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Understanding risk: representing fire danger using spatially explicit fire simulation ensembles

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Abstract
Forest fires are periodic occurrences in many parts of the world. Where they coincide with human populations, they have the potential to have substantial impacts on human values. Consequently, strategies are adopted by land managers to reduce the probability of fire occurrence and, in the event of a fire, reduce subsequent impacts. One such strategy has involved the adoption of fire danger ratings. These are levels of alertness that are applied at a regional level on a daily basis. They are based on preceding and forecast weather and provide an indication of the potential severity of fire behaviour. Danger ratings are generally based on weather derived indices and have limited ability to represent the contribution of landscape attributes to potential impacts, including the properties of vegetation (fuels) and the amount and spatial configuration of vulnerable assets. We propose an alternative method for representing fire danger using fire simulation. An ensemble approach is demonstrated whereby thousands of virtual fires are ignited on a regular grid and simulated on a daily basis using forecast weather with the model PHOENIX RapidFire. Each fire is simulated in succession and burns for a specified period. Fire simulations integrate the contributions of local fuel, topography and weather to fire behaviour. The resultant fires can be aggregated to provide spatially explicit representations of potential spread patterns. These maps can be combined with asset registers to quantify potential impacts and assist with the prioritisation of response and protection measures.

***Keywords**: bushfire; PHOENIX RapidFire; Monte-Carlo; risk; simulation; vulnerability; weather; wildfire*

1. Introduction

Fire danger ratings are used to influence the behaviour of the community at times of high fire risk. They are used to provide warnings, set preparedness levels and invoke regulations that reduce risky behaviour (Taylor and Alexander 2006). They are valuable tools to reduce the probability of fire occurrence and, in the event of a fire, enable the planning of effective responses to reduce subsequent impacts. As a consequence, they have been widely adopted throughout the world (Lin 2000). They provide an indication of the likelihood of a fire starting and for fires that do occur, an indication of the difficulty of suppression and potential damage.

In the context of this article, we define fire danger ratings as the descriptive classes used to communicate fire danger to the public. These danger ratings are typically based on quantitative indices of fire behaviour. Fire danger index systems are used worldwide, including the United States National Fire Danger Rating System (Cohen and Deeming 1985), the McArthur Fire Danger Index (FFDI) used in Australia (Noble *et al.* 1980) and the Canadian Forest Fire Weather Index used in a number of different countries (van Wagner 1974). Fire Danger Indices are calculated using models that are specific to broad landscape types (i.e. forest or grass) and are computed for specific points in space and time using preceding and forecast weather parameters (typically rainfall, temperature, wind speed and humidity (Fujioka *et al.* 2008; Matthews 2009)). To disseminate this information to the public, these indices are summarised on a regional basis using ordinal 'adjective classes' that describe increasing levels of potential fire behaviour (e.g. high, very high and extreme) (Hardy and Hardy

2007). While predominantly derived from fire danger indices, fire danger ratings can also incorporate some expert adjustment to account for additional considerations such as assets at risk, seasonal population movements and public holidays.

For communication purposes fire danger ratings are applied over defined regions, districts or management areas. As a consequence, large geographic areas can be given the same danger rating even though there can be substantial heterogeneity in the expected fire potential resulting from differing combinations of fuel (Duff *et al.* 2012), expected weather, topography (Schunk *et al.* 2013), ignition likelihood (Penman *et al.* 2013) and vulnerable assets (Cheney and Gould 1995; Bones *et al.* 2007). While the zoning of fire rating districts can be optimised to minimise within-district variation (Gouma and Chronopoulou-Sereli 1998), the dynamic nature of fuel and weather means that a single rating is unlikely to be representative of the entire mapped region it denotes (Cheney and Gould 1995). This may contribute to confusion in the community with regards to the intended meaning of danger ratings, or what the most appropriate action should be (Dawson 1988; Reid and Beilin 2013).

As fire danger indices are more quantitative, they can be more easily represented at higher spatial resolutions (e.g. Chowdhury & Hassan (2013)). However, as they were designed for informing land managers about fire spread potential and suppression difficulty, they are not necessarily suitable to provide to the public as information of fire hazard to the community (Cheney and Gould 1995). Current indices are generated from fixed (fuel and topography) and varying (weather) parameters, but are effectively point estimates. They have no way of incorporating landscape context related elements that can greatly contribute to expected fire impacts. These include predominant wind direction, changing patterns of weather throughout the day, the scale and relative position of fuels to assets and variation in the likelihood of human caused ignition. Furthermore, despite the use of the word 'danger' in the term 'fire danger index', there is no explicit evaluation of danger in the context of values at risk. As values in the landscape are unevenly distributed, two fires under similar weather conditions can have substantially different impacts. This can be seen in a recent study by Blanchi *et al* (2010), where high fire danger indices were clearly correlated with maximum house loss potential (extreme days had the potential to result in greater house loss) but only weakly associated with average house loss potential (fires under extreme conditions did not necessarily impact settlements).

We propose an alternative method for representing fire danger at a regional and local level utilising the ability of dynamic fire behaviour models to simulate of fire spread and characterise impacts. Such models have been used to estimate long term fire danger (e.g. Weise *et al* (2010)) however we suggest that ensembles of predictions can be effectively used as indications of daily fire danger potential. To do this, ensembles of fires can be ignited on a regional grid using each day's forecast weather to guide fire progression. Maps of the resulting fires impact characteristics can then be used to differentiate areas of varying fire danger. These maps can be combined with asset registers in order to quantify potential asset impacts and assist with the prioritisation of fire prevention and protection measures. Combined with ignition probability maps, hazard (combining likelihood and consequences) to specific assets can also be quantified. The process was demonstrated using the state of Victoria, Australia, as a test case with fires simulated from gridded weather forecasts using the simulator PHOENIX RapidFire (Tolhurst *et al.* 2008).

2. Methods

2.1. Method framework

Dynamic fire behaviour models have developed rapidly in recent years. Advances in computing power mean that fires can be rapidly simulated on a desktop computer. We propose that a parallel processing framework be used to simulate a large (>1000) ensemble of independent fires within the jurisdiction of interest using a regular ignition grid. These can be run on a daily basis using weather forecasts. The results of these simulations can then be combined to produce daily products that represent fire danger to particular assets of interest. The process is outlined in Fig 1.

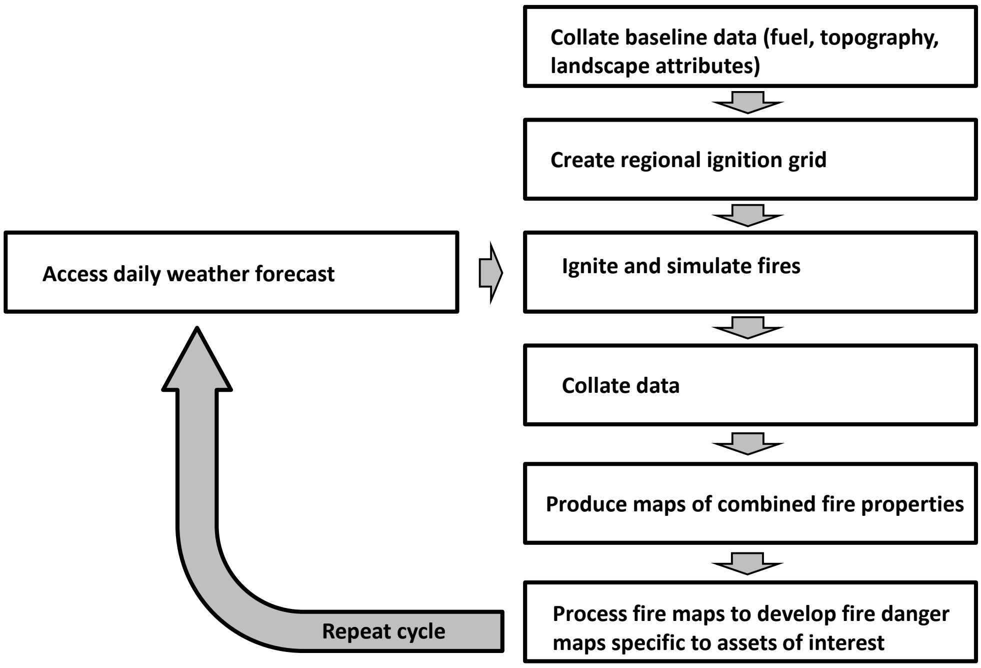

Figure 1. Framework methodology for producing simulation based fire hazard maps

2.2. Case study

We used the state of Victoria, Australia, to demonstrate the proposed methodology. Covering an area of 227 000 km^2, Victoria has a Mediterranean type climate and has been subject to a number of severe wildfires, including the Black Saturday fires of 2009.

To capture the spatially and temporally explicit nature of fire spread and resulting fire characteristics, we selected the model *PHOENIX RapidFire* (Tolhurst *et al.* 2008), a dynamic fire model developed explicitly for Australian conditions and used operationally by fire management agencies (Paterson and Chong 2011). The baseline data (fuel hazard, topography, roads, fuel barriers, fire history and wind modifiers) necessary to run simulations was sourced from the Department of Environment and Primary Industries (DEPI), Victoria.

Four days where total fire bans had been declared for the entire state of Victoria were selected from the 2013/2014 fire season. The dates and maximum temperatures at Melbourne Airport (a location of relatively central latitude in the state) are presented in Table 2. These days all had a similar level of alertness communicated to the public.

Table 1. State wide total fire ban days for 2013/2014 fire season showing a reference maximum daily temperature at Melbourne Airport (source Australian Bureau of Meteorology)

Total Fire Ban Date	Daily Max Temperature (ºC)	Total processing time (hrs)
15 January 2014	41.7	0.19
28 January 2014	42.0	0.30
8 February 2014	41.0	0.23
9 February 2014	40.4	0.82

Weather forecasts for the selected days were sourced from the Australian Bureau of Meteorology in the form of state wide NetCDF grids containing the required weather parameters for PHOENIX RapidFire. Inputs of wind speed and direction, temperature, relative humidity and cloud were supplied at hourly intervals, whilst curing and drought factor were daily values. The NetCDF grids had a longitudinal resolution of 0.03 degrees (approximately 2.6 km) and a latitudinal resolution of 0.02 degrees (approximately 2.2 km). PHOENIX RapidFire continuously interrogates the forecast weather grids at all points along the modelled fire perimeter in order to capture the spatial and temporal variability of the weather across the landscape.

Daily fire potentially was evaluated by modelling ignitions on a regular 5 km grid across the entire state. For each day, ignitions times were calculated using a diurnal fuel moisture content derived FFDI as described by the Matthews fuel moisture model (Matthews 2006) and a nominal threshold FFDI value of 23 to capture the point at which fires become difficult to contain (Mason *et al.* 2011). Where the threshold value is not met, the peak FFDI value between 6am and 6am the following day is used. Ignitions are then modelled until 6am the following day. Grid ignition simulations were run with a nominal 'first attack' suppression allocation to reflect current operational practices. Each daily iteration consisted of a set of 9088 ignitions. The extent of each modelled fire is processed on completion, whereby they are aggregated to provide a state wide spatially explicit indication of the number of impacts affecting each point in the landscape. In addition, an expected house loss map was generated by combining the probability of house loss with the number of houses impacted in each fire (Tolhurst and Chong 2011). House loss results for each fire were represented at the ignition locations. Ignitions were processed in parallel using a 24 core, 2.7 GHz Xeon desktop running Windows 7 Professional with 64 GB of ram. Fires were modelled at 180m resolution which is the recommended resolution for operational use of PHOENIX RapidFire. This is also the reporting resolution for the aggregated results from all ignitions.

To contrast the method, we compare the ensemble generated maps with maps of the daily maximum FFDI sampled at the ignition grid points.

3. **Results**

All four days were processed in under an hour respectively, with the maximum ignition grid simulation time of .82 hours and the fastest day processed in 0.23 hours (Table 2).

Despite all four days being classified as total fire bans and the very similar maximum temperatures at Melbourne airport, all four days exhibited substantial spatial variation and range of fire impact values across the state.

The calculated maps showing peak FFDI display a large spatial variation of daily maximums across the state and within defined fire ban districts (Fig 2). Peak values range from the danger classes Low (<12) to Code Red (>100). There were substantial differences between days. In particular, the 9th of February had substantially elevated FFDI in the north and east of the state. The 28th of Janurary had substantially elevated FFDI In the west of the state.

The simulated burn frequency maps were generated for all days (Fig 3). In these, there were some key differences to the FDI maps. In particular, there were a number of parts of the state that had low impacts despite high FDIs (i.e. north-central, south and North West). There were also substantial differences in pattern between days. For example, the 9th of February shows an increased burn frequency in the east of the state.

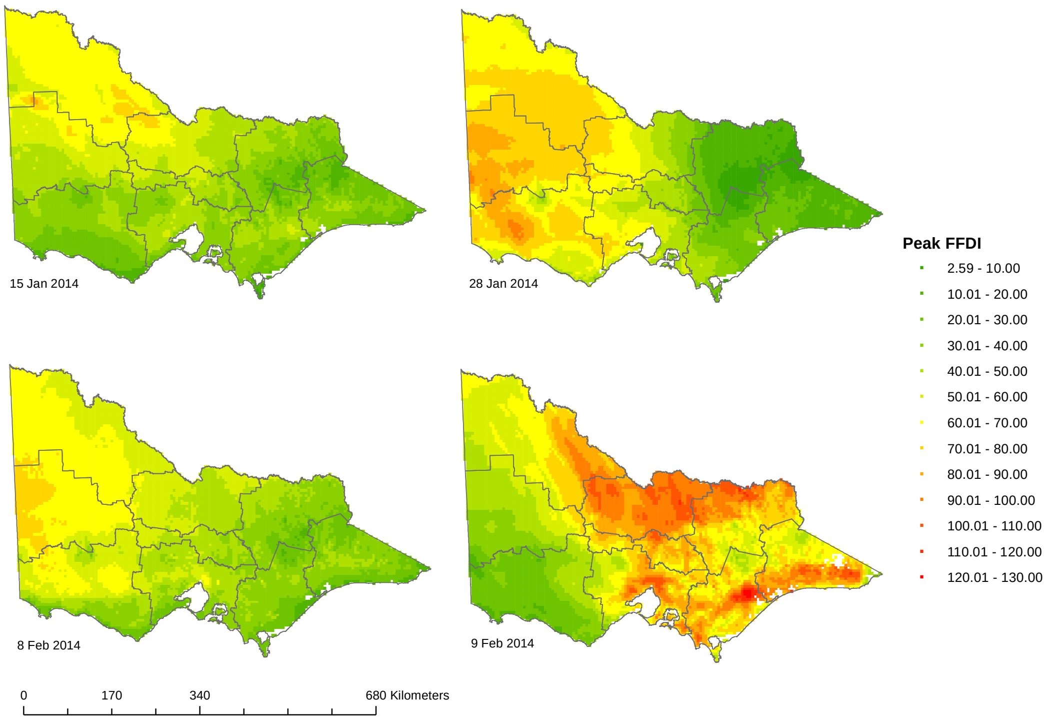

Figure 2. Calculated daily maximum Forest Fire Danger Index values for the state of Victoria, Australia

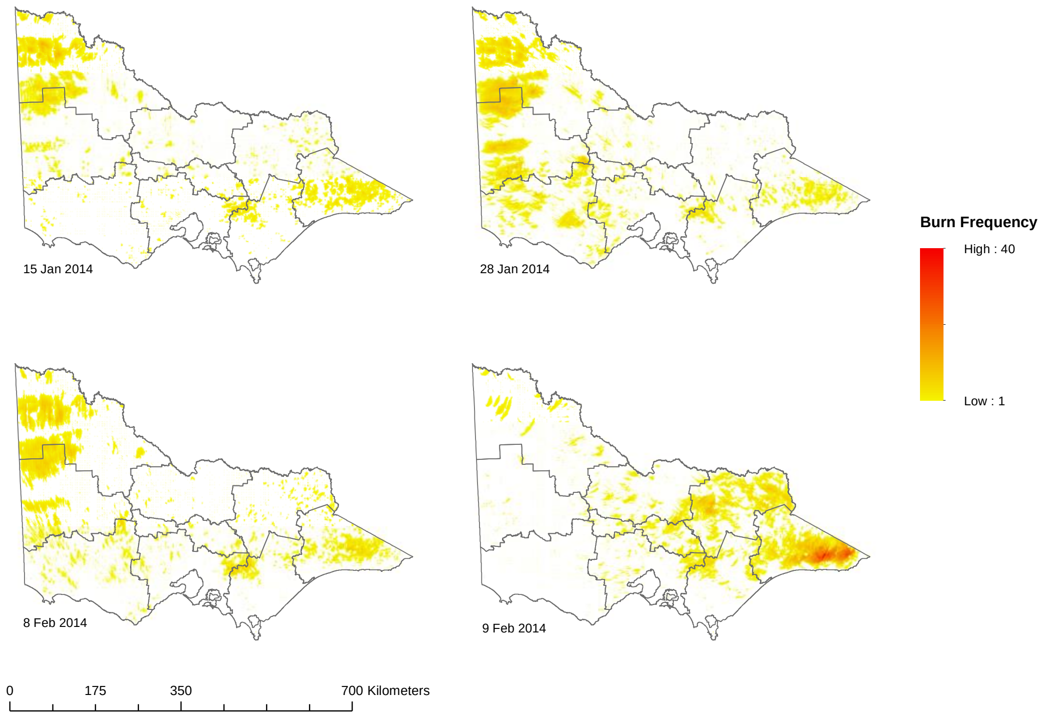

Figure 3– Cumulative burn simulated frequency for fires simulated from gridded ignitions in the state of Victoria, Australia

Resulting house loss values displayed against source ignition points (Fig 4) also show a large spatial variation in impacts across the landscape on each day. In contrast to FDI and burn frequency, there were proportionally higher expected house losses in the centre of the state.

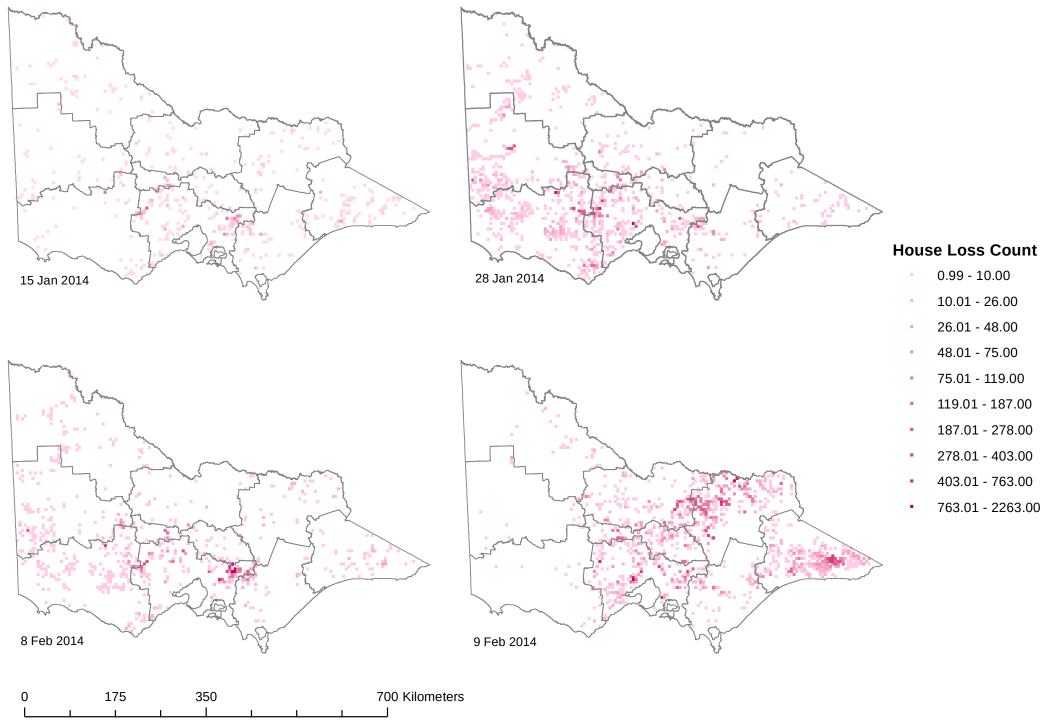

Figure 4– Modelled expected house loss for fires simulated from gridded ignitions in the state of Victoria, Australia

Closer examination of individual fires around the regional centre of Bendigo on the days of the 9th of February and the 28th of January show a clear difference in spread direction and area impacted (Fig 5).

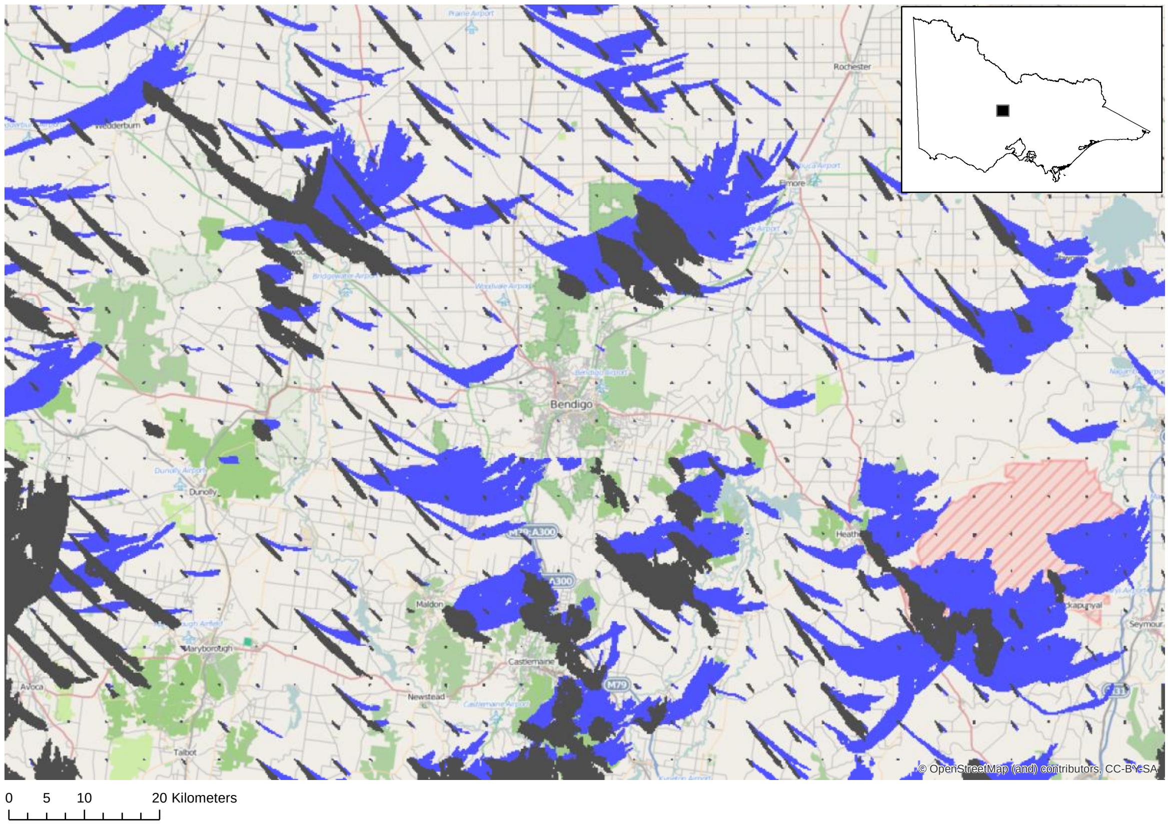

Figure 5- Simulated fire footprints from 9th February (Blue) and 28th January (Dark Grey) surrounding Bendigo, Victoria, Australia

4. Discussion

The ensemble fire prediction process was demonstrated to have the potential to produce forecasts of fire impacts in operationally useful timeframes. Forecasts of fire potential at operational resolutions for an entire state were all calculated on a desktop computer. As fires were processed in parallel, there is the potential to further decrease processing times with additional hardware.

Such simulation derived products of fire behaviour have substantial advantages over maps of fire danger indices. As they emulate the process of a spreading fire, they have much greater potential to consider temporal dynamics (such as the likely influences of weather fronts or wind changes influencing an area throughout the day) and spatial dynamics (such as the spatial context of varying fuel levels) in relation to values of interest. This means that fire simulations can provide more detail on likely fire behaviour and results will be more locally relevant than what can be produced by pure weather indices.

This is evident in Figure 3, where on all days there was low fire activity in the north-central part of the map due to grassland fuel types. The temporally dynamic nature of fire is evident in the map for the 9th of February, where there was limited fire behaviour in the north and west of the map despite declared total fire ban due to the wind change passing through early in the day bringing cooler conditions. In addition, In Figure 5, the orientations of the fires are markedly different on different days. This is due to the timing of the weather front moving from west to east throughout the day, a common fire weather pattern in South Eastern Australia (Long 2006). Wind changes that occur during fires can greatly effect on the size and overall impacts of a fire (Cheney *et al.* 2001). This means that in addition to the degree of fire threat that a point in the landscape faces, detailed information on the nature of the threat can also be obtained that can be used to guide daily readiness measures. Furthermore, while single day predictions were produced for case study purposes, the method can be validly applied to longer term outlooks. In localities where there is a 7 day weather forecast, there is the potential to produce equivalent fire behaviour forecast maps for each day of weather available. Fire behaviour forecasts could be automatically generated when weather forecasts become available (in Victoria, approximately 5am and 5pm daily).

An additional advantage of the use of ensemble simulations is that a wide variety of products that can be produced. In the example presented, we represent potential fire impacts as the number of fires impacting on a particular point in the landscape. However, other fire properties can also be represented; dynamic fire models can also produce a range of other outputs including fire intensities, cumulative ember loads, rates of spread and flame heights. Empirical data can be used to relate these to impacts on particular values of interest. By overlaying this information with other data sources, a single ensemble prediction can be processed to yield a wide range of information, including potential impacts to water resources, carbon storage, critical infrastructure, biodiversity, houses and human lives. In this study we demonstrated this by assessing the expected impact to houses of each fire (Fig 4). Of note are the higher expected house losses in the centre of the state in all cases. This phenomenon is due to the high concentration of houses in association with wildland fuels in this part of the state. This effect is also evident with the contrast between high FFDI forecasts, high fire impacts and low expected house loss in the north west of the state. While there is high fire potential in the north west, the housing density is very low, so the threat to the community is reduced. As simulation approaches are a way to integrate weather, the landscape, fire behaviour and impacts, they are an ideal way to get a clear idea of potential fire impacts on particular values.

The method presented here can be further extended by incorporating ignition probabilities. The maps presented here represent a regular grid of fires where each fire is given the same weighting. By weighting by ignition probability the likelihood of fires can be represented in the final output. By combining the likelihood of fires and empirically derived consequences (such as house loss in the example above) the method we present can be used to spatially represent fire hazard in a quantitative manner. This means that potential fires can be considered objectively and preparedness measures can be efficiently designed to be proportional to expected impacts. In contrast, methods based purely on weather derived ‘danger’ indices cannot truly represent danger as there is no potential to objectively incorporate values at risk.

Ensemble derived maps are able to provide a more nuanced indication of fire risk to the public than regional fire danger ratings. This has the potential to reduce of type I ‘false alarm’ errors (Taylor and Alexander 2006). However, as sources of public information, weather forecast style fire danger outlooks may not be ideal for all uses. When weather conditions become extreme, members of the public may look for ‘threshold’ style indicators to spur them to undertake a particular response (Reid and Beilin 2013). Currently total fire bans and ‘red alert’ warnings used by agencies as unambiguous triggers for action. While the prediction ensemble products may assist in declaring fire bans, bans are likely to remain a valuable tool in fire management. As with fire danger ratings, fire bans are declared over particular regions. While our results have indicated that the regions are not representative of fire behaviour, by aggregating the results of many daily ensembles, there is the potential to use fire simulation to better redraw fire danger declaration regions to create districts with more homogenous expected fire behaviour (Gouma and Chronopoulou-Sereli 1998).

5. Conclusion

Our results indicate that there is substantial spatial heterogeneity in fire impact within fire danger rating districts. This means that the daily rating applied to a district is unlikely to relevant to all parts of that district. For a particular area, if fire danger ratings are commonly too high, complacency may result. Conversely if ratings are conservative, the residents may not understand the true level of threat. Our methods provide an alternative way to understand and represent fire danger that is more locally relevant. In addition, simulation approaches can give a greater indication of the nature of the fire threat that particular localities may face.

6. Acknowledgements

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