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A fire regime risk management tool

T.D. Penman[a], **D. Ababei**[a], **D.M.O. Chong**[a], **T.J. Duff**[a] **and K.G. Tolhurst**[a]

[a] *School of Ecosystem and Forest Sciences, University of Melbourne, Creswick, VIC 3363*
Email: trent.penman@unimelb.edu.au

Abstract: Wildfires can cause significant damage to people, property and the environment. For example, the 2009 Black Saturday Fires resulted in the loss of 173 lives and over 2000 houses. These fires affected large areas of natural forest with a high value to society, in particular as catchments that provide Melbourne with drinking water and the habitat of threatened biodiversity. While these fires were the most destructive in human terms, the quantification of the existing and future risk posed from wildfire to multiple assets requires consideration of the total fire regime over a multi-decadal scale (Penman *et al.* 2014) and not just single events.

Fire regimes are the spatial expression of area burned over multiple years which includes consideration of fire frequency, intensity, heterogeneity and seasonality (Gill 1975; Whelan 1995). Fire management agencies seek to alter the fire regime to reduce risk to all assets however no actions universally reduce risk to all asset types. For example, fuel treatments are commonly used to reduce risk to people and property, but this can be to the detriment of environmental assets (Penman *et al.* 2011a). The challenge is therefore to develop management strategies that simultaneously satisfy the gamut of management objectives (Driscoll *et al.* 2010).

Here we present a new fire regime tool which builds on the PHOENIX RapidFire Fire Behaviour Simulator, hereafter PHOENIX. PHOENIX simulates fire behaviour based on empirically derived models for a range of environments based on fuel loads, topography and weather. The fire regime tool provides a novel simulation approach to quantify the risk to houses, ecological assets, water and carbon posed by natural and anthropogenic fire regimes. In doing so, the model allows for comparison of risk to assets over a range of realistic fuel management strategies across a landscape, as well as basic suppression responses.

Keywords: *Risk management, fire management, trade-off, Bayesian Networks, assets*

1. INTRODUCTION

Wildfires can cause considerable damage to people and property with the effects on communities and individuals lasting for many years after the event. The Black Saturday fires in Victoria, Australia, resulted in the damage or destruction of over 2000 houses and the loss of 173 lives (http://www.royalcommission.vic.gov.au/Commission-Reports/Final-Report.html). Similarly, the 2007 wildfires in California resulted in the evacuation of 300 000 people and the loss of 2223 houses (McCaffrey and Rhodes 2009). Wildfires have considerable economic impacts on communities, local business and production (e.g., agriculture and forestry) (Ganewatta 2008). Societal impacts continue for decades as many residents suffer post-traumatic stress as a result of the wildfire (Langley and Jones 2005; McFarlane *et al.* 1997; Papadatou *et al.* 2012). Minimising the damage of wildfires to people and property will therefore have a range of economic and social benefits.

Fire management agencies attempt to reduce the risk of fires reaching property through investment in a range of management strategies (Berry *et al.* 2006; Calkin *et al.* 2005). These are primarily fuel treatment (e.g. thinning, clearing, prescribed burning) and fire suppression (i.e. the coordinated use of fire-fighting resources such as trucks, helicopters and aircraft, in an attempt to contain or extinguish the fire). Optimal placement of fuel treatments and resources can reduce the risk to the interface, i.e. those houses which form the boundary between native vegetation and urban areas (Bradstock *et al.* 2012; Finney *et al.* 2007; Penman *et al.* 2014; Plucinski 2012; Wilson and Wiitala 2005). However, these actions are not expected to contain all wildfires, particularly under more severe fire weather conditions (Cary *et al.* 2009; LaCroix *et al.* 2006; Penman *et al.* 2011a; Price and Bradstock 2010). Furthermore, optimising fire management strategies for the protection of people and property may also come at the cost of environmental assets in the landscape (Driscoll *et al.* 2015; Driscoll *et al.* 2010; Penman *et al.* 2011a).

Management of human assets in the landscape predominantly focuses on the next “big event” likely to result in loss. However, environmental assets are generally not impacted by the entire fire regime rather than a single fire. Fire regimes are the combination of the frequency, intensity, heterogeneity, extent and type(s) of fire experienced (Gill 1975). Changes to natural fire regimes have been demonstrated to alter the diversity, composition and structure of vegetation (Baeza *et al.* 2007; Franklin *et al.* 2001; Higgins *et al.* 2007; Keith 1996; King *et al.* 2006; Penman *et al.* 2008; Russell-Smith *et al.* 1998). These changes impact on a range of fauna species (Clarke 2008; Hannah *et al.* 1998; Russell *et al.* 1999; Sitters *et al.* 2014; Woinarski *et al.* 2004a; Woinarski *et al.* 2004b). Other environmental assets such as carbon and water are similarly impacted with a change in fire regimes (Bennett *et al.* 2014; Bennett *et al.* 2013; Collins *et al.* 2014; Fernández *et al.* 2006; Morris *et al.* 2014; Nolan *et al.* 2014; Smith *et al.* 2011).

Developing fire management approaches that protect or maintain both anthropogenic and environmental assets in the landscape is vital. Few studies have attempted this process. Of those that exist they generally focus on single management strategies and/or fail to consider the full range of assets in the landscape (Cary *et al.* 2009; Driscoll *et al.* 2015; King *et al.* 2006; Penman *et al.* 2014). There are a number of fire regime simulators that currently exist (for discussion see Cary *et al.* 2009) however these are either localized in the fuel/fire behaviour model or are limited in the range of management strategies that can be implemented. In this paper, we describe a new fire regime model that builds on the strengths of existing regime tools, but utlises the PHOENIX RapidFire Fire Behaviour Simulator for fire behaviour and Bayesian Networks to capture the uncertainty in the model system.

2. CONCEPTUAL MODEL

A conceptual model was developed and refined through workshops with the authors of this paper and is presented in Figure 1. In the model, we begin with a daily weather stream which inputs into the ignition model to predict whether any ignitions will occur on each one day and, if so, how many. If the model predicts one or more ignitions, the fire behaviour model is initiated with an hourly weather stream. Each ignition is also assigned a level of suppression response depending on the scenario settings. All ignitions on a given day are run concurrently in the landscape to allow for interactions between fires. Once the fires are completed for a day or days, outputs from the fire behaviour model are then used to determine fuel consumption and estimate the remaining fuel at each site. At the end of the season the fuels are grown based on fuel accumulation curves. There also exists an option for fuel treatment options, primarily prescribed burning. At the end of each fire season, fuel treatments can be implemented. These treatments will also be run through the fire behaviour simulator to determine fuel consumption and within burn heterogeneity. At the end of each wildfire and planned fire season, annual estimates of risk to assets are calculated for a range of asset types. There is scope for risk values to feed back to fuel treatments, but this is not currently implemented.

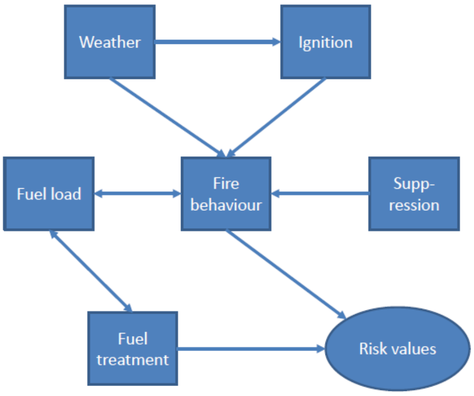

Figure 1. Conceptual model for the fire regime tool

Each simulation is set to run for a period of years to decades. Determination of ignitions occurs at a daily time step, and fires, when they occur, run on hourly weather data. Risk values and fuel treatments are calculated on an annual time step or across the study period of years to decades. For any one management scenario, a large number of simulations will be run to assess the mean and uncertainty for each risk value.

3. FIRE BEHAVIOUR SIMULATION

Early development of the model is based on the PHOENIX RapidFire Fire Behaviour Simulator (Tolhurst *et al.* 2008), however the program is written such that other fire behaviour simulators could be used in the future. PHOENIX simulates the two dimensional growth of fires in landscapes using Huygen's principle (Knight and Coleman 1993). Within PHOENIX, fire behaviour models have been developed from the CSIRO southern grassland fire spread model (Cheney *et al.* 1998; Cheney and Sullivan 1997) and the McArthur Mk5 forest fire behaviour model (McArthur 1967; Noble *et al.* 1980). The model incorporates the effects of topography and vegetation type on wind, based on the Wind Ninja program (http://www.firemodels.org/index.php/windninja-introduction Accessed August 2015) and fire spotting (via ember propagation, spread and spot-fire ignition (Saeedian *et al.* 2010)).

PHOENIX RapidFire was selected for a number of reasons. Firstly, the model is capable of simultaneously incorporating varying fuel types and Australian fire behaviour models in a single landscape. Secondly, the model incorporates long distance spotting (Saeedian *et al.* 2010) which is considered to be a major mechanism of fire spread in eucalypt forests (e.g. Sullivan *et al.* 2012). Thirdly, PHOENIX is currently used in fire management agencies in all eastern states, as well as South Australia. This is important as the model has potential to be implemented as a risk planning tool for fire management agencies. Fourthly, it is able to simulate fires rapidly, making it suited for the analysis of large numbers of scenarios. Finally, PHOENIX is one of the few models that incorporates dynamic suppression modelling (Penman *et al.* 2013), i.e. suppression effectiveness is a function of number of suppression units, local environment and local fire behaviour.

The fire regime model uses the PHOENIX engine for the simulation of fire behaviour, however a number of aspects of the PHOENIX program have been externalized for the fire regime tool. It is beyond the scope of this paper to describe them all in detail. The most important variant is the issue of fuel accumulation. In the PHOENIX RapidFire program surface, elevated and bark fuel loads are a function of vegetation type and time since the last fire. Such an approach does not allow for varying fire intensities resulting in varying levels of fuel consumption. In the fire regime model, fuel consumption and growth are calculated externally using a Bayesian Network model and fuel loads for each stratum are then provided directly to PHOENIX for future simulations.

4. BAYESIAN NETWORKS

One of the key objectives of any simulation program is to capture and model the uncertainty in the model system. Like all land management systems, fire management is subject to uncertainty at various levels. Within our fire regime model we capture uncertainty through modelling relationships using Bayesian Networks (BNs) (Pearl 1986). BNs have previously been used for a range of environmental applications including fire (Dlamini 2010; Mendes *et al.* 2010; Penman *et al.* 2011b) and are considered one of the best statistical tools for risk management (Marcot *et al.* 2006).

We use Uninet, a standalone uncertainty analysis software package to model and integrate the BNs. Each node in the graph corresponds to a random variable and the arcs represent direct dependence relationships. Each node is assigned a distribution (continuous or discrete, parametric or empirical) and each arc is assigned a rank or conditional rank correlation coefficient. The marginal distributions, rank correlations and a choice of copula determine the joint distribution underlying the BN, which can be sampled. Uninet uses the normal copula for fast conditioning/inference. It does not use the normal joint distribution and there are no assumptions about the node distributions (Hanea *et al. in press*).

BNs have been implemented in a number of points within the fire regime tool – weather, ignitions, fuel accumulation and risk values. Weather observation data often contain missing values particularly for the uncommon variables, such as cloud cover. These values are estimated from an empirical BN based on other weather variables. Two BNs are used in ignition determination. The first examines the relationship between Fire Danger Index (FDI), month of the year and the number of ignitions per day and the second calculates the probability of ignition at a point based on FDI and environmental variables. Fuel accumulation is also calculated through multiple BNs, one for each fuel type and strata. Each fuel model allows the user to specify the accumulation equation and the uncertainty around fuel growth parameters. Historically all fuel strata have been modelled using the negative exponential model, our approach overcomes this limitation by allowing the most appropriate equation for accumulation. Many of the risk output value models have also incorporated a BN but it is beyond the scope of the paper to discuss these.

5. RISK VALUES

The primary purpose of the model is to examine risk trade-offs for varying values in the landscape. A major component of the model development is devoted to developing meaningful and measurable metrics of risk for the range of assets in the landscape. The challenge is to develop metrics that can be either generic enough to be applicable to multiple (or all) landscapes or are implemented in a flexible manner to allow users to input regionally appropriate values. All risk metrics are being modelled within the software framework to maximize the program efficiency and avoiding the use of third party software to avoid problems with version changes or unsupported software.

Risk values that will be represented in the fire regime model include a range of environmental and anthropogenic assets. Risk metrics are being developed around biodiversity, carbon, water, houses, social values and critical infrastructure. From these values, economic impact of treatments and wildfires can be estimated. Combining the risk and cost values allows for a fulsome multi-criteria decision analysis as advocated by Driscoll *et al.* (2010; 2015). While it is beyond the scope to detail all these metrics we present the methodology for three asset types (house loss, water, biodiversity) by way of example.

House loss is a major impact from wildfire which has economic and social impacts on society (e.g., Langley and Jones 2005; McFarlane *et al.* 1997; Papadatou *et al.* 2012). To date, house loss has been the major focus of fire management decision making (DSE 2012) and as such the methodology is relatively well advanced. PHOENIX RapidFire has implemented a house loss function based on convective strength of the fire and the number of embers impacting the property (Tolhurst and Chong 2011). These equations were developed from the 2009 Black Saturday fires and have yet to be tested elsewhere. Regardless, the model considers the two major causes of house loss (direct contact of heat or flame and embers) which is not available in other similar studies.

Water supplies for most Australian capital cities lie within flammable vegetation. Fires have been demonstrated to impact both the quantity and quality of the water supply. There are long established relationships with water supply for mountain ash forests (Kuczera 1987) and recent developments for mixed forests (Nolan *et al.* 2015). Combining these relationships allows for an annual estimate of water yield based on simple relationships with annual rainfall and time since fire. Water quality can be affected by post fire erosion (Morris *et al.* 2014) and debris flows (Smith *et al.* 2011) with debris flows having the largest impact. Debris flows are complex processes that incorporate local storm cells, fire history and topography to estimate a load of material reaching the water catchment. Models developed by Langhans *et al.* (2016) will be implemented within the fire regime framework.

Biodiversity is a complex concept and understanding the impacts of fire on biodiversity is similarly complex. Early implementations of the fire regime tool will estimate impact of fire on biodiversity through two metrics – age class distribution and connectivity. Age class distributions seek to identify an optimal distribution of age classes in the landscape to maximum biodiversity or a subset of biodiversity (Di Stefano *et al.* 2013). Departure from the optimal age class distribution provides a measure of the impact on biodiversity or the expected species decline (Di Stefano *et al.* 2013). Departure from the optimal distribution will be calculated annually. Connectivity in the landscape presents opportunity for gene flow through dispersal which is vital for the long term diversity of species at the genetic, population and species level. Using the methods of McRae *et al.* (2008), annual landscape connectivity over time will be measured and average values, as well as bottlenecks will be recorded.

6. CONCLUSIONS

Our fire regime model represents a novel approach to simulation of the fire management space. We have developed a simulation tool that fits with current modelling systems, but is capable of updating with future developments in fire behaviour. By incorporating Bayesian Networks into the model structure we explicitly model the uncertainty in the system. As these models of the system develop, we can easily update the BNs within the simulation tool. Finally, all risk values are calculated within the tool thereby avoiding post-processing and the errors associated with the storage and handling of large datasets.

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