Chapter 5

Forest Fire Occurrence and Modeling in Southeastern Australia

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Abstract

Forest fire is one of the major environmental disturbances for the Australian continent. Identification of occurrence patterns of large fires, fire mapping, determination of fire spreading mechanisms, and fire effect modeling are some of the best measures to plan and mitigate fire effects. This chapter describes fire occurrence in New South Wales (Australia), the Australian National Bushfire Model Project (ANBMP), fire propagation modeling methods, the McArthur's model and current forest fire modeling approaches in the state of New South Wales of Australia. Among the established fire models, PHOENIX Rapidfire predicts fire spread and facilitates loss and damage assessments as the model considers many environmental and social variables. Two fire spread models, SPARK and Amicus, have been developed and facilitated fire spread mapping and modeling in Australia.

Keywords: fire modeling, fire occurrence, PHOENIX Rapidfire, simulation, SPARK

1. Introduction

Forest fire is a ponderous and major threat with negative impacts sometimes lasting more than 10 years from the combustion period [1]. The degree of environmental damage due to forest fires is related to many environmental factors including topography, climatic factors, and vegetation types [2]. Topographic factors, ignition points, fire weather conditions, and fuel characteristics are contributing factors to the intensity and magnitude of fires [3, 4].

The vegetation in Australia is influenced and shaped by forest fires, due to the diverse varieties of floral composition, undulated terrain and a varied climate pattern, the vegetation in Australia [5]. The northern part of Australia represents tropical and subtropical climates and the south and south-east have temperate wet and seasonally dry climatic characteristics. The south-western part has a Mediterranean type climate and the central part of the continent is mainly arid and mainly free from large fires due to limited vegetation coverage [6]. The vegetation communities of Australia are largely fire adapted and dependent on fire for regeneration. In particular, the abundant Eucalyptus forests of Australia have high fuel loads, create large amounts of litter, and have higher volatile oil contents in leaves [7]. These forests are highly inflammable and more frequent to fires. Higher temperature, gusty wind, and scarce rainfall create the extreme fire weather condition which instigates big fires in the southeastern regions of Australia. New South Wales including the Australian Capital Territory (ACT) and Victoria and Tasmania are notable forest fire affected areas in the world [6, 8].

The temperate and tropical regions of Australia are affected differently by their weather systems. The southern part of Australia has a higher fire danger during the hot and dry summer months, whereas northern Australia has a higher fire risk during winter [9]. On average, Australia's worst forest fires occur in late summer and early autumn; although this does not specify that they cannot happen at any time or at a certain time of the year [10]. One of the worst events in world fire history is the Black Saturday Bushfire (7 February–14 March, 2009), which burned across Australia's Victoria State. If rain increases vegetation growth in the preceding winter, then the following summer season therefore has a higher fire danger. Topography, vegetation and climatic conditions play significant roles in fire spreading and in short- and long-term fire effects in southeastern Australia (**Table 1**).

Fires instigated in remote forest areas are difficult to manage and generally result in more environmental damages. People living close to fire-prone areas are much more vulnerable to loss of property and their lives due to fire [11]. The forest fire hazard in Australia results from the complex interaction of highly disparate natural and anthropogenic drivers. Natural variables include the type, as well as the amount, of living or dead plant substance, and the weather conditions that ordain the flammability and combustibility of vegetation.

The spread of fire relies mainly on topography and weather conditions though other associated factors (e.g., fuel type, fuel moisture content, and fire ignition) are also driving factors [12]. Rainfall and temperature regulate the short- and long-term fuel moisture content and fuel availability, which have significant impacts on fire occurrence [13]. Clarke derived trends in the Forest Fire Danger Index (FFDI) examining historical records of fire. There were 38 weather stations that recorded forest fire from 1973 to 2010 and no decreasing trend of forest fire events was found in NSW [10]. Fires have different characteristics based on existing vegetation types, fuel loads, and combustibility [14]. Consequently, fire danger prediction relies on vegetation types and climate conditions [15]. Topographic factors and vegetation influence weather patterns, creating microclimates for fire ignition, occurrence, and spread. Apart from environmental factors, human activities at the wildland-urban interface can impact fire occurrence and can increase fire danger [16–18].

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Fire event (name)	Area burned (ha)	Date
Southern Highlands bushfires	250,000	5–14 Mar, 1965
1980 Waterfall bushfire	>1,000,000	3 Nov, 1980
1979 Sydney bushfires	>1,000,000	24 Dec, 1979
1994 Eastern seaboard fires	~400,000	27 Dec, 1993–16 Jan, 1994
Lithgow bushfire	400,000	2 Dec, 1997
Black Christmas	300,000	25 Dec, 2001–7 Jan, 2002
2006 Central Coast bushfire	160,000	1 Jan, 2006
Jail Break Inn fire	30,000	1 Jan, 2006
Pulletop bushfire	9000	6 Feb, 2006
Warrumbungle bushfire	54,000	18 Jan, 2013
2013 New South Wales bushfires	100,000+	17–28 Oct, 2013

Reference: https://www.canyonleigh.rfsa.org.au/australian-bush-fire-history; http://edition.cnn.com/WORLD/9712/04/australia.fires/; http://royalcommission.vic.gov.au/Finaldocuments/volume-1/HR/VBRC_Vol1_AppendixB_HR.pdf (Accessed on 19 February, 2018).

Table 1. Large fire events and burned areas (in hectares), where known, in New South Wales, Australia.

Researchers have used empirical models [generalized linear model (GLM)] to assess the characteristics of fire occurrence [19]. In most Australian eco-regions, vegetation structure and composition vary spatially and vegetation formations regulate fire occurrence patterns. The aims of this chapter are to describe the big fire events and the major driving factors of fires in New South Wales, basics of forest fire modeling and previous and present fire models of New South Wales of southeastern Australia.

2. Fire in Eucalyptus forests of Australia

Fire is an integral part of the dry and wet Eucalyptus forests of Australia [20, 21]. Eucalyptus species in Australia are fire adapted and regeneration of eucalypt species also depends on fire [22]. Grasslands and sedge lands of the *Sclerophyll* forests are driving factors for fire intensity and propagation in these forests. The understory vegetation of the dry *Sclerophyll* forests plays key roles in fire frequency and intensity [22]. Wet *Sclerophyll* forests have lower fire dangers compared to dry forests. In Tasmania, changes in fire occurrence and burned areas have profound impacts on the composition and structure of the dry *Sclerophyll* forests [23]. Eucalypt species that grow in a severe fire climate can generally survive in a high-intensity fire. In the case of a young tree burned severely, the branches and stems die, but the tree can survive by producing several new stems from buds near ground level. Older trees survive through producing epicormic shoots from bud strands on the stem and larger branches. Dry *Sclerophyll* forests tend to be affected by a fire every 4 to 20 years.

3. Forest fire occurrence in southeastern Australia

Hilly areas, forests, savannas, and densely vegetated landscapes are more prone to forest fires than grasslands and shrublands; buildings and infrastructures in these areas are also at higher risk. Incorporating socioeconomic variables with environmental variables can bring about a more efficient management tool, incorporating fire occurrence prediction to assist management. To understand the spatial pattern of fire, it is necessary to understand the characteristics that control the area burned, e.g., vegetation growth, dry fuel abundance, fire weather, and ignition; unavailability of any of these factors can limit the area burned. In Penman et al., spatial ignition patterns of *Sclerophyll* forests in the Sydney basin were compared with northern hemisphere coniferous forests [17]. Patterns of lightning ignition and arson procured were very similar to the results obtained from the North American coniferous forests and other ecosystems. Speculation based on the Sydney area of southeastern Australia showed that while fires ignited by arson tended to occur at ridges near anthropogenic infrastructures, fires ignited by lightning tended to start at ridges further from infrastructure. The results also showed that fires ignited by lightning tended to occur in fuel older than 25 years, while fires from arson tended to occur in fuel younger than 10 years. It was suggested that since arson ignitions occur at shorter distances to urbanized regions, these fires pose higher threats to highly valued resources and assets (HVRA) compared to fires from lightning; therefore, forest managers should prioritize and emphasize management of arson ignitions since the goal is to constrict the social and economic loss [17].

4. Australian national bushfire model project

The first personal computer-based bushfire model, Australian national bushfire model (ANBM), in Australia, was developed under the National Bushfire Research Unit in 1987. This real-time model was to facilitate decision-making in emergency condition and for the bushfire management. The inputs of the ANBM were fuel types and conditions, topographic factors, and economic modules. Rothermel and McArthur's fire model were embedded in the processing engine to delineate the fire spread and fire perimeter spatially. The model was the first initiative to integrate geographic information system (GIS) with real-time data. The outputs of the ANBM were graphical and were able to show fire front (using Huygens principle) at any desired scale. The ANBM was a successful first initiative and nowadays, many fire models have similar model architecture like ANBM, though the computational capabilities and input parameters have increased in the recent developed fire spreading models [24].

5. The McArthur Forest Fire Danger Index (FFDI)

McArthur's model, a tool to simulate complicated weather variables, is still being used all over Australia for fire danger rating and forecasting [26]. The first fire scientist of Australia,

Category	Forest	Grassland
Catastrophic	>100	>150
Extreme	75–99	100–149
Severe	50–75	50–99
Very high	25–49	25–49
High	12–24	12–24
Low moderate	0–11	0–11

Table 2. Australian fire danger rating for Australian forests and grasslands [25].

A. G. McArthur, developed this fire danger index and this fire danger index has been utilizing to disseminate fire danger information all over Australia. The McArthur FFDI includes rainfall, evaporation, wind speed, temperature, and humidity to describe the fire danger level of the fire-prone areas of Australian continent. The developed fire danger rating scale for forest and grassland are given in **Table 2**.

McArthur's fire danger scale and meters are significant achievements for forecasting fire and fire spread. The spatial distribution of FFDI was calculated for NSW using the McArthur's equation [26]. McArthur's meter was for the grasslands, known as McArthur's Mark 3 meter and McArthur's meter for forests (known as McArthur's Mark 5 meter) was developed especially for the Eucalyptus forests of Australia. These two models, Mark 3 and Mark 5, are commonly used for grassland and forest fire danger forecasting, respectively, today [27].

6. Forest fire modeling and simulation: concepts, types, and examples of models

Forest fire modeling is classified by the nature of underling equations into theoretical, empirical or semiempirical. Two types of forest fire models are being used: wildland fire spread and fire-front property models. According to physical systems, these models are divided into surface-fire models, crown fire models, and spotting and ground fire models. While theoretical models are based on fluid mechanics, heat transfer and combustion laws, empirical models rely on statistical correlations derived from previous studies of forest fires, and semiempirical models are theoretical models fused with statistics [28].

From the perspective of variables, wildland fire spread models give physical estimates of the fire perimeter and fire-front models illustrate the features of the fire geometrically. Furthermore, when divided based on physical systems—surface-fire models consider vegetation of the lowest strata, that is, less than two meter height, crown fire models consider surface and aerial strata of vegetation, spotting models consider fuel beyond the main fire area, and ground fire models consider the humus layer on the ground.

Theoretical surface-fire models incorporate fuel, terrain, and climatic parameters in a simplified way so that mass, momentum and energy-conduction, convection, and radiation-transfer can be quantified to describe fire propagation. Empirical surface-fire models, initially developed by McArthur, use statistical correlations from experimental fires. The aim of crown fire models is to analyze fire transition conditions from surface to crown, and to study behavior variables. Therefore, crown fire models are classified as initiation and spread models [28].

Modeling forest fires from a combination of mathematical equations allows descriptive predictions of the spatial and temporal evolution of fire behavior variables. Forest fire modeling is a multi-scale concept and integrating natural physical processes into the model environment is a challenging task. Simplification of physical processes reduces computation and output processing time. Large fires have multifarious impacts on nature and the human environment and are complex to simulate as complicated fire meteorology, spatial heterogeneity and complex fuel structure and availability are associated with fire propagation. Forest fire spread forecasting depends on accurate weather prediction, precise ground information about fuel types, conditions, and topographic factors. Any complexity and errors in predicting these factors can induce incorrect forest fire hazard prediction and forecasting [29].

6.1. Mathematical models

Mathematical modeling has been used to predict the fire propagation and fire effects. Mathematical models are important tools for predicting fire effects, fire suppression actions, and in strategic fire management and planning. Nowadays, mathematical models have been used to predict the vegetation response in fire severity forested areas and park managers are using mathematical modeling techniques for fire planning and management. The validated and experimented mathematical fire models are reducing uncertainty through providing robust assessment of fire propagation, fire effects, and in generating future fire regime scenarios. These modeling techniques are reducing the range of variables and facilitating data-processing through constructing empirical relationships [30]. Integration of fire intensity, flame height, and wind speed in a mathematical modeling framework is allowing fire researchers and scientists to predict the possible fire impacts on emergency and after-fire management [31].

6.2. Physically based forest fire simulation model

Physical fire models are utilized to understand the fire behavior and spread rate scenarios in heterogeneous landscapes. The modification of terrain and physical environmental parameters in a small scale provides realistic results to understand the fire spreading and behavior. Two-dimensional physical fire models are built based on energy conservation laws, heat transfer, and convection mechanism which are commonly used all around the world. Two-dimensional fire models integrate wind and slope effects under different fuel type conditions and provides actual understanding of the natural fire environment-climate interactions in a controlled environment [29]. Three-dimensional or complex physical fire models integrated with fluid dynamics concepts can help generating robust and factual experiments. NCAR's

Coupled Atmosphere-Wildland Fire-Environment (CAWFE) model [32], WRF-Fire model [29], FIRETEC model [33], and fire dynamics simulator [34] are the examples of physical fire models, which are being used to understand the fire behavior and propagation.

6.3. Data assimilation model

Data assimilation models use dynamic data-driven application system (DDDAS) techniques to simulate scenarios [35]. DDDAS toolbox is widely used to incorporate additional data to execute a model and can reverse the action of steering the measurement process. A fire combustion model is developed integrating single semi-empirical reaction rate in the assimilation model. In other words, reaction-convection-diffusion processes are integrated in the Arrhenius equation to understand the chemical reactions and to estimate the fire-front temperature. This fire combustion model can generate output scenarios for predicted combustion waves, fire-front temperature, and post-frontal burned area, predict combustion zone and can model fire propagation and direction [36].

6.4. Statistical fire models

Statistical methods have significant role in forest fire prediction. The statistical science can make significant contributions to improve the forest fire prediction in case of local to global scales. The integration of stochastic statistical estimation in fire phenomena can provide decision-making supports for better fire planning and management. Statistical predictive models have been used to model fire spreading, burned area estimation, and fire impacts. In a study [37] of forest fire modeling in southern Australia, logistic regression was used to integrate land cover, topographic data, vegetation indices, and socioeconomic variables along to delineate the spatial pattern of a forest fire on a grid of 1 km^2 over a period of 11 years. This study found that densely vegetated landscapes, mountainous regions, savannas, and forests are most prone to forest fires. Grasslands and shrublands are relatively less preferable zone for forest fires. Moreover, socioeconomic phenomena are useful in the overall results of the prediction and environmental factors play individually strong roles in the prediction of fires [37].

6.5. Empirical and simulation models

The quantitative estimation of the risk of damage of properties is necessary for the implementation of an evidence-based approach in case of the management of forest fire [17]. The empirical and simulated results of predicted fire spread and possible impacts on properties and natural environment are helpful in assessing wide range of risk-reduction techniques. Simulated weather warnings are the main drivers of forecasting fire danger index in Australia [38]. Advancements of the simulation modeling allowed us to quantify fire risk and have been widely used not only in Australia [39] but also in the USA [40] and Europe [41]. Fire empirical models are widely used in assessing likelihood of fire ignition [17], ignition, and spread distance of fires [42], fire risks, and prescribed burning planning [1, 43], and fire impacts in wildland-urban interfaces (WUI) [44]. In southern Australia, FIRESCAPE-ACT was used [45]. FIRESCAPE-SWTAZ is an updated version of the FIRESCAPE-ACT to forge fire rules for the heterogeneous landscapes in Tasmania, Australia [46]. A sophisticated state-and-transition model is embedded in the FIRESCAPE-ACT model for the heterogeneous landscapes [46].

In southeastern Australia, LAndscape MOdeling Shell (LAMOS) is used to emulate the progressive dry *Sclerophyll* forest [47]. LANDscape Succession Model (LANDSUM) is a spatially-explicit stochastic simulation model which has been used to understand fire occurrence and fire spreading at local and regional scale [48]. In [49], the researchers compared LANDSUM and other four landscape fire models in Australian continent. LANDSUM model has different purposes to use as a fire and forest management tool.

7. PHOENIX Rapidfire, SPARK, and AUSTRALIS model examples from Australia

Many fire models were analyzed already and still many are in ongoing process. Some statistical fire models in Australia are developed using the binomial (logistic) regression. Binomial regression techniques are used to model the fire behavior in relation to distance, weather, fuel types and conditions, and fire barriers [50]. Fire weather has significant roles in defining fire regimes of southeastern Australia and the associated fire weather parameters are critical to integrate and model in the real-time or empirical modeling framework. In [50], researchers integrated fire weather parameters, fuel treatment, and terrain factors to predict the fire risk in Greater Sydney using logistic regression and achieved 98% predictive accuracy in fire risk modeling which can be considered as a complement to simulation methods. Fire simulation modeling in southeastern Australia integrated fuel types, quantity and conditions, and topography to understand fire spreading and fire behavior [39, 51]. The fire behavior models in southeastern Australia are developed under a limited range of controlled considerations. Researchers found that fire behavior and propagation simulation results showed a moderate level of prediction accuracy comparing with the real fire scenarios [52–54].

Prediction methods based on formal bushfire behavior have been in development for nearly a century [55]. Most models here have focused on the deterministic prediction of the spread rate of the front of the fire as this is critical to the application and control of fire [56]. Physical and quasi-physical models were used to represent the chemistry and physics of fire spread, while statistical relationships between variables observed during field and laboratory experiment can be delineated using quasi-empirical and empirical models [56, 57]. Physical fire spread models are generally computationally heavy as these models are driven by environmental forces and are not operationally practical [56]. Empirical models utilize readily usable fuel and weather data as inputs and as they are generally relatively simple, analytical models that do not attempt to include any physical understanding of the combustion processes involved, can be solved relatively quickly [55].

7.1. PHOENIX Rapidfire

Although there are numerous fire spread simulators, their scale is way larger than necessary for the highest loss risk zones, which are known as the wildland-urban interface, where the interaction between vegetation and humans happens. In Australia, PHOENIX Rapidfire (PHOENIX) is the fire simulator which has been modeled to illustrate fast spreading and large fires. PHOENIX combines firebrand transport and ignition's contribution to the spreading of the fire [58]. In [58], researchers used the illustrated example of the forest fire in Cavaillon, France, where spotting was a major trend and hot coal was flowing from high peaks and flown to adjacent channels to spread the fire. Afterward, to make the spotting pattern comparable to the ones in Cavaillon, the thresholds were recalibrated manually. For fires like the Cavaillon fire, where spotting is the key spreading mechanism, it is necessary to first simulate small-scale spotting. Moreover, the ember density modeling is useful in predicting the effects on HVRA; this can be auxiliary to other thresholds of standard intensity. Nevertheless, it was suggested to conduct further detailed testing of its use in other types of fire events before employing it widely. PHOENIX has the capacity to analyze the characteristics of fire spreads in the scale as small as WUI; this makes it a very useful tool in estimating the risk of impact, fire behavior reconstruction, vulnerability modeling, evaluation of fire management plan, and suppression process [58]. In [59], researchers derived simulated fire severity values using PHOENIX. PHOENIX Rapidfire was simulated to understand the fire extent and behavior of the Black Saturday fire [60].

7.2. SPARK model

SPARK is a fire spread simulation toolkit for Australia. SPARK uses set method which is directed by a user-defined algebraic spread rate for the fire propagation modeling [61]. Small-scale and complex bushfire scenario can be simulated within this modular-workflow based bushfire simulation package. SPARK allows user-defined spread models which makes SPARK a flexible modeling package which is free from complex-coded spread models.

The easy to implement user-defined models enables SPARK as a different spread modeling testing platform as well. The level set method of SPARK facilitates integrating fire perimeter and other environmental parameters to assess fire spreading. SPARK includes a workflow environment allowing faster processing and visualization using high-performance computation capabilities. A fire propagation module (spark propagation solver) can be run from the workflow environment. The model inputs are atmospheric parameters, fuel types and conditions, topographic factors, and fire ignition points. The input parameters are flexible and can be sourced from a range of databases based on the scenario. SPARK has many in-built operation packages and the output of the model is raster-based which can be modified and integrated with other social and environmental parameters in any remote sensing software or in GIS platforms. The final output shows the spreading over time which is important to predict and take necessary initiative for fire management.

7.3. AUSTRALIS simulator

AUSTRALIS is a high-performance forest fire simulator that allows the location of a forest fire to be rapidly predicted. A methodology used to evaluate the accuracy of forest fire simulators using historical fire data is presented and applied to the AUSTRALIS forest fire simulator using the four distinct phases of a large-scale forest fire occurring in Western Australian sand-plain heathlands. The AUSTRALIS forest fire simulator allows the future location of a forest fire to be rapidly predicted, and geographical information systems (GIS) maps with forecast fire-lines overlaid on them to be quickly made available to fire managers, the accuracy of such simulators needs to be examined by application to high-quality datasets from prior fires. AUSTRALIS employs a discrete event simulation technique that is based on partitioning the landscape into a collection of two-dimensional cells and calculating the propagation delay between an "ignited" cell and each of its "unburnt" neighbors. The discrete event simulation approach of AUSTRALIS relies on spatial discretization, where the landscape is partitioned into cells that are assumed to have homogeneous attributes, such as vegetation, slope, and aspect. Each cell contains state information ("unburnt" and "ignited") and many attributes relevant for calculating propagation delay, including location, elevation, and fuel characteristics such as vegetation type and fuel load. In contrast to other cell-based approaches to forest fire simulation, the cell locations are distributed randomly, rather than regularly, across the landscape [62].

8. Conclusion

There are many fire spread models in the different regions of Australia. In Western Australia, AUSTRALIS simulator is widely used for fire propagation mapping and modeling. The Commonwealth Scientific and Industrial Research Organization (CSIRO) has developed a new fire knowledge base platform (Amicus) for Australia and Amicus will be used as a complimentary knowledge base with the PHOENIX Rapidfire. SPARK is a new toolkit for fire spread prediction and modeling for Australia which is also developed by CSIRO. These established fire spread models have been utilized for better fire management planning and forest management.

Conflict of interest

The authors declare no conflict of interest.

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