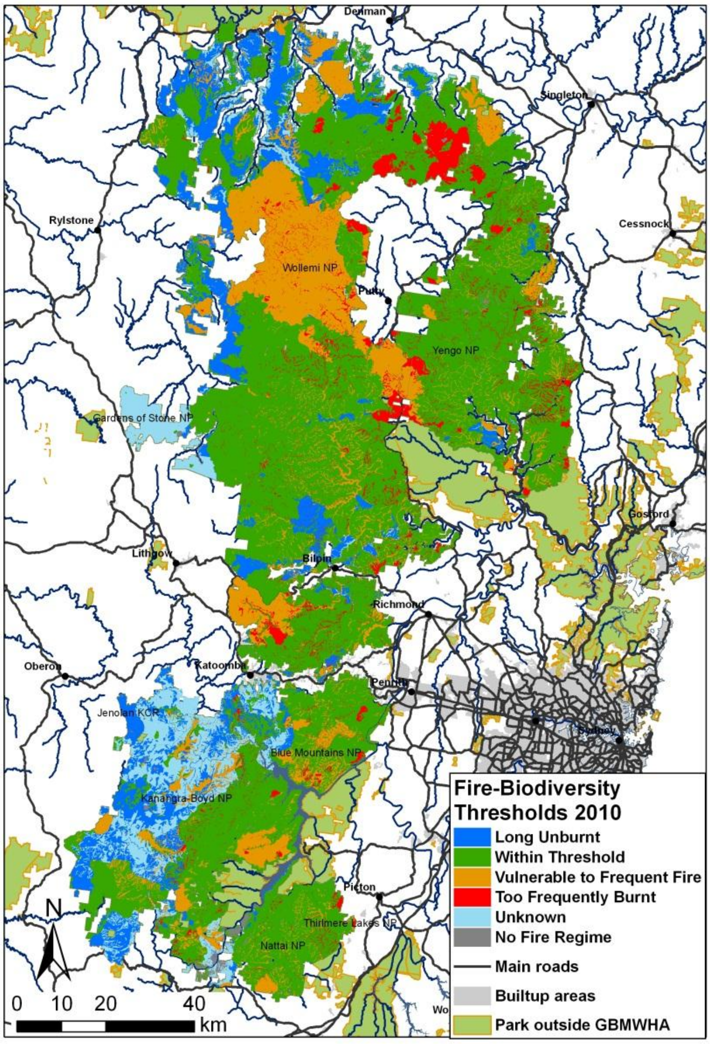
Table 4. The fire-biodiversity guidelines for New South Wales (Kenny *et al.* 2004).

Vegetation formation (Keith 2004)	Minimum interval	Maximum interval
Rainforests	Fire should be avoided	
Alpine Complex	Fire should be avoided	
Saline Wetlands	Fire should be avoided	
Wet Sclerophyll Forests (shrubby subformation)	25	60
Wet Sclerophyll Forests (grassy subformation)	10	50
Forested Wetlands	7	35
Grassy Woodlands	5	40
Dry Sclerophyll Forests (shrub/grass subformation)	5	50
Dry Sclerophyll Forests (shrubby subformation)	7	30
Semi-arid Woodlands	6	40
Semi-arid Shrublands	6	40
Heathlands	7	30
Grasslands	2	10
Freshwater Wetlands	6	35

The analysis revealed that the majority of the landscape (74%) is currently within the suggested thresholds (i.e. ’within threshold‘ or ’vulnerable to frequent fire‘), while 12% is ‘long unburnt’, 5% is considered ‘too frequently burnt’ and a further 8% is ‘unknown’ (Fig 3). The ‘too frequently burnt’ category coincides with areas burnt by five or more fires since the 1960s or with vegetation for which any fire is considered ‘too frequent’ (i.e. rainforest) or with vegetation for which the suggested minimum interval is very long (i.e. wet sclerophyll forests; see Table 1). ‘Too frequently burnt’ areas are of particular concern because of the potential for loss of floristic diversity and/or changes in vegetation structure. Some of the areas in this category identified by this study have been targeted for field-based surveys as part of ongoing work (not reported here).

The suggested fire-biodiversity intervals are based on the principle of maintaining floristic diversity by minimising plant species extinctions in the long-term. While there are other important components of biodiversity, such as vegetation structure and faunal diversity, these are not explicitly considered in the current thresholds. Application of the thresholds also does not currently take into account fire season, patchiness or severity, all of which modulate the impacts. The levels of existing mapping and analysis to date have not allowed this to be done, however the current work and other ongoing projects will make this possible in the future.

Fig 3: Current status of fire-biodiversity thresholds for the Greater Blue Mountains World Heritage Area.



Fire Severity Mapping

Fire intensity (the amount of heat energy released by a fire) is one of the key attributes of fire regimes (Gill 1981) and is an important determinant of the impacts of fire, for biodiversity, human life and property. For example, high intensity fires are associated with a higher loss of biomass and slower subsequent fuel accumulation, changes in soil properties including deterioration of soil structure and porosity, increased propensity for post-fire erosion (Doerr *et al*. 2006) and increased loss of soil organic matter and nutrients (Certini 2005). High intensity fires are also associated with greater mortality of some plants and animals (e.g. Vivian et al. 2008; Newsome *et al*. 1975), but increased germination of many plants (e.g. numerous hard-seeded *Acacia* species and others in the Fabaceae family; Auld & O'Connell 1991). Trees can be lost through collapse after severe fires but there can also be increased production of hollows in remaining trees (Collins *et al*. submitted a, b).

Fire intensity is difficult to measure during large bush fires, however it is closely correlated with fire severity (the degree of loss or change in organic matter above- and below-ground; Keeley 2009). Remote sensing offers the opportunity to detect and map the latter following a fire and can be used to retrospectively infer the intensity of the fire.

Prior to this study fire severity maps were available only for one season (2001-02) and for only some of the parts of the GBMWHA (Hammill & Bradstock 2006; Bradstock *et al.* 2010). We prepared new fire severity maps to increase the coverage of the 2001-02 season and to cover the other major fire seasons (2006-07, 2002-03, 1997-98 and 1993-94) using the following approach.

We obtained post-fire satellite imagery, captured as soon as possible after the dates on which the fires of interest were out. Both Landsat and SPOT (Satellite Pour l'Observation de la Terre) imagery are suitable for fire severity mapping in south-eastern Australian landscapes, but for reasons of availability and cost (see below) we predominantly used Landsat. Wherever possible we also obtained pre-fire imagery of the area, captured as close in time before the fires as possible.

We used *ERDAS Imagine* (© 2009 ERDAS, Inc.) image processing software and *ArcGIS* to map the pixel values of the ratio between light wavelengths that show "greenness" (see example in. Fig 4). Two different ratios were commonly used (depending on suitability), the Normalised Difference Vegetation Index (NDVI) and the Normalised Burn Ratio (NBR). NDVI is the ratio of the visible red to near infra-red wavelength bands and is available for both Landsat and SPOT imagery. NBR is the ratio of the near infra-red to far infra-red bands and is only available for Landsat images. If paired pre- and post-fire images were available, then the difference in greenness before and after the fire was mapped (i.e. dNDVI or dNBR).

We used field-based assessments and post-fire photographs (where available) of fire severity to validate the remote sensing data. The degree of vegetation scorch and consumption of the canopy, understorey and ground-layer was identified as well as possible at numerous replicate sites (in different vegetation types and severity categories) at geo-referenced point localities. Field-based assessments were not possible for the earlier fires, and in such cases the fire severity was estimated from historic aerial or ground-based photos taken shortly after the fire. The site assessments of severity were matched against the pixel value for each point location and used to determine the range of values representing different categories of fire severity, namely: 'low' (understorey scorched, canopy unburnt), 'high' (all or most vegetation scorched) and 'extreme' (all or most vegetation consumed; Hammill *et al.* 2010). Once the thresholds in pixel values were determined, the fire severity maps were generated using a tailored image classification decision tree (Fig 5).

Because of the limited availability of satellite imagery for some of the fire seasons, and the impossibility of carrying out detailed field-based assessments of fire severity for the older fires, a range of methods were used to prepare the fire severity maps (Table 2). While an image differencing approach (i.e. a pre/post-fire comparison) is the most widely-used method for fire severity mapping (Brewer *et al.* 2005; Lentile *et al.* 2006) and is generally accepted as the best method, single-image fire severity mapping is also common when the alternative is not feasible (e.g. Koutsias & Karteris 2000; Brewer *et al.* 2005).

Fig 4: Map and cross-section of pixel values of the Normalised Difference Vegetation Index for the 2006-07 Lawsons Long Alley Fire in the upper Blue Mountains and Grose Valley. The dark area in the image (at left) indicates the fire area. The histogram of pixel values (at right) shows the NDVI values along the cross-section across the fire area (see vertical line in the image at left)— the highest NDVI values indicate unburnt areas; lower NDVI values indicate higher severity).

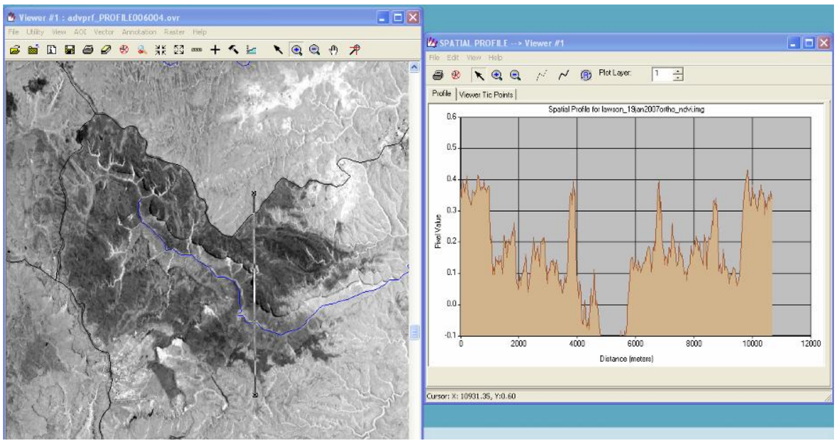


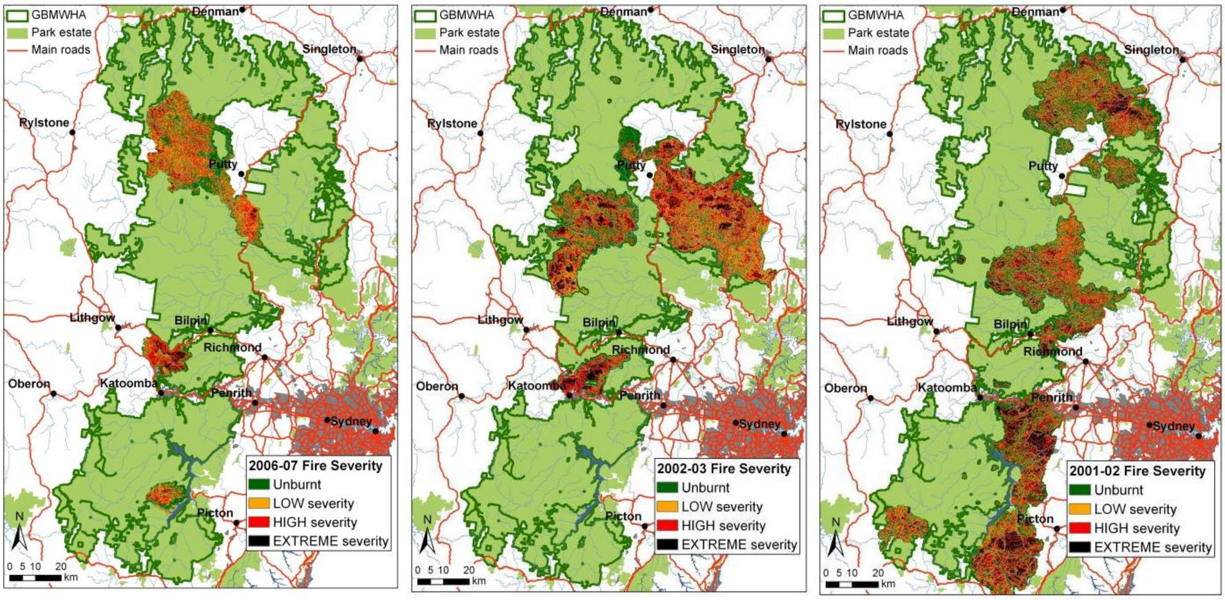
Table 2: Methods used to map fire severity for the major bush fire seasons since 1990.

	2006-07	2002-03	2001-02	1997-98	1993-94
Landsat 7 (NDVI or NBR)	Y (part)	NBR	NDVI	Y	Y
SPOT 2 (NDVI)	Y (part)				
Pre-/post-comparison		Y	Y		
Single post-fire image	Y			Y	Y
Validation data	Photos	Field	Field	Photos	Photos

The resulting fire severity maps show that even during the biggest of fires, a range of fire severities occur. More detailed analysis of the patterns and how they relate to weather at the time of the fire, topography and vegetation (Hammill & Bradstock 2006; Bradstock *et al.* 2010) reveal that weather can be the over-riding influence on severity in these landscapes, with topography and vegetation playing lesser roles and almost none on extreme fire weather days. While such detailed analyses have been completed on only a subset of fires from the 2001-02 season, using the new information produced by our current study, such analyses could now be extended to different fire seasons, and more broadly across the GBMWHA.

Both Landsat and SPOT have advantages and disadvantages (Table 3). While Landsat images are coarser resolution and are captured less frequently, they cover a bigger area (Fig 6), are less expensive, are available retrospectively and have wavelengths that enable them to penetrate light smoke. We found that Landsat images (including Landsat 5) are highly useful. Based on our analyses, we also confirm that the image-differencing approach is preferable since it is less sensitive to vegetation type and date of image capture. Nevertheless, if only a single post-fire image is available, a reasonable fire severity map can still be prepared if a vegetation map is available and particular effort is made to incorporate vegetation effects into the severity mapping. This is because there are strong differences in reflectance resulting from contrasting vegetation types (i.e. swamps and moist forests have inherently higher NDVI than dry heaths and woodlands). These difference need to be distinguished from differences due to fire severity.

Fig 5: Fire severity maps produced in this study for the five major bush fire seasons since 1990.



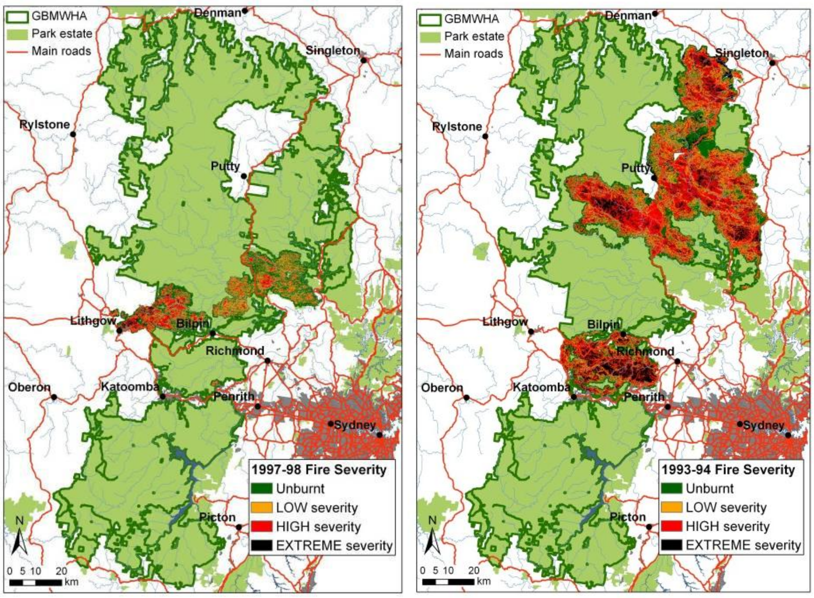
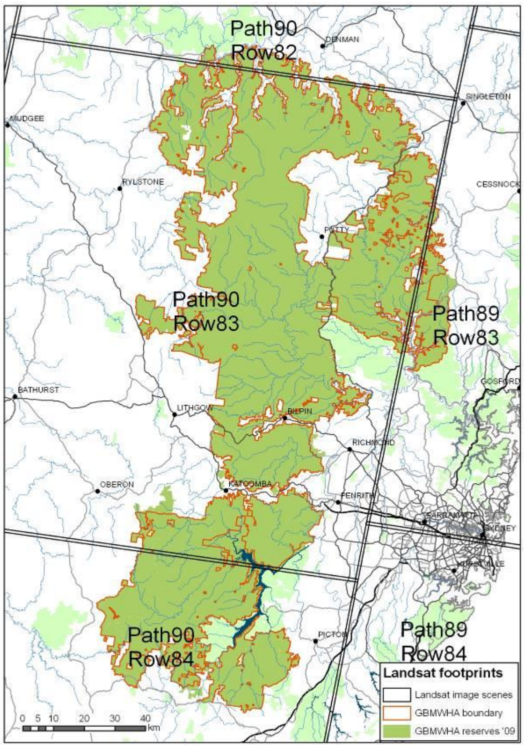


Table 3: Advantages and disadvantages of Landsat 7 versus SPOT 2.

LANDSAT	**SPOT**
NDVI and NBR	NDVI
Cheaper (~$1,700 per image)	More expensive ($2,500+ per image)
Available retrospectively	Imagery not archived
185 x 185 km scenes	60 x 60 km scenes
Multiple infra-red bands penetrate smoke	Cannot penetrate smoke
Lower resolution (30m)	Better resolution (10m)
Less frequent (16 days)	More frequent capture (2-3 days)
Images captured in eastern Australia midday so terrain shadows less	Images captured in eastern Australia approx 10am so greater terrain shadows



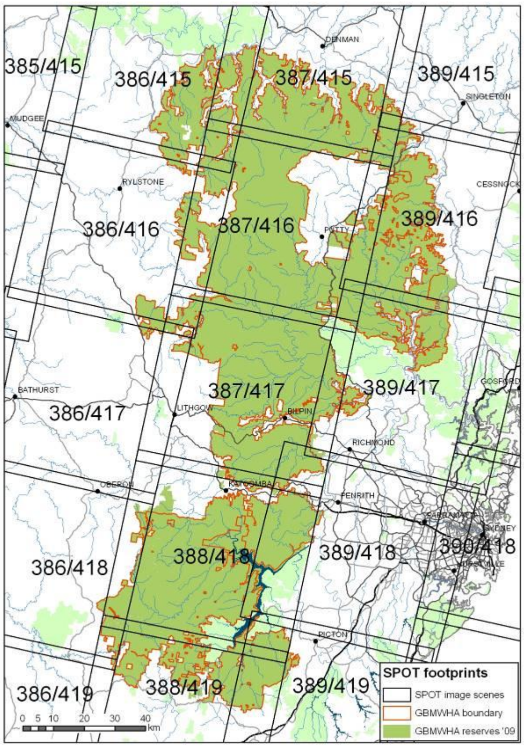


Fig 6: Comparison of image extent and coverage for Landsat and SPOT of the Greater Blue Mountains World Heritage Area.

Conclusions

As an increasing range of satellites become available over the next few years with a greater range of band widths and higher spatial and temporal coverage, the exact choice of satellite may not be the same as used here. However we suggest that as a general principal, a pre-/post-fire image comparison will remain more accurate for fire severity mapping. A single post-fire image supplemented by a vegetation map can produce acceptable results if the alternative is not feasible.

Keeping good fire history information is fundamental to be able to detect changes in fire regimes over time, predict patterns of fire occurrence and plan where to target fuel reduction activities. It is also fundamental for the study of fuel patterns, fire behaviour, impacts of fires on biodiversity, vegetation, erosion, soil nutrients and soil carbon.

The detailed fire history compiled in this study is already being used as a substantial input to a number of research projects. These include modelling of fuel accumulation rates and soil carbon, and testing impacts of repeated high-intensity and low-intensity fires on plant diversity and faunal habitat values. The fire history for the GBMWHA compiled in this study is one of the most comprehensive currently available in Australia, and provides invaluable baseline data against which to monitor future change in fire regimes.

References

Auld T. D. and O'Connell M. A. (1991). Predicting patterns of post-fire germination in 35 eastern Australian Fabaceae. Australian Journal of Ecology **16**(1): 53-70.

Bowman D. M. J. S., Harris S. (1995) Conifers of Australia’s dry forests and open woodlands. In ‘Ecology of the Southern Conifers’. (Eds NJ Enright, RS Hill) pp. 252–270. (Melbourne University Press: Melbourne)

Bradstock R. A., Davies I. D, Price O. and Cary G. J. (2008). Effects of climate change on bush fire threats to biodiversity, ecosystem processes and people in the Sydney region. Sydney, NSW, NSW DECC.

Bradstock R., Hammill K., Collins L. and Price O. (2010). Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology **25**(4): 607-619.

Brewer C. K., Winne J. C., Redmond R. L., Opitz D. W. and Mangrich M. V. (2005). Classifying and Mapping Wildfire Severity: A Comparison of Methods. Photogrammetric engineering and remote sensing **71**(11): 1311-1320.

Certini G. (2005). Effects of fire on properties of forest soils: a review. Oecologia **143**(1): 1-10.

Clarke H. G., Smith P. L. and Pitman A. J. (2011). Regional signatures of future fire weather over eastern Australia from global climate models. International Journal of Wildland Fire **20**(4): 550-562.

Collins L., Bradstock R. A., Tasker E. M. & Whelan R. J. (submitted, a). Impact of fire regimes, logging and topography on the presence, abundance and size of hollows in fallen logs in eucalypt forest in south eastern Australia. Biological Conservation

Collins L., Bradstock R. A., Tasker E. M. & Whelan R. J. (submitted, b). Can gullies mitigate the effect of frequent fire on forest structure? A case study examining hollow-bearing trees, fallen logs and vegetation complexity. Biological Conservation

Cunningham C. J. (1984). Recurring natural fire hazards : a case study of the Blue Mountains, New South Wales, Australia. Applied Geography **4**(1): 5-27.

Doerr S. H., Shakesby R.A., Blake W.H., Chafer C.J., Humphreys G. S. and Wallbrink P.J. (2006). Effects of differing wildfire severities on soil wettability and implications for hydrological responses. Journal of Hydrology **319**:295–311

Gill A. M. (1981). Adaptive responses of Australian vascular plant species to fires. Fire and the Australian biota. A. M. Gill, R. H. Groves and I. R. Noble. Canberra, Australian Academy of Science**:** 243-272.

Gill A. M. and Bradstock R. A. (1992). A national register for the fire responses of plant species. Cunninghamia **2**(4): 653-660.

Hammill K. A. and Bradstock R. A. (2006). Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity. International Journal of Wildland Fire **15**: 213–226.

Hammill K. A., Tasker E. M. and Reid J. (2010) Monitoring Fire Regimes and Biodiversity in the Greater Blue Mountains World Heritage Area. Final Report on Caring for Our Country (TAFA) 2008-2009 Project 5, NSW Department of Environment, Climate Change & Water, Sydney.

Hennessy K., Lucas C., Nicholls N., Bathols J., Suppiah R. and Ricketts J. (2006). Climate change impacts on fire-weather in south-east Australia. Marine and Atmospheric Research, CSIRO Australia.

Keeley J. E. (2009). Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire **18**(1): 116-126.

Keith D. A. (2004). Ocean shores to desert dunes: the native vegetation of New South Wales and the ACT. NSW Department of Environment and Conservation, Hurstville, NSW.

Kenny B., Sutherland E., Tasker E. and Bradstock R. A. (2004). Guidelines for ecologically sustainable fire management. NSW National Parks & Wildlife Service, Hurstville.

Koutsias N. and Karteris M. (2000). Burned area mapping using logistic regression modeling of a single post-fire Landsat-5 Thematic Mapper image. International Journal of Remote Sensing **21**: 673-687.

Lentile L. B., Holden Z. A., Smith A. M. S., Falkowski M. J., Hudak A. T., Morgan P., Lewis S. A., Gessler P. E. and Benson N. C. (2006). Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire **15**(3): 319-345.

NPWS and Environment Australia (1998). The Greater Blue Mountains Area, World Heritage Nomination. New South Wales National Parks & Wildlife Service, Hurstville.

Newsome A. E., McIlroy J. and Catling P. (1975). The effects of an extensive wildfire on populations of twenty ground vertebrates in south-east Australia. Proceedings of the Ecological Society of Australia **9**: 107-123.

Noble I. R and Slatyer R. O. (1980). The use of vital attributes to predict successional changes in plant communities to recurrent disturbances. Vegetatio **43**: 2-21.

OEH (2010). New South Wales Flora Fire Response Database. Unpublished data of the Office of Environment and Heritage (available on request), Hurstville.

OEH (2011). Fire Tools. Unpublished technical note of the Office of Environment and Heritage, Hurstville.

RFS (2006). Bush Fire Environmental Assessment Code for New South Wales. NSW Rural Fire Service.

van Wilgen B. W. and Scott D. F. (2001). Managing fires on the Cape Peninsula, South Africa: dealing with the inevitable. Journal of Mediterranean Ecology **2**: 197-208.

Vivian L., Cary G., Bradstock R. and Gill A. M. (2008). Influence of fire severity on the regeneration, recruitment and distribution of eucalypts in the Cotter River Catchment, Australian Capital Territory. Austral Ecology **33**: 55-67.

Design of a valid simulation for researching physical, physiological and cognitive performance in volunteer firefighters during bushfire deployment.

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Abstract.

Every year, Australian firefighters protect our nation from the devastation of bushfire. Understanding the impact of consecutive long shifts in hot, smoky conditions is essential for making decisions during campaign fires. At present, the evidence-base for such decisions is limited to laboratory studies with little relevance to bushfire suppression or field research where the impact of environmental and workload stressors cannot be measured. To counter these limitations, we have developed a three-day simulation that mimics the work and environment of campaign bushfire suppression. Construction of the simulation involved three stages; 1) data collection and analysis; 2) design and development; and 3) trial and refinement. The frequency, intensity, duration and type of physical work performed on the fireground is well documented and a modified applied cognitive task analysis, using experienced firefighters was used as a framework to describe in detail the non-physical aspects of the work. The design and development of the simulation incorporated the physical and non-physical aspects of the work into simulated tasks. Finally, experienced firefighters participated in trials of the simulation and reviewed digital recordings to ensure that the simulation accurately represented campaign bushfire suppression work. The outcome of this project is a valid, realistic, and reliable simulation of the physiological, physical and cognitive aspects of a volunteer firefighter on a three-day bushfire deployment.

Introduction

Every year, Australian firefighters protect our nation from the devastation of bushfire. The risks to firefighter health and safety are significant and need to be managed using an evidence-based risk management framework, as is the norm in all Australian workplaces (NOHSC 2002). One of the steps in this process is to identify the risks in order that they be assessed and managed. For individuals fighting campaign fires in particular, the risks extend beyond the obvious ones associated with the fire itself (e.g. burnover, radiant heat). Impaired performance as a result of cognitive fatigue, physical exhaustion or physiological strain can lead to errors in judgement, poor decision-making, diminished levels of work performance and deviations from standard operating practices (Belenky, Wesesten *et al.* 2003; Hancock, Ross *et al.* 2007; Harrison and Horne 2000; Takeyama, Itani *et al.* 2005). Occupational challenges such as consecutive long shifts that require extended wake and restrict sleep represent one risk (Aisbett and Nichols 2007; Cater, Clancy *et al.* 2007). Further, environmental challenges such as extreme heat and smoke exposure are also known to impact cognitive, physical and physiological performance (Amitai, Zlotogorski *et al.* 1998; Benignus, Muller *et al.* 1987; Nybo 2008; Walter, Ackland *et al.* 2001). Understanding the individual and interactive effects of these occupational and environmental challenges is essential for making decisions about manning, scheduling, workload and work tasks during campaign fires that manage extant risks. At present however, the evidence-base for such decisions is limited to laboratory studies with little relevance to bushfire suppression and to observational field research. While some aspects of the bushfire suppression task are well described by field studies, it is very difficult to assess the individual and interactive effects of occupational and environmental challenges on performance in any systematic manner.

To provide an evidence base, a large-scale program of work was designed to assess the effects of sleep restriction, smoke and heat on various aspects of firefighter performance. In order that the research is conducted in a controlled and replicable environment for all participants in each condition, a simulation was designed to assess the effects on physiological, physical and cognitive performance. Here we describe the stages in simulation development and the processes that were used for data collection, design/development and trial/refinement of the volunteer firefighter bushfire deployment simulator.

Stages of simulation development

A critical first stage was to construct a simulation that could create physical and cognitive workload comparable to real bushfire suppression work, whilst having a high level of realism (known as fidelity) for firefighters. At the same time, the research requires tightly controlled and repeatable conditions. Simulation in the research environment must therefore, achieve a balance between various dimensions of fidelity and the rigours of experimental control. This balance results in inevitable trade-offs, each of which must be carefully considered in order to maximise the overall value of the research process.

The design of the simulation must achieve an appropriate level of fidelity to ensure the research is successful, but does not require a completely faithful reproduction of the fire-ground. Research of this nature involves manipulation of certain variables (such as temperature), which are called the independent variables. At the same time other variables (such as light) must be controlled to ensure they are kept constant and do not influence the research in unanticipated or unmeasured ways - these are called confounding variables. The fire-ground is a highly dynamic environment in which a wide range of variables (e.g., heat, wind, noise, etc) is constantly changing. Thus, a truly high-fidelity simulation would be unable to provide sufficient experimental control to examine the effects of the key variables of sleep restriction, smoke and heat for our program of research. Accordingly, a simulated representation of key tasks and skills involved in safe and efficient fire-ground performance was designed, which balanced the need for fidelity in simulating the work of rural firefighters, but simultaneously allowed for effective measurement of key performance variables.

Construction of the simulation, assessment of fidelity issues, and ensuring appropriate research design involved three stages; 1) data collection and analysis; 2) design and development; and 3) trial and refinement.

Data collection and analysis.

Table 1 highlights dimensions of simulation fidelity derived from the extant literature (Hays 1980; Liu, Nikolas *et al.* 2008; Rehmann, Mitman *et al.* 1995; Stanton 1996) that are relevant to the current research design. Each of these dimensions was considered with respect to the design of the simulation.

The frequency, intensity, duration and type of physical work performed on the fireground is well documented; (Phillips, Netto *et al.* 2011)) and represents the first dimension of fidelity (Table 1). Specifically, seven physically demanding tasks were identified as common during bushfire suppression activities for all rural firefighters. Three of the tasks involved fire hoses (dragging hose to position, lateral repositioning of hose or returning hose to tanker) and four tasks involved the use of hand tools (e.g., digging and raking to build mineral earth fire breaks; (Phillips, Payne *et al.* 2011)) In addition to identifying the major tasks of tanker-based bushfire suppression crews, the researchers also determined the average time spent doing each task . The specific work tasks and the time spent engaged in each task were included in a simulation in a manner that mimicked the work done on the fireground. In particular, pilot testing of the physical test battery incorporated physiological measures collected on the fireground. Physiological parameters are used routinely to validate simulations and demonstrate high levels of fidelity (Lord, Netto *et al.* In Press).

Focus groups were conducted with experienced firefighters using the framework of an applied modified applied cognitive task analyses to define and dissect the non-physical aspects of the volunteer firefighter role (Militello and Hutton 1998). The process involved asking the firefighters to talk through the various aspects of their work, from the moment the initial page or phone call is received, through to the drive home after the completion of the shift or incident. Researchers asked participants to expand on specific aspects of task elements where necessary. For rural firefighters working on the ‘back of the truck’ undertaking fire suppression activities, a number of key cognitive elements were drawn from the analysis. Specifically, information retention from short-term memory was discussed in relation to the key details about the incident (time, place, event etc). Participants also identified communication and decision-making as cognitive elements of the work. Vigilance, concentration, and maintaining awareness of critical cues in the environment, while simultaneously focusing on the primary task were also identified as being key cognitive elements of the work. As outlined in Table 1, key dimensions of simulation fidelity are cognitive task representation and the degree of similarity between cognitive workload in the real task and the simulated task.

Another aspect of data collection relevant to the simulation design relates to the scheduling of volunteers for campaign fires (those extending beyond a single work period or shift). The most commonly used pattern of work for tanker-based crews on campaign fires involves 12-hour shifts, and generally up to three shifts in succession (Cater, Clancy *et al.* 2007). Firefighters travel to the incident as soon as they are required, and stay in the area for the length of their deployment. As fires frequently flare in the heat of the afternoon, volunteers who have worked during the day experience an extended period of wake (and work) on the first shift of fire suppression. Given the role of volunteers in fighting bushfires in Australia, this is a common and largely unavoidable circumstance and was therefore deemed important to incorporate into the simulation. Thus, key elements of scheduling that were included in the simulation were: 12-hour shifts, three consecutive shifts, ‘passive travel time’ to incident, extended wake/work period on first ‘shift’.

Environmental data related to smoke and heat have been studied in Australian rural firefighters during bushfires (Raines, Petersen *et al.* Accepted August 14 2011; Reisen and Brown 2009) and are both important to the simulation design. Ambient temperatures will be manipulated in the simulation to mimic the higher end of the range of temperatures experienced on the fireground (with lower but still relatively high temperatures during the night). Further, as previous research has shown that CO strongly correlates with other elements within bushfire smoke (e.g., particulate matter, formaldehyde, etc) (Reisen, Hansen *et al.* 2011), smoke will be simulated using CO in the air.

The simulation includes the requirement for participants to be dressed in their own personal protective clothing (PPC), as they would be on the fireground (Table 1). This includes trousers, coat, goggles, helmet, gloves and safety boots. Participants will wear full PPC during the completion of the physical task batteries and remove helmet, gloves, goggles and coat for physiological and cognitive testing. In addition, physical tasks will involve the use of couplings and dimensions of hose that are identical to those used in the field. Lengths of hose will also be filled to mimic the weight of charged (i.e., pressurized) water ensuring that the physical and functional characteristics of the equipment match the real world task (Table 1).

Each dimension of simulation fidelity relevant to the current simulation design required the collection or collation of data such that all elements were based bushfire suppression deployment tasks. Data on physical, physiological, cognitive, environmental and logistical elements of these tasks were then incorporated into the simulation design in such a way as to maximise fidelity and control relevant variables.

Design and Development

Design involves four major components:

Structure of whole ‘deployment’;

Structure of each day/night within the ‘deployment’ which includes scheduling of meals, breaks, toilet breaks, shower opportunities and bed times and wake times;

Structure of individual test sessions; and

Structure of days preceding and following the actual data collection period.

Each element is discussed below.

The length of the simulation was set at three days and three nights, based on existing scheduling information from observational studies in Australia (Cater, Clancy *et al.* 2007). Each day was designed to mimic a workday on the fireground – breakfast, work, lunch, work, dinner, preparation for bed, and sleep. The work periods were then divided into six two-hour blocks for physical tasks (55 minutes), physiological measurements (25 minutes) and cognitive testing (20 minutes). The remaining 20 minutes in each two-hour block was provided for hydration, toilet breaks and snacks. Confounding factors such as food and fluid intake will be recorded and included in analyses. The time allocated to physical and ‘non-physical’ data collection was based on the work patterns of Australian rural firefighters during emergency bushfire suppression shifts (Aisbett, Phillips *et al.* 2007) as described above.

The test batteries were designed to tap into key elements of the work as determined through the data collection phase. The time spent engaged in each physical task in the battery is representative of the time firefighters spend doing each task on the fireground. For example, lateral repositioning of hoses was done on average 103 times in each shift for a period of approximately twenty seconds each time (Phillips, Netto *et al.* 2011). The rakehoe task was performed on average 24 times for approximately 25 seconds each shift (Phillips, Netto *et al.* 2011). The distribution of each task in each test battery is thus indicative of the work done in the field.

The cognitive elements of the work are not as well defined as the physical elements. Further, based on the information provided by the subject matter experts, many of the cognitive aspects of the work occur simultaneously with physical tasks. In developing the cognitive test battery, the cognitive skills identified in the initial data collection from the subject matter experts were mapped onto components of a cognitive task battery that could be integrated into the simulation design. Accordingly, the cognitive task battery is composed of well-validated, neurocognitive tests that are known to tap into the critical cognitive functions identified in the data collection phase, despite the fact that they do not necessarily ‘look like’ firefighting. For instance, short-term memory is assessed by asking participants to recall pieces of information provided to them on a pager. This approach provides some face validity for the abstracted cognitive assessment task. Other cognitive skills identified by the subject matter experts such as vigilance, reaction time and hand-eye coordination are assessed using tools that have been validated for use in laboratory and field settings (Dinges and Powell 1985; Lamond, Dawson *et al.* 2005).

In addition to the days of testing that occur during the three-day simulation, activities prior and following the deployment are important for the research and are therefore included in the simulation. Participants arrive on-site the evening prior to day 1 and sleep with recording electrodes affixed to their head and face. The adaptation night is important in ensuring the participants' first night of sleep is not compromised by the lack of familiarity with the equipment. Further, sleep/wake patterns during the three days prior to the study will be collected to account for any sleep restriction on entering the study. A pre-briefing will be conducted prior to the 'deployment' to ensure participants are fully prepared and informed. Post-deployment interviews will allow participants to provide feedback for future refinements or improvements to the processes.

Following design and development of the simulation, trial and refinement were conducted.

Trial and refinement

Trial and refinement of the simulated bushfire suppression deployment is ongoing. To date the steps have included:

reliability testing of physical work battery

trial runs of test batteries with non-firefighters both off-site and on-site

trial run with firefighters across two-days on-site, including aspects of the simulation such as test batteries, meals, sleep recording and simulation debrief

videos of all trials reviewed by subject matter experts at various forum

a full simulated deployment with five participants on-site for four days

Refinements of the simulation were based on recommendations from participants and other subject-matter experts at each step of the trial and refinement stage. The final step will involve a fidelity evaluation exercise with subject matter experts in the fields of volunteer firefighting (bushfire suppression), cognitive psychology, human factors, exercise science and human physiology. Results of the fidelity evaluation will be reported elsewhere.

Summary.

The development of the volunteer firefighter bushfire deployment simulator involved three stages - data collection, design and development, and trial/refinement. The outcome is a valid, realistic, and reliable simulation that will produce meaningful research outcomes for the current program of work but may also be extended to use answer future questions about team-work, recovery from deployments and alternative work practices such as split shifts. The bushfire deployment simulator may also be adapted for use in training or testing protocols.

Table 1 – Dimensions, constructs and definitions of simulation fidelity. Compiled from (Hays 1980; Stanton 1996)

Dimension	Constructs	Definition
Physical/Behavioural	Task Realism	*How well the simulated task matches the real work-task.*
	Physical Workload	*The degree of similarity between workload experienced in the real and simulated tasks.*
Psychological	Perceived Realism/Perceptual	*The degree to which the simulation is perceived by participants as being a duplicate of the real world.*
	Cognitive Task Representation	*How well the simulated tasks match the types of cognitive activities during real work.*
	Cognitive Workload	*The degree of similarity between workload experienced in the real and simulated tasks.*
Environmental	Temperature	*The degree of similarity between temperature ranges during the real and simulated tasks.*
	Light	*The degree of similarity between light ranges during the real and simulated tasks.*
	Noise	*The degree of similarity between noise ranges during the real and simulated tasks.*
	Additional Stressors	*The inclusion of additional work stressors present in the real working environment.*
Equipment	Physical	*The degree to which the physical characteristics of the equipment used matches that used in the real world task.*
	Functional	*The degree to which the equipment works in the same way to that used in the real world task.*

References

Aisbett B, Nichols D (2007) Fighting fatigue whilst fighting bushfire - an overview of factors contributing to firefighter fatigue during bushfire suppression. *Australian Journal of Emergency Management* **22**, 31-39.

Aisbett B, Phillips M, Raines J, Nichols D (2007) Work patterns of tanker-based bushfire suppression by Australian volunteer firefighters in south-east Australia. . In 'Human Dimensions of Wildfire Conference'. (Fort Collins, Colorado)

Amitai Y, Zlotogorski Z, Golan-Katzav V, Wexler A, Gross D (1998) Neuropsychological impairment from acute low-level exposure to carbon monoxide. *Archives of Neurology* **55**, 845-848.

Belenky G, Wesesten NJ, Thorne DR, Thomas ML, Sing H, Redmond DP, Russo MB, Balkin TJ (2003) Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. *Journal of Sleep Research* **12**, 1-12.

Benignus V, Muller K, Barton C, Prah J (1987) Effect of low level carbon monoxide on compensatory tracking adn event monitoring. *Neurotoxicology and Teratology* **9**, 227-234.

Cater H, Clancy D, Duffy K, Holgate A, Wilson B, Wood J (2007) Fatigue on the fireground: The DPI experience. In 'Australasian Fire Authorities Council/Bushfire Co-operative Research Centre Annual Conference'. Hobart Grand Chancellor. (Ed. R Thornton)

Dinges DF, Powell JW (1985) Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments and Computers* **17**, 652-655.

Hancock P, Ross J, Szalma J (2007) A meta-analysis of performance response under thermal stressors. *Human Factors* **49**, 851-877.

Harrison Y, Horne JA (2000) The impact of sleep deprivation on decision making: a review. *Journal of Experimental Psychology* **6**, 236-249.

Hays RT (1980) 'Simulator Fidelity: A Concept Paper.' U.S. Army Research Institute for the Behavioral and Social Sciences, Technical Report 490, Alexandria, VA.

Lamond N, Dawson D, Roach GD (2005) Fatigue assessment in the field: validation of a hand-held electronic psychomotor vigilance task. *Aviation Space and Environmental Medicine* **76**, 486-489.

Liu D, Nikolas M, Dennis V (2008) Simulation Fidelity. In 'Human Factors in Simulation and Training' pp. 61-73. (CRC Press)

Lord C, Netto K, Petersen A, Nichols D, Drain J, Phillips M, Aisbett B (In Press) Validating 'fit for duty' test for Australian volunteer fire fighters suppressing bushfires. *Applied Ergonomics*.

Militello LG, Hutton RJB (1998) Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands. *Ergonomics* **41**, 1618-1641.

NOHSC (2002) 'National OHS Strategy 2002-2012.' National Occupational Health and Safety Council, Commonwealth of Australia, Canberra.

Nybo L (2008) Hyperthermia and fatigue. *Journal of Applied Physiology* **104**, 871-878.

Phillips M, Netto K, Payne W, Nichols D, Lord C, Brooksbank N, Onus K, Jeffries S, Aisbett B (2011) The frequency, intensity, speed and duration of tasks performed by Australian rural firefighters during bushfire suppression. In 'Australasian Fire Authorities/Bushfire Co-operative Research Centre Annual Conference Science Day Proceedings.'. Sydney Australia

Phillips M, Payne W, Lord C, Netto K, Nichols D, Aisbett B (2011) Identification of physically demanding tasks performed during bushfire suppression by Australian rural firefighters. *Applied Ergonomics* **doi:10.1016/j.apergo.2011.06.018**.

Raines J, Petersen A, Nichols D, Snow R, Aisbett B (Accepted August 14 2011) Pre-shift fluid intake: effect on physiology, work and drinking during emergency wildfire fighting. Applied Ergonomics.

Rehmann AJ, Mitman RD, Reynolds MC (1995) 'A Handbook of Flight Simulation Fidelity Requirements for Human Factors Research.' Crew System Ergonomics Information Analysis Center (CSERIAC), DOT/FAA/CT-TN95/46, Wright-Patterson AFB, OH.

Reisen F, Brown S (2009) Australian frefighters' exposure to air toxics during bushfire burns of Autumn 2005 and 2006. Environment International 35, 342-352.

Reisen F, Hansen D, Meyer C (2011) Exposure to bushfire smoke during prescribed burns and wildfires: Forefighters' exposure risks and options. Environment International 37, 314-321.

Stanton NA (1996) Simulators: a review of research and practice. In 'Human Factors in nuclear safety'. (Ed. NA Stanton) pp. 114-137. (Taylor and Francis: London)

Takeyama H, Itani T, Tachi N, Sakamura O, Murata K, Inoue T, Takanishi T, Suzumura H, Niwa S (2005) Effects of shift schedules on fatigue and physiological functions among firefighters during night duty. *Ergonomics* **48**, 1-11.

Walter S, Ackland T, Dawson B (2001) The combined effect of heat and carbon monoxide on the performance of motorsport athletes. *Comparative Biochemistry and Physiology - Part A: Molecular and Integrative Physiology* **128**, 709-718.

Frequency, intensity and duration of physical tasks performed by Australian rural firefighters during bushfire suppression

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ABSTRACT

The current study combined, for the first time, video footage of individual firefighters wearing heart rate monitors and personal GPS units to quantify the frequency, duration and intensity of tasks performed by Australian rural fire crews when suppressing bushfires. Across the four fireground 'shifts', the firefighters performed 34 distinct fireground tasks. Per shift, the task frequency ranged from once (raking fireline in teams, carrying a quick fill pump) to 103 times (lateral repositioning of a 38-mm charged firehose). The tasks lasted between 4 ± 2 s (bowling out 38-mm firehose) and 461 ± 387 s (raking fireline in teams). The task intensity, as measured by average heart rate ranged between 97 ± 16 beats·min^{-1} (55.7 ± 8.7 %HR$_{max}$) and 157 ± 15 beats·min^{-1} (86.2 ± 10.8 %HR$_{max}$). The tasks were performed a speeds that ranged from 0.12 ± 0.08 m·s^{-1} (manual hose retraction of 38-mm charged firehose) to 0.79 ± 0.40 m·s^{-1} (carrying a 38-mm coiled hose). Tasks found to be simultaneously frequent, long and intense (or two of these three) are likely to form the basis for job-specific testing of Australian rural firefighters suppressing bushfires.

Introduction

Several approaches have been utilised to capture firefighter's task demands including; subjective job task analyses (Gledhill and Jamnik 1992b; Phillips *et al. in press*), physiological and biomechanical analysis of isolated tasks (Gledhill and Jamnik 1992a; Brotherhood *et al.* 1997; Bilzon *et al.* 2001; Gregory *et al.* 2008), time and motion analysis of simulated bushfire suppression (Budd *et al.* 1997b) and urban emergency (Bos *et al.* 2004),and remote monitoring of heart rate or energy expenditure during emergency fire shifts in the United States of America (US) (Ruby *et al.* 2002; Ruby *et al.* 2003; Cuddy *et al.* 2007) and Spain (Rodríguez-Marroyo *et al.* 2011). Limitations of these approaches include; the highly variable recall of task frequency and duration by subject matter experts (SMEs; Morgeson and Campion 1997; Lindell *et al.* 1998), work intensity measures during isolated task simulations that do not provide insight into the frequency with which a task occurs, or the duration of successive task repetitions on shift and lastly, whole shift measures of energy expenditure (Heil 2002) or heart rate (Rodríguez-Marroyo *et al.* 2011) that are unable to isolate task demands specifically.

Three studies have used direct observation to characterise the inherent requirements of physically demanding occupational work. Budd et al (Budd *et al.* 1997b) recorded the frequency and duration of Australian land management crew firefighting activities via direct observation but did not record real time physiological measurements to quantify task 'demands'. Bos et al (Bos *et al.* 2004) utilised video analysis and wireless heart rate monitoring to quantify the frequency and duration of physical demands on urban Dutch firefighters during a 24-hour shift. They reported that urban firefighting could be characterised by a low frequency of incidents which are short in duration with a moderate to occasionally high workload. However, they relied only on heart rate alone which typically has a delayed reaction to activity changes, resulting in either residually lower or higher heart rate for subsequent tasks. Lastly, Wyss and Mader (2011) recently advocated the use of video analysis to verify task analysis of physically demanding Swiss military tasks along with personal monitoring (e.g., HR, physical activity).

To date, our group has undertaken subjective job task analyses (Phillips *et al. in press*), quantified oxygen uptake and heart rate during simulations of isolated tasks (Phillips *et al.* 2008) and measured heart rate and activity across multiple shifts (Raines *et al. in press*) but neither our group or others has quantified the frequency, intensity, duration and type of tasks firefighters perform on the fireground. Therefore the aim of this study was to use video footage of individual firefighters wearing heart rate and GPS monitors to characterise these parameters during a bushfire suppression shift. Particular attention was focussed on tasks that were simultaneously frequent, intense and / or long-lasting. Such tasks were identified as 'critical'; modifying the previous 'cumulative stress' paradigm used in job task analyses of Australian Naval clearance divers (Taylor and Groeller 2003).

Methods

Twenty eight operationally active volunteer firefighters (22 males and six females) from local brigades of the Tasmanian Fire Service (TFS) participated in one of four single-day bushfires in dry eucalypt forest of North Eastern and South Western Tasmania during September – October, 2008. Across the four days, the temperatures ranged 18 to 24°C with 0.6 to 3.2 mm of rainfall and light winds. The fires were lit as part of large scale prescribed burning operations, facilitating the current research, similar to earlier work with Australian land management firefighters (Budd *et al.* 1997a).

Recruitment to the study occurred at pre-shift briefings before deployment to their normal work shift. All participants were fitted with a portable 1-Hz GPS monitor (WiSPI, GPSports, Australia), worn in the manufacturer's harness mounted between the shoulder blades. Heart rate data was received through the GPS device from a chest strap. Firefighters also wore full protective gear (approx. 5kg in weight) as per standard operating procedures. Throughout the shift each firefighter was followed by a researcher and a fire-service provided safety advisor. The researcher used a handheld digital video camera to capture footage of their firefighter's work tasks and movements although they did not film during rest periods or during vehicle transit.

Data analysis

At the conclusion of each shift, logged GPS coordinates were downloaded from the devices and converted into distance and velocity information using Team AMS software (GPSports, Australia). Heart rate and velocity data were downloaded at one-second epochs and digital video was captured by Dartfish TeamPro® (Fribourg, Switzerland) and the types of tasks analysed were identified using a custom made rural firefighting specific tagging profile drawing on our previous job task analysis (Phillips *et al. in press*). The tagging profile was used to quantify the frequency and duration for each discrete task performed by the firefighters. The footage was then time-synchronised to within one epoch with heart rate and velocity data to isolate the intensity (heart rate and velocity of each task). This was performed using the functionality of the Dartfish software which allows input of other measures. Task velocity is expressed in $m \cdot s^{-1}$ and heart rate in both absolute units ($beats \cdot min^{-1}$) and relative to age-predicted maximum (%HRmax) using the predictive formula: *HRmax = 207 – (0.7 x ag*e; Gellish *et al.* 2007).

Statistical analysis

All tasks (34 in total) were ranked in terms of frequency, intensity and time and the top three for each list are presented in the results section. Thereafter, tasks that appear in the top ten on two or more of these lists were presented to physical tasks that were simultaneously frequent, intense, and/or long lasting in an effort to identify critical fireground duties.

Results

Across the four 'shifts', 34 distinct fireground tasks were performed. Of these, nineteen tasks were classified as hose work, five as handtool (primarily rakehoe) and the remaining eight were classed as miscellaneous.

Frequency

The three most frequent tasks were performed between 66 and 103 times across a six-hour fireground shift and were; laterally repositioning a 38-mm diameter charged (i.e., filled with pressurized liquid) fire hose (103 repetitions), purposeful or 'targeted' walks (95), and supporting a colleague using a 38-mm diameter charged fire hose (66).

Intensity

Intensity was measured as the highest relative heart rate (% of age-predicted heart rate maximum) and ranged from 82.1 ± 12.9 $\%HR_{max}$ to 86.2 ± 10.8 $\%HR_{max}$. The three most intense firefighting tasks were; building firebreaks using handtools, in teams (86.2 ± 10.8% $\%HR_{max}$), carrying a tightly coiled 38-mm diameter fire hose (83.4 ± 13.7 $\%HR_{max}$) and tightly coiling a 38-mm diameter firehose (82.1 ± 12.9 $\%HR_{max}$).

Speed

The speed of movement during the three fastest firefighting tasks ranged from 0.76 ± 0.51$m \cdot s^{-1}$ to 0.79 ± 0.40 $m \cdot s^{-1}$. These tasks included; carrying a tightly coiled 38-mm fire hose (0.79 ± 0.40 $m \cdot s^{-1}$), supporting crew on the fireline (0.78 ± 0.71 $m \cdot s^{-1}$) and purposeful or 'targeted' walks (0.76 ± 0.51$m \cdot s^{-1}$). This category of tasks was excluded from the composite list of tasks (Table 1) so as not to bias the scaling towards two measures of intensity (ie. , mean HR and speed)

Duration

The three longest tasks ranged from 119 ± 112 s to 461 ± 387 s. These tasks (time in seconds) included building firebreaks using handtools, in teams (461 ± 387 s), using a 25-mm diameter charged firehose to douse burnt debris during post-fire cleanup work (130 ± 138 s) and extracting water from a water point (i.e., lake, dam; 119 ± 112 s).

Frequency, Intensity, Duration

A composite list of five tasks that were ranked in the top ten for two or more of frequency, intensity and duration is presented (along with frequency, intensity and duration data) in Table 1. These tasks (with the lists on which they featured on the top ten in brackets) included using a 38-mm diameter charged firehose during post fire clean up (duration, frequency and intensity), building firebreaks using handtools, in teams (duration and intensity), laterally repositioning a 38-mm diameter charged firehose (duration and frequency), operating a 38-mm diameter charged fire hose (duration and frequency) and tightly coiling a 38-mm diameter firehose (duration and intensity).

Discussion

This is the first study that has quantified the frequency and duration with which firefighting tasks are performed during a bushfire suppression shift. As such, comparisons are limited to previous work using SMEs (Phillips *et al. in press*) and other firefighting jurisdictions, including urban, naval and forestry firefighting.

The most frequent tasks were performed between 29 (mount/dismount fire tanker) and 103 (lateral reposition of a 38-mm charged fire hose) times across a six-hour fireground shift. In a previous study (Phillips *et al. in press*), task frequency was estimated per four-month Australian bushfire season making it difficult to precisely compare to the 'per shift' observations in the current study. However, when relative 'rankings' are compared, both SMEs and our current observations places lateral repositioning a 38-mm diameter charged firehose as the most frequent task, followed by full repositioning of a 38-mm diameter charged firehose and hand tool work during post fire clean up duties. Solo and team based hand tool work were amongst the least frequent tasks in both studies (Phillips *et al. in press*).

Heart rates obtained in the current study were lower than those recorded in simulations of Australian bushfire suppression (Phillips *et al.* 2008), Canadian urban (Gledhill and Jamnik 1992a), British naval (Bilzon *et al.* 2001) and Australian land management crew (Brotherhood *et al.* 1997) firefighting tasks. Possible explanations for this include shorter task durations, slower task speeds and in some cases, lighter equipment. Nevertheless, the most intense tasks in this study could be classified as moderate to hard (vigorous) work by the ACSM (ACSM 2010). Vigorous work can precipitate adverse cardiac events in individuals with underlying cardiovascular disease (ACSM 2010). To reduce the risk of adverse cardiac events during vigorous exercise, health and fitness settings usually require that participants undergo some form of medical screening prior to starting an exercise regimen. In volunteer firefighting, this type of screening is not mandatory, potentially putting volunteers at risk if they are working in the vigorous heart rate zone (ACSM 2010).

The longest tasks observed on the fireground ranged 54 s to 7.6 min. The duration of these tasks was generally shorter than those simulated for Canadian urban (Gledhill and Jamnik 1992a), US forestry (Sharkey 1999), Australian land management (Ellis and Gilbert 1997) and Australian rural fire authority (Phillips *et al.* 2008) firefighting. The comparative differences between these previous studies and the current work could arise from genuine differences in task length between firefighting types and jurisdictions. Furthermore, single-repetition simulations are often designed to elicit steady-state cardiovascular responses and, as such, are much longer than self-paced work durations performed across a shift (Brotherhood *et al.* 1997).

In urban and land management firefighters (AFAC 2002), recruit, seasonal and sometimes incumbent personnel are required to pass physical employment standards before deployment on the fireground. In Australia, rural authority firefighters do not have a purpose-built physical selection test (Lord *et al.in press*). In order to be able to identify the representative tasks that could feature in such a test, the current study identified tasks that ranked in the top ten for two or more of frequency, intensity and duration (Table 1). This attempt to isolate ‘critical’ tasks is similar to the ‘cumulative stress’ paradigm used by Taylor and Groeller (2003) which ranked tasks based on the product of difficulty and frequency. Tasks found to be simultaneously frequent, long and intense (or two of these three) included using a 38-mm diameter charged firehose during post fire cleanup, building firebreaks using handtools in teams, laterally repositioning a 38-mm diameter charged firehose, operating a 38-mm diameter charged fire hose and tightly coiling a 38-mm diameter firehose (Table 1).

The current results are based on four whole-day shifts in one Australian state. The data collected, though comprehensive, may need to be supplemented by input from other regions. The collection of frequency, intensity and duration data during actual firefighting using video analyses is, however, time consuming, expensive and requires dedicated agency support. For agencies and researchers seeking to apply these current findings to other Australian regions, a more time and cost effective approach may be to use workshops where video footage and physiological data can be interrogated by multiple stakeholders so that inter-region variations in work practices can be captured, discussed and resolved.

The current study combined, for the first time, video footage of individual firefighters wearing heart rate monitors and personal GPS units to quantify the frequency, intensity, duration and type of tasks performed by Australian rural fire crews when suppressing bushfires. Task frequency has not yet been quantified in previous emergency service literature. Fireground tasks were, generally speaking, slower, performed at slower speeds and elicited lower heart rate responses than simulated tasks in Australian bushfire, Canadian and Dutch urban, British naval or US or Spanish forestry contexts. Five hose tasks and one raking task were found to be simultaneously frequent, intense and long-lasting (or two of these) and should be considered when designing a work-specific simulation or physical selection test for Australian rural firefighters suppressing bushfires.

References

ACSM (2010) ACSM's Guidelines for Exercise Testing and Prescription. (Wolters Kluwer / Lippincott Williams & Wilkins: Philadelphia).

AFAC (2002) AFAC guidelines for health and fitness monitoring of Australiasian fire and emergency service workers. Australasian Fire Authorities Council, East Melbourne Australia, p. 95.

Bilzon J, Scarpello E, Smith C, Ravenhill N, Rayson M (2001) Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. *Ergonomics* **44**, 776-780.

Bos J, Mol E, Visser B, Frings-Dresen M (2004) The physical demands upon (Dutch) fire-fighters in relation to the maximum acceptable energetic workload. *Ergonomics* **47**, 446-460.

Brotherhood J, Budd G, Hendrie A, Jeffrey S, Beasley F, Costin B, Zhien W, Baker M, Cheney N, Dawson M (1997) **Project Aquarius 3.** Effects of work rate on the productivity, energy expenditure, and physiological responses of men building fireline with a rakehoe in dry eucalypt forest. *International Journal of Wildland Fire* **7**, 87-98.

Budd G, Brotherhood J, Hendrie A, Jeffery S, Beasley F, Costin B, Zhien W, Baker M, Cheney N, Dawson M (1997a) **Project Aquarius 1**. Stress, Strain, and Productivity in Men Suppressing Australian Summer Bushfires With Hand Tools: Background, Objectives, and Methods. *International Journal of Wildland Fire* **7**, 69-76.

Budd G, Brotherhood J, Hendrie A, Jeffrey S, Beasley F, Costin B, Zhien W, Baker M, Cheney N, Dawson M (1997b) **Project Aquarius 5.** Activity distribution, energy expenditure, and productivity of men suppressing free-running wildland fires with hand tools. *International Journal of Wildland Fire* **7**, 105-118.

Cuddy JS, Gaskill SE, Sharkey BJ, Harger SG, Ruby BC (2007) Supplemental feedings increase self-selected work output during wildfire suppression. *Medicine and Science in Sports and Exercise* **39**, 1004-1012.

Ellis S, Gilbert L (1997) Job related taskbased assessments. AFAC Guidelines: National Approach to Physical Performance Assessment for Firefighters. Australasian Fire Authorities Council, East Melbourne, Australia, p. 9.

Gellish R, Gosliin B, Olson R, McDonald A, Russi G, Moudgil V (2007) Longitudinal Modeling of the Relationship between Age and Maximal Heart Rate. *Medicine and Science in Sports and Exercise* **39**, 822-829

Gledhill N, Jamnik VK (1992a) Characterization of the physical demands of firefighting. *Canadian Journal of Sports Sciences* **17**, 207-213.

Gledhill N, Jamnik VK (1992b) Development and validation of a fitness screening protocol for firefighter applicants. *Canadian Journal of Sports Sciences* **17**, 199-206.

Gregory D, Narula S, Howarth S, Russell C, Callaghan J (2008) The effect of fatigue on trunk muscle activation patterns and spine postures during simulated firefighting tasks. *Ergonomics* **51**, 1032 - 1041

Heil DP (2002) Estimating energy expenditure in wildland fire fighters using a physical activity monitor. *Applied Ergonomics* **33**, 405-413.

Lindell MK, Clause CS, Brandt CJ, Landis RL (1998) Relationship between organisational context and job analysis task ratings. *Journal of Applied Psychology* **83**, 769-776.

Lord C, Netto K, Petersen A, Nichols D, Drain J, Phillips M, Aisbett B (*In press*) Validating `fit for duty' tests for Australian volunteer fire fighters suppressing bushfires. *Applied Ergonomics*.

Morgeson FP, Campion MA (1997) Social and cognitive sources of potential inaccuracy in job analysis. *Journal of Applied Psychology* **82**, 627-655.

Phillips M, Payne W, Lord C, Netto K, Nichols D, Aisbett B (*in press*) Identification of physically demanding tasks performed during bushfire suppression by Australian rural firefighters. *Applied Ergonomics*.

Phillips M, Raines J, McConell G, Nichols D, Aisbett B (2008) The Aerobic Energy Demands Of Simulated Tanker- Based Wildfire Fighting Tasks. *Medicine and Science in Sports and Exercise* **40**, S354.

Raines J, Snow R, Petersen A, Harvey J, Nichols D, Aisbett B (*in press*) Pre-shift fluid intake: Effect on physiology, work and drinking during emergency wildfire fighting. *Applied Ergonomics*.

Rodríguez-Marroyo J, López-Satue J, Pernía R, Carballo B, García-López J, Foster C, Villa J (2011) Physiological work demands of Spanish wildland firefighters during wildfire suppression. *International Archives of Occupational and Environmental Health*, 1-8.

Ruby B, Schoeller D, Sharkey B, Burks C, Tysk S (2003) Water Turnover and Changes in Body Composition during Arduous Wildfire Suppression. Medicine and Science in Sports and Exercise 35, 1760-1765.

Ruby B, Schriver T, Zderic T, Sharkey B, Burks C, Tysk S (2002) Total energy expenditure during arduous wildfire suppression. Medicine and Science in Sports and Exercise 34, 1048-1054.

Sharkey B (1999) Development and validation of a job-related work capacity test for wildland firefighters. International Association of Wildland Fire, Sydney, Australia.

Taylor NA, Groeller H (2003) Work-based physiological assessment of physically-demanding trades: a methodological overview. Journal of Physiological Anthropology and Applied Human Science 22, 73-81.

Wyss T, Mäder U (2010) Recognition of military-specific physical activities with body-fixed sensors. Military Medicine **175,** 858-864.

Table 5 Tasks that were ranked in the top ten for two or more of frequency, intensity (mean relative heart rate), and duration during bushfire suppression

Task	Frequency	Average HR (beats.min^{-1}) (%HR max)	Peak HR (beats.min^{-1}) (%HR max)	Speed (m.s^{-1})	Duration (s)	Type (Hose, Rake, Misc)
38-mm hose blacking out work	41	126 ± 24 (71.9 ± 15.3)	131 ± 24 (75.0 ± 15.0)	0.26 ± 0.19	76 ± 70	Hose
38-mm hose lateral repositioning	103	127 ± 23 (71.5 ± 12.6)	130 ± 23 (73.2 ± 12.5)	0.40 ± 0.29	17 ± 14	Hose
38-mm hose operating	41	124 ± 19 (69.8 ± 10.6)	129 ± 20 (72.4 ± 10.8)	0.34 ± 0.37	40 ± 69	Hose
Tightly coiling a 38-mm hose	5	155 ± 24 (82.1 ± 12.9)	164 ± 25 (86.8 ± 13.2)	0.40 ± 0.26	62 ± 47	Hose
Team hand tool line building	1	157 ± 15 (86.2 ± 10.8)	168 ± 10 (92.2 ± 7.7)	0.14 ± 0.08	461 ± 387	Rake

All data are means ± SD, HR; heart rate, min; minutes, % HRmax; percentage of age-predicted heart rate maximum [19], m.s^{-1}; metres per second, SD; standard deviation, Misc; miscellaneous task, mm; millimetres

The changing nature of emergency services multi-agency coordination

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Abstract

One of the key issues arising from the 2009 Victorian Bushfires Royal Commission was whether organisational changes would benefit or hinder future emergency management response. This paper will report on research conducted in the first Bushfire CRC research program. The research included a survey to obtain emergency management personnel perceptions about the suitability of the relevant Incident Control Systems (ICS) in use during fire and emergency management of natural disaster events. The survey was completed with organisational survey data collected from 870 respondents engaged in emergency management work across 25 agencies in Australia and New Zealand.

The research indicates that the original functional purpose of the (ICS) used in Australia (Australasian Inter-Service Incident Management System or AIIMS) and its complement in New Zealand (Coordinated Incident Management System or CIMS) works well, particularly in predictable and routine emergency events. There is, however, evidence to suggest that AIIMS/CIMS processes are strained under conditions of escalation - when emergencies are complex - and that this creates different kinds of tensions for personnel working in different parts of the system.

This paper develops and tests a model of emergency management coordination based on key attributes identified in a factor analysis, and tests the model using structural equation modelling. The findings show that the coordination through organisational processes and distributed collaboration between teams better explained satisfaction with information quality and inter-agency interoperability than within-team communication. Implications for the future of managing dynamic events through the formation of supra-organisational temporary configurations are discussed.

Introduction

What is the role of organisation in emergency management response? This question has been raised repeatedly in various inquiries into emergency events (e.g., Teague, 2009; QFCI, 2011; Keelty, 2011). In the 2009 Victorian Bushfires Royal Commission, for example, a considerable amount of time was spent attempting to understand whether organisational changes would benefit or hinder emergency management response in the future. A range of experts was called to give opinion (e.g., Boin & t'Hart, 2010; Leonard & Howitt, 2010). In its report, the Commission concluded that major structural reform was needed to meet the increasing expectations of community and government. Emergency management performance needed to be able to provide high quality and timely information that could yield suitable warnings to communities and enable strategic emergency management by Government and other stakeholders. According to expert opinion provided to the Commission (Boin & t'Hart, 2010), impediments that needed to be overcome included (in part):

- An obsession on the part of the emergency responders to obtain full information before engaging in action or providing advice to affected communities;
- A total reliance on command and control, rather than a recognition of the variety of stakeholders involved including those who do not fit within a command and control paradigm;
- Under estimating the crisis after the emergency.

Emergency services organisations need to quickly manage the event and in doing so bring together a variety of people drawn from many other agencies to cooperate on the problem. In this respect, emergency management requires the coordination of multiple organisations forming a temporary or incidental supra-organisation. Coordination is defined as "mutually agreed linking of activities of two or more groups" (Quarantelli, 1986, p. 9). In this paper it is argued that those different groups may be different teams operating within a command and control organisation or may represent distributed communication between teams in different organisations. This is important because when multiple organisational stakeholders are involved, there will frequently be differences and sometimes conflicting priorities and goals (Briscoe, 2007; Schraagen & Ven, 2011; Sonnenwald & Pierce, 2000).

The dilemma of multi-agency coordination in emergency management settings is that on the one hand there is a need for tight structuring, formal coordination and hierarchical decision making to ensure a clear division of responsibilities, prompt decision processes, and timely action. However, on the other hand, because of the need for rapid action in an uncertain environment, there is a competing need to rely on organisational structures that support decision making, as well as informal and improvised coordination mechanisms (e.g. Bigley & Roberts, 2001; Brown & Eisenhardt, 1997; Weick & Roberts, 1993).

The aim of this paper is to report on research conducted as part of the first phase of the Bushfire CRC. The purpose of this research study was to:

- Review information and communication flows;
- Review how teams work with the AIIMS/CIMS systems;
- Identify opportunities for improvement.

The research was guided by a number of research questions which included:

- To what degree are the processes embedded within AIIMS to support information flow and coordination practiced by personnel engaged in emergency incident management?
- What collective practices and organisational processes can be identified that need to be improved in order to enhance IMT/ICS work performance?

According to the literature, emergency management coordination raises many challenges. Comfort and Kapucu (2006) have noted that:

> The need for integration intensifies as the number of organisations engaged in response operations increases and the range of problems they confront widens. Since all organizations in the damaged area are affected, private and nonprofit actors, as well as public organisations, become participants in the response system (p. 310).

The challenge then, is to better understand the extent to which existing approaches to emergency incident management support effective information flow, and coordination (Comfort & Kapucu, 2006; Sonnenwald & Pierce, 2000). At issue is the need to find suitable enablers that can help reshape emergency management organisation in the future. The following theoretical constructs have been identified as important in the literature.

Effective incident and emergency management relies on successful team performance. Teamwork is defined as the processes that individuals use to coordinate their decisions and activities, such as sharing information and resources to attain shared goals (Cannon-Bowers & Salas, 1998). It is important that team members have both technical expertise and social interactions that will lead to adaptive coordinated action (Salas, Rosen, Burke, Goodwin & Fiore, 2006). Critical to teamwork is psychological safety that enables personnel to speak up and to have trust in each other (Edmondson, 2005).

Much emergency management work involves work groups coordinating in different locations. This involves enhancing communication across boundaries and enabling personnel to speak up and share what they know (Carmelli & Gittell, 2009). Clark and Jones (1999) and Stewart, Clarke, Goillau, Verrall and Widdowson (2004) all emphasise the importance of developing effective distributed collaboration across different teams and work environments. Teamwork and distributed collaboration occurs in an organisational context, something that is frequently mentioned but rarely systematically examined in the literature (DeChurch & Zaccaro, 2010). Both individual and collective performance is contingent upon the degree to which organisational procedures and processes are sensitive to the work demands to enable shifts in roles and structures (Guise & Segel, 2008; Salas et al., 2006; Vogas & Sutcliffe, 2007). According to Smith and Dowell (2000) “an incident organisation develops organically, both in the sense of growing and transforming during the incident, and in the sense that individual roles are determined and adjusted flexibly”. This requires appropriate organisational processes to allow and support movement in authority and decision-making and to enable improvisation. A key issue in emergency response organisations in particular is ensuring the appropriate level of resourcing and personnel support is available (Smith & Dowell, 2000; Wise, 2006).

In the command and control literature in particular there is an emphasis on inter-operability between organisations. Interoperability is defined as “. . . the ability of systems, units or forces to provide services to and accept services from other systems, units or forces and to use the service so exchanged to enable them to operate effectively together without altering or degrading the information exchanged” (Stewart, Clarke, Goillau, Verrall & Widdowson, 2004, p. 4). Therefore the inter-operability between organisations (i.e., the way technical systems, policies and procedures and cultures align between agencies) is of obvious importance.

Research method

The research conducted during 2006-2010 included interviews with 130 personnel experienced in emergency incident management; observations of six real-time events as well as 18 exercise simulations of incident management in four states (Queensland, New South Wales, Victoria and Tasmania), and a survey of 870 personnel who have worked within 25 agencies representing all Australian states and territories and New Zealand.

Given space limitations, the focus here will be on the survey data with references to cross validation of some findings from other methods. In terms of the survey component, a questionnaire was constructed to assess perceptions of (i) teamwork during emergency events; (ii) how well responders working on the fire- or incident-ground worked with others who were operating away from the incident but who were responsible for managing the event as well, and (iii) perceptions of the organisational processes underpinning the AIIMS/CIMS systems. A number of likert-type statements were developed on these areas based on the teamwork and organisational behaviour literature. For details of the data collection, reporting and analysis please see Owen and Dwyer (2009), and Owen and Dwyer (2011).

It should be noted that unless otherwise stated the items were Likert-type where the statement offered a ranking of 1 = low and 7 = high. Respondents also had the opportunity to state that they were unable to answer. The use of Likert type subjective measures of individual perceptions of personal, interpersonal and collective performance is consistent with other studies (Frazier, Johnson, Gavin, Gooty, & Snow, 2010; Moon, 2010).

Next, we checked that the assumptions of normality could be met by using the SPSS random selection tool and randomly selecting 50 cases from the data set on the indicator items. On this we conducted Kolmogorov-Smirnov tests to assess the normality of the distributions on relevant items. The assumption of normality of the distribution was met for all items.

Given the limited theoretical development that has occurred in multi-organisational coordination, the analysis first proceeded to explore patterns in the data and to evaluate these in terms of their insights for change. A Principal Components Factor Analysis was undertaken to identify latent patterns and structures in the data.

The factor analysis achieved a Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) of .943 and the six factors reported 71% of the variance. The scores were then standardized so that they could be compared across work groups. Standardised scores result in a normal curve distribution of total responses for the construct which then also has a mean of 50 and a standard deviation of 10. This standardisation then means that scores for different groups can be compared.

A summary of the factors identified from the analysis can be found in Table 6. These factors were then used to indicate perceptions about different aspects of emergency management operations in different parts of the system. The levels included on the fire- or incident-ground, within an Incident Management Team (IMT) as well as within a regional or state level of coordination. It is interesting to note that one in every three personnel also reported in the survey that they experienced factors that inhibited them from being able to effectively carry out their job. Table 7 provides outlines the distribution of the standardized scores on the factors. The Table shows where the standardised score was more than one standard deviation above the mean (Positive); distributed within one half a standard deviation above and below the mean (Neutral); between 0.5 and a full standard deviation below the mean (some concerns); 1-1.5 standard deviations below the mean (Attention required) and more than 1.5 standard deviations below the mean (Serious concern). The Table therefore illustrates areas of dissatisfaction and thus systemic tension when personnel are under pressure. In the Table, the rows represent each of the factors identified and the columns represent each of the work groups in operation within the ICS structure. The Table as a whole represents a colour-coded synthesis of all data analysed. It identifies key areas proposed for intervention in order to improve emergency incident management performance.

Theory development and theory testing

To further develop an explanatory model for the data, a two-step model of theory building and theory testing was used. The factors and their indicators were reviewed in light of the literature outlined above and constructs developed, see Table 3.

A confirmatory factor analysis was conducted to assess the dimensionality of the key constructs using maximum likelihood estimation and varimax rotation. The factor analysis achieved a Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) of

.925 and the six factors reported 75% of the variance. This indicated that the items were loading as single dimensions. Two dependent variables *information quality* and *interoperability* were developed. *Information quality* was based on perceptions of the timeliness, accuracy, relevance and completeness of information available; *interoperability* was based on perceived effectiveness of technical systems, policies and procedures and culture to support inter-organisational coordination.

Given the factors identified, the following hypotheses were proposed:

- H1- that organisational processes would positively support team communication;
- H2 - that both teamwork and organisational processes would be positively associated with information quality and interoperability;
- H3 - that both organisational processes and team communication would support distributed communication;
- H4 - weak signals and organisational impediments would be negatively associated with the information quality and inter-operability;
- H5 - that distributed collaboration between groups would mediate the impact of team communication and organisational processes on information quality.

The hypothesized model was then measured using Structural Equation Modeling (SEM). Although there are a variety of ways of estimating models, SEM was chosen because it can be used to assess both the direct and mediating effects as well as the latent structure of the model (Hoyle, 1995). For example, the latent variable *Team Communication* is a hypothetical construct inferred by the items measured in Table 1. SEM enables measurement error to be controlled by using multiple indicators for each latent variable in the models (Arbuckle, 2008).

To address potential non-independence of groups within the emergency management structure (i.e., that personnel might report differently depending on whether they work at a local, regional or state level) or type of emergency management agency (e.g., urban, land management, rural fire service), these observed variables were also included in the model with paths established to all variables of interest to control for this potential bias.

In order to develop and test the model, the data set was randomly split using the SPSS function into two separate databases. The theory development database contained 444 cases and the theory test database contained 426 cases. The hypothesized model was then measured using Structural Equation Modeling (SEM) on the theory-development dataset. Various measures of fit were used in combination with the chi-square. These included the goodness of fit index (GFI) along with the comparative fit index (CFI) and the root mean square error of approximation (RMSEA). The indexes of the GFI, CFI can range from zero (no fit) to one (perfect fit), with values of 0.9 indicating an acceptable fit and 0.95 a good fit (Arbuckle, 2008). The RMSEA values of less than 0.08 indicate an acceptable fit and less than 0.5 a good fit (Arbuckle, 2008). The model was then revalidated using the theory testing dataset.

Findings

This includes the descriptive analysis of the Factor Scores by various groups as well as the theoretical development and testing.

Descriptive findings

On the fire- or incident-ground

The concerns of personnel on the fire- or incident-ground are, not surprisingly, for resources. Also highlighted are concerns regarding securing needed support from the IMT in a way that is temporally responsive.

Incident Management Teams

IMTs are comprised of smaller functional units that sometimes have considerable difficulty in getting their own needs met from the “core” IMT members, here called IMT Officers (i.e. the Incident Controller, Operations Officer, Planning Officer and Logistics Officer). Personnel working within functional units of the IMT reported lowest levels of satisfaction with interactions supporting distributed collaboration (see Table 6) between the IMT and the incident-ground. There is a need to strengthen the interconnections between planning and operational functional units within the IMT because it is between these two units where the first disconnects and coordination breakdowns occur. At IMT officer level, the analysis indicated a need for better inter-operability in technical systems, policies and procedures and supporting culture. This is likely to require better systemic connections within the ICS (between the IMT and regional/state levels of coordination) as well as between the IMT and other supporting emergency arrangements (e.g. Municipal Emergency Coordination Centres) and other supporting agencies.

Regional levels

People working at a regional level suffered most from concerns about personnel capability. They reported lower levels of certainty of what needed to be done; less familiarity with the incident management systems being used at that level and less understanding about whom to contact for information or expertise. These indicate a lack of definition and ambiguity of the regional coordination function and of its roles within the overall Incident Management System.

State levels

The State level (in New Zealand this is the national level) had the highest reporting of experiencing *organisational impediments*. This was also mentioned in the interviews conducted where it was evident that coordinating demands at this level emphasise – in addition to the demands associated with control – a need for a different way of coordinating that is more closely associated with what Gittell (2008) calls 'relational coordination' within multi-agency networks. In the survey, personnel at a state level reported experiencing higher levels of contradictions in policies; experienced higher levels of competing demands; reported a greater degree of having to go outside normal procedures, as well as being asked to go outside the chain of command.

Theoretical modeling: Measuring model specification

An initial run of the model using Structural Equation Modeling suggested a moderate fit for the variables. The constructs *weak signals* and *organisational impediments* were removed due to their limited influence in the model. Theoretically this is supportable since the two variables reporting negative impacts are likely to be acting in a different way and probably need to be included in a different model (Sonnenwald & Pierce, 2000).

The chi-square values, associated degrees of freedom, and probability levels for the model are presented in Table 4 and the final estimates presented in Table 5 – see also Figure 1.

Hypothesis 1 stated that *organisational processes* would support *team communication.* The results support this view: (β = .71, t(426) = 7.10). Hypothesis 2 stated that (2a) *team communication* and (2b) *organisational processes* will be positively associated with (2c) *information quality* and (2d) *interoperability.* The results partially support this view. As with the model development dataset, team communication was again not significantly associated with *information quality* (β = .01, t(426) = .20) ns or with *interoperability* (β = .01, t(426) = .14) ns. However, *organisational processes* was significantly associated with *information quality* (β = .43, t(426) = 3.67) and with *interoperability* (β = .60, t(426) = .4.46).

Hypothesis 3 stated that (3a) *team communication* and (3b) *organisational processes* would be positively associated with *distributed collaboration.* The results support this view, with (β = .18, t(426) = 2.68) for *team communication* and β = .86, t(426) = 7.76) for *organisational processes.* The final hypothesis tested within the validation model was that *distributed collaboration* would mediate the impact of *team communication* and *organisational processes* on *information quality.* Again the results support this view (β = .50, t(426) = 8.24).

Discussion

The research reported here provides guidance about areas that could be targeted to achieve improvements in incident management work and organisation. By reviewing perceptions about the teamwork, coordination and organisational processes, the analysis provides a systematic evaluation and diagnostic framework that identifies areas for improvement and suggests different levels of possible intervention. The findings also illustrate that there is a need to build stronger teamwork practices as well as strategies to enhance coordination between groups.

It is interesting to note that *team communication* was not significant in *information quality* or in *inter-organisational interoperability*, which is surprising. It was also interesting to note that *organisational processes* provided the strongest support for *team communication*, *distributed collaboration* and for *information quality* and *inter-organisational inter-operability*. There are a few possible explanations for these results.

First, given the strength of teamwork found in other research studies, it is suggested that the reports on emergency management response teams here may not be engaging in strong teamwork practices that enable best possible performance outcomes. There are validating supports for this finding in other research collected as part of this broader study. For example, in the observational component of the research, teamwork training was found to be focussed on assisting team members to learn their individual roles and responsibilities – in the literature a practice known as team building not teamwork. These findings suggest there is a need to examine more closely how teamwork performance may be further developed in order to achieve better outcomes.

The findings in the model related to distributed collaboration and organisational processes are also supported in other research. There is some evidence emerging to suggest that it is not effective teamwork *per se* that makes the difference in complex multi-layered multi-team systems, but how the boundaries between teams are managed that is important (DeChurch & Zacarro, 2010). In this respect effective internal processes within teams are an important and necessary, but not sufficient, condition to enable coordination. There were some indications of this in the observation data where teams with Incident Controllers who were engaging in particular types of team coaching practices were yielding higher team performance outcomes. These practices coalesce around three dimensions: *boundary riding* (coaching behaviours and giving explicit feedback to team members on team and internal integration expectations); *boundary spanning* (coaching to support internal coordination between functional units within the team) and *boundary crossing* (coaching to support external coordination between groups).

To return to the issues raised by the Victorian Royal Commission of Inquiry, the challenges facing emergency services organisations include how to provide a coordinated and fully accountable response, and at the same time providing high quality and appropriate information that could yield timely warnings to communities and enable strategic decision-making by Government and other stakeholders.

The findings discussed here suggest a strong reliance on organisational processes and less on team communication. However, is this the appropriate mix to yield timely and adaptable response? Greater attention to getting the most from teams through teamwork (through, for example, training in team communication skills) may be needed to improve team performance. In addition there is a need to develop enhancements between teams involved in the emergency response.

These findings also raise questions about the types of organisational processes that are needed to support coordinated action between multiple stakeholders. If command and control paradigms are insufficient (Helsloot, 2008) – and emergency services organisations are frequently criticised because of their total reliance on command and control, rather than a recognition of the variety of stakeholders involved including those who do not fit within a command and control paradigm – what are the alternative models for these dynamic and safety-critical contexts?

In considering the outcomes of an inquiry like the Victorian Bushfires Royal Commission and its implications for change in the future, the following questions emerge from considering the data presented:

- If the conceptual distinction between routine and crisis events is valid for emergency events, what are the implications for organising the emergency response?
- If decentralisation is to be strengthened, as suggested by experts in the domain, what appropriate triggers are needed and what are the implications for training, doctrine and technology?
- What enablers are required to make unitary command and control on the one hand and inter-agency collaboration on the other effective in producing a successful emergency response?

The findings presented here suggest a need to re-examine the ways in which organisational processes support distributed collaboration in ambiguous circumstances if we are to achieve the resilience and flexibility needed. This is arguably more than a mission command approach to decentralised decision-making which works well when the coordination action required can be located within the boundaries of one organisation. As Elliott and Macpherson (2010) contend, in emergency management agencies there still remains an over emphasis on compliance and standards, but not on how organisational resilience may be developed to support adaptation and emergence – and it is argued based on the findings presented, this is particularly important in the context of distributed collaboration between teams.

How do organisational processes enable the level of bricolage when existing technological and organisational procedures are not able to anticipate the demands faced? These issues need addressing if theory development is to appropriately support emergency management work.

In conclusion, it is critically important that emergency management is underpinned by theoretical models that support evidence-based practice within multi-team complex systems. These issues need to be understood and addressed before the fire and emergency services industry faces the next challenge-test of a complex and overwhelming event where there may once again be failures in both legitimacy and resilience.

References

Arbuckle, J. L. (2008). *AMOS 17.0 User's Guide*. Chicago: SPSS Inc.

Bigley, G. A., & Roberts, K. (2001). The incident command system: high-reliability organizing for complex and volatile task environments. *Academy of Management, 44*(6), 1281-1299.

Boin, A., & 't Hart, P. (2010). Organising for effective emergency mangement: lessons from research. *Australian Journal or Public Administration, 69*(4), 357-371.

Briscoe, F. (2007). From iron cage to iron shield? How bureaucracy enables temporal flexibility for professional service workers. *Organization Science, 18*(2), 297-314.

Brown, S., & Eisenhardt, K. (1997). The Art of Continuous Change: Linking Complexity Theory and Time-paced Evolution in Relentlessly Shifting Organizations. *Administrative Science Quarterly, 42*, 1-34.

Burns, T., Stalker, G.M. (1961). *The Management of Innovation*. London: Tavistock.

Cannon-Bowers, J. A., & Salas, E. (1998). Team performance and training in complex environments: recent findings from applied research. *Current Directions in Psychological Science, 7*(3), 83-87.

Carmeli, A., & Gittell, J. H. (2009). High-quality relationships, psychological safety, and learning from failures in work organizations. *Journal of Organizational Behavior, 30*(6), 709-729.

Chapman, J., & Bearman, C. (2011). Framework for Eliciting Shared Mental Models for use in Bushfire Fieldwork (Report Prepared for the Bushfire CRC Under the Project: Organizing for Effective Incident Management). Melbourne, Australia: Bushfire CRC

Clark, T., & Jones, R. (1999). *Organisational interoperability maturity model for C2*. Paper presented at the Command and Control Research and Technology Symposium.

Comfort, L. K., & Kapucu, N. (2006). Inter-organizational coordination in extreme events: the world Trade Center attacks, September 11, 2001. *Natural Hazards, 39*, 309-327.

DeChurch, L. A., & Zaccaro, S. J. (2010). Perspectives: Teams won't solve this problem. *Human Factors, 52*(2), 329-334.

Edmondson, A. (2005). Psychological safety and learning behaviour in work teams. In C. L. Cooper & W. H. Starbuck (Eds.), *Work and workers* (Vol. 3, pp. 291-329). London, Thousand Oaks, New Delhi: Sage Publications.

Elliott, D., & Macpherson, A. (2010). Policy and Practice: Recursive Learning From Crisis. *Group & Organization Management, 35*(5 Supp), 572-605.

Frazier, M.L., Johnson, P.D., Gavin, M., Gooty, J. & Snow, D.B., 2010, Organizational justice, trustworthiness and trust: A multifoci examination: Group & Organization Management, v. 35, p. 39-76.

Gittell, J. H. (2008). Relationships and resilience. *The Journal of Applied Behavioural Science, 44*(1), 25-47.

Guise, J.-M., & Segel, S. (2008). Teamwork in obstetric critical care. *Best Practice & Research Clinical Obstetrics and Gynaecology, 22*(5), 937-951.

Helsloot, I. (2008). Coordination is a prerequisite for good collaboration, isn't it? *Journal of Contingencies and Crisis Management, 16*(4), 173-176.

Hoyle, R.H., 1995, Structural Equation Modeling: Concepts, Issues and Applications, Thousand Oaks, CA: Sage Publications.

Keelty, M. J. (2011). *A Shared Responsibility: The Report of the Perth Hills Bushfire: February 2011 Review*. Perth, Western Australia: Public Sector Commission, Government of Western Australia.

Leonard, H. B., & Howitt, A. M. (2010). Organising response to extreme emergencies: the Victorian Bushfires of 2009 *The Australian Journal of Public Administration, 69*(4), 372-386.

Moon, T., 2010, Organizational Cultural Intelligence: Dynamic Capability Perspective: Group & Organization Management, v. 35.

Owen, C. (under development) Bulldogs and boundary spanners: contested visions of leadership in emergency management

Owen, C., & Dwyer, I. (2009). *Review of Incident Management Teamwork and multi-agency collaboration*. Melbourne, Australia: Bushfire CRC.

Owen, C., & Dwyer, I. (2011). Strategic implications for incident control systems in Australia and New Zealand. *Bushfire CRC / AFAC Fire Note,* (73). Retrieved from http://www.bushfirecrc.com/managed/resource/strategic_implications_for_imts.pdf

QFCI. (2011). *Queensland Floods Commission of Inquiry - Interim Report 1 August 2011*. Brisbane: Qld Floods Commission.

Quarantelli, E. L. (1986). *Disaster Crisis Management* (No. #113): Disaster Research Centre, University of Delaware

Salas, E., Rosen, M. A., Burke, C. S., Goodwin, G. F., & Fiore, S. M. (2006). The making of a dream team: when expert teams do best. In K. A. Ericsson, N. Charness, P. J. Feltovich & R. R. Hoffman (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 439-453). New York: Cambridge University Press.

Schraagen, J. M., & Ven., J. v. d. (2011). Human factors aspects of ICT for crisis management. *Cognition, Technology & Work. , 13*(3), 175-187.

Smith, W., & Dowell, J. (2000). A case study of coordinative decision-making in disaster mangement. *Ergonomics, 43*(8), 1153-1166.

Sonnenwald, D., & Pierce, L. (2000). Information behavior in dynamic group work contexts: interwoven situational awareness, dense social networks and contested collaboration in command and control. *Information Processing & Management, 36*(3), 461-479.

Stewart, C. E., Clarke, H., Goillau, P., Verrall, N., & Widdowson, P. (2004). *Non technical interoperability in multinational forces.* Paper presented at the Power of Information Age Concepts and Technologies 9th Command and Control Research and Technology Symposium.

Teague, B., McLeod, R., & Pascoe, S. (2010). *2009 Victorian Bushfires Royal Commission Final Report*. Melbourne: VBRC.

Weick, K. E., & Roberts, K. (1993). Collective mind in organizations: heedful interrelating on flight decks. *Administrative Science Quarterly, 38*, 357-381.

Wise, C. R. (2006). Organizing for homeland security after Katrina: Is adaptive management what's missing? *Public Administration Review, 66*(3), 302-318.

Table 6: Description of Factors identified in the analysis

Team Working	The processes decisions and activities that individuals use to coordinate their behaviour, including information sharing and resources to attain shared goals.
Pre-occupation with Failure	Taking note of ALL small warning signals and openly discussing them in a constructive manner.
Shift Resources	The resources available on the shift that were available to meet logistical requirements including fatigue management and continuity of information between shifts.
Temporal Responsiveness	The capacity of the IMT to respond and meet needs in a timely way.
Distributed Collaboration	The ways in which IMT and fire-ground personnel communicate with one another to share information and risks in a constructive manner.
Flexibility	The capacity to be able to adapt performance strategies quickly and appropriately to changing task demands.
Systemic Capability	The organisational systems in place that support information sharing and adaptability vertically within a hierarchy and laterally to external networks
Personnel Capability	The level of confidence personnel have that their training and informal knowledge of the incident provides them with sufficient familiarity with incident management systems in use, including policies and procedures and confidence to do what needs to be done.
Organisational Impediments	The degree to which personnel experienced demands where they needed to go outside normal procedures and/or outside of the chain of command; and where they experienced contradictions in policies guiding the management of the incident.
Inter-operability	The technological systems, policies and procedures and culture that enables the effective inter-operability between agencies.

Table 7: Diagnosis of Incident Management Teamwork and Coordination

		State Coord	Regional Coord	IMT IC/ Officers	IMT Func units	Div/Sc Comm	Crew/ Strike
Within Teams	Team-working	Positive	Neutral	Some Concerns	Some Concerns	Positive	Positive
	Preoccupation with failure	Positive	Positive	Positive	Neutral	Some Concerns	Neutral
	Shift Resources	Attention Required	Positive	Neutral	Neutral	Some Concerns	Some Concerns
	Temporal responsivenes	Positive	Some Concerns	Neutral	Neutral	Attention Required	Serious Concern
Between Teams	Distributed Collaboration	Neutral	Positive	Some Concerns	Attention Required	Some Concerns	Some Concerns
	Flexibility	Positive	Positive	Neutral	Some Concerns	Attention Required	Some Concerns
Intra-organisational	Systemic Capability	Positive	Neutral	Neutral	Some Concerns	Attention Required	Attention Required
	Personnel Capability	Positive	Serious Concern	Neutral	Neutral	Neutral	Serious Concern
	Organisational Impediments	Serious Concern	Some Concerns	Neutral	Neutral	Some Concerns	Attention Required
Inter-organisational	Inter-operability	Positive	Positive	Attention Required	Some Concerns	Neutral	Neutral

Serious Concern | Attention Required | Some Concerns | Neutral | Positive

Table 3: Constructs and items included in the theoretical modelling

Latent Variable	Item Label	Hypothesized Item
Organisational Processes	CtctInf	Processes to aid knowing who to contact for information and expertise you needed during the incident
	UseSkl	Your ability to use your skills to maximum benefit
	ComChl	Clearly defined channels for communicating a safety concern
	FrmWk	The effectiveness of the organisational framework for the level of the current incident
Shift Resources	FtgCntl	There were effective provisions used to control fatigue
	ChgOvr	The changeover arrangements were effective
	Trnspt	The transport and logistics arrangements were effective
Team Communication	InfWk	Team members kept each other well informed about work related issues
	Honest	Team members operated in an open and honest manner
	ShrKno	Team members shared their individual knowledge to gain better understanding of the situation at hand
	ShrInf	There were genuine attempts to share information
Distributed Collaboration	Togthr	IMT and Fire/Incident Ground personnel exhibited a strong 'we are in this together' attitude
	FdBck	IMT and Fire/Incident Ground personnel provided constructive feedback to each other
	ExchInf	IMT and Fire/Incident Ground personnel exchanged information clearly and accurately
	Advice	IMT and Fire/Incident Ground personnel provided helpful advice to each other
Information Quality	Time	Timeliness of information
	Cmplt	Completeness of information
	Accrcy	Accuracy of information
	Relev	Relevance of information
Interoperability		Effectiveness of the following in supporting interoperability between agencies
	TchSys	Technology systems
	PolProc	Policies and procedures

Culture Culture

Table 4: Model Fit indices of this study's independence, measurement and validation models

Model	χ^2	*df*	χ_{χ^2}	GFI	CFI	TLI	RMSEA
Independence model	6606.82	229	23.94	.164	.000	.000	.232
Measurement model	596.23	229	2.60	.930	.966	.959	.049
Validation model	434.6	276	1.89	.919	.968	.961	.046

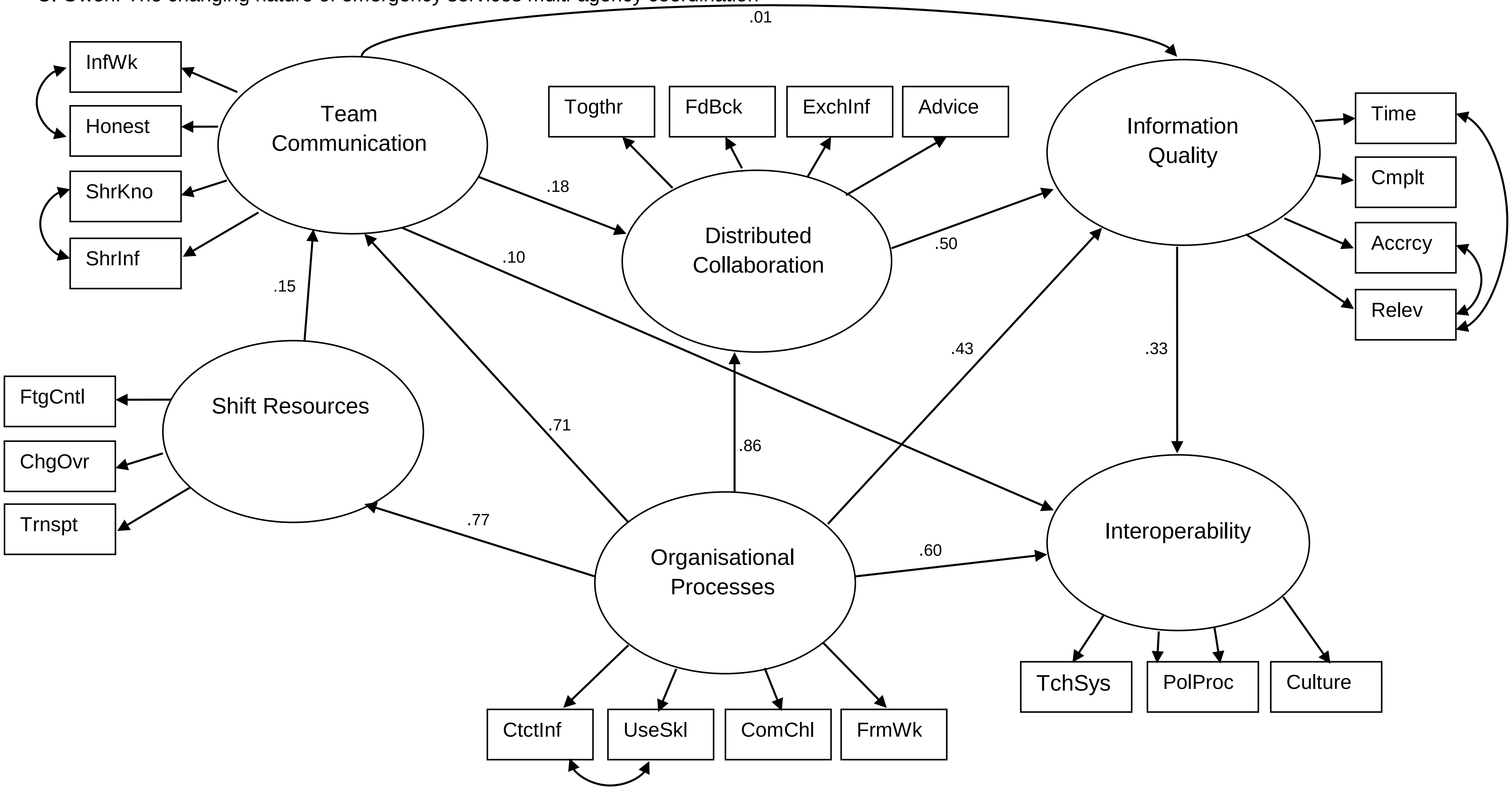

Figure 7: Structural Equation Model showing the relationships between the emergency management coordination factors used in the stud [control for non-independence of group responses from agency type and ICS work layer included in model but not shown for ease of reference]

Table 5: Validated structural equation model

Factor		Factor	Estimate	S.E.	C.R.	P
Shift Resources	←	Organisational processes	.768	.090	8.580	***
Team communications	←	Organisational processes	.709	.100	7.101	***
Team communications	←	Shift Resources	.148	.064	2.301	.021
Distributed collaboration	←	Team communications	.185	.069	2.674	.007
Distributed collaboration	←	Organisational processes	.858	.111	7.758	***
Information quality	←	Distributed collaboration	.502	.061	8.241	***
Information quality	←	Organisational processes	.429	.117	3.669	***
Information quality	←	Team communications	.013	.065	.201	.841
Interoperability	←	Information quality	.327	.062	5.238	***
Interoperability	←	Organisational processes	.603	.135	4.456	***
Interoperability	←	Team communications	.011	.078	.136	.892

Note: *** = .0005

Essential aspects of effective simulation-based training for incident management personnel

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Abstract.

An important implication of the changing Australian bushfire environment and highlighted by the 2009 Victorian Bushfires Royal Commission (VBRC) is that fire agencies will need to increase the amount of training and exercising that their Incident Management Team (IMT) personnel undertake. A training method particularly suitable for developing and exercising IMT personnel is simulation. Bushfire Cooperative Research Centre funded research has previously used simulation to investigate IMT performance. This research has highlighted three issues which are important to address in using simulations to comply with the VBRC recommendations for training. The first issue is *simulation fidelity*. More attention needs to be given to ensuring that simulations demand the same knowledge and skills as those required for actual IMT roles, with perhaps lesser emphasis on re-creating the physical environment. The second issue is *participant debriefing*. Although there is a positive shift towards using after-action reviews of training exercises, there is still considerable opportunity to better consolidate learning with more effective post-session debriefing. The final issue is *performance assessment*. Well designed simulations provide the opportunity not only for participants to self-assess but also for objective assessment of participant performance by observers.

Additional keywords: IMTs, assessment, bushfire, wildfire, development

Introduction

Bushfires are proto-typical examples of situations in which dynamic decision making (DDM) is required (Brehmer and Allard 1991; Brehmer 2000). Bushfires can be challenging incidents to manage, demanding considerable skill and coordinated performance by Incident Management Teams (IMTs) (McLennan *et al.* 2006). As a DDM task environment, bushfires are often time critical, have high stakes, fluid, and ambiguous, requiring rapid situation assessment and the implementation of suitable strategy to resolve the incident (Kozlowski and DeShon 2004; McLennan *et al.* 2006). The successful management of bushfires requires IMTs with high levels of expertise in developing effective strategy and coordinating action.

The training and development of IMT personnel to manage bushfires is no simple task, especially for the larger and more complex (level 3) incidents[1]. Fire and land management agencies in Australasia have created a variety of training programmes to develop and maintain the competency of their IMT personnel. The competency requirements for incident management personnel are considerable and involve a range of knowledge, skills, and attitudes (Hayes and Omodei 2011).

The increasing need to manage larger and more frequent bushfires (e.g., AFAC 2010) is likely to increase the size of an incident management workforce and as a result the amount of IMT training that fire and land management agencies undertake. Gould (2010) identified a number of factors that will increase the threat of bushfire and the fire management challenges for fire agencies. Gould observes there is general consensus about the threat posed by the “cumulative effects of climate change, fuel management, population and demographic changes (i.e., increased bushland interface communities), sustainability, and biodiversity management” (p.2). Gould suggests that fire and land management agencies will have the added challenge of operating within increasingly tight budget constraints in the next two to three years.

An important driver of adverse bushfire conditions is climate change (AFAC 2010). Lucas *et al.* (2007) suggested that Australia is entering a period of elevated mean temperatures. For south-eastern Australia this means that the fire season is likely to be more intense and moreover, starting earlier and ending slightly later. Lucas *et al.* predicted the effects of climate change are likely to be apparent by 2020 and very pronounced by 2050. Cleary a shift towards a longer and hotter fire seasons is likely to lead to a greater number of bushfires that are more difficult to manage.

A second factor that is likely to influence the number of IMT personnel required and the training that these teams receive is the increasing community expectations of emergency managers (O’Neill 2004). Whittaker and Handmer (2010) observe that communities now expect up-to-date information on bushfires and the timely provision of warnings. The need for IMTs to ensure that bushfire warnings are provided to communities was also highlighted in the recommendations of the 2009 Victorian Bushfires Royal Commission. We understand that this has resulted in agencies training additional personnel to fulfil public information roles within IMTs and the provision of additional training for incident controllers.

A third factor that is likely to influence the complexity of bushfire management operations and therefore demands on IMTs are the increasing number of communities located in more bushfire prone areas. The Australian peri-urban population continues to grow (e.g., Hugo 2002), and as Haswell and Brown (2002) note these areas are most vulnerable to fire given their mixture of bushland, houses, paddocks, livestock, and people.

Gould (2010) notes that a number of large bushfires over the last 30 years, and most recently the Victorian fires on February 7th 2009 has also shaped the fire management environment. Gould suggests that these events have meant that Australian fire agencies have recognised the need to adopt new levels of bushfire management activity. The recommendations of the 2009 Victorian Bushfires Royal Commission (VBRC) have helped highlight some of the changes needed, particularly in regards to the incident management workforce and IMT training programs. For example, the VBRC recommended that agencies recruit and train sufficient personnel to staff all level 3 incident control centres in the State on days of catastrophic fire danger and ensure these personnel are regularly exercised. The VBRC also recommended that agencies establish effective accreditation and performance review processes to assure the competency of all level 3 incident controllers, and that a traineeship scheme be developed to progress personnel from level 2[2] to level 3 IMT roles.

Taken together the ongoing changes in the bushfire environment highlighted by Gould (2010) and the VBRC recommendations have several important implications for agencies. First, there is a requirement to undertake additional training and exercising of IMT personnel. Second, agencies will need to ensure that IMT training programs develop a demonstrably competent workforce. Lastly, such IMT training will need to be time efficient and cost effective. There are a variety of training and development methods available to prepare IMT personnel (e.g., classroom instruction, field-based activities, simulation, and self-directed learning) and agencies have generally used a mixture of these. In light of the VBRC recommendations, a key challenge for agencies is how to best select from and use these methods to develop and maintain an appropriately prepared IMT workforce.

Simulation-based training offers some particular advantages for preparing and regularly exercising IMT personnel, enabling both individuals and teams to practice and integrate key competencies in a safe environment (Moroney and Lilienthal 2008; Simpson and Oser 2003). However, our experience of developing role-play and computer-generated simulations to assess the performance of individuals and teams managing bushfire scenarios (e.g., Omodei *et al*. 2005) has highlighted three key issues that agencies need to pay special attention to if they are to get the best results from using simulation training. The first issue is simulation fidelity, in other words a simulation's level of realism (Alessi 1998). Kozlowski and DeShon (2004) observe that organisations more often focus on maximising the physical fidelity of simulations (i.e., equipment and environment) and tend to overlook the psychological fidelity of simulations, such as cognitive demands and interpersonal elements. The second issue is participant debriefing. Salas and Cannon-Bowers (2001) note that unfortunately some organisations focus on the learning presumed to take place while undertaking the simulation scenario itself and neglect the learning opportunities by a post simulation review with participants. Effective debriefing offers the opportunity for participants to critically reflect on how they can improve their performance (Bond *et al*. 2007; Ericsson 2009; Kriz 2003; Thatcher 1990). The third issue is performance assessment. Without appropriate measurement processes in place it is difficult to provide constructive feedback to participants or assess the competence of an organisation, region, or team (Kruger and Dunning 1999). Moreover, without good performance assessment processes it is not possible to evaluate the training programs designed to develop and maintain IMT competencies (Morrison and Hammon 2000; Salas *et al.* 2003; Salas *et al.* 2009a).

Goldstein and Ford (2002) observe that trainees in general face two types of challenge, skill acquisition and training transfer. Skill acquisition involves the initial learning of the knowledge and skills required for successful performance, whereas training transfer involves the application of the learned skills and knowledge from the training context to the workplace and includes the associated issues of maintenance and generalisability (Baldwin and Ford 1988; Blume *et al.* 2010; Kraiger *et al.* 1993). The next section of this paper discusses the concepts of training design and training transfer and links these to the three issues that are central to simulation-based training – fidelity, debriefing, and performance assessment.

The design and transfer of training

A training system can be described as a series of experiences that systematically build and develop skills (Kozlowski 1998). Training design focuses on planning these experiences to facilitate learning and skill development (Gagne and Briggs 1979). Effective training design should support both learning and the transfer of the acquired knowledge and skills to the work setting (Kraiger *et al.* 1993).

Barnett and Ceci (2002) suggested that training transfer has two main elements, training content (i.e., what is transferred) and training context (i.e., when and where something is transferred). A key concept from this research is the concept of near and far transfer. This can be thought of as how closely the training context matches the environment that the learned skill may be used in and can also be thought of as the realism or fidelity of the training. For example, we would suggest that deploying classroom trained firefighters to participate in the physical clean-up of a maritime oil spill would involve far transfer. This concept has particular relevance if an agency is seeking to develop adaptive expertise, thus enabling IMTs to manage all-hazards (e.g., bushfires, earthquakes, cyclones, industrial incidents). Near and far transfer can also be considered in terms of the time elapsed between when training is undertaken and when the skills are used in the workplace. Immediate use of the trained skills would be considered near transfer while use of the trained skills more than one year later would be considered far transfer (Barnett and Ceci 2002).

Simulation-based training

Jacobs and Dempsey (1993) note that the use of simulation-based training by organisations to develop and maintain the competency of personnel has become common. Simulation-based training methods involve “a working representation of reality... [that] may be an abstracted, simplified, or accelerated model of process” (Galvao *et al.* 2000; p. 1692). Regardless of whether totally role-played, totally computer-generated or a combination of both, simulations vary in their cost, functionality, and fidelity (Salas and Cannon-Bowers 2001). There is growing evidence for the effectiveness of simulation-based training both in terms of learning and cost efficiencies (e.g., Cannon-Bowers and Bowers 2008; Fletcher 2009; Fletcher and Tobias 2006; Moroney and Lilienthal 2009; Salas *et al*. 1998; Salas *et al*. 2001).

Simulation-based training offers several advantages over other training methods (Cannon-Bowers and Bowers 2010): (1) it can provide the opportunity for personnel to practice managing or operating in environments that may be too dangerous to be practiced in the real world; (2) offers opportunities for personnel to practice tasks or manage events that may not occur very often (e.g., level 3 bushfire incidents); (3) provide opportunities to practice when actual equipment or facilities may not be available; (4) can include embedded instructional features that may provide a richer learning environment (e.g., feedback); and (5) provide considerable cost savings when compared to the use of operational equipment or large numbers of additional personnel for field exercise training.

Fidelity of simulations and transfer

The fidelity of simulations has been clearly linked to the transfer of training (Liu *et al.* 2009). A key issue in the use of simulation is often not the physical similarities of a simulated environment to the real world (i.e., physical fidelity), but the underlying structure of the problem or task that requires the use of particular cognitive processes and interpersonal processes that underlie the relevant competencies, that is, psychological fidelity (Cannon-Bowers and Bowers 2010). It is acknowledged that a certain level of physical fidelity is important to perceptually immerse participants and not mislead them as to key aspects of the situation for which they are training (Salas *et al*. 2002). However, training designers have tended to overly focus on developing the physical fidelity rather than the psychological fidelity of simulations (Hays and Singer 1989). From a training perspective, physical and psychological fidelity are not competing alternatives - they are complementary approaches (Kozlowski and DeShon 2004).

The psychological fidelity of simulations for incident management training requires particular attention for three important reasons. First, learning is multi-dimensional and involves at least three types of outcomes: cognitive, skill-based, and affective (Kraiger *et al.* 1993). It is important that training targets the development of each of these psychological components. Second, the generalisability of training is important for IMTs. Each bushfire is unique; the aim of effective simulation-based training is to develop the generic psychological processes that will be used in the management of any bushfire incident (e.g., decision making and analytical skills) (Hayes & Omodei 2011). Finally, the crew resource management literature highlights that failures in team performance are often due to poor team processes which are fundamentally psychological in nature (Cooper *et al.* 1980; Helmreich *et al.* 1999). For example, poor team coordination, leadership, communication and lack of shared situation awareness have contributed to a variety of aviation and other high reliability organisation accidents (e.g., nuclear and offshore oil power installations; merchant navy; surgical medicine) (Cooper *et al.* 1980; Flin *et al.* 2002).

Kozlowski and DeShon (2004) emphasize that psychological fidelity of simulations is an important aspect of training design. In developing simulation scenarios we need to think carefully about fidelity in light of the participants' characteristics (e.g., novice or experienced), task complexity (e.g., a level 2 or a level 3 incident), and type of skill development (e.g., new competencies or maintenance of existing competencies; routine or adaptive expertise) (Andrews and Bell 2000; Liu et al. 2009). Clearly a complex, high fidelity scenario for IMT personnel with limited experience is likely to overwhelm them and provide little training value, whereas highly skilled participants generally require more complex and higher fidelity scenarios to maintain their competencies (Andrews and Bell 2000; Beaubien and Baker 2004). If we want to develop personnel with competencies that can be used in other incident management settings (e.g., all-hazards) then the simulation scenarios with higher psychological fidelity (e.g., time pressured decision making) will provide superior transfer of training for this purpose (Salas *et al*. 2005).

Other training design factors may also impact on the fidelity of the simulation. If the simulation is designed to develop competencies (i.e., mastery), then it can be important to remove competitive elements (i.e., performance) from the simulation (Goldstein 1993). We have observed situations where competition between participants has led them to focus on “winning” rather than taking advantage of the learning opportunities that the simulation may offer. For example, employing high risk tactics to minimise the area burnt rather than developing a more balanced approach to containing the fire.

Well-designed simulations with sufficient psychological fidelity enable the creation of novel circumstances for participants, providing the opportunity to practice competencies in different contexts and thus supporting training that will generalise and be more adaptive. We suggest that the appropriate level of fidelity for simulation-based training can be particularly important when training personnel to work in conditions different from those they would normally encounter (e.g., inter-state). Recently one of the authors conducted role-play based simulations with personnel that usually manage bushfire in conditions of higher relative humidity (circa > 35%). Almost all of the teams in this location were keen to back-burn in conditions that fire personnel from south-eastern Australia generally would not consider as sensible to back-burn in (unpublished study). A second example is where statutory arrangements may be significantly different. For example, in the role-play based simulations mentioned above, some fire agency personnel struggled when the police did not operate in the same way as they would in their State (i.e., they could not order the evacuation of residents).

Debriefing simulation participants

Debriefing is an essential component of simulation-based training (Bond *et al.* 2007). Recent research has shown that simulation-based training for dynamic decision makers that incorporates debriefing improves subsequent task performance and the time required to make decisions (Qudrat-Ullah 2007). Unfortunately some organisations tend to view the simulation session as the key learning component, failing to recognise the important role of good quality feedback and effective debriefing (Salas and Cannon-Bowers 2001). We have on a number of occasions observed personnel spend several hours in a simulation session yet only receive a brief collective debrief. We suggest that the adoption of more structured after-action reviews by some Australian fire and emergency agencies is improving the opportunities for personnel to reflect on their performance following simulation-based training. However, we note that after-action reviews often tend to be conducted at the team-level and thus unlikely to offer individuals the opportunity to critically reflect on the various challenges they may have personally encountered during the exercise.

Organisations invest considerable time and money developing simulation-based exercises yet often do not maximise the learning opportunities for participants by fully debriefing such exercises (Crookall 1992). Effective debriefing encourages deeper processing and superior transfer of learning (Thatcher 1990). One-on-one debriefing in an environment where they feel able to interact free of criticism and embarrassment (i.e., psychologically safe) helps ensure participants critically reflect on their experiences (Edmondson 1999). The aim of debriefing is to assist the participants to develop self-critical thinking skills so that they can reflect on their own thoughts and actions and identify possible improvements in managing these (Thatcher 1990). As suggested by Andrews and Bell (2000) the opportunity for self-reflection during debriefing helps participants learn more from the sessions (i.e., greater mastery) and to further develop their metacognitive skills (i.e., think about their own thinking). Well-trained personnel with a sound knowledge of incident management, excellent interpersonal skills, and a good understanding of human factors should conduct the debriefings. A particularly useful tool for debriefing is the replaying of audio or video material from the session (also known as cued debriefing). Cued debriefing following a simulation can re-engage participants in their thoughts, emotions and behaviours at play during key moments of a scenario (McLennan *et al.* 2005). Effective debriefing helps participants focus on achieving enduring mastery of key competencies rather than on merely optimising observed performance in the particular exercise.

Performance assessment

The effectiveness of simulation-based training is also dependent on the quality of the associated performance assessment practices (Salas *et al.* 2009*a*). Information collected about the performance of personnel undertaking training provides core data for three important purposes: (1) to support the learning and development of the participants; (2) to generate evidence of the competency of participating personnel; and (3) to evaluate the effectiveness of training programs (Goldstein and Ford 2002; Kirkpatrick 1979). In some instances simulation sessions may also provide the opportunity for organisations to pilot or test new protocols, processes or technologies (Jones and Hutchinson 2008; Thompson *et al.* 2009).

Goldstein and Ford (2002) observe that many organisations fail to properly assess the effectiveness of their training programs. Ralph and Stephan (1986) found in their survey of Fortune 500 companies that most organisations only assessed the first two components of Kirkpatrick's (1979) four-level training evaluation framework (i.e., *reaction, learning, behaviour and results*). Ralph and Stephan noted that while most companies in their survey “usually” assessed whether trainees' were engaged by the training (*reaction*), only a smaller number of organisations tested trainees' learning at the end of a course (*learning*). Unfortunately very few of the surveyed organisations assessed whether training influenced the behaviour of trainees' on-the-job (*behaviour*) and even fewer organisations assessed whether the training translated into results that benefited the organisation (*results*). To ensure successful IMT training it is important that fire agencies evaluate the effectiveness of these programs including any simulation-based components. This requires agencies to conduct performance assessment at a variety of points in time including during instruction programs, whilst trained personnel are working on-the-job, and during subsequent IMT exercises and to collate and analyse this data.

We suggest that clear communication of the purpose of the simulation is particularly important because it is likely to influence the behaviour of the participants. For instance, participants should be aware of whether the session is being used as a training opportunity, or whether they are being assessed for accreditation purposes (e.g., Level 3 Operations Officer). If the session is training-oriented then participants may be more likely to be mastery-oriented, that is to experiment in the way they manage their responsibilities so that they might learn from failure and otherwise test the boundaries of their skills (Kozlowski *et al.* 2001). However, if the purpose of the simulation session is for accreditation or promotion purposes, then we suggest that the participants' focus will most likely be performance-oriented.

Regardless of the purpose of the simulation-based training, effective performance assessment should allow trainers to monitor participant performance, diagnose possible performance issues, and ensure that appropriate feedback is provided (Salas and Rosen 2010). To do this a variety of data needs to be collected at several different levels. For IMT training there is a requirement to consider both individual and team levels of performance. In using the term performance we also need to recognise that it is important to distinguish between performance in terms of sets of desirable behaviour (e.g., timely decision making) and performance in terms of the outputs produced by an individual or team (e.g., high quality situation report delivered on time). This distinction of performance as both a process and outcome indicates that both behavioural and outcome data should be collected.

Salas and colleagues have published a useful set of principles for the performance measurement of simulation-based training. The seven principles that we suggest are most important for training and assessing IMT personnel from Salas *et al.* (2009*b*) are:

Know the behaviours, attitudes, and cognitive competencies required for performance

Derive behavioural markers of performance for each learning outcome

Develop metrics that are diagnostic of performance

Capture performance at multiple levels of analysis

Develop and implement training programs for observers and instructors

Provide structured tools or protocols for observations

Do not overburden observers and maintain a good ratio of observers to trainees

Good psychological fidelity is particularly important for providing performance assessments (Morrison and Hammon 2000). We suggest that psychological fidelity increases the opportunity to observe a greater range of behaviours in simulations while providing greater insight as to underlying competency of participants. A particular advantage of simulation-based training is the opportunity to assess teamwork and interpersonal skills in a fairly realistic setting, providing greater clarity about how the individual or team may perform on-the-job (Kozlowski 1998).

Conclusion

The challenge of effectively training and maintaining the competency of a large IMT workforce is considerable. A key question for agencies is how to maximise skill acquisition and transfer of training for the workforce within existing time and cost constraints. Given the current need to swiftly develop additional IMT personnel and ensure regular exercising, simulation-based training provides an excellent method to develop and maintain the competency of these personnel. However, to get best value from an investment in simulation-based training, agencies need to ensure that the scenarios used are appropriately designed so that they offer appropriate psychological fidelity, ensure participants have the opportunity to undertake effective post-session debriefing, and carefully measure the performance of individuals, teams, and the adequacy of the training program itself.

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Notes

The Australasian Inter-agency Incident Management System (AIIMS) classifies incidents into three levels with Level 1 the simplest and Level 3 the most complex (AFAC 2005). In Level 3 incidents the three functions (i.e., Planning, Operations, and Logistics) are usually delegated into separate units, and Divisions on the fireground are typically established for effective management. Generally these incidents involve large numbers of personnel (> 100) and run for anywhere between a few days and weeks.

Level 1 incidents are usually resolved through the use of initial response of local resources, whereas Level 2 incidents are more complex and require: (a) the deployment of additional resources beyond initial response, or (b) the deployment of resources into sectors for management, or (c) the setting up of functional sections (Planning, Operations, and Logistics) due to the complexity of the incident, or (d) a combination of (a), (b), and (c) (AFAC 2005).

References

2009 Victorian Bushfires Royal Commission Final Report - Summary (2010) (Parliament of Victoria: Melbourne)

AFAC (2005) 'The Australasian Inter-service Incident Management System.' (Australasian Fire Authorities Council: Melbourne)

AFAC (2010) 'Climate change and the fire and emergency services sector: AFAC Discussion Paper April 2010' (Australasian Fire Authorities Council: Melbourne)

Alessi SM (1988). Fidelity in the design of instructional simulations. *Journal of Computer-Based Instruction* **15**, 40-47.

Andrews DH, Bell HH (2000) Simulation-based training. In 'Training and retraining: A handbook for business, industry, government, and the military' (Eds S Tobias and JD Fletcher) pp. 357-38. (Macmillan Reference: New York)

Baldwin TT, Ford JK (1988) Transfer of training: A review and directions for future research. *Personnel Psychology* **41**, 63-105.

Barnett SM, Ceci SJ (2002) When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin* **128**, 612-637.

Beaubien JM, Baker DP (2004) The use of simulation for training teamwork skills in health care: How low can you go? *Quality and Safety in Health Care* **13**, i51-i56.

Blume BD, Ford JK, Baldwin TT, Huang JL (2010) Transfer of Training: A Meta-Analytic Review. *Journal of Management* **36**, 1065-1105.

Bond WF, Lammers RL, Spillane LL, Smith-Coggins R, Fernandez R, Reznek MA, Vozenilek JA, Gordon JA (2007) The use of simulation in emergency medicine: A research agenda. *Academic Emergency Medicine* **14**, 353-363.

Brehmer B (2000) Dynamic decision making in command and control. In *The human in command: Exploring the modern military experience* (Eds C McCann and R Pigeau), pp. 233-248. (Kluwer Academic/Plenum Publishers: New York).

Brehmer B, Allard R (1991) Dynamic decision making: The effects of task complexity and feedback delay. In 'Distributed decision making: Cognitive models for cooperative work' (Eds J Rasmussen, B Brehmer and J Leplat) pp. 319-334. (Wiley: Chichester)

Cannon-Bowers JA, Bowers CA (2008) Synthetic learning environments. In 'Handbook of research on educational communication and technology'. (Eds JM Spector, MD Merrill, JJG van Merrienboer and MP Driscoll) pp. 317-328. (Lawrence Erlbaum: Mahwah, NJ)

Cannon-Bowers JA, Bowers CA (2010) Synthetic learning environments: On developing a science of simulation, games, and virtual worlds for training. In 'Learning, training, and development in organizations'. (Eds SWJ Kozlowski and E Salas) pp. 229-261. (Routledge: New York)

Cooper GE, White MD, Lauber JK (1980) Resource management on the flightdeck. In 'Proceedings of a NASA/industry workshop'. (NASA-Ames Research Center: San Francisco)

Crookall D (1992) Editorial: Debriefing. *Simulation & Gaming* **23**, 141-142.

Edmondson A (1999) Psychological safety and learning behavior in work teams. *Administrative Science Quarterly* **44**, 350-383.

Ericsson KA (2009) Enhancing the development of professional performance: Implications from the study of deliberate practice. In 'Development of professional expertise: toward measurement of expert performance and design of optimal learning environments.' (Eds K A Ericsson) pp. 405-431.(Cambridge University Press: Cambridge)

Fletcher JD (2009) Education and training technology in the military. *Science* **323**, 72-75.

Fletcher JD, Tobias S (2006) Using computer games and simulations for instruction: A research review. In 'Society for Applied Learning Technology Meeting'. pp. 1-34. (Orlando, FL)

Flin R, O'Connor P, Mearns K (2002) Crew resource management: improving team work in high reliability industries. *Team Performance Management: An International Journal* **8**, 68-78.

Gagne RM, Briggs LJ (1979) 'Principles of instructional design.' (Holt, Rinehart and Winston: New York)

Galvao JR, Martins PG, Gomes MR (2000) Modeling reality with simulation games for a cooperative learning. In '2000 Winter Simulation Conference'. (Eds JA Joines, RR Barton, K Kang and PA Fishwick) pp. 1692-1698. (Orlando, FL)

Goldstein IL (1993) 'Training in organizations: Needs assessment, development, and evaluation' (Brooks/Cole: Pacific Grove, CA)

Goldstein IL, Ford JK (2002) 'Training in organizations: Needs assessment, development, and evaluation.' (Wadsworth: Belmont, CA)

Gould J, (2010) Australian bushfire science and technology: trends, innovations and initiatives. Statement for 2009 Victorian bushfire Royal Commission. Document No. WIT.7545.001.0001. Available at http://www.royalcommission.vic.gov.au/getdoc/8dec002d-018d-48f3-a9f7-bb5a8d628c61/WIT.7545.001.0001 [Verified 7 November 2011]

Haswell D, Brown N (2002) Approaches to community safety and bushfires in southwestern Australia. In 'Proceedings of the Symposium: Fire in ecosystems of South-west Eastern Australia: Impacts and management: Volume 2 Community perspectives about fire' pp. 47-57. Available at http://www.dec.wa.gov.au/images/stories/nature/science/fire/fire_sym_community.pdf [Verified 7 November 2011]

Hayes PAJ, Omodei MM (2011) Managing emergencies: Key competencies for incident management teams. *The Australian and New Zealand Journal of Organisational Psychology* **4**, 1-10.

Hays RT, Singer MJ (1989) 'Simulation fidelity in training and system design: Bridging the gap between reality and training.' (Springer-Verlag: New York)

Helmreich RL, Merritt AC, Wilhelm JA (1999) The evolution of crew resource management training in commercial aviation. *International Journal of Aviation Psychology* ***9***, 19-32.

Hugo G. (2002) Changing patterns of population distribution in Australia. *Joint special issue, Journal of Population Research and NZ Population Review* ***Sept 2002*** 1-21.

Jacobs JW, Dempsey JV (1993) Simulation and gaming: fidelity, feedback, and motivation. In 'Interactive instruction and feedback'. (Eds JV Dempsey and GC Sales) pp. 197-227. (Educational Technology Publications: Englewood Cliffs, NJ)

Jones C, Hutchinson D (2008) *Can simulation replace on the job training?* Paper presented at the Queensland Mining Industry Health and Safety Conference 2008

Kirkpatrick DL (1979) Techniques for evaluating training programs. *Training & Development* **33**, 78-92.

Kozlowski SWJ (1998) Training and developing adaptive teams: Theory, principles and research. In 'Making decisions under stress: Implications for individual and team training'. (Eds JA Cannon-Bowers and E Salas) pp. 115-153. (American Psychological Association: Washington, DC)

Kozlowski, SWJ, Gully SM, Brown KG, Salas E, Smith EM, Nason ER (2001) Effects of training goals and goal orientation traits on multidimensional training outcomes and performance adaptability. *Organizational Behavior and Human Decision Processes* ***85***, 1-31.

Kozlowski SWJ, DeShon RP (2004) A psychological fidelity approach to simulation-based training: Theory, research and principles. In 'Scaled worlds: Development, validation and applications'. (Eds SG Schiflett, LR Elliott, E Salas and MD Coovert) pp. 75-99. (Ashgate: Aldershot)

Kraiger K, Ford JK, Salas E (1993) Application of cognitive, skill-based, and affective theories of learning outcomes to new methods of training evaluation. *Journal of Applied Psychology* **78**, 311-328.

Kriz WC (2003) Creating effective learning environments and learning organizations through gaming simulation design. *Simulation & Gaming* **34**, 495-511.

Kruger J, Dunning D (1999) Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self assessments. *Journal of Personality and Social Psychology* **77**, 1121-1134.

Liu D, Macchiarella ND, Vincenzi DA (2009) Simulation fidelity. In 'Human factors in simulation and training'. (Eds DA Vincenzi, JA Wise, M Mouloua and PA Hancock) pp. 61-73. (CRC Press: Boca Raton, FL)

Lucas C, Hennessy K, Mills G, Bathols J (2007) *Bushfire weather in southeast Australia: recent trends and projected climate change impacts*. (Melbourne: Climate Change Institute of Australia)

McLennan J, Pavlou O, Klein P, Omodei MM (2005) Using video during training to enhance learning of emergency incident command and control skills. *The Australian Journal of Emergency Management* **20**, 10-14.

McLennan J, Holgate AM, Omodei MM, Wearing AJ (2006) Decision making effectiveness in wildfire incident management teams. *Journal of Contingencies and Crisis Management* **14,** 27-37.

Moroney WF, Lilienthal M (2009) Human factors in simulation and training: An overview. In 'Human factors in simulation and training'. (Eds DA Vincenzi, JA Wise, M Mouloua and PA Hancock) pp. 3-38. (CRC Press: Boca Raton, FL)

Morrison JE, Hammon C (2000) 'On measuring the effectiveness of large-scale training simulations.' (Alexandria, VA: Institute for Defence Analysis)

Omodei M, Elliott G, Walshe M, Wearing A, J. (2005) Networked Fire Chief: A research and training tool that targets the human factors causes of unsafe decision making in wildfires. In 'International Association of Wild Fire Safety Summit'. (Eds BW Butler and ME Alexander). (Missoula, Montana)

O'Neill P (2004) Developing a risk communication model to encourage community safety from natural hazards. Australian Com Safety Program. Available from http://www.ses.nsw.gov.au/content/documents/pdf/research-papers/42904/Developing_a_risk_communication_model.pdf [Verified 7 November 2011]

Qudrat-Ullah H (2007) Debriefing can reduce misperceptions of feedback: The case of renewable resource management. *Simulation & Gaming* **38**, 382-397.

Ralph LT, Stephan E (1986) HRD in the Fortune 500. *Training and Development Journal* **40**, 69-76.

Salas E, Bowers CA, Rhodenizer L (1998) It is not how much you have but how you use it: Toward a rational use of simulation to support aviation training. *International Journal of Aviation Psychology* **8**, 197-208.

Salas E, Burke CS, Bowers CA, Wilson KA (2001) Team training in the skies: does crew resource management (CRM) training work? *Human Factors* **43**, 641-674.

Salas E, Cannon-Bowers JA (2001) The science of training: A decade of progress. *Annual Review of Psychology* **52**, 471-499.

Salas E, Oser RL, Cannon-Bowers JA, Daskarolis-Kring E (2002) Team training in virtual environments: An event-based approach. In 'Handbook of virtual environments: design, implementation, and applications'. (Ed. KM Stanney). (Lawrence Erlbaum: Mahwah, NJ)

Salas E, Milham LM, Bowers CA (2003) Training evaluation in the military: misconceptions, opportunities, and challenges. *Military Psychology* **15**, 3-16.

Salas E, Wilson KA, Burke CS, Priest HA (2005) Using simulation-based training to improve patient safety: What does it take. *Joint Commission Journal on Quality and Patient Safety* **31**, 363-371.

Salas E, Rosen MA, Held JD, Weissmuller JJ (2009a) Performance measurement in simulation-based training: A review and best practices. *Simulation & Gaming* **40**, 328-376.

Salas E, Rosen MA, Weaver SJ, Held JD, Weissmuller JJ (2009b) Guidelines for performance measurement in simulation-based training. *Ergonomics in Design: The Quarterly of Human Factors Applications* **17**, 12-18.

Salas E, Rosen MA (2010) Experts at work: principles for developing expertise in organizations. In 'Learning, training, and development in organizations'. (Eds SWJ Kozlowski and E Salas) pp. 99-134. (Routledge: New York)

Simpson H, Oser RL (2003) Evaluating large-scale training simulations. *Military Psychology* **15**, 25-40.

Thatcher DC (1990) Promoting learning through games and simulations. *Simulation & Gaming* **21**, 262-273.

Thompson TN, Carroll MB, Deaton JE (2009) Justification for the use of simulation. In ‘Human factors in simulation and training’ (Eds DA Vincenzi, JA Wise, M Mouloua and PA Hancock) pp. 39-48. (CRC Press: Boca Raton, FL)

Whittaker J, Handmer J (2010) Community bushfire safety: a review of post-Black Saturday research. *The Australian Journal of Emergency Management* **25** 7-13.

The Complex Network within Bushfire Investigation Strategy

An international comparative analysis of internal and external dynamics between post-bushfire investigative departments

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Abstract.

Worldwide, almost 90% of all bushfires can be attributed to human action either unintentional or malicious. In this light, it is evident that all bushfires should be investigated to some level, not just for reconstructing the event of bushfire itself, but also for planning an appropriate bushfire protection strategy through policy and program development.

Unfortunately 40% of all fires attended across Australia do not have a cause assigned by the responding fire and police agencies. This situation is similar to many other jurisdictions around the world.

The investigation of the origin and cause of major fires is a complex procedure undertaken jointly by fire and police agencies and often involving personnel from other organizations such as forensic science and insurance companies.

Given that bushfire has become a devastating global dilemma the opportunity to collaborate with investigators from other jurisdictions in the sharing of data and investigation techniques provides an important opportunity to pool expertise and collective understanding. Unfortunately there is very little evidence of collaboration at either the national- or international-level. Furthermore, even in those cases where state-level collaborations on these events have been developed, it is usually based on informal structures comprising an exchange of information and ideas, rather than a formal system constituted by a sharing of knowledge. Thus, identifying and understanding the opportunities for inter-organizational collaboration, and above all, the likely communicational impediments, represents a key step to improve the integration and application of efficient forensic investigation activities by fire and police agencies.

Introduction

The incidence and impact of bushfires in Australia and globally has increased over the past several decades to the point that these blazes are affecting approximately 350 million hectares of land a year (FAO 2010) with incalculable costs in terms of lives, nature and properties.

According to the Centre of Fire Statistics (CTIF) at the beginning of the 21st century, the population of the Earth was 6.3 billion, who annually experienced a reported 7 - 8 million fires with 70.000 –80.000 fire deaths and 500.000 –800.000 fire injuries (CTIF 2006).

In this scenario, the population of Europe is 700 million, who annually experience a reported 2 -2.5 million fires with 20.000 –25.000 fire deaths and 250.000 –500.000 fire injuries. In the table below we can see that the European countries most affected by bushfires are in the south of the continent.

Table 1: Bushfires in Europe (2000-2008)

COUNTRY	NUMBER	AREA (HA)
Bulgaria	709	15.944
Croatia	4.800	46.926
Czech Republic	933	356
Estonia	143	995
Finland	837	616
France	4.362	22.935
Germany	942	430
Greece	1.765	50.782
Hungary	382	1.889
Italy	7.463	85.047
Latvia	875	1.007
Lithuania	699	367
Poland	10.371	7.566
Portugal	24.819	157.066
Romania	272	1.449
Slovakia	433	570
Spain	18.664	125.687
Sweden	5.290	2.662
Switzerland	62	216
Turkey	2.128	11.067

Source: EFFIS (*European Forest Fire Information System*)

So it is not a mere coincidence the fact that Italy, Spain and Portugal, along with Greece and France, have participated in the European project denominated FIRE 5 (Force d'Intervention Rapide Europeenne 5) to become "experts" in the process of exchanging of information, experiences, knowledge.

In the Southern hemisphere, Australia is also one of the most fire-prone countries on Earth.

Each year 'disaster-level' bushfires (where the total insurance cost of the event was more than $10 million) cost Australia an average of $77 million. "In Australia more people were injured by bushfires than all other disasters combined, creating 48 per cent of the total death and injury cost from natural hazards" (AIC 2004).

Therefore, the management of bushfires represents an extremely significant issue that has social, criminological and environmental consequences. The need to recognise and to actively manage bushfires is an unavoidable step in planning an appropriate bushfire management strategy through policy and program development.

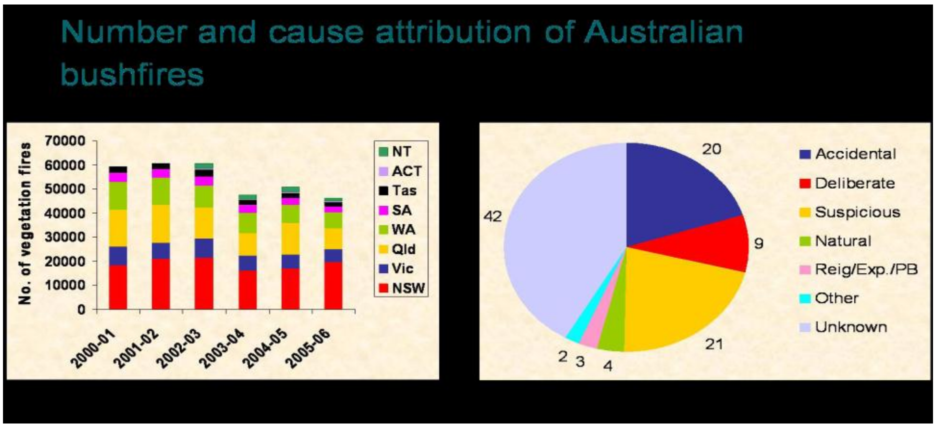
Context

The forensic investigation of fire is a particularly demanding area of expertise in which managing uncertainty is a relevant element (Biedermanna *et al.* 2004). In particular, t*he attribution of the causes of fire and, more specifically, the motivations of any individuals involved is a key factor.*

In 2007 the Australian Institute of Criminology completed the classification of the numbers and causes of bushfires in Australia. The final pie graph (Fig. 1) is based on an analysis of nearly 300,000 records from 18 fire agencies over five years, from 2000 to 2006. Nonetheless, the scenario seems to be characterized by a lack of clearness concerning the major causes behind bushfires. As can be seen in Figure 1, the majority of bushfires (42%) does not present a clear cause attribution and are, therefore, defined as 'Unknown'. The second largest group, representing 21% of all causes, has been classified as 'Suspicious'. This means that it will be necessary a further investigation carried out by police agencies in order to understand if the fire was ignited either in a deliberate or accidental way. In both cases, it is likely related to human action; these constitute 50% of all bushfire causes. The natural causes represent just the 4% of the total of causes.

Fig. 1: Proportion of vegetation fires in Australia by assigned cause

Past data collection in Australia

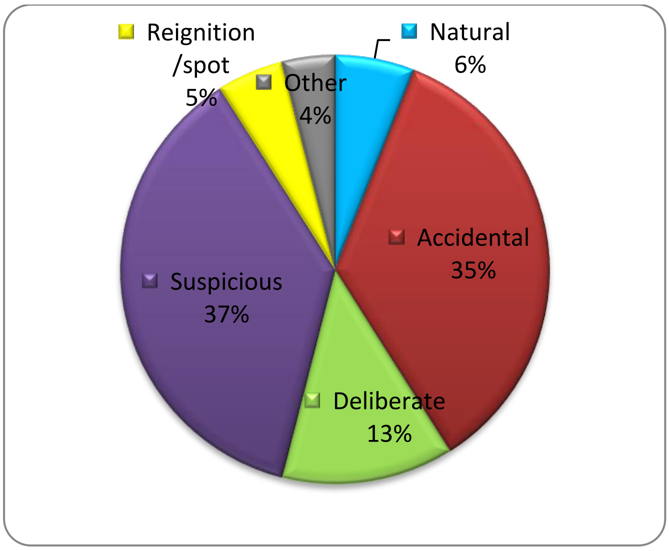


Source: Productivity Commission 2007 (AIC Computer File - Combined Australian fire agencies)

This same classification was rewritten according to the new system of attribution compiled a few years later as shown in figure 2. So, in 2009, the situation appears dramatically changed. Indeed, while both pie graphs show a similar number of 'Natural' (6%) and 'Other' (4%) causes of fires, in Figure 2 the group "Unknown" has disappeared. Thus, the major cause is now ‘Suspicious’ (37%), immediately followed by “Accidental’ (35%). If we add 13% “deliberate”, 85% of all bushfires are caused by human action – see above.

Fig. 2: Proportion of vegetation fires in Australia by assigned cause

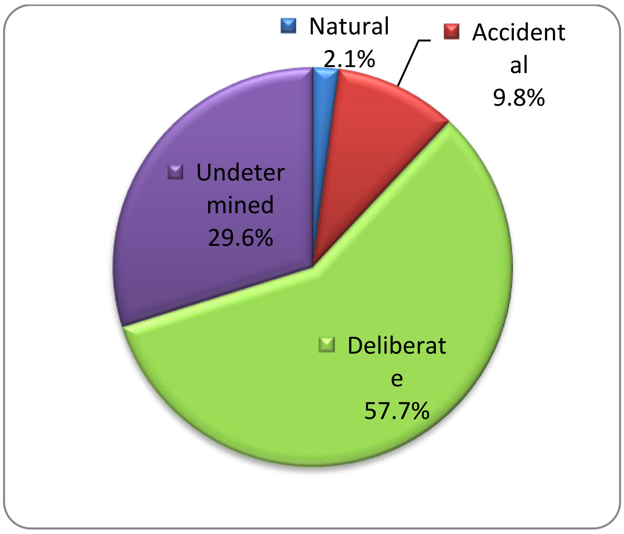
Current data collection in Australia



Source: Combined Australian fire agencies [computer data file], October 2009, AIC.

In terms of causes of fires, we can witness a very similar outcome in Italy. However proportions of attributions appear to be slightly different. As can be seen in Figure 3 (Italian Fire Brigate 2007), this is particularly true for ‘Deliberate’ fires which, with 58%, represent the major cause of all Italian fires. The second major group, representing almost 30%, corresponds to ‘Undetermined’ causes. Despite what has been said, however, the cause of the majority Italian fires is to be assigned to human actions (70% approximately). This statistic, indicating that human action is the major cause of fires, is what makes the phenomenon of bushfire a global issue. Even two so different countries, as Italy and Australia, have more similarities than it would appear.

Fig. 3: Proportion of fires in Italy by assigned cause



Source: Italian Fire Brigade - 2007

The crucial point is that more than half of all bushfire across Australia do not have a cause assigned or, at the best, they are defined as suspicious or uncertain by the responding fire and police agencies. As also noted by the Victorian Bushfires Royal Commission (2009) the extent and causes of this global dilemma are not well understood. The lack of reliable data of the reason and cause of a fire represents an impediment to the interpretative aspect of fire investigation which is important in order to have better targeted and informed programs (Drabsch 2003).

The causes of bushfires

There has been much discussion on the causes that lead to fires, often with some degree of superficiality. For a long time this discussion has not gone beyond the attribution of fires to natural phenomena. In Australia, therefore, it has been thought that "lightning" would be the main reason for most bushfires (Bond and Keeley 2005; Darwin 1859; Johnson, Miller, Fogel, Magee, Gagan, and Chivas 1999; Bowman and Murphy 2011).

In Italy, self-ignition has been seen as the principal cause behind bushfires, even if it is a rather rare event (DeHaan 2002; Eric Stauffer 2005). The reality, however, is very different and complex and it certainly deserves a further examination. It now is known that almost 90% of all bushfires as well as structural fire can be attributed to humans, for actions that are either unintentional or malicious, while natural causes have less relevance (Provincia di Genova 2003; Willis 2004; Kapardis 1983; Bryant 2008).

Many of those people who cause fires do so for specific and well planned reasons. This is the case with arson which is further subdivided on the basis of the reason behind the act of crime (Rebekah Doley 2003). Fires, then, can be set for economic gain, to hide a crime, for revenge, as a political act, for actions of pyromaniacs or simply to attract attention. It is precisely for these reasons that the Crime Classification Manual classifies arson among the three main violent crime typologies, alongside sexual violence and homicide (Douglas *et al.* 1997).

Many psychologists, psychotherapists and psychiatrists have worked on these complex and varied behavioral typologies without, however, managing to reach a well defined “fire setter’s syndrome”. Moreover, it has to be taken into consideration the fact that all causes and reasons behind an arson have been conducted in urban settings and, mostly, in Europe and the United States of America. Little attention has been paid to the motives of bushfire arsonists, especially in Australia.

Moving from this presumption, Willis (2004) has studied the incidence and motivations of deliberately lit bushfires in arson, identifying five major types with a range of sub-types.

1 - <u>Bushfires lit to create excitement or relieve boredom</u>

Vandalism (by individuals or groups)

Stimulation (the author is interested in doing something ‘really’ extraordinary and exciting)

Activity (an attempt to generate activity and relieve boredom)

2 - <u>Bushfires lit for recognition and attention</u>

Heroism (through reporting the fire and helping the fire services during the suppressions activity, it is possible for the arsonist to become an ‘hero’)

Pleading (it is defined and thought as a ‘cry for help’)

3 - <u>Bushfires lit for a specific purpose or gain</u>

Anger (intended as a form of revenge or protest)

Pragmatic (a practical activity that leads to an uncontrolled bushfire, e.g. land clearing)

Material (e.g. firefighters seeking to obtain overtime)

Altruistic (e.g. gain funding for small rural fire services)

4 - <u>Bushfires lit without motive</u>

Psychiatric (psychological or psychiatric impulses derived from mental disabilities)

Children (simply driven by curiosity, as a private form of experimentation)

5 - <u>Bushfires lit with mixed motives</u>

Multiple (different reasons at the same time)

Researchers agree on the four main reasons: for curiosity (Fineman 1995; Kolko and Kazdin 1991; Vreeland and Waller 1980); by crisis, when the behavior represents a mean to communicate stress or the efforts to seek a relief to their own tensions (Fineman 1995; Koike and Kazdin 1991); delinquent, when the use of fire becomes a mean of rebellion against the authority (Sakheim and Osborn 1994; Koike and Kazdin 1989a); and pathological when we are dealing with those who have psychiatric disorders (Rice and Harris 1991; Fineman 1995).

In conclusion, it can be said that there will always be fire-setting acts differentiated in function, modality and significance (Laxenaire and kuntzburger 2001).

For this reason, data on these aspects are of priority to understand specific reasons and causes for these events. Large intense bushfires are undoubtedly terrifying and can be lethal. Nonetheless, these human-caused fires are potentially preventable rightly because they are caused by humans (Willis 2005).

The project

The most challenging aspect in ensuring an effective investigation is that there are many factors need to be considered often by more than one agency (Webster 2008). The need to collect more data over a much larger area and, above all, in a coordinated and efficient manner is seen as a 'key need'. Indeed, improved quality data capture will help increase our understanding of wildfires. In other words, to improve efficacy and efficiency in understanding and predicting the complex interactions of fire management, data collection and fire investigation knowledge should be better developed and, above all, shared across agencies and state boundaries (Lewis, symposium 2010). This approach constitutes the most suitable basis for an integrated and strategic fire investigation program.

Undoubtedly, investigating the reasons and causes of major fires is a complex procedure recognized as a joint undertaking between fire officers, police officers, crime investigation personnel, forensic scientists and representatives from insurance and other emergency service organizations. In Australia, fire agencies and police have separate and complementary roles in the investigation process (AIC 2006). The initial decision as to whether a bushfire is investigated as arson rests with the firefighters who attend the fire; if the fire investigator suspects the fire was deliberately lit they will then refer the matter to the police for a criminal investigation. It is clear, at this stage, that a strong relationship between police and fire agencies, including well understood protocols of responsibility and efficient information sharing, can increase capacities for the successful investigation and prosecution of bushfire arson.

The root of this assumption is the observation that agencies cannot provide effective investigation activity in isolation, as affirmed also by Dwyer and Esnouf (2008), particularly in a complex system, such as bushfire. The best way to guarantee a safe and secure environment for everyone is to share knowledge and form collaborations between all stakeholders in this field, at both national and international levels. The Council of Australian Governments (COAG) has highlighted that cooperation and information sharing between bushfire agencies and police services are key elements within a bushfire reduction strategy (Ellis *et al.* 2004).

The same necessity has been also confirmed and underlined by several organizations and researchers both in Australia and globally. For example, Tomkins clearly showed the desire for cooperation between different policing institutions (Tomkins 2005). Similarly, an innovative project was delivered in UK with the purpose of sharing “Best Practice in Arson Prevention and Investigation” by creating a European network. This network developed Fire Investigation Training Modules, to be utilised by all European countries (Northumberland Gov. 2009). In this scenario, the strong commitment of both Bushfire Cooperative Research Centre and The Australasian Fire and Emergency Service Authorities Council on adopting a holistic and multidisciplinary approach of bushfire management across Australia is also well known.

Unfortunately, it is difficult to find evidence of national- and international-level collaboration-building efforts between and across sectors. Furthermore, even in those cases where state-level collaborations are present, what we can witness is, at maximum, an informal structure based on an exchange of information and ideas, rather than a formal system constituted by a real and sharing of knowledge. Identifying and understanding inter-organizational connections and dynamics, above all in terms of impediments, is a necessary step to improve the integration and application of efficient forensic investigation activities by fire and police agencies.

The *central questions* are:

- How do organizations deal with post bushfire investigation and what is their remit?
- What are the factors that enable or prevent effective collaboration within bushfire investigation?
- How does professional communication within and between organizations lead to a successful complex collaboration?
- How can organizations structure themselves to deal effectively with a post bushfire investigation? Is there an international dimension to such investigation actions?

Aims and approach

The aim of the project is to identify strengths and weaknesses of knowledge sharing between bushfire investigative related agencies as well as their internal practices and procedures in undertaking bushfire investigation. This analysis will focus on the role of professional communication, seen as one of the most relevant facilitator in inter-organizational bushfire investigation activities.

The main issue seems to be the fact that despite the investigation of the causes of bushfires is a shared responsibility in Australia between fire and police services they take different paths. This difference could inhibit a joint approach. Some practical examples include police not attending suspicious fire reports or fire agencies not advising police of suspicious fires.

Some reasons for these different paths may include organisational vision which appears to strongly influence the level of commitment of agencies. The differing bushfire investigation cultures of fire and police agencies in respect of thinking, approach, training and language can be perceived either as an inhibitor or as a strength for an effective inter-organizational collaboration (Mitchell 1999). To explore this, a symbolic-interpretive perspective will be adopted within the broader framework of organizational theory so to be able to analyze these complicated situations.

The research methodology, therefore, is guided by a philosophical approach in promoting understanding and cross-national learning rather than by a specific technique focused on obtaining precise measurement. To effectively address the complex nature of business communication to which this project aims, it will be utilized a qualitative case study approach that is international in its scope, cross-sector in its breadth, and multidisciplinary in its conceptualization. More specifically, it will be adopted an interpretative and social constructivist approach in order to satisfy the desire of working with a plurality of perspectives and of using participatory methods (Carey 1992).

It is necessary to keep in mind that those organizations who are involved in the post bushfire investigation such as police, fire services and state emergency services have a common organizational feature; they are primarily emergency service organizations. More specifically to the research project, five post bushfire investigation departments will be studied as five different case studies through interviews, focus groups and document analysis. These organizations will be: Victoria Police, Department of Sustainability and Environment (DSE) and Country Fire Authority (CFA) in Victoria; Anti-Forest Fire Investigative Unit (NIAB) and Fire Investigative Unit (NIA), in Italy.

Although Victoria and Italy may differ in many aspects regarding to bushfire investigation strategy including policy, procedures and even the organizations involved, they present some common characteristics. Indeed, both countries:

- have to deal with the same devastating dilemma and with the same degree of alarm;

- have more than one organization involved within the bushfire investigation network;

- are in the need of an efficient and efficacy extent of professional communication (intra and inter organization).

In addition to the main characteristic of the above mentioned agencies is that, as emergency organizations, all of them follow a military style structure, especially in terms of management and ranking system. In working with continuous improvisation and coping with a high degree of uncertainty after-action-reviews, lessons-learned and knowledge management become essential for the entire military and emergency organizational system (Rostis 2007).

In this light, organizational learning plays an important role in the creation of a 'culture of reliability', which is essential in order to operate in very dynamic and high risk environments (Argyris 1999). Activities that support this, such as expert meetings or management development programs, lead to the creation, sharing and transfer of knowledge, are called organizational learning mechanisms.

Furthermore, organizational learning occurs within a dialectical process (Berends and Lammers 2006). This means that organizations are necessarily involved in continual transaction with their internal and external environments which are constantly changing both as a result of forces external to organization and as a result of organizational responses to their situations. The whole process of interaction, therefore, is strongly based on the concepts of interpersonal communication and information flow.

Yet, even if we deal with these communication obstacles through dialogue and enhanced understanding, this still does not mean that we have any level of conformity between bushfire stakeholders or that they can actually work together in a meaningful way. Indeed, learning requires common codes of communication and coordinated search procedures (Beyerlein, Beyerlein and Kennedy 2005).

Conclusion

There is still a strong need to equip bushfire stakeholders with common terminology, data collection and information-sharing processes in order to assist the development of evidence-based prevention measures as well as to identify and share best-practice approaches (Royal Commission - Final Report 2009). To develop effective international policies, there is a requirement to coordinate the process of collecting and evaluating global bushfires data. This will represent a first step in order to improve the ways in which communication takes place within and between bushfire investigative departments. This project is based on the assumption that communication, conceptualized as a dynamic process, is the key factor in creating, sustaining, and transforming learning organizations.

From a holistic perspective, fire and police agencies can improve, by studying their structural and operative barriers, in the awareness of what are the major weaknesses in their own bushfire investigation and, by maximising communication and collaboration with other fire stakeholders, in the quality of their interconnections as well as of their knowledge.

This self-awareness can be seen as the basis for a better understanding, which is essential to provide these agencies with an appropriate level of power and knowledge, required in any process of growth. The final aim should be the building of reciprocal trust and lasting collaboration between different fire stakeholders. This can be reached through the establishing of an international network based on inter-agencies agreements, once the prime causes of the miscommunication and inadequate data collection are identified.

References

Argyris C (1999) On organizational learning 2nd ed. Blackwell publishing. United Kingdom.

Australian Institute of Criminology (2004) The cost of Bushfires. *Bushfire Arson bulletin* **2**. Canberra. November, 2004, http://www.aic.gov.au/%20publications/current%20series/bfab/1-20/bfab002.aspx.

Australian Institute of Criminology (2006) Bushfires Arson Investigation. *Bushfire Arson bulletin* **37**. Canberra. October, 2006.

Berends H and Lammers I (2006) Contrasting Dynamics of Organizational Learning: A Process Theory Perspective. OLKC 2006 Conference at the University of Warwick, Coventry on 20th - 22nd March 2006.

Beyerlein MM, Beyerlein ST, Kennedy FA (2005) Advances in Interdisciplinary Studies of Work Teams. Volume 11 - Collaborative Capital: Creating Intangible Value.

Biedermanna A, Taronia F, Delemonta O, Semadenid C, Davisond AC (2004) The evaluation of evidence in the forensic investigation of f ire incidents (Part I): an approach using Bayesian networks. June 2004.

Bond WJ, Keeley JE (2005) Fire as a global 'herbivore:' the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution* **20**: 387-394. doi: 10.1016/j.tree.2005.04.025.

Bowman DMJS, Murphy BP (2011) Australia - A Model System for the Development of Pyrogeography. *Fire Ecology* **7**, *Issue 1. doi: 10.4996/fireecology.0701005.*

Bryant C (2008) Understanding bushfire: trends in deliberate vegetation fires in Australia. *Technical and background paper series* **27**. Canberra: Australian Institute of Criminology.

Carey JW (1992) Communication as Culture. Routledge, London.

Country Fire Authority (1983) The Major Fires Originating 16th February 1983, CFA, Melbourne.

CTIF (2006) World fire statistics report № 10 of centre of fire statistics of CTIF - Dr. Ing. Peter Wagner.

Darwin C (1859) On the origin of species by means of natural selection, or, the preservation of favoured races in the struggle for life. John Murray, London, United Kingdom.

DeHaan J (2002) Kirk's fire investigation. 5th ed. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Doley R (2003) Making sense of arson through classification. *Psychiatry, psychology and law* **10**.2 (2003): 346-352.

Doley R M (2009) A Snapshot of Serial Arson in Australia. Köln, Germany: Lambert Academic Publishing.

Douglas JE, Burgess AW, Burgess AG, Ressler RK (1997) Crime Classificàtion Manual, New York, Lexington Books.

Drabsch T (2003) Arson: Briefing Paper 2/2003. NSW Parliament, Sydney. Http://www.parliament.nsw.gov.au .

Dwyer G and Esnouf G (2008) The international bushfire research conference 2008. The Adelaide Convention Centre, Australia 1-3 September 2008. Inquiries and Reviews in Victoria: Key Recommendations and Outcomes 1939 – 2008.

Ellis S, Kanowski P, Whelan R, (2004) National Inquiry on Bushfire Mitigation and Management. Commonwealth of Australia, Canberra.

Flneman K (1980) Firesetting in children and adolescents. *Psychiatric Clinics of North America*, **3**, n. 3.

Food And Agriculture Organization - FAO (2010) Will help countries to detect fire hotspots in real time. www.fao.org/news/story/en/item/44613. 11 August 2011.

Harris GT, Rice ME (1984) Mentally disordered firesetters: Psychodynamic versus empirical approaches. *International Journal of Law and Psychiatry* **7**.

Johnson BJ, Miller GH, Fogel ML, Magee JW, Gagan MK, Chivas AR (1999) 65,000 years of vegetation change in central Australia and the Australian summer monsoon. *Science* **284**: 1150-1152. doi: 10.1126/science.284.5417.1150.

Kapardis A, Rawson R, Antonopoulos N, (1983) Research note: mancaused forest fires in Australia. *Australian and New Zealand Journal of Criminology* **16**.

Kolko DJ, Kazdin A (1989) Assessment of Dimension of Childhood - Firesetting Among Patients and nonpatients: the Firesetting Risk Interview. *Journal of Abnormal Child Psychology* **17**, n. 2.

Laxenaire M, Kuntzburger F (1995) Les incendiaires, Masson, Paris (trad. It. Gli incendiari, Centro Scientifico Editore, Torino 2001).

Lewis C (2010) Improving multi-agency approaches to arson prevention. Workshop at the Symposium Advancing Bushfire Arson Prevention in Australia. Melbourne, 25-26 March 2010.

Mitchell B (1999) Integrating emergency services. *The Australian Journal of Emergency Management* **14**, No 1, Autumn 1999.

Productivity Commission (2007) AIC Computer File - Combined Australian fire agencies. www.aic.gov.au.

Provincia di Genova (2003) Primo Rapporto sullo Stato dell'ambiente, *Natura e Biodiversità* in ww2.provincia.genova.it/agenda21/Cap.10%20Natura%20e%20Biodiversit%E0.pdf – Provincia di Genova – Anno 2003.

Rostis A (2007) Make no mistake: the effectiveness of the lessons-learned approach to emergency management in Canada. *Int J. Emergency journal* **4** n.2 pp. 197-210.

Royal Commission (2009) Final Report. Volume 2; chapter 5: Deliberately-Lit bushfire. www.royalcommission.vic.gov.au/Commission-Reports/Final-Report.

Sakheim GA, Osborn E (1994) Firesetting children. Risk assessment and treatment. Washington, DC: Child Welfare. League of America.

Stauffer E (2005) A Review of the Analysis of Vegetable Oil Residues from Fire Debris Samples: Spontaneous Ignition, Vegetable Oils, and the Forensic Approach. *J Forensic Sci* **50**, No. 5, Sept. Available online at: www.astm.org.

Tomkins K (2005) Police, Law Enforcement and the Environment [online]. *Criminal Justice* **16**, Issue 3; Mar 2005; 294-306.

VIC. Gov. (24/11/2009) Media Release, www.premier.vic.gov.au

Vreeland RG, Waller MB (1978) The psychology of Fire-Setting: a Review and Appraisal, in Us Dept of Commerce, National Bureau of Standards, Washington, DC.

Webster J (2008) Essential bushfire safety tips. 2nd ed. CSIRO publishing, Victoria, Australia.

Willis M (2004) Bushfires Arson: a review of the Literature. *Research and Public Policy Series* **61**. Australian Institute of Criminology, Canberra.

Willis M (2005) Bushfires-How can we avoid the unavoidable? *Global Environmental Change,* part B: environmental Hazards, **6**, issue 2, 2005 pages 93-99.

Websites

www.ag.gov.au/www/ministers/mcclelland.nsf/

www.corpoforestale.it

www.effis.jrc.ec.europa.eu

www.ec.europa.eu

www.fao.org

www.incendiboschivi.org

Incendi boschivi in Italia dal 1970 a12001

Gli incendi più gravi del 2000 e del 2001

www.northumberland.gov.uk/default.aspx?page=1311

www.redcross.org.au

Capturing Community Members' Bushfire Experiences: The Lake Clifton (WA) Fire

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Abstract

On Monday January 10, 2011 a fire broke out in the Lake Clifton district, which is 109 km by road from Perth CBD and 68kms from Bunbury. More than 40 houses were saved but 10 houses were lost together with a number of other structures in the rural subdivision development known as Armstrong Hills at Lake Clifton. The fire caused much of the damage during the initial six hours, and after that time it was more a matter of containing the fire and extinguishing where it was burning than defending further property and homes. Although the fire never reached the area, residents of neighbouring Tuart Grove were evacuated. No lives were lost. However, in addition to the 10 destroyed dwellings, losses included many outbuildings, farming equipment, livestock, and fencing.

During the week after the fire, the Bushfire Cooperative Research Centre (Bushfire CRC) and the Fire and Emergency Services Authority of Western Australia (FESA) assembled a taskforce with the brief to investigate the events of the day from the perspective of the local residents. This report is written with a view to providing a methodological framework from which to build future like research. Nonetheless, several of the key findings are also discussed so as to expand on the existing database of community responses to bushfire threat (e.g. Galea & McNally, 2010; McLennan & Elliott, 2010). More detailed discussions of the results can be found in the recent report on the fire by McLennan, Dunlop, Kelly, and Elliott (2011).

Method

Research Taskforce

The research taskforce comprised nine individuals from two disciplines: four members of the taskforce were affiliated with research institutions (via the Bushfire CRC), and the remaining five were affiliated with FESA. Prior to the start of data collection, three taskforce representatives met with the local community recovery group to discuss the goals of the research project and gain an understanding of the issues the community was facing in the wake of the fire. This proved to be very critical for quickly building credibility within the community as it enabled us to establish a formal and sanctioned presence in the area. The taskforce then established a 'home base' near the fire affected area to act as a central point of contact and from which to conduct planning activities. All members of the taskforce were dressed in branded outfits (either Bushfire CRC or FESA, as appropriate) and all wore name tags.

Materials

Prior to the commencement of the data collection, a map of the area, showing the fire scar and the locations of all affected properties, was shared amongst the taskforce members. The map also included a list of all addresses and the corresponding status of the property (vacant, structure[s] damaged, structure[s] destroyed, or structure[s] intact) and was used throughout the project as a means of monitoring which properties were visited. Each interview pair was also equipped with the following items: a digital audio recorder, pens/pencils, a laboratory note book, a laminated copy of the interview protocol, and a ring binder containing project information sheets, support information sheets, and demographic questionnaires. All interviewers were provided with ample supplies of water throughout the day and food was provided at lunchtime.

A semi-structured interview protocol was developed, based on that used by the Bushfire CRC Research Taskforce following the 2009 Victorian bushfires (Whittaker et al 2009). Residents were asked about their awareness of bushfire risk, fire plans, awareness of official and informal warnings about the fire, and actions on the day of the fire. Interviewers were also encouraged to ask further probing questions or deviate slightly from the protocol, where appropriate, so as to elicit more detailed responses.

Procedure

***Planning**.* All data were collected during the period January 18 – 21, 2011. On each day, all taskforce members who were rostered to work met at the home base at an agreed starting time. The taskforce members that were rostered for that day were then divided up into pairs. At no stage did any pair comprise two individuals from FESA as it was considered very important that the research be seen by participants as being at arm's length from the emergency services authority. At all times, one member of each pair wore a blue tabard with "Researcher" appearing in clear lettering.

Each day was divided up into two three-hour blocks: a morning block (10am-1pm) and an afternoon block (2pm-5pm). Pairs were mixed so that no two individuals worked together for more than a single block in order to randomise any systematic researcher effects that may have emerged. Prior to the commencement of each time block, each pair was assigned a list of addresses to visit in sequence during the time block. All addresses were selected on the basis that there existed homes which had come under significant fire threat on the day. The taskforce then drove to locations near the assigned addresses and the research pairs began visiting their assigned addresses.

Interviews. All participants were approached in their properties. Where the home was undamaged, a door-knock approach was used. In some cases, residents of homes which were destroyed were seen within the bounds of their properties and, where appropriate, they were approached directly by the researchers. In almost all cases, residents agreed to be interviewed at the time, though some asked if they could reschedule their interviews. Only two residents declined to be interviewed, although one other individual requested that his/her interview not be digitally recorded. One participant was willing to discuss the events of the day but did not wish to be formally interviewed.

Before commencing the formal interview, residents were informed of the purpose of the study and that, though they would be recorded, all responses would be de-identified and presented in an aggregated form only. Residents were also advised that they could terminate the interview at any time they wished and had the right to refuse to answer any question. Within each research pair, one member acted as the lead interviewer and in all cases, this person was an employee of a research institution. Where it seemed appropriate, participants were advised that, if they so desired, the FESA representative would be willing to exit the interview, thereby allowing the participant to freely express any opinions about FESA. None of the participants took this option, but all seemed to appreciate it. At the conclusion of the interview, all participants were provided with information on the support services being offered.

A total of 40 interviews were conducted, involving 52 adults (at 12 properties two adults participated in joint interviews). The 52 interview participants were 21 men and 30 women (one 'not recorded'). Their mean age was 54 years and ages ranged from 26 to 77 years. The 40 households comprised 24 with no children; and 16 households with a total of 32 dependent children: an average of 2 per household, range 1 – 4. Not all interviewees were asked how long they had resided at the property, however, of those provided the information, their period of residence ranged from 2 to 26 years. A division was evident between a group of long-time residents who were retired and a somewhat smaller, younger group of mostly couples (and a few single parents) with children who had moved into the area relatively recently, largely for family lifestyle reasons.

Results and Discussion

Analytical Strategy

Each interview was transcribed by a third party organisation and each transcript was content-analysed via a coding system. The coding system was developed so as to capture participants' fire plans, their actions on the day, the outcome, the degree of exposure to threat, their level of preparation, their awareness of the fire danger weather, their physical readiness on the day, their fire knowledge, their awareness of the fire and readiness to respond, and the sources of information they referred to during, and prior to, the event. Transcripts were also analysed for evidence of the processes that governed participants' decision making during the event, and any issues they had encountered unexpectedly. Community members' attachment to their community/neighbours as well as their own homes was also coded as appropriate. Note, however, that not all participants discussed all topics, thus the numbers reported in the following sections do not necessarily add up to the total number of interviews.

Results (note that full results are available in McLennan, Dunlop, & et al., 2011)

***Awareness of Bushfire Risk**.* Of the 28 participants who provided information about past experience with fires, 12 reported that they had received training or been exposed to fire in the past. In most cases, the training had taken place at their workplaces. Information about bushfire safety also appeared to be reaching many community members with 24 of 31 reporting that they had read at least some of the materials published by FESA and distributed by the local council. Only four interviewees, of the 17 who discussed the topic, exhibited extensive knowledge of bushfire safety, though almost all of those interviewed believed that the area they lived in was at risk of bushfire (though it should be noted, with caution, that these responses are made in hindsight, after a fire had struck).

***Preparedness and Readiness for a Fire**.* In only one of the interviews was there strong evidence of extensive long-term preparedness for bushfires while 18 people were only minimally prepared, if at all. Nonetheless, almost all of those interviewed reported that they had sufficient levels of insurance, though eight respondents felt they were under-insured. On the day of the fire, only two of the 27 participants who discussed the topic were aware of the high fire-danger weather conditions, and almost all (30 out of 33) reported that they were ill-prepared to respond effectively to the threat as it emerged. In only three of 35 interviews was the interviewee able to provide detailed descriptions of the fire's approach, whereas 15 people reported either no awareness at all, or only that they knew there was a fire somewhere in the area.

***Fire Plans/Intentions and Resulting Actions**.* Clear evidence of fire plans/intended actions emerged in 37 of the 40 interviews conducted. Most participants (26) reported intentions to leave their homes early in the event of a fire. In fact, 19 of these individuals left their homes late. Three of the four households who had planned to remain and defend their homes did so, with the fourth leaving late. The remaining seven households either had no plan, or planned to wait and see what the fire was like before taking action. Of these, two stayed to defend their homes, two left late, one left early and two were absent just by chance.

***Sources of Information about the Fires**.* The sight of smoke was the most oft-cited cue which alerted residents to the fire threat in the area. In addition to this, it appeared that many residents were receiving phone calls from family and friends. Only five interviewees indicated that they received information from the radio and another five were contacted directly by local police and/or emergency services personnel.

***Factors that Contributed to, and Potentially Compromised, Survival**.* Interviewees described many factors which they thought may have facilitated their capacity to make sound decisions during the bushfire threat. Most often cited was practical assistance received by family, friends, and neighbours (21 interviewees), though it was also clear that having information about the fire also contributed to survivability for many people (17 interviewees). Twenty-eight percent noted that it was important to be able to regulate their emotions, controlling their fears and anxiety, whilst one-quarter of interviewees stressed that maintaining a focus on survival-related tasks was critical. Many of the interviewees (31) indicated that *not* knowing about the location of the fire would likely have impinged on their ability to survive, whereas nine interviewees reported that panicking would also be counterproductive to survival.

Discussion

The analyses of the interview transcripts suggested a worrying 'awareness-actions' gap: despite reporting a great deal of concern about bushfire risk, few residents had formulated a detailed fire plan, and few had undertaken significant preparations for a possible fire. Whilst information about bushfire safety seemed to be received by community members, it appeared that many residents had a very different understanding of "leaving early" to that of community bushfire safety professionals. Many residents reported that their decision was "always to leave early", but on the day they waited until they could see flames before hastily quitting their properties. The few residents who chose to defend their homes appeared to be reasonably well-prepared, but those interviewed seem to have behaved at times in such a way as to have risked death or serious injury. These findings appear consistent with the outcomes reported following the events of Black Saturday and the Roleystone/Kelmscott fires (Heath et al., 2011).

While the Lake Clifton community was distressed as a result of the bushfire incident, the community members responded to the research project in an overwhelmingly positive manner, as evidenced by the very low turn-down rates experienced. Many of the participants also expressed gratitude for being given the opportunity to articulate their thoughts and provide their perspectives on the events of the day. While some participants shared some frustrations with the responses of the emergency services authorities on the day, this did not prevent them from speaking candidly to the interviewers. We therefore believe that this research project provides a useful template from which to undertake field research in bushfire affected communities, in collaboration with emergency services authorities.

Limitations

Whilst the method of undertaking community research following bushfires presented here is robust, some caution is suggested. Chiefly, it is critical to note that interviews are imperfect data collection devices. Interviews rely on participants' ability to accurately recall past events, whereas it is well known that memory is fallible, particularly when individuals have experienced distress (see McLennan, Elliott, & et al., 2011). Consequently, without being probed on specific areas, a participant might neglect a critical component of his or her story, thus the statistics presented here may under-represent the true population statistics. It is suggested here that future researchers in this area utilising interviews also develop a set of specific probing questions so as to ensure all participants are presented with primers to facilitate the recall of information. As a second limitation, because it was impossible to interview all residents, the generalisability of the observed results to the broader study population remains questionable. Whilst, in the present case, a high degree of coverage of the study population was achieved, it would have enhanced the generalisability of the results if more attention had been assigned to households that were near to the fire scar, and thus exposed to fire-related warnings, but not directly affected by the fire itself.

References

Galea, N., & McNally, L. (2010). An investigation into fire-related perceptions and behaviour in the community of Toodyay, WA: University of Western Australia.

Heath, J., Nulsen, C., Dunlop, P. D., Clarke, P. J., Burgelt, P. T., & Morrison, D. L. (2011). The February 2011 fires in Roleystone, Kelmscott and Red Hill. Melbourne: Bushfire Cooperative Research Centre.

McLennan, J., & Elliott, G. (2010). Community members' decision making under stress of imminent bushfire threat - Murrindindi fire. Melbourne: Bushfire Cooperative Research Centre.

McLennan, J., Elliott, G., Omodei, M. M., McNeill, I. M., Dunlop, P. D., & Suss, J. (2011). Bushfire survival-related decision making: What the stress and performance research literature tells us. Paper presented at the Australasian Fire and Emergency Services Council / Bushfire CRC Conference, Sydney, Australia.

McLennan, J., Dunlop, P.D., Kelly, L., & Elliott, G. (2011). Lake Clifton Fire 10 January 2011: Interview taskforce report. Melbourne: Bushfire Cooperative Research Centre.

Whittaker, J., McLennan, J., Elliott, G., Gilbert, J., Handmer, J., Haynes, K., & Cowlishaw, S. (2009). *Human behaviour and community safety*. Victorian 2009 Bushfire Research Response Final Report October 2009, Melbourne: Bushfire Cooperative Research Centre.

Governments and emergency response

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Introduction

This paper introduces the next stage of the 'Mainstreaming Emergency Management into law and policy' research project. So far researchers have considered the impact of laws and legal proceedings on the community's ability to prepare for and respond to emergencies[5] and the true picture of litigation against the fire agencies. The next stage of the project will be to identify what is the responsibility of governments and government agencies, such as the fire brigades and various emergency services, to take action to protect individuals from harm. Identifying what are or should be the objectives of emergency management policy is important; unless governments know what they are trying to do and what they are trying to achieve, it is impossible to know whether or not they have succeeded. It is important from a legal perspective because the key issue in a legal action, such as those arising from the 2003 Canberra, and 2009 Black Saturday fires, is 'did the government via its fire and other agencies, meet it's 'duty of care'?' That, in turn, begs the question of 'what is (or was) the government's duty in emergency management?'

This project will consider these issues from a focused legal perspective. It will contribute to, and link with, CRC funded projects on land use planning and emergency management (being conducted by Professor Barbara Norman and Dr Kate Sullivan at the University of Canberra) and on sharing responsibility (being conducted by Professor John Handmer and Dr Blythe McLennan at RMIT University, Melbourne).

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5 Michael Eburn and Bronwyn Jackman, 'Mainstreaming fire and emergency management into law' (2011) 28(2) *Environmental and Planning Law Journal* 59-76; Michael Eburn and Stephen Dovers, 'Australian Fire Litigation' *International Journal of Wildland Fire*, accepted for publication.

What is the role of government?

Schneider asks

‘(1) Why are disasters viewed as legitimate public problems, requiring governmental action? and (2) What role should the government play in disaster related activities?’[6]

Ellis starts her history of the South Australian Country Fire Service with this:

'The man on the land should find his own fire- fighting appliances,' argued one South Australian parliamentarian in the 1930's. 'Landowners as a whole do not want charity.' But is it really 'charity' to supply firefighting equipment to rural groups? Just who is responsible for action? Should every household look after itself, or should people help their neighbours? Or should local government be involved, helping groups of neighbours to organise and to buy or make equipment? Perhaps the whole State has a responsibility to assist, since the main function of a State government is to ensure the safety and security of its citizens on a daily basis?[7]

Australian governments have recently made a clear commitment to developing resilient communities where the community and all levels of government share responsibility for hazard management.[8] The Teague Royal Commission also called for ‘shared responsibility’,[9] that is ‘a situation in which the State, municipal councils, individuals, household members and the broader community all contribute to mitigating bushfire risk …’[10] Agreeing to share responsibility does not, however, define who is responsible for what.

State parliaments have enacted counter disaster and emergency services legislation to establish the emergency services and vest various officers and officials with powers to respond to a disaster, but they have not expressly stated what the objectives of the emergency response are. In New South Wales, the Minister for Police and Emergency Services is responsible for:

(a) ensuring that adequate measures are taken by government agencies to prevent, prepare for, respond to and assist recovery from emergencies, and

(b) co-ordinating the activities of government agencies in taking those measures, and

(c) approving Displan or any alterations to Displan.[11]

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6 Saundra K Schneider, *Flirting with Disaster: Public Management in Crisis Situations* (M. E. Sharpe, 1995), 7.

7 J-A Ellis, *Tried by Fire: The story of the South Australian Country Fire Service* (South Australian Country Fire Service, 2001), 1.

8 Council of Australian Governments, *National Strategy for Disaster Resilience: Building our nation’s resilience to disasters* (13 February 2011) < http://www.coag.gov.au/coag_meeting_outcomes/2011-02-13/docs/national_strategy_disaster_resilience.rtf>.

9 Victoria, 2009 Victorian Bushfires Royal Commission, *Final Report* (2010), Volume II (Part Two), 351-358.

10 Ibid 352.

11 *State Emergency and Rescue Management Act 1989* (NSW) s 10.

The measures must be 'adequate' but adequate for what purpose? Further the Minister is charged with managing the government preparation and response to emergencies but that in no way identifies the extent of government responsibility in responding to emergencies.

Organized fire brigades were developed by insurance companies[12] and local councils. Over time the various brigades were brought under the control of an organising authority or board but they remained largely independent brigades.[13] In enacting legislation the governments did not necessarily see their role as protecting people from fire. Victoria's first fire brigade legislation, the *Fire Brigades Act 1890* (Vic) was an Act to improve the administration of fire brigades.[14] This Act empowered the local municipalities that had an interest in providing fire protection to do so, if they wished.[15] It did not require them to do so. There was clearly no expectation that local government, let alone State government, would necessarily set up brigades to provide protection for the community, let alone for private assets, or that emergency response was a central government activity.

Today emergency management is seen as a core or central government activity. In Victoria, statutory authorities, the Metropolitan Fire and Emergency Services Board and the Country Fire Authority manage fire brigades and the delivery of fire services, subject to the direction and control of the Minister.[16] In New South Wales, the emergency services are centrally located as divisions of the Government service, rather than independent statutory authorities.[17] Australian governments have moved from a laissez-faire approach to disaster response, to providing direct personal assistance.[18]

Governments are now direct providers of emergency services to the community, but, as noted above, the end that they are to achieve is not clear. The most recent inquiry into Australian fires said:

There remains one question the answer to which eluded the Special Inquiry but it is an answer that requires further examination and that is: What is the measure of success of the outcome of a bushfire. Is the loss of no lives the only performance measure? If so, how many houses is an acceptable number to lose? Does one performance indicator have the potential to cloud the 'Shared Responsibility' of all to build resilience of our community?[19]

What is missing is a clear policy statement about the objectives to be achieved in emergency management and why it is that governments see emergency response as a government policy issue. The Victorian Bushfires Royal Commission recognized the need for 'a clear statement of objectives, expressed as measurable outcomes'[20] but did not recommend such a statement for all of government. Rather they recommended the need to specify objectives

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12 T Ruoff 'Links with London' (1966) 40 *Australian Law Journal* 211, 212-213.
13 Ellis, above n 7.
14 Victoria, *Parliament Debates*, Legislative Assembly, 18 June 1890, 381 (Mr Deakin).
15 Ibid 377.
16 *Metropolitan Fire Brigades Act 1958* (Vic) ss 6,7 and 8; *Country Fire Authority Act 1958* (Vic) ss 6 and 6A.
17 *Public Sector Employment and Management Act 2002* (NSW) s 4C and Schedule 1
18 Rutherford H Platt, *Disasters and Democracy* (Island Press, 1999), 20.
19 Michael Keelty, *A shared responsibility: The report of the Perth Hills Bushfire February 2011 Review* (Government of Western Australia, 2011), 3.
20 2009 Victorian Bushfires Royal Commission, above n 9, Recommendation 59.

for various government departments.[21] This is evidence of a lack of 'mainstreaming'; even after the events of Black Saturday 2009 the Royal Commission was not looking at emergency management as a whole of government activity or asking government to specify what it's whole of government objectives for fire management are.

What is the *duty* of government?

Governments go to great lengths to protect people from harm and to protect their private assets. In his book *Great Australian Bushfire Stories,* Ian Mannix tells the story of a fire crew valiantly saving a private house.[22] As a story it tells of the attributes we value in our firefighters - selflessness, courage and community self-reliance, but viewed another way, those firefighters were exposed to a high risk of death or injury and the state went to a large expense in providing the fire fighting resources to protect a private asset.

In the United States, the objectives of the US Forest Service have been to protect forest assets but it has been noted that over 87% of their commitment is devoted to protecting private property, with the result that resources are diverted to protect private property whilst more valuable, natural resources burn.[23] The Inspector General of the Department of Agriculture has argued that 'In order to reflect the fact that the Federal Government is not primarily responsible for structure protection… [Forest Service] managers need to delineate Federal protection responsibilities' that is clearly define what they are responsible for, and what they are not.[24] The Australian fire services, both urban and rural are responsible for providing fire protection services including structural fire response but the limitation of that responsibility, and when the government should put protection of government and public assets ahead of private assets is not clearly 'delineated'.

In land use planning regimes restrictions are made on developments to increase the properties ability to withstand hazards. It may be a condition of development consent that there is a prescribed asset protection zone (APZ) but what can, or should be done, after the development is completed, to ensure that the zone is maintained? Are governments under a duty (and by duty we refer to a legal duty) to protect people and to ensure they take steps to protect themselves?

Governments, like citizens are not under a duty to come to the aid of others and are not under a duty to protect people from the harms they expose themselves to. In *Graham Barclay Oysters v Ryan*[25] Gleeson CJ said:

Ordinarily, the common law does not impose a duty of care on a person to protect another from the risk of harm unless that person has created the risk. And public authorities are in no different position. A public authority has no duty to take reasonable care to protect other persons merely

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[21] The State with respect to land use planning provisions ((recommendation 39), the Department of Sustainability and Environment with respect to prescribed burning (recommendation 57) and fire management on public land (recommendation 59), and VicRoads with respect to road side fire risk assessment (recommendation 62).

[22] Ian Mannix, *Great Australian Bushfire Stories* (ABC Books, 2008).

[23] D Farber, J Chen, R Verchick and LG Sun, *Disaster Law and Policy* (2nd ed, Wolters Kluwer, 2010) pp 41-42.

[24] Ibid 43.

[25] (2002) 211 CLR 540.

because the legislature has invested it with a power whose exercise could prevent harm to those persons. Thus, in most cases, a public authority will not be in breach of a common law duty by failing to exercise a discretionary power that is vested in it for the benefit of the general public. [26]

The fire and emergency services do not generally create the risk of fire and flood and, by analogy, are not under no legal duty to protect others form the harm that these events can cause.[27]

In *Stuart v Kirkland-Veenstra*[28] the High Court found there was no duty on police to prevent the suicide of a man they earlier found in his car with a pipe leading from the exhaust into the passenger compartment. Gummow, Hayne and Heydon JJ identified that the plaintiff's claim was one based on an alleged duty, owed by police, to '… prevent harm to the deceased at his own hand, not at the hand of another.'[29] They said:

On its face, the proposed duty would mark a significant departure from an underlying value of the common law which gives primacy to personal autonomy …

Personal autonomy is a value that informs much of the common law. It is a value that is reflected in the law of negligence. The co-existence of a knowledge of a risk of harm and power to avert or minimise that harm does not, without more, give rise to a duty of care at common law.[30]

A duty of care will usually not be found when the duty would impose on personal autonomy[31] but how governments manage their role may change the result in specific cases. Specific powers given to allow authorities to manage the specific risks may give rise to a duty of care.[32] The more governments exercise, or attempt to exercise, control over hazards, the more responsibility governments take on, and the more people rely on government[33] to manage the hazard then the more likely it is that governments will find themselves subject to a legal duty, and therefore liable to pay compensation, should an adverse hazard event take place.

The need for articulated policy

There is no clear statement of measurable, identifiable policy objectives that are to be met by emergency managers and governments generally. Rather public policy in this area appears to be developed from one Royal Commission or inquiry to the next. Inquiries such as the *2009 Victorian Bushfires Royal Commission*[34] or the *2011 West Australian Special Inquiry into the Perth Hills fires*[35] are not charged with setting policy, but in effect they do. All Australian fire agencies have taken some steps to implement the recommendations from

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26 Ibid [81] (McHugh J).
27 See also *Capital and Counties v Hampshire County Council* [1996] 1 WLR 1553.
28 (2009) 237 CLR 215.
29 Ibid [85] (Gummow, Hayne and Heydon JJ).
30 Ibid [87]-[88] (Gummow, Hayne and Heydon JJ).
31 *Caltex Refineries (QLD) Pty Limited v Stavar* [2009] NSWCA 258, [102-105] and in particular [103(n)] (Allsop P).
32 *Pyrenees Shire Council v Day* (1988) 192 CLR 330.
33 *Caltex Refineries (QLD) Pty Limited v Stavar* [2009] NSWCA 258, [102-105] (Allsop P).
34 2009 Victorian Bushfires Royal Commission, above n 9,
35 Keelty, above n 19.

the Victorian Bushfires inquiry even though that inquiry was looking at a particular set of circumstances in only one jurisdiction.

The *2009 Victorian Bushfires Royal Commission* called for the preservation of life to be the ultimate priority, this was adopted by the West Australian authorities and implemented in their response to the 2011 Perth Hills fires. Mick Keelty, said, however, 'the fact no lives were lost should not be used to claim that the response to this fire was an unmitigated success'.[36] The policy objectives of encouraging people to prepare their homes and to develop resilient communities is lost if people are not allowed to 'stay and defend',[37] and people were traumatised by the process of evacuation and dislocation.[38] Emergency managers, having heard from, and implemented the recommendations of the Victorian Bushfires Royal Commission to the effect that saving life over property was the overriding priority, now find themselves criticised for doing that very thing in Perth.

Allowing government policy to develop by increment rather than by clearly articulated goals may also lead to the unintended result that governments become liable for the impact of hazard events even in circumstances where people could, and should, have taken steps to protect themselves or been left to face the consequences of their own choices.

Setting policy is an inherently political task[39] and achieving the set policy objectives requires specific tools and practices. As Eburn and Jackman argued:

Whatever objectives are selected, different legal and policy tools will be required to achieve them. A clear, specific and measurable goal may be "no one will die in a bushfire" but that will lead to a very different policy response than if the goal is to ensure that "there will be no bushfires". The latter is unachievable. The former might be achievable but the methods to achieve that may range from improving building design, communication, education and preparing people to live with fire. An alternative objective may be that "people can choose to live with the risk of fire but only if they informed of and understand that risk". That, again, would require a different policy response to ensure that people are informed, rather than to address the risk of the outbreak of fire.[40]

Balancing the competing objectives and demands should be a matter for the elected government, not Royal Commissioners. Politicians need to determine and communicate how the balance has been struck and then ensure that government agencies are resourced to achieve the stated objectives. Emergency services can then expect to be judged on whether or not they have achieved the stated objectives.

From both a policy and legal perspective clearly articulated aims and objectives will help everyone, the emergency managers, the community and the next Royal Commissioner, know what it is that governments are seeking to achieve and what they can expect from the government and its emergency services. It would give a benchmark against which

36 Ibid 135.
37 Ibid 41-42.
38 Ibid 136-137.
39 Davis et al, cited in Stephen Dovers, *Environment and Sustainability Policy* (2005, The Federation Press), p 26
40 Eburn and Jackman, above n 5, 75.

performance could be judged so that we can see whether the loss from an event shows how well the policy worked to mitigate or minimise losses, or whether governments failed to achieve their stated objectives. At the risk of being insensitive, it allows the community to ask whether the loss of 173 lives in Black Saturday represents policy success, as the death toll could have been much worse, or is it evidence of policy failure? Without knowing what governments and the community were trying to achieve, it is impossible to answer that question.

Conclusion

The policy objectives of government in emergency management appear to have grown by stealth rather than clearly articulated policy aims.[41] The rationale for the change, from government as observer to emergency manager, has not been clearly addressed or articulated. Determining what is the role of government, particularly in a culture with competing values including respect for the environment, the free market and personal autonomy, will have significant impacts upon how governments and their agencies prepare for the next event and their legal responsibilities for responding to emergencies.

The way forward

The work on this research theme is in the early stage. Our project will put the role of government and the fire agencies within the context of Australia's current legal and constitutional arrangements. We will ask:

Is there a clear policy statement that identifies the problem, the policy direction, implementation and monitoring process?[42]

Are policy objectives clearly articulated, measurable and commonly understood?

Who sets emergency response policy? The emergency services, the government, the media or the chair of the last inquiry?

What should be the measure of success?

What should be the measure of failure?

Would the Minister, the electorate or the popular press agree?

This is a much narrower focus than the work being undertaken by McLennan and Handmer but will, in due course, contribute to that work and to our understanding of what shared responsibility means now, and may mean in the future.

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41 Platt above n 18, 20.

42 Stephen Dovers, *Environment and Sustainability Policy* (Federation Press, 2005), 100.

Effectiveness of rural fire danger warnings to New Zealand communities

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Abstract

In recent years like many other parts of the world, New Zealand has incorporated social fire research on improving preparedness and recovery of communities following bushfires into its fire research programme. This paper describes one component of the Scion Rural Fire Research Group's social fire research on the effectiveness of communications of fire danger warnings in New Zealand which spans the last 6 years.

As a first step, a literature review documented international knowledge which questioned the value of fire danger warnings in influencing positive public behaviour to reduce unsafe fire use practices, and the ability of roadside fire danger signs and media campaigns to identify and encourage the behaviour changes that fire authorities are seeking. These concerns were explored through interviews with fire and land managers in two regions of New Zealand – Canterbury and Northland. This revealed that managers had a number of concerns about these issues that warranted further investigation. A public survey then explored the general public's perception of rural fire danger communication in the same two regions. This found that, while most people are aware of fire danger warning signs and other communications, they frequently do not understand what the ratings mean or what behaviour is expected of them. The research has made a number of recommendations to clarify key messages and improve fire risk communication.

Introduction

The research documented in this paper features social research undertaken by the Rural Fire Research Group at Scion, which was initiated in 2005 and has been supported by the Foundation for Research, Science and Technology (now Ministry of Science and Innovation) and various rural fire sector organisations. An international literature review which was undertaken at the outset to document international knowledge (Bones *et al.* 2007) led to questioning: (i) the value of fire danger warnings in influencing positive behaviour to reduce unsafe fire practices amongst the public, and (ii) the ability of the media campaign to identify and encourage the behaviour changes that fire authorities are seeking. These concerns were subsequently explored through interviews with fire and land managers in two regions of New Zealand – Canterbury in the South Island (Langer and Chamberlain 2007), and Northland in the North Island (Langer *et al.* 2009). These interviews revealed that the managers had reservations about the effectiveness of current fire danger warnings, and raised a number of other concerns that warranted exploration through a public survey. Subsequently, the resulting survey explored the general public's perception of rural fire danger communication in the same two regions (Hide *et al.* 2010, 2011) and the literature review has been updated.

Fire danger rating systems

Fire danger rating systems evaluate and integrate factors of the fire environment, including topography, fuels and weather (Countryman 1972), to produce qualitative and/or numerical indices of fire potential (Stocks *et al.* 1989). Most countries around the world utilise some form of formal fire danger rating system to aid fire management decision-making (Taylor and Alexander 2006). In New Zealand, assessment of how fire environment factors influence both fire danger and fire behaviour potential is carried out through use of the New Zealand Fire Danger Rating System (NZFDRS), which is based on the Canadian Forest Fire Danger Rating System (Anderson 2005). The NZFDRS is used by New Zealand fire authorities to assess the probability of a fire starting, spreading and doing damage, and it supports a wide range of fire management activities, spanning fire reduction, readiness, response and recovery.

At the core of the NZFDRS, the Fire Weather Index (FWI) System is used to monitor the effects of weather and fuel moisture on changes in daily ignition potential and probable fire behaviour. The FWI System codes and indices are used in conjunction with fire behaviour models, contained in the New Zealand Fire Behaviour Prediction (FBP) System, to determine daily fire danger classes. The criteria defined by Alexander (2008) identifies five fire danger classes ('Low', 'Moderate', 'High', 'Very High' and 'Extreme') based on fire intensity that reflect the increasing difficulty of suppressing a potential fire as intensity increases.

Communication of fire danger warnings

The primary purpose of the fire danger rating scheme is to inform the general public of impending fire danger conditions to limit the number of potential ignitions (Alexander 2008). The intention is to warn the public of the increasing difficulty of controlling potential fires as the fire danger level increases, in the hope that they will be more cautious in their use of fire or with activities that might cause a fire (Bones *et al.* 2007).

Currently the main mechanisms to communicate fire danger to the public in rural areas are fire danger warning signs. In New Zealand, ‘half grapefruit’ signs are positioned at the roadside in rural areas and other high-risk locations which indicate ‘Low’ through to ‘Extreme’ fire danger depending on conditions. The sign may also be supplemented with additional wording or add-on panels describing fire season status or permit requirements. Other mechanisms include the national fire prevention publicity campaign using the cartoon character ‘Bernie’ to educate people about rural fire danger in television and radio advertisements, pamphlets and information provided on Rural Fire Authority (RFA) websites.

People’s perceptions of risk vary according to their personal beliefs and value systems (Slovic *et al.* 2004; Morgan *et al.* 1992). Evidence has consistently shown that even when the public believe they are at risk from wildfire and other hazards, this perception does not correlate to their mitigation behaviour (Cortner and Gale 1990; Mileti 2003; Nelson *et al.* 2005; McGee *et al.* 2005; Monroe and Nelson 2004).

Risk communication research/literature has recommended that the most effective way of encouraging people to mitigate risks is through two way dialogue, rather than through one way communication mechanisms such as social marketing (Christianson *et al.* 2011; Jardine 2008). Studies have found that two way communication between residents themselves, or residents and a trusted risk manager have been effective in encouraging people to mitigate their behaviour in relation to wildfire (McCaffrey and Kumagai 2007; McGee *et al.* 2005). However it is important that the risk managers are highly knowledgeable and have effective risk communication skills (Zaksek *et al.* 2006).

Key findings from the literature review were that:

- Rural fire danger is communicated in similar ways in most Western countries through the use of fire danger warning signs located around the countryside to indicate the current class of fire risk according to a calculated fire danger rating;
- Media campaigns are intended to provide backup and instruction on appropriate behaviour required at different levels of fire danger;
- There are various limitations to these communication methods, mostly relating to confusion amongst the public;
- Very little assessment of the effectiveness of these methods in changing behaviour and reducing ignitions has been attempted;
- Literature from a wide range of sources, such as risk communication, can be used to identify potential ways of improving the effectiveness of rural fire danger messages;

The message needs to be matched to the behavioural changes that the fire authorities are trying to encourage, and interpretation by members of the public also must be considered;

The message itself benefits from being communicated through a variety of media in ways that acknowledge a diverse audience;

In New Zealand, more attention needs to be paid to how effective the rural fire messages are at achieving the aims of rural fire managers.

The most effective ways of encouraging people to change their behaviour in relation to wildfire are through two way dialogue; and

The public's risk perception tends to be linked to their own internal values, and even when they believe there is a high risk of wildfire this does not correlate to their mitigation behaviour.

Methods

An evaluation of fire danger warnings in New Zealand and overseas literature in 2005-06 (Bones *et al.* 2007) highlighted two key areas of interest that were targeted in subsequent research – firstly, to identify the intended 'message' and, secondly, to establish how this was perceived by the public. The study of the expectations of fire and land managers' regarding fire danger communications was undertaken through qualitative interviews with seven fire and land managers involved in rural fire safety in the Canterbury region in January 2007 (Langer and Chamberlain 2007), and a further twelve managers in the Northland region in May/June 2009 (Langer *et al.* 2009). These two regions were selected because of their high incidence of wildfires (Anderson *et al.* 2008) and anticipated ease of access by the researchers to both rural dwellers and urban visitors. Each area, however, differed in the way they managed rural fire. Canterbury aimed for a consistent region-wide fire danger communication policy across RFAs (although the region had some different rules and regulations for different jurisdictions). Northland comprised three districts (Kaipara, Whangarei and the Far North) where fire danger communication differed across the region according to land authority or ownership (such as District Councils, DOC, forest companies), with no consistent approach.

The managers interviewed represented RFAs, District Councils, New Zealand Fire Service, Department of Conservation (DOC), Federated Farmers of New Zealand and forestry companies. The same qualitative interview structure was used on both occasions, with 29 open questions put to each manager that concerned: fire danger warning signs, fire restrictions and permits, the national 'Bernie' publicity campaign, and general questions on rural fire safety. Interviews ranged from 40-90 minutes in length, with responses summarised under these same four headings.

The concerns identified by fire and land managers' regarding their expectations of fire danger communication were used as a foundation from which to generate questions for a survey of the general public's perceptions. Members of the public were interviewed in the same two regions about their understanding of fire danger communications. A pilot study, including 12 people, was undertaken at the Whangarei **Agricultural and Pastoral (**A&P) show in Northland in December 2009. Following a few modifications, a further 106 adults (53 Canterbury, and 53 Northland) were interviewed at five different locations in both regions in January 2010 and captured 68 people living locally (41 rural and 27 urban residents), 28 New Zealanders visiting on holiday (19 urban and 9 rural visitors), and 22 international visitors. The findings are described by region and by home base when specific differences were noted.

The survey interviews explored public perspectives on issues relating to three themes:

1. The fire danger sign - its location; perceived meaning, accuracy and relevance; and ease of understanding;
2. Knowledge of fire danger, and public behaviour expected under different levels of fire danger; and
3. Knowledge and perception of publicity initiatives.

Results and Discussion

Rural fire and land managers' perspectives

Both regional studies of fire and land managers' expectations regarding fire danger communications undertaken by Scion's Rural Fire Research Group found that there was differing views amongst fire managers on the behavioural changes that they expected of the public from their communications of fire danger. Hence they felt there was likely to be public confusion regarding the messages being conveyed in these communications. Significant issues highlighted included that:

There was considerable overlap in the application of the fire danger warnings signs, intended to portray current fire danger, and their use to convey seasonal conditions and/or fire permit requirements;

Many of the messages being associated with fire danger signs and classes by fire managers are at odds with the purpose of the fire danger class criteria as outlined by Alexander (2008, p.1): i.e. "to inform the lay person of impending fire danger conditions" (and therefore of the increasing difficulty of controlling fires as the fire danger level increases) "so as to limit the number of potential ignitions";

There was no clear, distinguished information on fire danger warning signs to instruct the public in the behaviour they should adhere to under different fire danger ratings, so more direct links are required between the fire danger warning sign and the desired actions/behaviours;

There was no clear consensus among fire managers on what the behaviours expected from members of the public should be as the fire danger level varied;

The 'Bernie' figure and associated prevention messages need to be updated as questions were raised about whether he is still relevant to members of the public outside the present

'Bernie' target demographic (perceived by some as rural, white, middle-aged males as opposed to the current younger males);

The effectiveness of the 'Bernie' campaign needs to be accurately measured to determine what it is saying, and who hears it;

Associations between the NZ Fire Service's Firewise campaign and RFA fire danger communication strategies need to be established and maintained; and

Region-wide policies on fire safety need to be developed to provide consistent information to the public.

Public perceptions

The surveys of the general public's perceptions of rural fire danger communications conducted in Canterbury and Northland region revealed a number of positive aspects plus a variety of shortcomings. Positive aspects included a high awareness of the fire danger warning sign and its alerting function to the risk or danger of fire. For those that suggested a behavioural response to the fire danger warning, 'raised awareness' and 'taking more care' were amongst the most cited changes.

Findings did indicate some differences between interviewees in each region. Northland interviewees included a greater proportion of rural residents and urban visitors from within New Zealand. In contrast Canterbury interviewees included a greater proportion of urban residents and international visitors. Awareness of other methods of fire danger communication differed between regions, with those in Canterbury reporting less awareness of initiatives (n=23 of all participants, but over 40% of the Canterbury participants alone) than those in Northland (n=8 of all participants, but a smaller proportion of Northland participants). However, this Canterbury interviewee group also included a large number of international visitors and this may have contributed towards disparity in numbers between each region.

Nevertheless the data did identify a range of concerns relating to the public's perceptions of fire danger communications:

The sign itself

- Many participants (n=47, 40%) were unsure whether the sign information was current – for some vandalism and the lack of a date indicating last attention reduced credibility;
- Concerns were raised about possible interpretation difficulties, perhaps arising from visual problems, insufficient English language skills or poor literacy although this was not exclusively mentioned by international visitors; and
- Some (n=24) felt that the signs were directed at specific groups (e.g. campers, smokers) or reckless people (such as those throwing cigarette butts out of car windows), rather than to themselves.

Understanding of fire ratings

- Most commonly the rating was seen as a signal to identify hazard, risk or danger, but others saw the rating as an indicator of prevailing weather conditions or that it inferred some form of acceptable or unacceptable behaviour;
- It wasn't clear that the public 'see' each rating level with any distinction. Many (n=36) were more conscious either of general left to right arrow movement on the sign, or attributed most meaning to arrow position at the ratings 'Low' and 'Extreme' (and to a lesser extent 'High'); and
- Although greater numbers of people saw meaning in a 'High' fire danger rating than for 'Moderate' or 'Very High', numbers were still comparatively low and interpretation quite varied.

Translating fire danger ratings into behaviour change

- There was uncertainty about appropriate behaviour change for each rating. When describing how they would change their behaviour for each rating many guessed or were unable to provide an answer;
- Although many (n=78) acknowledged that the sign identified fire danger or risk level, only a third (n=40) reported that this also alerted them to change their behaviour; and
- Descriptions of expected behaviour for the central three ratings on the fire danger warning sign were much more varied (e.g. fire was considered to be both 'acceptable' and 'unacceptable' at a 'High' rating by different interviewees).

Knowledge of fire risk and behaviour change

- When asked about behaviour change according to each rating, or as the fire danger rating increased, responses varied. When not tied to a specific rating, the variety of examples provided was greater, as was in some cases the number of people reporting activity avoidance;
- A reasonable number of people emphasised that they undertook no high risk activities that might cause a fire; and
- When describing how they would actually change their behaviour with increased fire danger or risk, there were isolated statements about reducing use (sometimes in specific locations) of machinery or equipment that generate heat or sparks. The limited number of such responses raises concerns that the range of fire risk factors (i.e. that can cause fires) may not be widely understood. This may be influenced by the fact that 50 of the 118 participants were visitors (28 NZ visitors and 22 international visitors).

Fire season information

- An 'Open' fire season was generally well understood, but there were mixed responses for understanding of the meaning of 'Restricted' and 'Prohibited' fire seasons, and associated burning restrictions and fire permit requirements;
- Relatively few followed publicity (radio/newspaper) alerting the public to the need to have a fire permit; many felt that the need for a fire permit related more to the intended fire activity types (e.g. burning off vegetation on private land, or bonfire at a public function) and specific locations (e.g. a public place, private property, near DOC boundary) than to any fire use within restricted or prohibited fire periods; and

- Only a minority saw any association between the fire danger warning sign and fire season information.

Publicity initiatives

Although a small number of people were aware of fire communication slogans used in TV advertisements, almost half of the participants (n=58, 49%) were unaware of the message of the national publicity campaign's cartoon character 'Bernie'. This may be influenced by the fact that continuing to use long running mascots can mean that people become immune to the behaviours they need to take for fire prevention, and may be ineffective in targeting overseas visitors and younger generations (Rice 2001);

- Many of the respondents identified that the 'Bernie' message was to alert them to identify fire danger (n=28), risk level or to 'Keep it green' (n=17); fewer reported that the message alerted them to a need to change their behaviour;
- Fire danger communications by TV and/or radio were the alternative (non-fire danger warning sign) methods reported to be most useful. However, only about half of respondents reported awareness of such publicity. Awareness appeared much greater amongst Northland 27 interviewees (n=46) than those in Canterbury (n=18);
- 'Newspapers' were also ranked quite highly as useful; however, awareness of receiving information through this medium was relatively low; and
- There was poor awareness of rural fire danger communication amongst international visitors, as few international visitors were aware of the range of alternative methods used for fire danger communication. This was an area of need identified for improving publicity to specific groups.

The findings regarding fire danger sign awareness and understanding are similar to those found in a telephone survey commissioned by the NZ Fire Service (TNS 2010). This found that 88% of respondents recalled seeing a sign showing the current level of fire danger in rural and forestry areas. However, a much smaller percentage of respondents (31%) were able to identify that the message being communicated by the signs was to 'take care not to start a fire', and the majority (52%) were unable to define any message. Similarly, of the New Zealanders who indicated that they did take more care when the rural fire sign was pointing to 'High' or 'Extreme', 43% (or less than 20% overall) reported that they were more careful/aware of the dangers when fire danger was elevated.

A study commissioned by the National Rural Fire Authority and the NZ Forest Owners' Association (Mitchell Communication Group, 2011) to determine recognition levels of the national prevention campaign, the 'Bernie' character and other symbols used found high levels of recognition for 'Bernie' and his message of 'Keep it green' within the target audience (15-28 year old NZ males). The fire danger signs were also well recognised (82%), with 74% of respondents claiming they understood what the sign was telling them. However, only 19% indicated they always did something different when the sign indicated high fire danger, with a further 44% sometimes changing their behaviour. When asked specifically what they would do differently, 34% indicated they would 'take more care', and 41% either not light fires or think about whether they should light fires.

Conclusion and Recommendations

The literature review undertaken at the outset of the study to document international knowledge questioned the value of fire danger warnings in influencing positive public behaviour, and the ability of roadside fire danger signs and media campaigns to identify and encourage the behaviour changes that fire authorities are seeking. These concerns were used as the basis for subsequent research into fire and land managers' expectations of fire danger communication, and the general public's understanding of these communications.

The findings from the Canterbury and Northland studies of fire and land managers concluded that there were varying views on the behavioural changes managers expect of the public through communication of fire danger warnings. As a result, there is also likely to be public confusion regarding the fire danger messages being conveyed by fire managers.

In confirming this, results from the public survey suggested that most people are aware of fire danger warning signs, but they frequently do not understand what the ratings mean or what behaviour is expected of them as the fire danger level changes.

Overall study findings show that there are a number of areas of concern regarding the effectiveness of current fire danger warnings in New Zealand. Recommendations have been highlighted to clarify key messages and improve fire risk communication through improvements or changes to the existing system, and further research:

1. Greater clarity is required in communicating the range of risk factors for fire, as these do not appear to be widely known by the public.

2. Guidance is needed on expected behaviour – what the public can or should not do as fire danger increases, as there is a widespread lack of awareness on appropriate behaviour change for each fire danger rating on the 'half grapefruit' signs.

3. Efforts to clarify and simplify information relating to fire danger should be initiated concurrently with the guidance on recommended behavioural change, as the rating 'message' on signs was not clear to the public.

4. The 'fire danger warning sign' and 'fire season restrictions' systems operate in parallel, yet there are problems with understanding both the current fire danger 'message' and seasonal fire permit requirements. Nevertheless, the fire season system is a form of behavioural guidance, and the possibility of developing and integrating the two separate methods into a single sign 'graphic' should be explored. Any sign redesign should consider incorporating supplementary symbols to identify acceptable or 'prohibited' activities.

5. Further consideration should be given to the sign location, condition and 'up-to-datedness' to make signs more relevant and visible.

6. TV and radio were the most preferred and memorable publicity initiatives, but the 'Bernie' campaign appeared to have only moderate impact within the wider general public, with limited numbers perceiving guidance on behaviour change (although somewhat better results within the young male target audience; Mitchell

Communication Group 2011). The media campaign should be developed to more clearly target specific groups and include guidance on behaviour modification.

7. Further consideration be given to the range of communication avenues used, and if and how they need to be tailored for the different audiences.

An overarching feature of these recommendations is that the overall fire prevention objective would benefit from clarification of the links and distinctions between fire danger communications and fire season status, national publicity campaign and other varied fire prevention education methods. Implementation of the recommended improvements may also have implications for national rural fire sector risk management policy, legislation and practice. Accordingly, further research to facilitate understanding for agencies of the key behavioural changes expected, and target audiences and messages required to effect these, and for the public ongoing investigation into understanding these messages and the effectiveness of the communications in achieving these behaviour changes may be appropriate, as well as further research on risk communication methods. In the long term, any changes affecting both fire prevention objectives and risk management processes will require a robust communications strategy accommodating all affected agencies and communities.

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References

Alexander ME (2008) Proposed revision of fire danger class criteria for forest and rural areas in New Zealand. (2nd ed). 62 p. (National Rural Fire Authority, Wellington, in association with the Scion Rural Fire Research Group, Christchurch). [Reprint with corrections]

Anderson S (2005) Forest and rural fire danger rating in New Zealand. In: Colley M (ed). Forestry Handbook, pp 214-244. (New Zealand Institute of Forestry, Christchurch)

Anderson SAJ (2009) Future options for fire behaviour modelling and fire danger rating in New Zealand. Proceedings of the Royal Society of Queensland 115 (Bushfire 2006 Conference Special Edition): 119-127

Anderson SAJ, Doherty JJ, Pearce HG (2008) Wildfires in New Zealand from 1991 to 2007. New Zealand Journal of Forestry 53(3): 19-22

Bones H, Pearce HG, Langer ER (2007) Communication of fire danger warnings in New Zealand and overseas. Ensis Client Report No. 15572. 29 p. (Ensis Forest Biosecurity and Protection, Scion Bushfire Research Group, Christchurch)

Christianson A, McGee T, Jardine C (2011) Canadian wildfire communication strategies. The Australian Journal of Emergency Management 26(3): 40-51

Cortner HJ, Gale RD (1990) People, fire, and wildland environments. Population Environment 11(4): 245–257

Countryman CM (1972) The fire environment concept. 12 p. (USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California) [reprinted as: National Fire Equipment System (NFES) 2166 by National Wildfire Coordinating Group, Boise Interagency Fire Center, Boise, Idaho]

Hide S, Tappin D, Langer ER (2011) What is the general public's perception of rural fire danger communications? Fire Technology Transfer Note 41. 6 p. (Scion, Rural Fire Research Group, Christchurch)

Hide SA, Tappin DC, Langer ER, Anderson SAJ (2010) Assessment of the general public's perception of rural fire danger communications. Scion Contract Report No. 18088. 40 p. (Scion Rural Fire Research Group, Christchurch)

Jardine CG (2008) Considerations in planning for successful risk communication. In Everitt B, Melnick E (eds) Encyclopedia of Quantitative Risk Analysis and Assessment. (John Wiley & Sons, Ltd., London)

Langer ER, Chamberlain G (2007) Fire danger warning communication in New Zealand: Summary of a study of Rural Fire Authority communications in Canterbury. Fire Technology Transfer Note No. 34. 4 p. (Ensis Forest Biosecurity and Protection, Scion Bushfire Research Group, Christchurch)

Langer ER, Tappin, D, Hide S (2009) Fire danger warning communication in New Zealand: Summary of a study of Rural Fire Authority communications in Northland. Fire Technology Transfer Note No. 38. 6 p. (Scion Rural Fire Research Group, Christchurch)

McCaffrey S, Kumagai Y (2007) No need to reinvent the wheel: Applying existing social science theories to wildfire. In Daniel TC, Carroll MS, Moseley C (eds.) People, Fire, and Forests: A Synthesis of Wildfire Social Science. (Oregon State University Press)

McGee, T, McFarlane B, Varghese J (2005) Exploration of wildfire risk reduction in communities directly affected by wildfires in 2003. Final report. Public Safety and Emergency Preparedness. Ottawa, Ontario

Mileti DS (2003) Public hazards communication and education: The state of the art. (Natural Hazards Research and Applications Information Center, Institute of Behavioral Science, University of Colorado, Boulder, Colorado)

Mitchell Communication Group (2011) NZ Rural Fire Prevention Campaign: Research results. October 2011. (Mitchell Communication Group)

Monroe M, Nelson K (2004) The Value of Assessing Public Perceptions: Wildland Fire and Defensible Space, Applied Environmental Education and Communication 3:109-117.

Morgan MG, Fischhoff B, Bostram A, Lave L, Atman CJ (1992) Communicating risk to the public. Environmental Science and Technology 26(11): 2048-2056

Nelson KC, Monroe MC, Johnson JF (2005) The look of the land: Homeowner landscape management and wildfire preparedness in Minnesota and Florida. Society Nat. Resources 18(4): 321-336

Rice RE (2001) Smokey bear. In RE Rice & CK Atkin (Eds.), Public Communication Campaigns 3rd ed: 276-279. Sage

Slovic P, Finucane M, Peters E, MacGregor DG (2004) Risk as Analysis and Risk as Feelings: Some Thoughts about Affect, Reason, Risk and Rationality, Risk Analysis 24(2): 311-322

Stocks BJ, Alexander ME, Van Wagner CE, McAlpine RS, Lynham TJ, Dube DE (1989) The Canadian Forest Fire Danger Rating System: an overview. Forestry Chronicle 65(6): 450-457

Taylor SW, Alexander ME (2006) Science, technology, and human factors in fire danger rating: the Canadian experience. International Journal of Wildland Fire 15(1): 121-135

TNS (2010) Fire knowledge survey. Report prepared for the New Zealand Fire Service. TNS Conversa

Zaksek M, Arvai JL (2004) Toward Improved Communication about Wildland Fire: Mental Models Research to Identify Information Needs for Natural Resource Management. Risk Analysis 24(6): 1503-1514

Warning Fatigue: what is it and why does it matter?

An exploration and critique of the literature

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Abstract

'Cry-wolf' syndrome and 'warning fatigue' effect are generally recognised terms for cynicism or apathy that have been thought to result from being 'over-warned'. It has been anecdotally observed in disciplines of health, meteorology, military, emergency and disaster management. There is an assumption by end-users that warning fatigue not only exists but is a problem, yet much of the literature calls the phenomenon a 'myth', whilst at the same time acknowledging that false alarms have been observed to lead to public desensitization, emotional adaptation and risk normalization.

Overwhelmingly, the literature concentrates on disasters that appear and disappear quickly, ignoring disasters, like bushfires, which have a much longer lead time. This paper suggests that these two scenarios need to be differentiated and, underscored by empirical research a reconceptualization of warnings (and the public's response to them) developed.

Introduction

When individuals are exposed to recurring warning messages about an event which then does not eventuate, folklore like the fable 'The Boy Who Cried Wolf'[43] says that people become tired of hearing warnings. The story goes on to describe how the villagers turn off and become desensitised to the threatened danger, thereby endangering themselves even more. Over the years the term 'cry wolf' has morphed into a myth about a mischievous trickster who warns about a danger that does not exist. However, in the original story, the boy saw the wolf creeping near to the sheep and cried out to the villagers to come and help, and the noise the villagers made when they came out to protect the sheep scared the wolf away. Because the villagers did not see the wolf they thought he did not exist so after several repetitions where the wolf appeared, the boy warned, the villagers came to help and the wolf ran away, the villagers no longer came out to help, eventually allowing the wolf to capture and make off with the sheep. Through the telling and retelling of this story, the meaning or moral of it has changed. Whereas it used to mean that 'even if you do not listen to the boy, sooner or later he will be right', the dominant interpretation of the 'cry wolf' moral in the 21st century's is that the boy is a liar.

This paper examines the existing literature which has referenced or researched the phenomena of warning fatigue or the 'cry wolf' effect, and critically evaluates the validity of the research, highlighting inadequacies and gaps. This will be done by explaining why warning fatigue is important to both emergency managers and the public alike, briefly exploring the meanings of warnings (in a disaster-specific context), and the public's response. Existing literature is examined and constructs of warning fatigue hypothesised. As the phenomenon of warning fatigue has not been empirically conceptualised by any literature or research to date, this paper serves as a starting point for thinking about what may comprise warning fatigue; for this reason it is intentionally broad in its approach.

Why does it matter?

The meaning of warning fatigue has become a 'taken-for-granted' phenomenon and is regarded as conventional wisdom. For example, in 2010, the US National Weather Service stated it was actively seeking to reduce the problematic false alarm rate (FAR) related to weather warnings, because of anticipated community complacency (Barnes et al., 2007).

Rhatigan, Barnes and Gruntfest (2004) surveyed emergency managers after Superstorm of '93', and found that 'those issuing warnings may be more reluctant to issue warnings for the fear of issuing a false alarm' (Gruntfest and Carsell 2000; Weaver et al cited in Barnes et al, 2007:1143). Sandman (2006) acknowledged the dilemma of emergency officials when he says that it is hard for them to know just how aggressive to be when 'sounding the alarm' (p.1) as they have a two-fold problem; avoiding the accusation of panicking the public whilst running the risk of under-preparing them at the same time.

[43] 'The Boy Who Cried Wolf', one of more than 655 fables, supposedly written between 620 and 560 BC by a Greek slave and story-teller called Aesop

In a paper presented at the 2010 AFAC conference, Principal research scientist for CSIRO[44] Dr Garry Cook concluded that managing the 'cry wolf' effect was one of the three main recommendations that should be addressed in order to reduce residual risk from bushfires in the Australian context (Cook, Bradstock and Williams, 2010). At the 2011 AFAC conference when, Claire Johnson from the School of Psychological Sciences at La Trobe University explained how bushfire fighters make decision in worst case scenarios and identified warning fatigue as a one of seven factors that act as a barrier to effective management.

Warning fatigue is frequently cited as an issue in research wanting to manage public response to disasters, warnings and to provide solutions in how to reduce risk and enable effective preparedness; this is despite there being no definitive framework with which to measure or describe the phenomenon. Emergency managers and the public engage in debate about (and contribute to) the 'cry wolf' discourse, however they do so without knowing what it is or whether it is real; the purpose of this paper is to explore and reify, or make concrete, the phenomena of warning fatigue.

Warnings

Much of the emergency management literature describes optimal warnings as 'timely and effective' however, the 'timely' component for these best-practice warnings is seldom quantified.

A warning can mean different things depending on the threat: one is that the danger is real, its happening or arrival is certain and the timing can be predicted accurately; for example cyclone warnings where the equipment to predict these is sophisticated and highly developed. Another warning possibility is that the danger is real, but the arrival is in question and the timing is anyone's guess; health warnings about severe infectious outbreaks fall into this category. Volcanic eruptions are an example of a warning where the danger is real but its arrival is in doubt; geologists can observe abnormalities in the way a volcano is behaving, may even see some eruption evidence, but cannot predict how the volcano will behave. Yet other warnings are about dangers which may or may not exist (right now), may not arrive at all nor in the manner that is warned about. Bushfires, earthquakes, tsunamis all fall into this category – disastrous events involving these hazards have happened in the past, and because of a particular location or season it is possible it may happen again *but thus far,* nothing has happened. Even so, these dangers are continually warned about and preparation for them is recommended.

Bushfire warnings are most often issued in the absence of an actual fire. This is different from weather warnings which are issued based on sophisticated meteorological data that can be seen and plotted. Of course, high temperatures alone can be weather warnings, but a bushfire needs a combination of multiple factors coinciding over months and years to produce a potentially life-threatening bushfire. These include; very high temperatures, very low humidity, strong wind conditions, high fuel load, low ground moisture and specific terrain geography.

[44] The Commonwealth Scientific and Industrial Research Organisation is Australia's national science agency and one of the largest and most diverse research agencies in the world.

After a warning

What happens after a disaster warning of some magnitude is issued; more importantly, what do people typically do? Nigg (1995) explains that after a warning has been issued, life continues to be regarded as normal or not life-threatening, that is, *until* social and sensory cues demonstrate anything to the contrary. Interpretation of warning messages always occur within peoples 'frames of normal expectations' and in order for people to take action, this 'normalcy bias' needs to be overcome (p.374).

Literature shows that people most often revert to their own evaluation of their environment, checking the temperature, wind direction or horizon, looking for clues that will either confirm or invalidate the warning. Social networks come into play, where neighbours, or those acquaintances nearby are called upon to provide more cues not immediately available. To the observer, it may seem somewhat chaotic, but this 'social disorganisation', according to Turner (1984) is common and not necessarily unintentional or irrational, as it often involves trying to get to a safer location, find and reunite families and gather up frightened pets. Of course, some people seem to do nothing, but research has shown that even when people go about their daily routines, they have paid attention to the warning; they have just reacted to it in a different way.

Short lead time (SLT) and Long lead time (LLT) disasters.

Overwhelmingly, literature which refers to the myth of 'cry wolf' all do so on the basis of short-lead time (SLT) disasters. These disasters are typically weather related and come and go within a week. However, all disasters are not the same.

Janis (1962) was the first to make a distinction between two different types of disasters and posits that there is a marked difference between the reactions of people to warnings about precipitant or 'short-lead-time' disasters and those in non-precipitant or 'long-lead-time' situations. He cites the example of the great Kansas City flood and subsequent fire of 1951 where homes of 20,000 residents were damaged or destroyed. A major reason that people did not evacuate was a series of preliminary communications issued prior to the actual crisis; 'the very fact that it was possible to issue warnings long before the danger was imminent made possible a gradual, easy adaptation to the approaching danger, but at the same time, rendered the warnings less effective' (University of Oklahoma Research Institute, 1952:18., cited in Janis, 1962:79).

Drabek's (1999) research following Hurricanes Bob (1991), Andrew (1992) and Iniki (1992) showed that, amongst other factors, two event characteristics constrained the responses of tourists and residents alike; the availability of escape routes and warning lead time. These findings give credence to the hypothesis that the length of time before a disaster that a warning is issued, has 'considerable influence' in how messages are received and whether protective action is taken (p:521).Using as a case study a series of 'earthquake-near' predictions in 1976 of a 'great and destructive' earthquake in Los Angeles County, Ralph Turner (1983) explored several hypotheses about waiting for a disaster. One of them was that a false-alarm or a 'cry wolf' effect could result in people concluding that 'the entire alarm was unjustified in the first place' and that the forecasters or scientists 'did not know what they were doing' (p:308). But this paper argues that this definition is flawed and that the cry wolf effect is not a faulty premise at the *beginning* of a process but the *end* result of a series of warnings. In dismissing 'cry wolf' as a possibility but then linking his conclusion with the credibility of experts, Turner ignores the vast body of risk communication literature that has shown there is a strong correlation between trust and credibility of officials on one hand, and the public's uptake and belief of risk messages on the other.

Findings from these case studies revealed two additional differences between reactions to SLT as opposed to LLT disasters; the level of urgency and imminence of the threat. Often the perceived likelihood of the threat in SLT disasters is high, as is the perceived level of danger, leading to higher vigilance and heeding of warnings. But if a LLT threat has been 'anticipated by numerous antecedent warnings' (Janis 1962:81), then by the time a final and more urgent warning is given, the potential hazard is perceived to be less of a threat.

The Literature – what is 'known' to date

Most of the literature exploring the 'cry wolf' phenomenon was published over 30 years ago and only two research-based studies of warning fatigue have been done to date. The first empirical study which found a 'clear and reliable False Alarm Effect' was devised in the late 1970's by Shlomo Brezntiz, who felt that 'warning fatigue was too complicated a phenomenon to be studied in its natural environment' (p.23). To this end his research was lab-based and measured a fear reaction resulting from a known, contrived threat stimulus (an electric shock). Additionally, when testing for warning fatigue, Breznitz did not take the media and social context into consideration, something that both Barnes et al (2007) and Nigg (1995) suggest is important.

In the second study Atwood and Major (1996) used a prediction by a self-taught Mexican climatologist called Iben Browning; this paper was fraught with methodological limitations. However, it was useful in that it highlighted the need to examine the language used in warning scenarios, as terminologies were used interchangeably with no distinction made between 'warnings' or 'predictions', 'false alarms' or 'near misses', symbolizing the vague and contradictory nature of the literature. This is relevant because 'cry wolf' or warning fatigue is hypothesized as a phenomenon that results from being 'over-warned', not 'over-predicted'.

Much of the existing literature talks about the myth of the 'cry wolf' syndrome or effect, implying that it does not exist, however much of the same literature raises questions about the public's response and puzzlement as to their non-response. Sorenson (1993) calls 'cry wolf' a myth, yet when he explains what he means, he says that warnings 'are not *always* diminished by 'cry wolf' syndrome implying therefore that sometimes they are. As Joanne Nigg (1995) points out, a myth does not necessarily mean that a social phenomenon should be regarded as fiction, rather 'as a cultural explanation for events and phenomena that impact peoples lives' (p.374). Moreover, these myths are more likely to be associated with natural disasters (extreme weather, earthquakes, bushfires) than man-made technological ones (radioactive leaks, health scares) (Fischer and Bischoff 1998 cited in Nigg 1995).

The existing literature 'talks around' the issue of warning fatigue, for example, whilst Reser (1996) says there is little evidence to support warning fatigue, in the same paper he states 'repeated natural disaster warnings, as for example in the case of cyclones, can lead to inattention, complacency and desensitisation' (p.204). Sandman (2011) maintains that people stop taking warnings seriously if previous warnings do not eventuate and there are too many warnings about risks that do not materialize, resulting in people who ‘shrug off’ future warnings. In his earlier literature Sandman does not consider warning fatigue to be a problem however, stating that its effect is weak and that people ‘intuitively understand’ that a false alarm is a much smaller problem than a disaster they weren’t warned about’ (2008). He adds that warnings, such as those issued for weather events, are ‘calibrated’ to be conservative and that the public instinctively know this, in much the same way that smoke alarms in houses are programmed to be oversensitive. However, in an article about flu pandemics three years later, he thinks warning fatigue is a huge problem; because of these ‘false alarms’ the public will react with considerable scepticism should another pandemic be declared. Sandman’s article implies a warning fatigue reality (that it has an effect and can be overcome) without addressing some fundamental issues: those of cause, composition, consequences and solution.

The literature talks about puzzling reactions to warnings and hindrances to appropriate responses; the following sections ‘False Alarms’ and ‘Experience’ suggest that these are important issues to consider when trying to understand what constructs contribute to, or comprise, warning fatigue. The final section ‘Implications’ presents a hypothesis of further warning fatigue constructs.

False Alarms

The difference between a false alarm and a near miss needs to be examined as they may be different things to different people: scientists have vast amounts of data with which to predict and warn, however, the public may not be able to distinguish between a false alarm and a near miss, or credit a near miss as a false alarm and vice-versa. A paper by Simmons and Sutter (2009) that explored the false-alarm effect by plotting the level of tornado false alarms in the United States from 1986 to 2004 and comparing the death and injury rate, found that there was a statistically significant false alarm effect in areas with a higher false alarm ratio.

As Reser (1996) points out, the very idea of a false alarm is problematic as it implies that any response to the warning was a waste of time, maybe a bit foolish, certainly unnecessary. In terms of adaptive evolution, an alarm response to a life-threatening event is functional and productive. Warning fatigue therefore could be regarded as a maladaptive response to a hazard warning and Reser argues that the problem is that people are exposed to repeated warning messages in the absence of an actual event (p:204).

The difference between one false and several false alarms has been also highlighted by Dow and Cutter (1998, 2000), who argue that if the public understands why a false alarm has happened, their subsequent response to another alarm will not decrease. Additionally, they think that repeated false alarms may have an effect on not only response but on decisions to act (cited in Rhatigan et al, 2004:7).

Experience

In his book ‘Cry Wolf: the psychology of false alarms’ Breznitz (1984) claims that ‘a subsequent episode is automatically altered by past experience’ (p:16). For example, if someone has experience of a disaster, are they more likely to be aware of its consequences and pay more attention to subsequent disaster warnings? Or will they be more complacent, pay less attention to warnings and prepare less? According to Moore and Moore (1996) ‘people with prior experience of a natural disaster are likely to experience heightened stress and anxiety when warned about a subsequent event, as a result of remembering and re-experiencing the past events’ (cited in Reser 1996:207). The way that people reacted would of course depend on the outcome of their experience. For example, studies by Mileti and O’Brien (1992) suggest that a normalisation bias is evident for people who have had no experience or damage or loss in a previous disaster. ‘Even in the face of warning information these people are less likely to personalize risk and respond to pre-impact warnings’ (p:53). Drabek (2010) observes that experience has a ‘curious effect on peoples risk perceptions’ (p.207) and in relation to flood risk, if their immediate area has not flooded in their lifetime, then people take that as evidence that it will not flood in the future. Furthermore, the likelihood of a 100 year flood is dismissed because people just don’t understand basic probability theory – ‘gamblers fallacy’[45] is another way to understand this where people ignore the fact that random events are equally probable.

Implications

The existing literature dismisses the possibility of warning fatigue, yet paradoxically, state that people respond to warnings with apathy, become desensitised, complacent, sceptical, react less and prepare less if there have been alot of warnings. Moreover, no answers to these puzzling reactions are given. The literature is limited, dated and highlights issues that could contribute to the phenomenon of warning fatigue.

Arising from the literature, several warning fatigue constructs have been hypothesised; the table below presents these and the research questions that will be used to examine them.

[45] Gamblers Fallacy – The erroneous belief that if an event (slot machine pay-out for example) hasn't happened for a while, there is a higher likelihood of it happening as time goes on. The reverse fallacy is also true; where something has happened recently (50 year flood for example) leading to a belief that it won't happen again for a while.

Warning Fatigue Constructs	Research Questions
Long lead time disasters	Are warning responses different if people have been living with the risk threat for months and years?
Experience	Does experience include severity, familiarity and consequences of past events?
Trust and credibility	Has people's experience of disaster warnings been mediated by television, radio and newspaper?
Media	Do theories of audience reception, issue attention cycle, 3rd person effect and framing explain how people interpret the news and 'what they do with it'?
Risk	How is the idea of risk understood and to what degree does uncertainty influence how people pay attention to warnings?
Social and cultural considerations	How have bushfires in Australia been understood and talked about?
Cognitive biases	How do personality traits of optimism, anxiety, responses such as 'anticipatory stress', theories of attribution and adaptations of normalisation and desensitisation contribute to warning fatigue?

An important and additional research question is: Do all of these constructs need to be present in order for warning fatigue to result?

This paper suggests that the two disaster scenarios of short and long lead time need to be acknowledged and differentiated, and that when examining peoples warning responses these differing types of disaster scenarios be taken into consideration. This will enable a reconceptualisation of disaster warnings and will further an understanding of the conundrum that is warning fatigue.

References

Atwood, L.E & Major, A.M (1998) Exploring the 'Cry Wolf' Hypothesis, *International Journal of Mass Emergencies and Disasters*, vol 16(3) pp.279-302

Barnes, R.B., Gruntfest, E.C., Hayden, M.H., Schultz, D.M & Benight, C. (2007), False Alarms and Close Calls: A Conceptual Model of Warning Accuracy, *Weather and Forecasting,* vol 22, pp.1140-1145

Breznitz, S (1984) *Cry Wolf: The Psychology of False Alarms*, Lawrence Erlbaum Associates, London.

Cook, G.,Bradstock, R & Williams, R (2010) *Climate Change, Sea Change & Tree Change: Bushfire and Cyclone risk management,* CSIRO, Paper presented at the AFAC conference, Darwin, September 2010.

Dow, K & Cutter, S.L (1998) Crying Wolf: Repeat Responses to hurricane evacuation orders, *Journal of Coastal Management*, vol 26, pp.237-252

Dow, K. and S. L. Cutter. (2000). Public orders and personal opinions: Household strategies for hurricane risk assessment, *Environmental Hazards*, 2, 143-155.

Fischer, H.W & Bischoff, B.E (1987) *Perpetrating the Community Breakdown Model: Portrayal of Behavioral Response to Natural disasters in the National Print Media,* Paper presented at the annual meeting of the Mid-South Sociological Association.

Gruntdfest, E & Carswell, K (2001) *Impacts of a false alarm: The January 29, 2000 Ventura, California experience*. M.S. thesis. Dept. of Geography and Environmental Studies, University of Colorado at Colorado Springs

Janis, I.L (1962) Psychological Effects of warnings, in *Man and Society in Disaster*, G. Baker and D. Chapman (eds), Basic Books, New York, pp. 55-91.

Levanthal, H., Carriger, B.K., Hochbaum, G.M & Rosenstock, I.M (1960) Epidemic impact on the general population in two cities [in] *The impact of Asian influence on community life*, *Leventhal et al.,* Public Health Service, Washington

Moore, D.P. & Moore, J.W. (1996) Post hurricane burnout: An island township's experience. Environment and Behavior. 28, 134-155.

Nigg, J M (1995) Risk Communication and warning systems in T Horlick-Jones, A Amendola and R Casale (eds), *Natural Risk and Civil Protection*, E & FN Spon, chapter 33

Reser, J (1996) *Coping with Natural Disaster Warnings: The Nature of Human Response and Psychological Preparedness*, Conference on Natural Disaster Reduction, Gold Coast. Australia

Rhatigan, R., Barnes, L.R & Gruntfest, E (2004) *Looking Back at Superstorm '93:*

Perspectives of Emergency Managers in Southern Appalachia. Retrieved on 05 July 2011 from http://ccb.colorado.edu/superstorm/ss93Final.pdf

Sandman, P & Lanard, J (2006) Bird Flu: Communicating the Risk in 2005 Perspectives in Health, *Panamerican Health Organization*, vol 10, No. 2 Retrieved on 06 July 2011 from http://ykalaska.wordpress.com/2006/03/21/h5n1-risk-sandman/#comments

Sandman, P.M. (2008) 'The dangers of excessive warnings … and of over-reassurance', Sandman Guestbook, Retrieved 06 July 2011 from http://www.psandman.com/gst2008.htm

Sandman, P.M. (2011) Why U.K. nurses resisted swine flu vaccination – and why health care workers resist flu vaccination, Sandman Guestbook, Retrieved 06 July, 2011 from http://www.psandman.com/gst2011.htm

Sorensen, J.H (2000) Hazard Warning Systems: Review of 20 years of Progress, Natural Hazards Review, May, pp.119-125

Simmons, K.M & Sutter, D (2009) False Alarms, Tornado warnings and Tornado Casualties, *Weather, Climate and Society*, vol 1 pp.38-53

Turner, R.H (1983) Waiting for Disaster: Changing Reactions to earthquake Forecasts in Southern California, *Int. Journal of Mass Emergencies and Disasters*, vol 1 (2) pp.307-334

Weaver, J.F., Gruntfest, E & Levy, G.M (2000) Two Floods in Fort Collins, Colorado: Learning from a natural disaster, *Bull. Amer. Meteor. Soc*, vol 81 pp.2359-2366

Bushfire Survival-Related Decision Making: What the Stress and Performance Research Literature Tells Us

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Abstract.

We review the research literature concerning the effects of stress on human performance of complex tasks, and relate these to bushfire survival. The findings from the limited research involving potentially painful, injurious or life-threatening situations indicate that high levels of anxiety may compromise bushfire survival-related decisions and actions in four ways:
(a) threats may be overlooked and tasks may take longer than anticipated, with mistakes more likely; (b) attention is likely to become narrowly focussed on only a few aspects of the situation, while distracting thoughts may intrude; (c) it may be difficult to keep important things in mind and hard to remember survival-related information; and (d) forming sound judgements and making good decisions may become progressively more difficult. These have implications for community bushfire education and incident management.

Additional Keywords: wildfire, anxiety, cognition, community safety, disasters

Evidence gathered following the 2009 Victorian bushfires showed that many whose lives were threatened made decisions at the time which further jeopardised their safety (McLennan and Elliott 2010). Accounts by residents of communities threatened by bushfires indicate that many find the experience stressful (e. g., Kissane 2010; McLennan et al. 2011). It is tempting to conclude that residents' survival-related decision making and actions under the stress of imminent bushfire threat may be compromised by stress reactions of fear and anxiety. However, to date relatively little systematic attention has been given to the research evidence available that stress-related cognitive performance decrements are likely under such circumstances, and how stress might compromise survival-related decision making and actions by residents threatened by bushfire.

In this paper we examine research findings in the stress and human performance literature concerning fear/anxiety and cognitive abilities, and discuss their relevance for understanding the behaviour of individuals under imminent bushfire threat. We use the term 'stress' to refer to the totality of an individual's negative psychological experiences associated with a threatening bushfire: fear and anxiety in particular; but also worry, frustration, anger, and physical discomfort. We follow Lazarus and Folkman (1984) in conceptualising such psychological stress as resulting from interactions among three elements of an individual's appraisal of a bushfire threat situation under conditions of uncertainty: (i) the likely actions demanded of the individual; (ii) the individual's self-perceived ability to cope with these demands; and (iii) the perceived severity of threat posed. We distinguish *stress*, as a negative mood state, from *arousal* as activation or energisation (Cox and Mackay 1985). We acknowledge that individuals differ, both in tendencies to experience negative mood states such as anxiety and fear in the face of threats, and in the kinds of impacts their fear and anxiety might have on survival-related decision making; however, space constraints do not allow us to explore this.

Method

The research literature concerned with stress and human performance is extensive. We examined reviews by Kavanagh (2005) and Staal (2004) and then made electronic searches of data bases (such as PSYCHINFO and Web of Science) for studies of performance in the face of potentially life threatening stressors, in field or naturalistic settings. Table 1 summarises those deemed to be potentially relevant to civilians making survival-related decisions and taking actions under the stress of imminent bushfire threat. The criteria for inclusion were: (a) the stressors were likely to be perceived as having the potential to cause pain, injury, or death; and (b) cognitive performance was (with the exception of a study by Keinan *et al* 1987) assessed in a field or other naturalistic setting. The findings from each study are described below in relation to four major aspects of cognition: perceptual motor skills; attentional control, memory; and reasoning, judgement and decision making.

Results and Discussion.

Numerous studies have examined effects of different stressors on cognition and performance, including: fatigue, heat and cold, hunger and thirst, noise, sleep-deprivation, time-pressure, workload, and physical and psychological threats, in a range of settings including laboratory experiments, simulations, naturalistic environments such as combat training, and field settings such as parachuting. The findings, overall, are that stress of all kinds tends to degrade cognitive processes and impair performance (Kavanagh 2005; Staal 2004). However, there is only a small number of studies where the stressor generated fear or anxiety associated with threat of possible pain, injury or death, in a field or naturalistic setting. In the absence of systematic research involving bushfire survival-related decision making specifically, we used these studies (involving scenarios such as parachuting, diving, rock climbing, and military training) to infer likely effects of imminent bushfire threat on cognitive performance (Table 1).

Perceptual Motor Skills

Baddeley and Idzikowski (1985) compared the performance of 32 novice divers on a test of manual dexterity involving removing and replacing 16 small nuts and bolts in a metal plate, using fingers, as quickly as possible. The test was administered three times: practice; immediately before an open-sea dive; and at some other time well separated from a dive. Heart rate measures indicated somewhat elevated anxiety in the pre-dive condition[1] ($M_{control}$ = 77bpm; $M_{pre\text{-}dive}$ = 84bpm; increase = 9%). Mean time required on the manual dexterity test in the pre-dive condition was 6% slower than in the control condition.

Idzikowski and Baddeley (1987) compared the performances of 21 novice parachutists in a control condition on a pencil-and-paper letter-search task with those of 25 novice parachutists on the ground preceding a jump. Heart rate measurement indicated elevated anxiety in the pre-jump condition ($M_{control}$ = 77bpm; $M_{pre\text{-}jump}$ = 119bpm; increase = 55%). The mean letter-search time of those in the pre-jump condition was 23% slower than that of the control group. Idzikowski and Baddeley also used a pencil-and-paper abstract symbol-search task to compare the performances of 13 novice parachutists in a control condition with those of 15 novice parachutists tested on the ground prior to a jump. Self-reports indicated a higher level of anxiety for those in the pre-jump condition. The mean symbol-search time of those in the pre-jump condition was 40% slower than those in the control condition.

Jones and Hardy (1988) compared the performances of eight students on a computer-generated visual reaction time test under control and anxiety-arousing conditions. The anxiety was generated by informing the participants that following the test, they would be required to jump from a 4.57 metre platform into a dimly-lit foam-mattress filled pit. Self-reports indicated a higher mean level of anxiety pre-jump. Mean reaction time in the anxiety condition was 5% slower than in the control condition.

Pijpers *et al* (2006) asked 12 novice climbers to undertake two traverses of an indoor climbing wall, one starting at a height of 0.36 metres (Low condition), and the other at a height of 3.69 metres (High condition). The number of limb movements used and the time to complete the climb were recorded. Self-reports indicated that participants felt more anxious in the High condition (a safety rope meant it was not possible for a participant to fall to the floor). In the High condition participants used 19% more movements to complete their traverses, and took 72% longer.

Hammerton and Tickner (1968) asked 16 minimally trained parachutists to undertake a joy-stick controlled visual tracking task in a practice condition, and immediately prior to their first parachute jump. Mean heart rate was 81bpm in the practice condition and 118bpm immediately prior to jumping (46% increase). Immediately prior to jumping mean score on the visual tracking and control task was 232% worse (more errors) than during practice, and 162% worse than after their jump.

While the perceptual motor tasks varied across the six experiments, in each there was a decrement in performance associated with increased anxiety: environmental changes took longer to detect, and movements were slower and less coordinated. The implications are that residents experiencing high levels of anxiety due to the stress of imminent bushfire threat may: (a) be slow to detect some threatening developments in their environment; (b) take somewhat longer than normal to complete complex tasks; and (c) be clumsy in some of their actions.

Attentional control

Kivimaki and Lusa (1994) required 18 male firefighters to navigate an unfamiliar, dark, potentially hazardous rescue training labyrinth wearing breathing apparatus while thinking-aloud over a personal radio and wearing a heart rate monitor. Transcripts of the radio transmissions were analysed for task relevance. Mean heart rate at the beginning of the exercise was 93bpm and rose to 135bpm (45% increase). The relative amount of task-irrelevant thought rose by 28% over the course of the exercise, indicating greater distractibility as stress level rose.

Pijpers *et al* (2006) asked 17 novice rock climbers to undertake two identical hand- and foot-hold traverses of an indoor climbing wall, one in a Low condition, the other in a High condition, as described above. They were asked to climb as rapidly as possible, without falling, while being alert to report a projected light spot which appeared briefly at irregular intervals on the wall in their notional field of view (a safety rope meant that it was not possible to fall to the floor). Self-reports indicated that participants felt more anxious in the High condition, and they reported only 48% of the number of light spots reported in the Low condition, indicating an attentional narrowing, or tunnelling, effect of anxiety.

Weltman and Egstrom (1966) tested 15 novice divers with a peripheral-vision light-detection task apparatus mounted inside their face plate housing, in a training tank and during an open ocean dive. Mean detection performance was 31% worse during the open ocean dive compared with performance in the training tank, suggesting that the stress of an open ocean dive resulted in attentional narrowing.

Weltman *et al* (1971) used the same task as above to compare the performance of 30 students who believed that they were undertaking the task in a chamber pressurised to the equivalent of a depth of 60 feet (18.3 metres); in fact there was no pressurisation. Compared with their performance in the surface pressure (control) condition, mean peripheral detection was 50% worse. Mean heart rate in the (notional) pressure condition was 91bpm compared with 80bpm in the control condition (14% increase).

These four studies indicate that maintaining concentration on a primary task becomes more difficult; and attentional control is degraded by anxiety so that perception becomes more narrowly fixated, or tunnelled. The implications are that residents experiencing high levels of anxiety due to imminent bushfire threat may: (a) find it difficult to concentrate on tasks central to survival, and (b) fail to notice cues of newly emerging dangers—such as embers igniting a roof space.

Memory

Berkun (1964) reported that 15 US army recruits in a fear/anxiety condition involving their aircraft apparently having to undertake an emergency landing--'ditching'--on the ocean following engine failure recalled, on average, 28% less knowledge of how to survive a ditching compared with a non-anxious control group.

Idzikowski and Baddeley (1987) compared the performance of 35 novice parachutists in a control condition on a digit-span working memory capacity task with the performance of 34 novice parachutists on the ground immediately preceding a jump. The mean score of those in the pre-jump condition was 19% lower than the mean score of the control group.

Leach and Griffith (2008) compared the performance of 14 novice parachutists in a control condition, and immediately prior to exiting the aircraft, on an operation-span task involving both working memory capacity and processing efficiency. Mean heart rate was 73bpm in the control condition and 104bpm in the pre-jump condition, an increase of 42%. Pre-jump working memory capacity was 44% lower than in the control condition, and pre-jump working memory processing efficiency was 11% lower than in the control condition.

Robinson *et al* (2008) compared the performance of 10 nautical college students in a control condition and immediately after completing a helicopter underwater evacuation training survival exercise, using a mental arithmetic test of working memory processing efficiency. Post-escape mean working memory processing efficiency on the test was 33% less compared with that in the control condition.

The findings across the four studies suggest that high levels of anxiety are likely to reduce both working memory capacity and processing efficiency, and to interfere with retrieval of knowledge from long term memory. The implications are that individuals under imminent bushfire threat may have difficulty in: (a) keeping survival-relevant issues in mind; (b) correctly interpreting the significance of emerging threats; and (c) being able to remember survival-enhancing information—such as safe evacuation routes.

Reasoning, Judgement and Decision Making

Berkun (1964) reported three studies investigating the effect of fear/anxiety on ability to undertake complex tasks involving reasoning and judgement (detailed accounts are in Berkun *et al* 1962). In the first, 15 US army recruits in an aircraft apparently about to ditch (as described above) performed, on average, 10% worse on a form-completion task involving complex instructions compared with a non-anxious control group. In the second study, 24 US army recruits were required to adjust a radio unit by following complex written instructions, under the impression that they were about to be targeted by misdirected artillery shells during a live-fire training exercised. Compared with a control group, their mean performance decrement was 33%. In the third study, 27 US army recruits were required to follow complex written instructions to adjust a telephone, under the impression that they had caused serious injury to a fellow-soldier, in order to call for medical assistance. Compared with a control group, the mean performance decrement was 18%. Post-experiment de-briefing interviews and biochemical assays confirmed that the participants had been anxious (Berkun et al 1962).

Idzikowski and Baddeley (1987) compared the performance of 20 novice parachutists in a control condition on a pencil-and-paper logical reasoning task with the performance of 26 novice parachutists on the ground preceding a jump. Self-reports indicated a higher level of anxiety for those in the pre-jump condition. The mean percentage of correct answers by pre-jump participants was 7% lower than the mean score of the control group.

Keinan *et al* (1987) compared the performance of 19 undergraduates on a computer-generated multiple choice analogies reasoning test under control and anxiety-arousing conditions. Stress was generated by informing the participants that harmless but painful electric shocks might be administered if their performance did not meet a pre-set standard and that these shocks might occur at any point during the task (no shocks were actually administered). The mean performance in the stress condition was 36% lower than in the no-stress condition. This was found to be associated with more premature closures (failing to consider all alternatives), and more non-systematic scannings (inefficient pattern of considering alternatives).

These five studies indicate that high-level cognitive processes involved in reasoning, judgment and decision making are degraded by stress: there were decrements in the ability to apply logic in reasoning, and in the ability to fully and efficiently consider decision options. The implications are that residents experiencing high levels of anxiety due to imminent bushfire threat may engage in inappropriate survival behaviour, by (a) misunderstanding information made available to them; and/or (b) failing to effectively and efficiently consider all relevant options available before committing to an action.

In Table 1, the mean performance decrement of 232% in visual-motor coordination reported by Hammerton and Tickner (1968) appears to be an outlier. It is likely that the large decrement resulted from motivational factors rather than anxiety: the tracking task was unrelated to participants' impending jump and they were likely to be preoccupied with rehearsing jump procedures rather than undertaking an unrelated research task[2]. If this value is dropped, the unweighted mean decrement across the remaining 18 studies is 30%; (for perceptual motor skills = 29%; attentional control = 39%; memory functioning = 33%; reasoning, judgement and decision making = 21%).

Concluding Discussion

The findings from the stress and performance research literature confirm anecdotal accounts and general impressions: the potential negative effects of fear/anxiety on cognitive performance are not trivial; residents who experience high levels of fear/anxiety due to the stress of imminent bushfire threat are likely to make safety-compromising decisions and take actions which jeopardise their safety. Fearful and anxious residents are likely to: (a) be slow to respond to indications of threat and to be clumsy in their actions; (b) fail to notice cues of emerging threats and become distracted from essential tasks; (c) have difficulty keeping things in mind and remembering important information; and (d) find it hard to think issues through so as to select the best option to take.

The implications for community bushfire safety education include:

1. It is important to alert residents at risk of bushfire threat that becoming fearful and anxious in the face of bushfire threat increases the risk of their safety being

jeopardised, and there are actions to take which will lessen the effects of anxiety and reduce risk, particularly points 2 - 5 below.

2. A bushfire plan for the household is essential. Ideally, this should be as simple as possible, familiar to all, written, and displayed on a wall or similarly readily available—not (notionally) in peoples' minds, nor on a computer hard drive, nor in a drawer 'somewhere'.
3. The household fire plan should be discussed by members of the household and rehearsed at least once before the fire season. If the plan is to stay and defend, regular full practice involving use of all equipment is needed. If the plan is to leave then the planned evacuation route to safety should be travelled[3].
4. Household members should carry out a review following their rehearsal to identify how things might go wrong and how the bushfire plan might need to be changed.
5. As much preparation as possible should be completed prior to a day of predicted high fire danger weather—both for staying and defending, *and* if the plan is to leave.

The implications for those in incident management roles include:

(i) Assume, and plan for, anxious and fearful community members making safety-compromising choices during bushfires[4].

(ii) When conducting incident management training exercises, trainers should consider factoring-in illustrative instances of likely safety-compromising actions by anxious and fearful community members. For example, injecting a scenario in which a car convoy of evacuees is reported to be driving into the path of an advancing bushfire in spite of warnings.

(iii) When preparing alerts and warnings, construct these for a fearful, anxious, uncertain audience: be concise, clear, informative, and unambiguous.

For researchers, it is highly desirable that future post-bushfire research teams interviewing members of fire-affected communities seek information about survivors' experiences which will increase our knowledge of the effects of stress on bushfire survival-related decision making and actions. As two pioneers of disaster research observed:

> In the laboratory one can produce very frightening (and even traumatic) experiences but must stop short of those which constitute a real threat to the continued existence and health of the subjects involved--and actual disasters do not "stop short." An experiment cannot introduce the disaster stresses of overwhelming threat to life and limb... (Fritz and Marks 1954 p. 26)

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Notes

[1] There are large individual differences in resting and active heart rates. *Increase* in heart rate following exposure to a stressor is a frequently used minimally reactive measure of stress (Ice & James 2006).

[2] Berkun (1964) noted that in stress/performance research "...it is necessary to measure the performance of acts relevant to the stressful environment" (p. 22).

[3] While we are not aware of any research which demonstrates that practice of a household bushfire plan enhances bushfire survival there is research evidence from the general field

of training which suggests the benefits of practice for subsequent effective actions under stress (e.g., Keinan et al 1990; McClernon et al 2011; Zach et al 2007). In relation to training and practice to survive helicopter crash underwater escape, Taber (2010) cited research reporting overall survival rates from actual helicopter crashes in the ocean of 66% for those without escape training and practice, and 92% for those with training involving practice.

[4] Of 40 household interviews with residents impacted by the Lake Clifton (WA) fire of 10 January 2011 nine (23%) described taking potentially safety-compromising actions under the stress of imminent bushfire threat (McLennan et al 2011, Table 17).

References

Baddeley AD, Idzikowski C (1985) Anxiety, manual dexterity and diver performance. *Ergonomics* **28**, 1475-1482

Berkun MM (1964) Performance decrement under psychological stress. *Human Factors* **6**, 21-30

Berkun MM, Bialek HM, Kern RP, Yagi K (1962) Experimental studies of psychological stress in man. *Psychological Monographs: General and Applied* **76**(15), Whole Number 534 1962, 1-39

Cox T, Mackay C (1985) The measurement of self-reported stress and arousal. *British Journal of Psychology* **76**, 183-186

Fritz CE, Marks ES (1954) The NORC studies of human behavior in disaster. *Journal of Social Issues* **10**(3), 26-41

Hammerton M, Tickner AH (1968) An investigation into the effects of stress upon skilled performance. *Ergonomics* **12**, 851-853

Ice GH, James GD (2006) 'Measuring stress in humans: A practical guide for the field'. (Cambridge University Press: Cambridge)

Idzikowski C, Baddeley AD (1987) Fear and performance in novice parachutists. *Ergonomics* **30**, 1463-1474

Jones JG, Hardy L (1988) The effects of anxiety on psychomotor performance. *Journal of Sports Sciences* **6**, 59-67

Kavanagh J (2005) Stress and performance: A review of the literature and its applicability to the military. RAND Corporation, Technical Report 192. (Santa Monica, CA) Available at http://www.rand.org/pubs/technical_reports/TR192.html [Verified 5 July 2011]

Keinan G, Friedland N, Ben-Porath Y (1987) Decision making under stress: Scanning of alternatives under physical threat. *Acta Psychologica* **64**, 219-228

Keinan G, Friedland N, Sarig-Naor V (1990) Training for task performance under stress: The effectiveness of phased training methods. *Journal of Applied Social Psychology* **20**, 1514-1529

Kissane K (2010) 'Worst of days: Inside the Black Saturday firestorm'. (Hachette Australia: Sydney)

Kivimaki M, Lusa S (1994) Stress and cognitive performance of fire fighters during smoke diving. *Stress Medicine* **10**, 63-68

Lazarus RS, Folkman S (1984) 'Stress, appraisal, and coping'. (Springer: New York)

Leach J, Griffith R (2008) Restriction in working memory capacity during parachuting: A possible cause of 'no pull' fatalities. *Applied Cognitive Psychology* **22**, 147-157

McClernon CK, McCauley ME, O'Connor PE, Warm JS (2011) Stress training improves performance during stressful flight. *Human Factors* **53**, 207-218

McLennan J, Dunlop P, Kelly L, Elliott G (2011) Lake Clifton Fire 10 January 2011 – Filed interview task force report – Community bushfire safety. Bushfire CRC Extension Community Decision Making Under Stress (2) Project. (School of Psychological Science La Trobe University: Melbourne)

McLennan J, Elliott G **(**2010) Community members' decision making under the stress of imminent bushfire threat – Murrindindi Fire. Bushfire CRC Extension Community Decision Making Under Stress (2) Project. (School of Psychological Science La Trobe University: Melbourne)

McLennan J, Omodei M, Elliott G, Holgate A (2011) "Deep survival": Experiences of some who lived when they might have died in the February 2009 bushfires. *Australian Journal of Emergency Management* **26**(2), 41-46

Pijpers JR, Oudejans RRD, Bakker FC, Beek PJ (2006) The role of anxiety in perceiving and realising affordances. *Ecological Psychology* **18**, 131-166

Robinson SJ, Sunram-Lea SI, Leach J, Owen-Lynch PJ (2008) The effects of exposure to an acute naturalistic stressor on working memory, state anxiety and salivary cortisol concentrations. *Stress* **11**, 115-124

Staal M (2004) Stress, cognition, and human performance: A literature review and conceptual framework. Ames Research Centre, NASA/ TM—2004—212824. (Moffett Field, CA) Available at

http://human-factors.arc.nasa.gov/flightcognition/Publications/IH_054_Staal.pdf [Verified 5 July 2011]

Taber M (2010) Offshore helicopter safety report. Prepared for the Offshore Helicopter Safety Inquiry Newfoundland and Labrador-Canada. Canada-Newfoundland and Labrador Offshore Petroleum Board, Volume 2—Expert and Survey Reports, pages 211-290. Available at http://www.cnlopb.nl.ca/pdfs/ohsi/ohsir_vol2.pdf [Verified 7 November 2011]

Weltman G, Egstrom CH (1966) Perceptual narrowing in novice divers. *Human Factors* **8**, 499-505

Weltman G, Smith JE, Egstrom CH (1971) Perceptual narrowing during simulated pressure chamber exposure. *Human Factors* **13**, 99-107

Zach S, Raviv S, Inbar R (2007) The benefits of a graduated training program for security officers on physical performance in stressful situations. *International Journal of Stress Management* **14**, 350-369

Table 1: Fear/Anxiety-related Performance Decrements: Participants; Stressor; Potential Implications for Bushfire Survival

% Mean Decrement (Study)	Participants	Stressor	Potential Implications for householders under imminent bushfire threat
Perceptual Motor Skills			
6% reduction in manual dexterity (Baddeley & Idzikowski, 1985)	Novice divers	Imminent open-water dive	Difficulty in assembling and handling small objects, clumsiness
23% lower visual letter-search time; 40% slower symbol-search time (Idzikowski & Baddeley, 1987)	Novice parachutists	Imminent parachute jump	Slow to notice changes in the environment
232% more visual-motor coordination errors (Hammerton & Tickner, 1968)	Trainee parachutists	Imminent first parachute jump	Poor hand-eye coordination
5% slower choice-reaction times (Jones & Hardy, 1988)	Female university students	Imminent 4.6 m jump down to padded mats	Slow to respond to sudden changes in a threat situation
72% slower climbing time, associated with more, tentative, limb movements (Pijpers et al, 2006	Novice rock climbers	Height	Complex action sequences slower to complete successfully
Attentional Control:			
28% reduction in maintaining mental focus on the primary task (Kivimaki & Lusa, 1994)	Young adult male firefighters	Dark, potentially hazardous environment to be navigated wearing breathing apparatus	Difficulty in concentrating on an essential task

48% narrowing of attentional focus (Pijpers et al, 2006)	Novice rock climbers	Height	Attention is focussed narrowly on the main potential threat, so other emerging hazards may not be attended to
31% narrowing of attentional focus (Weltman & Egstrom, 1966)	Novice divers	Open ocean dive	Attention is focussed narrowly on the main potential threat, so other emerging hazards may not be attended to
50% narrowing of attentional focus (Weltman et al 1971)	Students in a pressure chamber	Simulated air pressure equivalent to 60 feet (18.3m)	Attention is focussed narrowly on the main potential threat, so other emerging hazards may not be attended to
Memory			
38% reduction in retrieval of survival information from long-term memory (Berkun, 1964)	Army recruits in basic training	Anticipated emergency aircraft 'ditching'	Difficulty in remembering important survival-related information
19% reduction in working memory capacity (Idzikowski & Baddeley 1987)	Novice parachutists	Imminent parachute jump	Difficulty in remembering a correct sequence of actions needed to successfully undertake complex tasks
41% reduction in working memory capacity; 11% reduction in processing efficiency (Leach & Griffith 2008)	Novice and experienced parachutists	Imminent parachute jump	Reduced ability to retain new information, to interpret the significance of changes in the environment and to remember a correct sequence of actions needed to successfully undertake complex tasks
33% reduction in working	Nautical	Helicopter	Reduced ability to interpret

memory efficiency (Robinson et al. 2008)	college students	underwater emergency evacuation training	the significance of changes in the environment
***Reasoning, Judgement & Decision Making*:**			
10% reduction in reasoning and judgement accuracy (Berkun, 1964)	Army recruits in basic training	Anticipated emergency aircraft 'ditching'	Errors in interpreting information; making safety-compromising decisions
33% reduction in reasoning and judgement accuracy (Berkun, 1964)	Army recruits in basic training	Fear of being accidentally shelled by artillery	Errors in interpreting information; making safety-compromising decisions
18% reduction in reasoning and judgement accuracy (Berkun, 1964)	Army recruits in basic training	Fear of having accidentally injured a fellow-soldier in a demolition exercise	Errors in interpreting information; making safety-compromising decisions
7% reduction in reasoning performance (Idzikowski & Baddeley 1987)	Novice parachutists	Imminent parachute jump	Difficulty in interpreting warnings and processing information in the environment so as to form an accurate assessment of the threat and matching this survival options
36% reduction in reasoning performance, associated with incomplete and inefficient scanning of decision alternatives (Keinan et al 1987	University students	Threat of electric shock if incorrect alternative selected	Hasty, incomplete and inefficient consideration of options for survival

Co-constructing Bushfire: Trust, Memory and Landscape on a ‘Code Red’ Day

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Introduction

There is a growing number of studies of homeowner perceptions of and responses to bushfire, however, this research has failed to adequately explain why so many homeowners do not take mitigating actions that accord with the technical assessments of risk (Brenkert-Smith 2006). Australia’s system of Fire Danger Ratings (FDRs), in which the highest rating is “Code Red or “Catastrophic”, has now been in place for two bushfire seasons. Research conducted in Victoria after the 2010 season found that only 54% of residents surveyed planned to leave their homes on a “Code Red” day (OESC 2010). There is an evident disconnect between the production of bushfire science and the way it is applied by people living in “at risk” communities. Failure to take actions deemed by fire authorities to be appropriate is usually characterised as a deficit in the publics’ understanding of bushfire. But as McCaffrey (2008) points out, householders may respond differently to bushfire based on how they interpret a diversity of factors which include environment and topography as well as more personal factors.

We argue that a new approach to research is required to understand the complex relationships between people, the landscapes they live and work in; the production and dissemination of the bushfire science intended to inform them; and how all of these factors influence the social meanings made of bushfire. Our interest is primarily in practice, what people actually *do* in relation to living with bushfire. Further, if the problem is framed as being a gap between expert and local understandings of bushfire, it is salient to understand how both experts and members of communities understand and use FDRs. In our analysis we draw upon the idea of ecological memory that is associated with resilience and complexity science to frame its use in conjunction with social memory in the landscape. We interpret the Bengtsson *et. al.* (2003) definition of ecological memory as providing a kind of ‘toolbox’ in which resides the ability of species, networks and the general environment’s ‘tools’—what we might understand as their seeds, genes, and adaptive capacities to create a similar system as existed prior to disturbance. Similarly, the resilience use of social memory originates with McIntosh (2002 in Folke *et. al.* 2002, p.72) and focuses on the accumulated experiences of management practices and ‘rules-in-use’ that enable social systems to monitor change in response to signals from the environment. We propose that both of these definitions are useful in considering how social and ecological memory interact in the monitoring of fire.

In this study we first interviewed residents of an “at risk” Victorian township about what they did on a “Code Red” rated day in January 2010 and how they interpreted FDRs. Second, we interviewed Victorian bushfire scientists about their roles in generating and disseminating the science of bushfire and how they interpret FDRs in their everyday lives. In this paper we discuss preliminary findings from each of the studies.[46] First, we present a brief account of our methods. We then report initial results from each of the two case studies and discuss potential implications of these findings and finally, we make some recommendations for future research.

Methods

The research was conducted as two complementary case studies. The purpose of a case study is to generate findings that can be generalised to theoretical propositions and as such do not represent statistical samples intended to be generalised to populations (Yin 2003). The goal of these case studies was to test and expand upon the ideas of social and ecological memory and how they contribute to people's everyday understanding of bushfire in the landscape.

Our first study was undertaken as a pilot study for a larger project, and was located at Halls Gap, a town in Victoria's Wimmera district listed by the State Government as being especially vulnerable to bushfire. Halls Gap is a tourist town located on the edge of the Grampians National Park. It has a permanent population of about 280 people (ABS 2011). Most residents are either tourism business operators, are otherwise dependent upon tourism, or are retired. This small population can be augmented by thousands of tourists on popular weekends (some of which occur during the height of the summer fire season). It has a recent history of bushfire. In 2006, a lightning strike ignited a fire that burned 130,000 hectares of the National Park and its surroundings. The fire surrounded Halls Gap, but fortunately no homes were lost (Witham 2006). During June and July 2010, semi-structured interviews were conducted with 13 residents representing a mix of the township's major demographic groups. The interviews were conducted "in place" in the participants' homes or workplaces, adding depth and richness to the analysis of the relationships between the people and their landscapes. The question of interest for this paper is how did residents understand and use FDRs in their decision making on the "Code Red" day in January 2010?

The second case study was of scientists doing bushfire research at Victorian universities and fire agencies. Six participants were selected by purposive and snowball sampling. They represent diverse scientific disciplines including fire ecology, forestry, psychology and meteorology. Semi-structured interviews were conducted to ascertain their views on a range of issues related to the production and communication of bushfire science. In this paper we focus in particular on their views about the usefulness of FDRs and how they would personally use FDRs to make decisions during a bushfire.

All of the names used in this report are pseudonyms.

[46] Completed analysis will be published in two articles currently in preparation:
Reid K & Beilin R, (forthcoming), "Where's the fire? Co-constructing bushfire in the everyday landscape"
Beilin R, Reid K. And Karim R. (forthcoming) "Signposting fire"

Preliminary Findings

The Halls Gap Case Study

Based on the recently published research (OESC 2010) it would be anticipated that around half of the residents of Halls Gap would have left their homes on the day declared “Code Red” in January 2010. Of the 13 participants in this study only one reported leaving her home, although she did not leave the township. Jennifer described packing her car in readiness to leave. On the day however, she made the judgement call that it would be safe to stay with friends whose home she described as being located on the main road, adjacent to a swamp. Jennifer said her decision was based upon her realisation, after the 2006 fire that she should not be on her own on a day of bad bushfire weather. So there is a social element to Jennifer’s decision, the security of being with friends. However, we also observe an element of local ecological and landscape understanding. Jennifer’s friends’ home is thought to be safer because it is on a main road and near a swamp; perhaps implicit in this is a means of protection from a fire or of escape or refuge. While none of the other participants in this study reported leaving their homes on the “Code Red” day, the common theme that emerges in our data is the role that local ecological memory and experience of the local landscape played in informing people’s action.

Part of the Halls Gap local bushfire narrative is that the township is *relatively* safe. This was in part attributed by participants to the history of bushfire in the area wherein fire has come very close to, but not into the township. But there is also a particular way of understanding the local landscape and weather evident in the data. Glenda, a local tourism business operator explained:

“Here in Halls Gap we’re actually relatively safe...you might laugh at that, but the fire can enter from the south and it can enter from the north. It’s not going to come over the hills, over the mountains that fast. The last fires in 2006 came over the mountains, there’s no wind behind it to push it, because wind just doesn’t blow down mountains. So the town has to be defended at two points which makes it easier to defend.”

Nested within this broader understanding of bushfire in the Halls Gap landscape is the commonly expressed view that the township is most vulnerable to bushfire coming from the north-west. Peter, also a local tourism business operator, puts it most succinctly:

“Knowing which way the wind is heading, you don’t have to rely on weather forecasts or ABC radio to tell you which way the wind’s blowing and how hot it is...and we know in this area here that if a fire is coming from the north-west on a very hot windy day, then you must consider evacuating.”

So while there is a general understanding that Halls Gap is not highly vulnerable to bushfire, participants in this study do not live in denial of the potential for bushfire. Rather, the local social and ecological memory of bushfire in their landscape can lead to a complex and nuanced understanding of factors. These in combination, can anticipate the likelihood of high bushfire danger. We argue therefore, that participants’ decision to stay in town on the “Code Red” day in January 2010 does not imply that they would never leave. Furthermore, we contend that a decision to stay on a “Code Red” day does not mean the message of the

FDR has been unheard, ignored or misunderstood. John explained his decision to stay as being based on what was going on around him on the day.

“I wasn’t all that concerned on that Code Red day. Just based on what was happening around me. I wasn’t ignorant of the warnings going out, and I was paying attention and I was listening in, but I wasn’t panicked to the point where I thought, I’ve gotta go.”

What John describes *is* taking action in response to the FDR. He may not have left his home but the actions he took were to pay attention to the FDR, evaluate them in the context of what he could see and feel in his landscape and to stay tuned in to events as the day unfolded. This is highly significant because it means that past behaviour (in relation to staying or leaving) is not necessarily indicative of future action. For example, at Halls Gap many participants observed that a contextual factor they take into account is wind speed and direction. Declaration of “Code Red” on a day when there was a strong northerly wind may lead to quite different action by residents from what they did on January 11th 2010 – a day described by some participants as just an ordinary hot summer day. Moreover, we argue that the discrepancy between the “Code Red” rating and participants’ observations of the local weather conditions accentuates an underlying lack of trust in FDRs. Many participants expressed cynicism about the motivations behind the implementation of FDRs. While recognising the political imperatives of action after the Black Saturday bushfires, many participants felt that the introduction of FDRs was more about government being “seen to do something” rather than effective policy. One participant also questioned the process “down in Melbourne” by which fire weather forecasts and FDRs are issued, reflecting both a lack of trust in the transparency of the process and the lack of local context.

In summary, the preliminary findings from the Halls Gap case study are that participants have a nuanced understanding of vulnerability to bushfire that is understood in both social and ecological terms. Furthermore, decisions not to leave home on the “Code Red” day should not be construed as a lack of action. For most participants the declaration of “Code Red” was a trigger to closely monitor conditions and sources of information, and most people were able to articulate the set of conditions under which they would be most likely to leave. One participant went so far as to acknowledge that if there had been a bushfire on that day, and her family found that their exits were blocked, that they would do what they could to survive and otherwise accept their fate. In the final analysis most participants’ decisions to stay while monitoring conditions did not mean that they thought they could defend their place in the face of Black Saturday-type conditions. Finally, there is an apparent lack of trust in the FDRs which may be related to the lack of local context and transparency in the way in which they are generated and used by government and agencies.

Case Study Two: the bushfire scientists

Most research into people’s responses to communication of science-based information about bushfire focuses on members of the public who are assumed to have limited expertise or scientific understanding. In this second case study we investigate how the ‘experts’, scientists and other individuals working in bushfire-related disciplines respond to FDRs.

Some of the fire scientists working with the McArthur Forest Fire Danger Index (FFDI) that underpins the FDR were concerned that the apparent simplicity of the FDR was “intoxicating” (Olivine, fire ecologist) and could be meaningless if it wasn’t correlated with a spatial sensibility in the landscape.   Jasper (whose work involves assessing bushfire impacts on property and business) pointed to the 2011 Perth fires that followed a long period of drought. He noted that the FFDI was not very high at all on that day but the landscape conditions were significant in combination with strong winds. In general there was apprehension from the fire ecologist, a meteorologist and risk analyst that the FDR was being "stretched" (Sapphire, meteorologist) because the underpinning FFDI is being inappropriately applied to contexts for which it was not designed.

There is also recognition from an agency psychologist working in community engagement that the scientific basis of the FDR is hidden from the communities who are meant to respond to its message. This creates a lack of trust in the "Code Red" message which may in turn have a negative impact on trust in the agencies responsible for its communication. It is difficult to establish or retain credibility when the key message is not accepted (Slovic 1999). Amethyst, a fire ecologist likened the difficulties experienced in providing trusted information to the situation of the 'boy who cried wolf'.

In addition to seeking their views on the production and communication of FDRs, we also asked the scientists how they use them in their everyday home lives during the bushfire season. The fire experts all have a nuanced understanding of the fire danger as represented by their actions on the days of a fire alert, or by their intended actions. This is understood in social terms (fire ecologist Jacinth for example described how he discussed joint risk with many of his neighbours) and in ecological terms shaped by their disciplinary background. Jasper, who lives in a bushfire prone area, described his use of FDRs as limited, noting that:

"How I use it [FDR] *is that initial decision...if it's a catastrophic code red, I will stay, work from home, and if it's… FDI* [FFDI] *70 or more probably tend to stay at home... that's the limit of my use of it, it's just for that initial decision."*

Implicit in this response is Jasper's understanding of the McArthur Index that underpins the FDRs. He knows that an FDI of 70 or more is significant. On a high risk day his inclination is to stay close to home. Some of the interviewed scientists who reside in areas classified by the government as "at risk" commented that their homes were in safe parts of town, or that they were confident in their ability to stay and defend. Amethyst, who lives in one of the bushfire-prone areas, described the social confusion he experienced on Black Saturday. He went out to purchase parts to fix broken sprinkler and due to police roadblocks was nearly unable to get back to his home and family. As a result of this experience he has decided that in future he will leave home on "Code Red" days.

In summary, the analysis of this particular question in relation to the scientists' personal use of FDRs is strikingly similar to the Halls Gap study. The FDR provides some background (or the basis of an "initial decision"), but their overall decisions take account of the broader landscape and wider social context.

Discussion and conclusion

In this paper we build on the definitions of ecological and social memory and show how they interact in the everyday construction of bushfire in the landscape. Fire is a physical reality, and the response to it is a social reality—a construction for example of ‘hazard’. The landscape is the place where these social and ecological systems entwine. Together they create a mediated platform for very local decision making. The physical is interpreted through the social understanding of landscape experience and assessed alongside the rules-in-use around fire; and this social understanding is created in response to information and experience of the physical landscape before, during and after fire. We conclude that if people do not engage with FDRs in the way that governments and fire authorities intended, it is not because the science is too complex to be understood, but that the message is too simple to be meaningful.

The results of our two case studies suggest that cues to decision making are found within our social and ecological memory and in the accompanying landscape. There is also evidence that people’s interpretations of the cues to understanding this interaction evolve with experience. If we harness resilience definitions of ecological memory, it points to the emergence of an integrated and dynamic response, a continuum rather than a point in time. Social memory acts as a mediator or interpreter of this continuum, which means it has limitations associated with the spectrum of information that is available. For example, understanding the components of the forest that ‘emerges’ after fire suggests that what germinates or responds to fire is subject to the heat and length of the fire. It would not be the same all the time. Studies in the Won Wron forest in Victoria by Victorian naturalists have indicated that repeat burnings of *Xanthorrhoea sp.* in logging coupes eventually leads to its demise. It is not fire resistant in the longer term when fire cycles are short and young seedlings have not developed their tough stems to tolerate burns (pers comm. Robyn Watson, 2001). This suggests a need to constantly revisit and reconceptualise the integration of local fire knowledge within a historical and scientifically constructed understanding of the particular landscape. The findings of this study indicate that people make meaning of bushfire via cues they take from landscape and ecological memory and we propose that this will be a fruitful theme for future investigation. And if, as these preliminary findings also suggest, that landscape context mitigates decision making for both experts and lay members of the community, then research and engagement with communities can incorporate respect for local knowledge actively engaged in understanding the social interpretation of ecological information rather than being based on the assumption of a “knowledge deficit.” Working with communities to co-construct meanings about bushfire becomes the co-construction of bushfire knowledge.

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References

ABS (2011) *Australian Bureau of Statistics 2006 Census,* http://www.censusdata.abs.gov.au/ABSNavigation/prenav/LocationSearch?locationLastSearchTerm=halls+gap&locationSearchTerm=halls+gap&newarea=UCL220200&submitbutton=View+QuickStats+%3E&mapdisplay=on&collection=Census&period=2006&areacode=UCL220200&geography=&method=Place+of+Usual+Residence&productlabel=&producttype=QuickStats&topic=&navmapdisplayed=true&javascript=true&breadcrumb=PL&topholder=0&leftholder=0&currentaction=104&action=401&textversion=false&subaction=1 accessed 22 August 2011.

Bengtsson, J., P. Angelstam, T. Elmqvist, U. Emanuelsson, C. Folke, M. Ihse, M. Moberg, and M. Nyström. (2003) Reserves, Resilience and Dynamic Landscapes, *AMBIO: A Journal of the Human Environment* 32(6):389-396. 2003 .doi: 10.1579

Brenkert-Smith, H. 2006. The Place of Fire. *Natural Hazards Review* 7 (7):105-113.

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, CS. Holling, B. Walker, J. Bengtsson, F. Berkes, J. Colding, K. Danell, M. Falkenmark, L. Gordon, R. Kasperson, N. Kautsky, A. Kinzig, S. Levin, K-G. Maler, F. Moberg, L. Ohlsson, P. Olsson, E. Ostrom, W. Reid, J. Rockstrom, H. Savenije, and U. Svedin. (2002) *Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations.* Scientific Background Paper on Resilience for the process of The World Summit on Sustainable Development. Environmental Advisory Council, Ministry of Environment. Stockholm. Sweden.

McCaffrey, SM. (2008) Understanding Public Perspectives of Wildfire Risk. In *Wildfire risk, human perceptions and management implications*, edited by W. E. Martin, C. Raish and B. Kent. Washington DC: Resources for the Future.

OESC. (2010) *"Where are they going?" People movement during bushfires*. Office of the Emergency Services Commissioner.

Slovic, P. (1999) Trust, Emotion, Sex, Politics, and Science: Surveying the Risk-Assessment Battlefield. *Risk Analysis* 19 (4):689-701.

Yin, RK. (2003) *Case Study Research: Design and Methods,* Thousand Oaks CA: Sage Publications.