PHOENIX RapidFire

Manual

PHOENIX

TECHNICAL REFERENCE GUIDE

A TECHNICAL GUIDE TO THE PHOENIX RapidFire BUSHFIRE CHARACTERISATION MODEL VERSION 4.1

Part one of a series of three documents including:

1. PHOENIX Technical Reference Guide
2. PHOENIX User Manual
3. PHONEIX Input Data Guide

Fire Prediction Services

This document was produced by Dr Kevin Tolhurst and Wayne Kington on behalf of Fire Prediction Services and AFAC, using various pre-existing technical reports and papers prepared by Dr Kevin Tolhurst, Derek Chong, Dr Thomas Duff and Brett Cirulis, and with guidance from Greg Esnouf.

Disclaimer:

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1. INTRODUCTION

1.1 PURPOSE OF THIS DOCUMENT

This document provides a technical overview of PHOENIX RapidFire 4.1 (often abbreviated to 'PHOENIX' in this document) for the benefit of:

- New users;
- Land and fire managers;
- Software technicians; and
- Others who wish to gain a greater understanding of the uses and components of PHOENIX.

This document provides the information necessary to allow PHOENIX to be compared to other similar systems. It contains technical detail and references technical detail contained in other documents where appropriate. It is part of a series of key documents about PHOENIX including:

PHOENIX Technical Reference Guide	PHOENIX User Manual	PHOENIX Input Data Guide
• A comprehensive technical reference for PHOENIX.	• How to interact with the PHOENIX software	• How to prepare the input layers that power PHOENIX

Be aware that in addition to the above, various government agencies have produced guidelines for PHOENIX that are specific to support their individual operating environments. Also, there are various technical papers that have been prepared by the University of Melbourne and the Bushfire CRC that this document draws upon, and which are referred to throughout.

1.2 NAVIGATING THIS DOCUMENT

This document starts by introducing the PHOENIX RapidFire fire simulation software, what it is, why it was developed and how it works **(Chapter 1)**. It goes on to discuss the development of and development philosophy behind PHOENIX **(Chapter 2)** and then describes in detail:

- How data is collected, represented and stored in PHOENIX using the **'Fire Grid' (Chapter 3)**;
- The **inputs** that are required or that are beneficial to support PHOENIX **(Chapter 4)**;
- How each **component** model of PHOENIX works **(Chapter 5: Fire Behaviour, 6: Fire Perimeter Propagation and 7: Assets)**; and
- The **outputs** that the user can generate from PHOENIX **(Chapter 8)**.

Appendix 1 lists the various versions of PHOENIX and what each version added to software functionality.

Appendix 2 lists the actual files read by PHOENIX and their relationship to the inputs discussed in this document.

Appendix 3 provides a discussion on the simulation process, from ignition, through to build-up, spotting and fire spread.

1.3 WHAT IS PHOENIX?

PHOENIX is a bushfire characterisation model that integrates fuel, terrain, weather conditions and suppression to simulate a fire's development and progression in the landscape. It is used by land and fire managers to support fire management and land-use planning and to support decision making during bushfires.

PHOENIX is a mechanistic continuous, dynamic, empirically-based model that simulates fire characteristics such as fire spread, flame height, intensity, size and ember density and stores the results in a database (using spatially gridded data), and can also simulate some the effects of suppression efforts and the impact of fire on various values and assets.

At a minimum, PHOENIX requires fuel data as an input. However, there are several inputs, including terrain, weather, suppression, fire history and assets that are required for realistic simulations. These inputs must be prepared correctly in a spatial format.

PHOENIX produces a range of outputs including fire spread, intensity, flame height, ember density, burn frequency and asset impact. The outputs of a simulation can be viewed in GIS, Google Earth, as images and in spatially gridded data provided in ASCII, XML, CSV and Shapefile file formats.

1.4 HOW PHOENIX WORKS

PHOENIX is a standalone executable program designed for operation under Microsoft Windows, but can also be easily converted to Mono to run on UNIX and LINUX operating systems. It has a graphical user interface (GUI), but can also be controlled via command line to allow integration with other software systems. It is standalone software that does not need to be installed and therefore can be run directly from a device such as a USB storage device. It is also designed to support running across more than one computer (where one computer is the master) or processor, for more complex simulations requiring more processing power.

In order to gain an overview of how the simulation process in PHOENIX works, an overview is offered below based on Figure 1. A more detailed explanation is offered in *Appendix 3: The Simulation Process.*
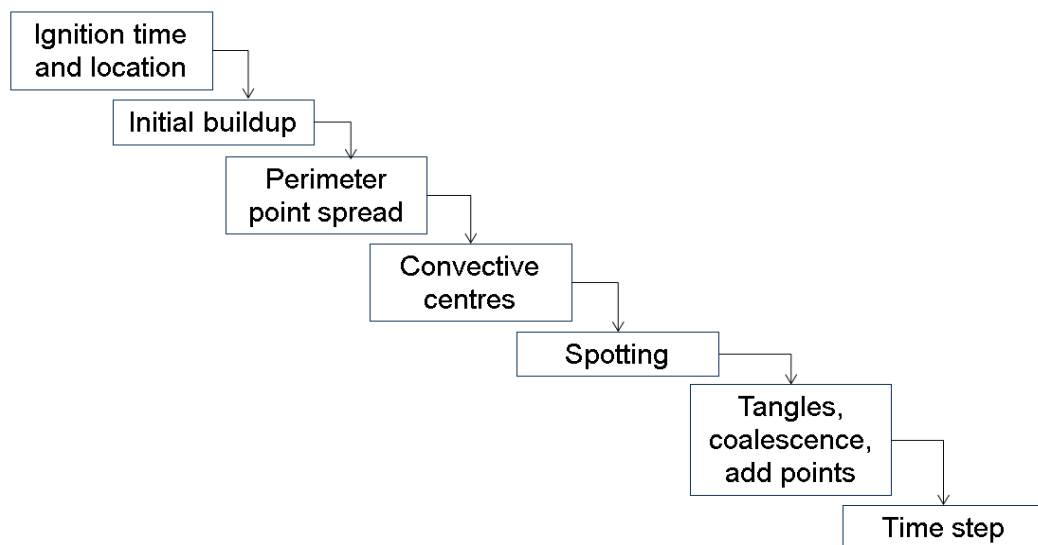
Figure 1. Simulation process used in PHOENIX RapidFire

To trigger a simulation the user specifies an ignition time and location. This is used to access the underlying input layers such as fuel, terrain and weather, in order to start the fire behaviour calculations.

Each new fire (including spot fires) has an initial build-up phase. The rate of build-up is based on the conceptual model described by Cheney (1981) modified so that the proportion of the available fine fuel and the wind speed affecting the build-up rate of spread is related to the proportion of the build-up.

Each point on the perimeter is dealt with individually using Huygen's spread principle (Andersen *et al.* 1982). Flame height is used to determine which fuel strata are incorporated in the fire behaviour. For non-grassland fuel types, flame height and maximum spotting distance for each point are based on a modified McArthur model (McArthur 1967), fire intensity and spread rates are based on a unique dynamic fire spread algorithm developed for PHOENIX and a modified CSIRO grassland model (Cheney *et al.* 1998) for fuel types that have no elevated fuel component.

The convection model in PHOENIX assumes that convection columns will form over the hottest areas of a fire. It uses this information, in conjunction with (terrain modified) wind speed and direction to determine potential ember impact patterns.

The convective strength and amount of bark fuel of each heat centre are used to determine the quantity of embers launched and the expected travel time for the embers once aloft. PHOENIX calculates the probability of embers igniting a spot fire. Once the probability of ignition is high enough, a spot fire is initiated. Any spot fires are run as independent fires and start by going through a build-up phase.

Perimeter expansion is modelled in discrete time steps. At the end of each time step, the fire perimeter is checked for any 'tangles' or coalescence with another fire such as a spot fire. As a perimeter grows additional vertices are added to the perimeter if required to keep the distance between each perimeter point less than the size of the Fire Grid defined for the simulation.

The computational sequence is now repeated for the new time step with fuels, weather and terrain conditions reassessed to find current conditions.

1.5 AN OVERVIEW OF THE COMPONENTS OF PHOENIX

Figure 2 provides a diagrammatic overview of each of the components of PHOENIX. Broadly speaking, components are divided into:

- **Fire Grid.** PHOENIX represents and stores data against a spatial grid called the Fire Grid. The Fire Grid is initially populated with inputs, and then outputs after the simulation.
- **Inputs.** The user provides inputs as spatial or temporal data to support PHOENIX.
- **Models.** PHOENIX accesses input data stored in the Fire Grid or other underlying data in order to run various calculations to support the simulated fire spread and asset impacts.
- **Outputs.** PHOENIX produces a range of outputs including fire perimeters and fire characteristics stored against the Fire Grid. Input values are also provided in the Fire Grid.

This document is structured based on Figure 2, and the numbers against each component of the figure correspond to section numbers within this document. The figure is repeated at the start of each chapter and section, as a visual aid to orientate the reader.

Table 1 offers a brief description of the purpose of each component. Later chapters describe these components in detailed.

Figure 2. Overview of the PHOENIX components including inputs, data representation, models and outputs. The numbers against each element refer to chapters or sections within this document.

Table 1. Purpose of each component of PHOENIX

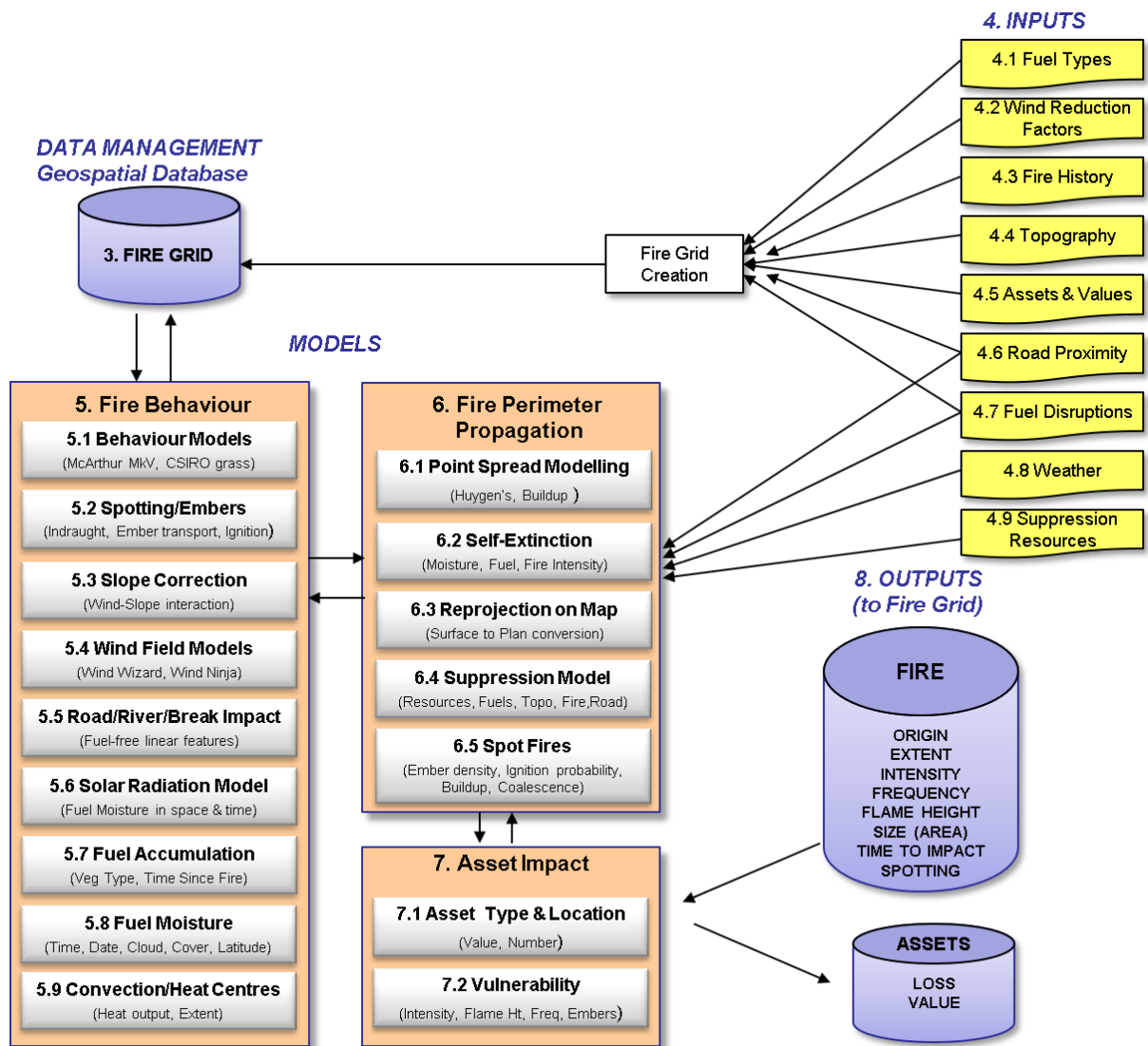| Chapter /section	CHAPTER NAME	Component name	Purpose
3	FIRE GRID		**The Fire Grid is central to PHOENIX in that it is used to manage and represent data. It is used for inputs, to feed data to the models and to store outputs.**
4	INPUTS		**Inputs are the underlying spatial or temporal data layers provided by the user that power PHOENIX.**
4.1		Fuel Types	Fuel type is a mandatory input layer required by PHOENIX to generate fine fuel levels for each fuel stratum.
4.2		Wind Reduction Factors	Forecast wind data is provided at 10 m above ground. PHOENIX takes this data and converts it to wind speeds at 1.5 m above ground for use by various PHOENIX models.
4.3		Fire History	Fuel types are used in conjunction with the fire history layer to generate fuel levels at the time of the simulation.
4.4		Topography	A digital elevation model (DEM) is required by PHOENIX to support various models, such as slope correction, wind field models and map reprojection.
4.5		Asset and Values	The user can provide data about asset types, value and vulnerability in order to support the Asset Impact PHOENIX model.
4.6		Road Proximity	PHOENIX uses the road proximity layer to assess how much, if any, roads will assist in suppression efforts.
4.7		Fuel Disruptions	The Fuel Disruption Layer defines the location and width of linear features such as roads, streams, firebreaks and railway lines that are generally devoid of fuel and may act as barriers to the progress of a fire.
4.8		Weather	PHOENIX requires weather data to support various fire spread models.
4.9		Suppression Resources	To provide the data necessary to run the PHOENIX suppression simulation model.
5	FIRE BEHAVIOUR		**The various models that drive underlying fire behaviour, including fire behaviour models, slope correction, convection, ember generation, fuel moisture and breaks in fuel.**
5.1		Behaviour Models	Fire behaviour models form the basis of simulations of fire spread and other fire characteristics within PHOENIX.
5.2		Spotting / Embers	Simulates ember generation, lofting, transport and distribution.
5.3		Slope Correction	Slope is derived by PHOENIX from the digital elevation model and is used to modify the outcomes of fire behaviour models.
5.4		Wind Field Models	PHOENIX can incorporate a wind modification layer that represents the deviation in wind speed and direction caused by local topography, to modify the outcomes of fire behaviour models.
5.5		Road / River / Break Impact	Linear fuel elements with no fuel such as roads and streams can be highly disruptive to fire spread, with their effect far exceeding the area they represent. PHOENIX implements a process that attempts to capture this effect.
5.6		Solar Radiation Model	PHOENIX incorporates a solar radiation model to determine the amount of solar radiation at each cell of the Fire Grid. Solar radiation is required as an input into the fuel moisture and suppression models.
5.7		Fuel Accumulation	Fuel levels are considered in a dynamic manner, using the time since the last fire to moderate total fuel levels for each stratum. These are then used in fire behaviour calculations.
5.8		Fuel Moisture	Fine fuel moisture is an important component for fire behaviour calculations. PHOENIX incorporates a fine fuel moisture model.
5.9		Convection / Heat Centres	The outputs of the convection model are used in conjunction with wind speed and direction to support simulation of ember lofting and distribution.

6	FIRE PERIMETER PROPAGATION		**Includes models that deal with the spread of the fire perimeter. This includes perimeter expansion, spot fire generation and how fire spread is ameliorated through suppression efforts.**
6.1		Point Spread Modelling	This model simulates the movement of the active fire perimeter.
6.2		Self-Extinction	A self-extinction process is incorporated into PHOENIX, in which parts of the perimeter are predicted to extinguish if heat output is less than a threshold value.
6.3		Reprojection on Map	During the perimeter modelling process, a surface-to-plan conversion of point spread is carried out to accurately capture the fire perimeter in three-dimensional space.
6.4		Suppression Model	The suppression model modulates fire spread based on suppression resources provided by the user.
6.5		Spot Fires	Starts new fires outside of the fire perimeter where burning embers land in suitably flammable fuels.
7	ASSET IMPACT		**PHOENIX provides for the intersection of fire attributes with maps of assets to allow estimates of fire damage. Characterising fires by asset impact provides an additional means of comparing fire management options.**
8	OUTPUTS		**PHOENIX produces a wide range of outputs. Vector perimeter isochrones are a standard output, produced both as ESRI Shapefiles and Google Earth KMZ files. In addition, a wide range of gridded cell values about fire characteristics can be outputted in various formats.**

2 DEVELOPMENT PHILOSOPHY OF PHOENIX

The development of PHOENIX RapidFire was driven by the need to have a way to realistically characterise bushfires across the landscape so as to be able to assess the relative bushfire risks to a wide range of values and assets in the landscape under a range of possible fire management regimes.

Initially, a review in the late-1990's was undertaken of the elements contributing to bushfire risk and the current state of knowledge. This was documented in 2000 (Shields 2000; Shields and Tolhurst 2003). With the establishment of the Bushfire Cooperative Research Centre (CRC) in 2004, funding was made available to continue with Bushfire Risk Assessment research. The first stage of this work was to define *the Fire Management Business Model* (Tolhurst *et al.* 2006). The fire management business model (or mitigation model) showed how 54 factors (or elements) of bushfire risk management (Figure 3) interacted to reduce bushfire risk for a given level of resources allocated to each element.
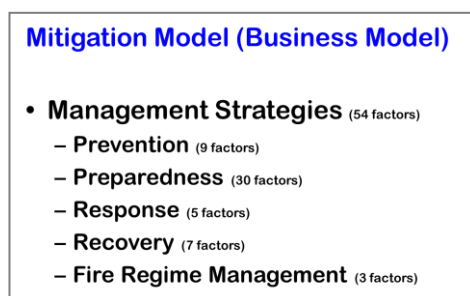
Figure 3. Elements (factors) of the bushfire management business model considered to interact in ways that affected the level of bushfire risk. (Based on Tolhurst et al. 2006).
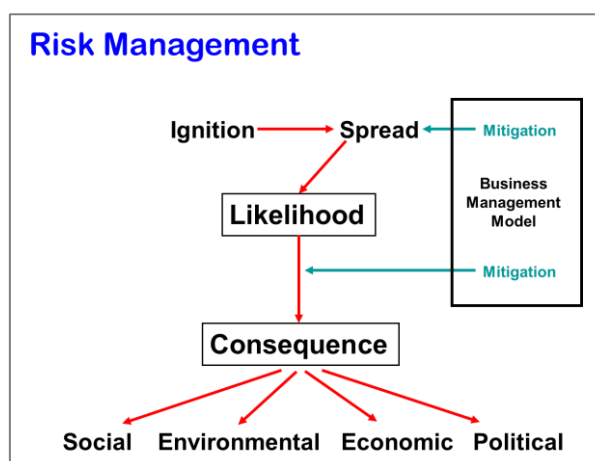
Figure 4. How the bushfire management business model affects bushfire risk mitigation (Based on Tolhurst et al. 2006).

Having established a bushfire management business model, it was then necessary to be able to characterise and quantify the effect of different bushfire management strategies on reducing the level of bushfire risk (Figure 4). It was seen that the best way to characterise fires across the landscape was to use a fire simulator as this would be spatially and temporally explicit and would also be objective and repeatable. Two international fire simulators were considered, but thought to be too difficult to adapt to Australian conditions. These were the Canadian-developed *PROMETHEUS* simulator (Tymstra *et al.* 2010) and the USA-developed *FARSITE* simulator (Finney 2004). Three Australian fire simulators were also considered: *SIROFire* (Coleman and Sullivan 1996), *CAFÉ* (Bradstock *et al.* 1998) and *FIRESCAPE* (Cary and Banks 1999; Cary *et al.* 2009), but *CAFÉ* and

FIRESCAPE simulators were designed for looking at the relative fire frequency in the landscape rather than more detailed bushfire characterization and risk analysis, and *SIROFire* did not capture the dynamics of high-intensity bushfires very well. As there seemed to be no suitable bushfire simulator readily available, it was decided, in 2005, to develop a new one which became known as *PHOENIX RapidFire* (Tolhurst *et al.* 2008).

The initial development of PHOENIX was primarily as a fire characterisation simulator and once that was adequately established, additional functionality was added to assist in assessing the relative level of bushfire risk. This revised simulator was renamed: PHOENIX RapidFire (Figure 5).
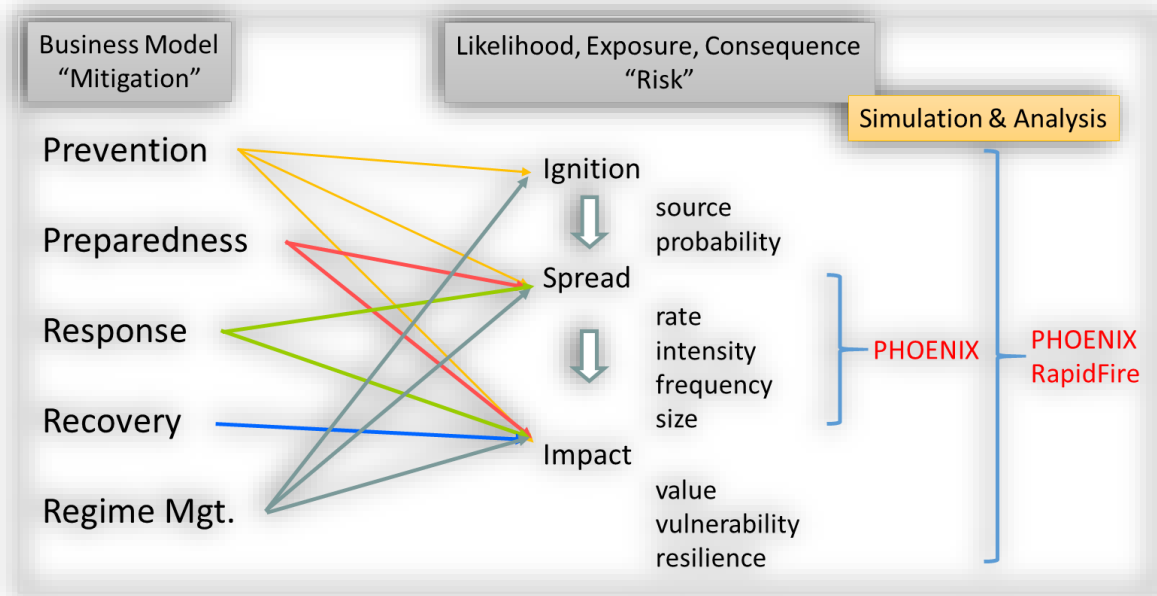
Figure 5. The connections between factors affecting the level of bushfire risk, the elements of the bushfire management business model that can mitigate some of the risks and the simulation and analysis environment to assess the relative risk using PHOENIX RapidFire.

A number of guiding philosophies helped guide the decision-making process in the development of PHOENIX RapidFire. An understanding of these philosophies will assist others in understanding the structure and logic of PHOENIX RapidFire and what makes it unique. These philosophies will be outlined here.

2.1 PHILOSOPHY 1 – EACH FIRE SIMULATION MUST BE REALISTIC

Based on the experience of how some existing bushfire models had worked, it was decided that it was important for each fire that was simulated to be as realistic as possible. Some previous models worked on the basis that, providing there were enough simulations made, the 'general pattern' of fire in the landscape, after thousands of fires, was sufficient to draw conclusions about changes to the various inputs to the models. The philosophy with PHOENIX RapidFire differed from this because it was required that each fire should be as realistic as possible if the potential impact at any point in space or time was to be credible.

2.2 PHILOSOPHY 2 – HIGH-INTENSITY FIRES BURN THE LARGEST AREAS AND DO THE MOST DAMAGE SO CONCENTRATE ON THEM.

The initial focus of the fire simulation development was on high-intensity fires burning under severe weather conditions. This was because the potential for bushfires to cause damage was greatest during major fire events. It was initially thought that lower intensity fires would be dealt with later.

2.3 PHILOSOPHY 3 – EMPIRICALLY-BASED VERIFICATION

Because of the desire to see spatially and temporally realistic fire simulations, real fire observations were used to develop, calibrate and test the models. A range of bushfire case-studies were used to calibrate and verify the simulations. The Black Saturday Fires in Victoria in 2009 were documented in detail for the Victorian Bushfires Royal Commission and so provide one source of fires for simulation calibration and development. Fire in other States under a wider range of conditions were useful for simulator verification (e.g. Cook *et al.* 2009; Jacobs 2017).

Other components of the simulator were also based on field observations, such as the convection and plume model. The modelled height of the plume was compared with the plume height measured with weather radar (Chong *et al.* 2012b). Similarly, the modelled 'convective strength' was verified by correlation analysis, using observed areas of tree-fall and simulated estimates of convective strength (Chong *et al.* 2012b).

Spotting distance and patterns were based on observed spot fires during the Black Saturday fires in 2009 and other experimental work (Sardoy *et al.* 2008; Chong *et al.* 2012b, 2012a).

2.4 PHILOSOPHY 4 – THE NATURE OF THE FIRE EXPOSURE AT ANY POINT IN SPACE OR TIME MUST BE REALISTIC

A corollary of the first point is that the nature of the bushfire exposure, in terms of radiation, convective heat, fire induced winds, ember density, fire intensity, and frequency of impact at any point in space or time across the bushfire landscape, must also be realistic if the potential impact on a range of values and assets is to be estimated.

2.5 PHILOSOPHY 5 – ESTIMATES OF VALUE OR ASSET LOSSES SHOULD BE BASED ON REAL-WORLD EXPERIENCE

In keeping with other philosophies, estimates of potential losses due to bushfires needed to be based on some known impacts. The best example of such an instance was the development of the 'House Loss' algorithm (Tolhurst and Chong 2011; Tolhurst *et al.* 2013; Tolhurst *et al.* 2017). House loss was found to be well correlated (about 80%) to the PHOENIX estimates of ember density, flame length and convective strength. All these factors have also been found to be the main causes of house loss in post-fire surveys (Blanchi and Leonard 2005; Blanchi *et al.* 2012).

2.6 PHILOSOPHY 6 – COMPUTATION OF INDIVIDUAL FIRES, UP TO 10,000 HA, ANYWHERE IN A STATE, SHOULD TAKE LESS THAN ONE MINUTE ON A LAPTOP COMPUTER

This philosophy is based on the desire for anyone to have access to the simulator regardless of where they are situated and regardless of whose computer operating environment they are working under. Therefore, the simulator should not need to be 'installed' and should even be able to be run

from a USB drive if desired. The ease of computation and rapid simulation time is also desirable for operational use in decision support for real fire events, as well as for making simulations of thousands or millions of fire scenarios relatively cheaply and easily on multi-processor computing platforms for bushfire risk analysis and planning.

2.7 PHILOSOPHY 7 – THE OUTPUTS FROM THE SIMULATION SHOULD BE VISUALLY DISPLAYED

The complexity of bushfires means that tabular or other numeric forms of output will not be immediately accessible to the user without significant further processing, including the use of specialist software. For this reason, the outputs from PHOENIX have always included a Google Earth overlay file for rapid and easy 4-D display (x, y, z, t) with a motion replay facility. This makes the outputs easy to manipulate and investigate and also quick to identify any errors or anomalies. However, full and rich spatial and temporal data outputs are also given so that they can be post-processed using GIS or other software.

2.8 PHILOSOPHY 8 – ONE FIRE BEHAVIOUR MODEL

Bushfires are great integrators of fuel, weather, and topography. As a fire burns across the landscape, it effectively integrates fuels as it simultaneously burns in grassland, forest, heathland and plantation, so we should emulate this in the computer simulation environment rather than try to arbitrarily divide the landscape into 'fuel types'. Fuel Type classification is an artefact of forest management where vegetation is divided (classed) into vegetation types. Separate fire behaviour models for each fuel type is an artefact of manual or tabular fire behaviour calculations (e.g. Cruz *et al.* 2015). Whilst this might be useful for some broad management planning purposes, it is not always relevant to fire behaviour. For example, in Victoria, all the Mountain Ash forests (*Eucalyptus regnans*) are classified in one class, however, the fuels in this vegetation type vary widely across the landscape and this is reflected in very different fire behaviours for given weather and terrain conditions. The age of the forest can vary from young regrowth to old-growth with a partial rainforest understorey. The understorey may be a dense layer of treeferns, dense mesophytic shrubs or relatively dry sclerophyll shrubs and grasses. Each variation burns quite differently, but it is classed as just one of over 600 vegetation types in Victoria. Therefore the aim of developing the fire behaviour model in PHOENIX was to make it generic and only rely on fuel descriptions rather than vegetation types *per se*. To this end, fuel inputs to PHOENIX are based on the Overall Fuel Hazard Guide (Hines *et al.* 2010) which describes fuel within layers or strata viz. surface, near-surface, elevated, bark and potentially canopy. This fuel description method is not fully developed, but has worked sufficiently well to know that it is a better approach than using vegetation or fuel type mapping. PHOENIX dynamically incorporates different fuel strata as indicated by the model at any point in time or location.

Based on the knowledge of there being different spread mechanisms other than just radiative heat transfer, PHOENIX explicitly incorporates the contribution of short- and long-distance spotting to the rate of fire spread. This was clearly apparent in the 2009 Black Saturday fires in Victoria (Tolhurst 2009; Cruz *et al.* 2012), but also occurs in lower-intensity fires too. The spotting effect is driven by the strength of the local fire-induced convection, the amount of ember material, the strength of the winds and the ignitability of the fuels where the embers land (Chong *et al.* 2012b). PHOENIX is unique in how it captures this phenomenon.

PHOENIX RapidFire effectively uses two fire behaviour models in its current version; 'grass' and 'non-grass' models. This separation is made because there is no current way to incorporate fuel fineness into the model, but this could be done and a single, universal fire model would result. An additional modification that would enhance the universal fire model approach would be to incorporate a flame height wind speed input to the fire spread model rather than using a single wind reduction factor. The underpinning algorithm has been developed to enable this to happen, but the fuel description needs to include parameters for total vegetation height and plant density (Moon *et al.* 2013; Moon 2016).

2.9 PHILOSOPHY 9 – MECHANISTIC NOT STOCHASTIC

An early decision was made that every time a PHOENIX simulation was run that it should always produce the same result if all the inputs remained the same – a mechanistic process. This is in contrast to using stochastic processes where variations in the simulation are produced due to the uncertainties of some of the processes in the modelling process, introduced as inputs varied randomly according to some pre-defined statistical distribution. The thinking here was that it was better to define the 'mean' conditions in the model and introduce any variations by deliberately varying the input values. This was considered a better option since the level of uncertainty in the input values would vary from one situation to another and the user knew the level of uncertainty being introduced and could control how uncertainty was dealt with. In the absence of applying a range of input values reflecting the range of uncertainty, PHOENIX would provide the 'best estimate' value.

Another rationale for using a mechanistic process was that to really capture the stochastic processes, hundreds of simulations might need to be run and then it is likely that some 'average' value would be derived which would be the same as using the 'mean' conditions in the first place, except having consumed a lot of computer and processing time to do it.

2.10 PHILOSOPHY 10 – USE ALL AVAILABLE DATA

PHOENIX was designed to make sure that it used all the available fuel, weather and terrain data. Spatial data was captured with a 'cell crawling' process which used all spatial data without 'jumping over' information. Temporal data, such as weather inputs, were used for every time step given with linear interpolation if finer time steps were needed.

Spatial data were aggregated and averaged into Fire Grid cells, but this was not found to cause any significant loss of accuracy, but it did improve computational efficiency. For example, the raw fuel data might have been captured at 25 m resolution, but then averaged into 200 m resolution Fire Grid data cells for simulation.

2.11 PHILOSOPHY 11 – CONTINUOUS FIRE SPREAD

Although the input and output data is represented in a square grid, the Fire Grid, the perimeter of the fire at each *time step* is shown as a continuous line; there may be several fire perimeter *time step* lines per Fire Grid cells.

Huygen's wavelet propagation principle (Anderson *et al.* 1982) was used to describe the fire perimeter growth. With Huygen's propagation process, the perimeter of the fire is represented as a series of points joined by straight lines. The distance between the points is relatively small (less than 100 m) and so it gives the appearance of being continuous. The advantage of this approach is that the fire characteristics (e.g. flame height, intensity, size, time, etc.) are known for each point. Fire

characteristic statistics for each Fire Grid cell are based on all the perimeter points that have passed through each Fire Grid cell. The fire characteristics of each perimeter point are also used in the dynamic suppression process in the simulation if it is being run.

2.12 PHILOSOPHY 12 – MODULAR SOFTWARE DESIGN

From the beginning of PHOENIX development, it was acknowledged that the understanding of bushfire science and computational science would change over time. The intention was to make PHOENIX as modular as possible so that elements of the simulation could be modified or swapped with better modules over time. The intention here was to 'future-proof' the simulator.

Unfortunately, with the limited resources available to the model development (less than one person full time), it was decided to just develop a model that worked and could be used by the end-users now. The logic was that if PHOENIX was to properly become operational, then time and effort would need to be spent on rewriting it and properly developing it for operational use. In this process, it was figured the coding could be made modular, but with the hindsight of what elements (modules) were needed in the simulator based on the original development and validation of PHOENIX.

2.13 CONCLUSIONS

The 12 philosophies of the development of PHOENIX RapidFire outlined here provide a very useful basis to understand how and why PHOENIX was developed the way it was. Many of these philosophies are quite fundamental to bushfire simulators for operational used regardless of what algorithms or computer systems are used.

3 THE FIRE GRID
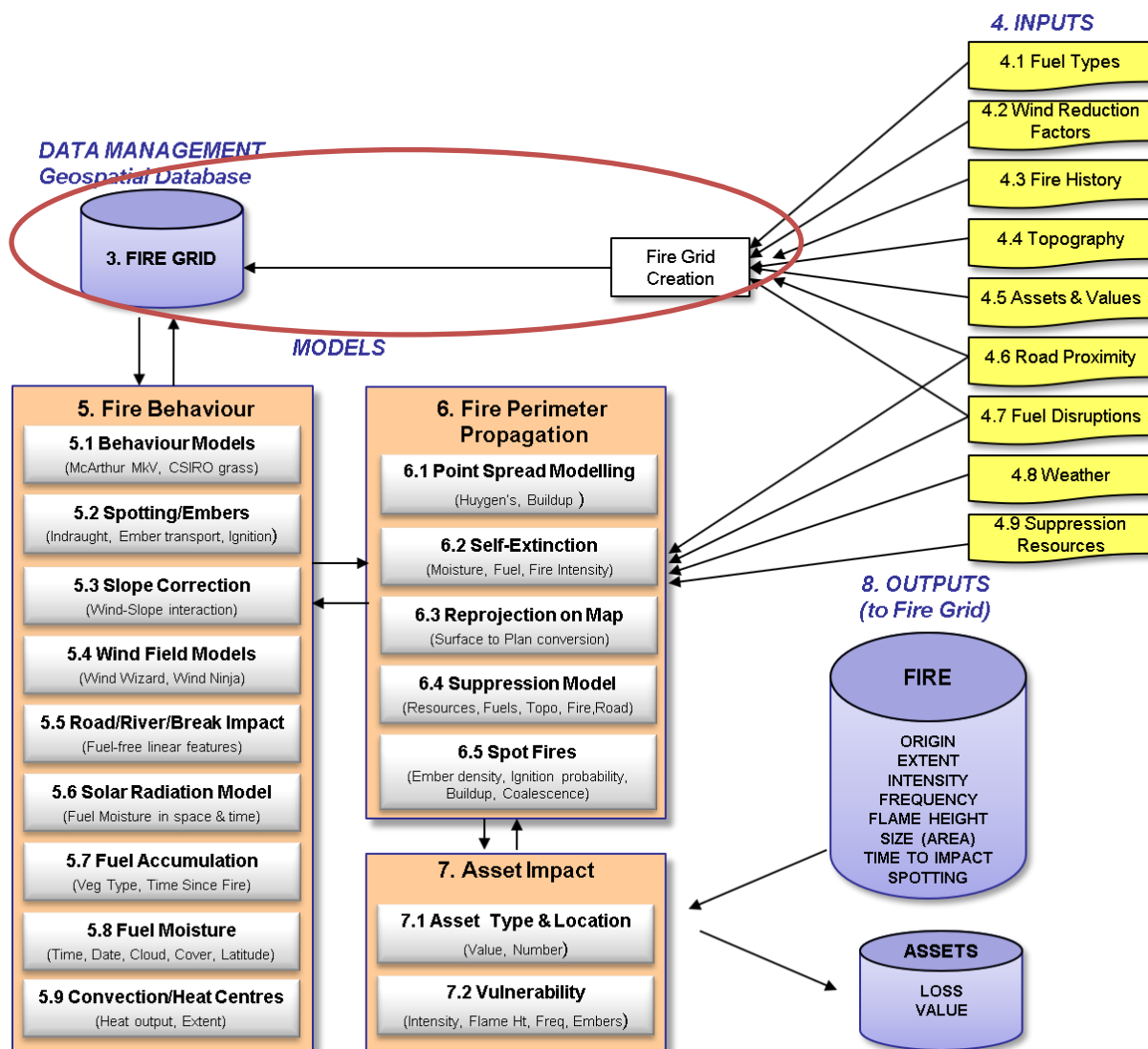
3.1 PURPOSE

The Fire Grid is central to PHOENIX in that it is used to manage and represent data. The Fire Grid function of PHOENIX is a means to capture input data and represent it in a gridded modular fashion that the various models can utilise. Additionally, it is a means to record and store the various outputs from PHOENIX.

3.2 BASIS

A geospatial grid that is created using various input data layers provided by the user.

3.3 INPUTS

- Fuel types;
- Wind reduction factors;
- Time since last fire;
- Topography;

- Assets and values;
- Road proximity; and
- Linear fuel disruptions.

3.4 USER INTERACTIONS

The user defines a grid resolution for the Fire Grid.

3.5 DESCRIPTION

Input data must be properly prepared in a GIS such as ESRI's ArcGIS or MapInfo (refer to Chapter 4: Inputs for more information). There is no fixed resolution requirement for the input data; however, a data resolution of 25 or 30 m is recommended for meaningful simulations.

PHOENIX reads, into computer memory, gridded data at the input data resolution (e.g. 30 x 30 m). The user defines a Fire Grid resolution for simulation calculations, as this improves processing speeds and makes the scale of the calculation more realistic. It is generally recommended this be between 120 – 210 m (e.g. 180 x 180 m) and be a multiple of the underlying input data. This cell size was found to strike a balance between data accuracy and computer processing efficiency and is consistent with the minimum fire width required to achieve a quasi-steady-state rate of spread (e.g. Cheney and Gould 1995).

3.5.1 Fire grid sampling

PHOENIX uses a sampling protocol to sample underlying input data for the purpose of running simulations.
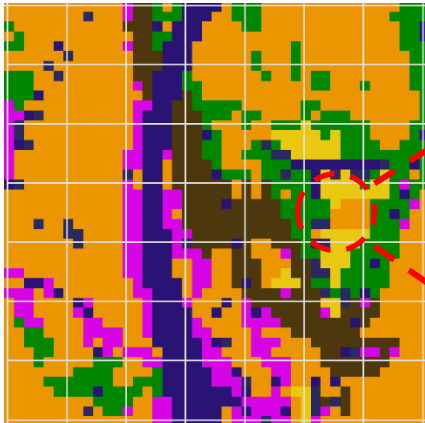
Figure 6. 180 m fire grid in white over a 30 m resolution fuel type input layer.
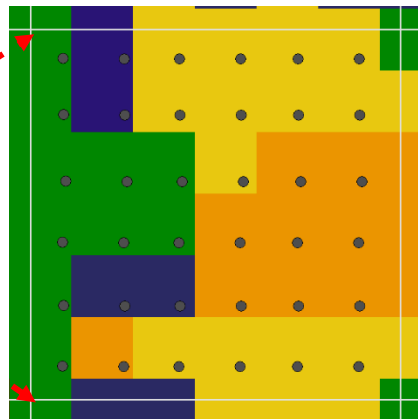
Figure 7. The 30 m resampling pattern shown as grey dots on a single 180 m fire grid cell.

In the case of Figure 6, a user-defined Fire Grid resolution of 180 m has been specified for simulation runs. However, the fuel type input data was provided as a 30 m grid, and the 180 m simulation grid and resolution of underlying data do not necessarily perfectly align. PHOENIX deals with this through a resampling protocol. Figure 7 is a closeup of one of the 180 m cells from Figure 6, and the grey dots illustrate how PHOENIX resamples underlying fuel type data. The sampling method varies depending on the cell attribute as illustrated in Table 2.

Table 2. Grid cell attributes and their sampling method

Cell Attribute	Fire grid cell sampling method	Description
Elevation	Centroid	In metres derived from DEM
Aspect	Centroid	In degrees derived from DEM
Slope	Centroid	In degrees derived from DEM
Grass load	Area weighted	Grass load in t/ha
Surface load	Area weighted	Forest surface fuel load in t/ha
Elevated load	Area weighted	Forest elevated fuel load in t/ha
Bark load	Area weighted	Forest bark fuel load in t/ha
Total fuel load	Area weighted	Total fuel load in t/ha
Wind reduction factor	Area weighted	Fuel type specific 10 m to mid flame height (1.2 m) wind reduction factor
Road proximity	Centroid	Distance from cell centroid to nearest road
Disruption	Area weighted	Effective linear disruption width in metres
Wind modifiers	Centroid	Terrain affected wind modifiers

Centroid sampling simply takes the centroid value of the input data cell (e.g. 30 m cell) and averages it for the Fire Grid cell (e.g. 180 m cell).

The area-weighted method samples each 30 m cell. Where the Fire Grid (e.g. a 180 m cell) contains a mixture of 'grass' and 'woody' fuel types, the fire spread calculations will be an area-weighted average of the fuel types. For example, if 12 of the underlying 30 m cells are 'grass', then the relative area of grass will be 12/36 or 33%. Thus, grass will contribute 33% to the weighted average fire behaviour attributes. Refer to Section 6.1: Fire Perimeter Propagation for more information on how weighted averages for fuel are used.

3.5.2 Fire grid data retrieval

Prior to simulating fire spread, PHOENIX loads the Fire Grid tiles within a 10-tile buffer of the ignition point into memory (see Figure 8). Tiling of data provides for efficiency: large domains do not need to be pre-loaded into memory and can be loaded on-demand in a progressive manner as the simulation proceeds. PHOENIX computes fire spread using dynamic time steps; time steps are partially determined by the resolution of the spatial information being affected by the fire. High data resolutions will result in an increased number of computations, slowing the overall simulation process. Data resolutions that are higher than the uncertainty around parameter estimates will not necessarily provide any benefit; in fact, analysis times will be increased, however, there may be limited or no improvement in the overall result.
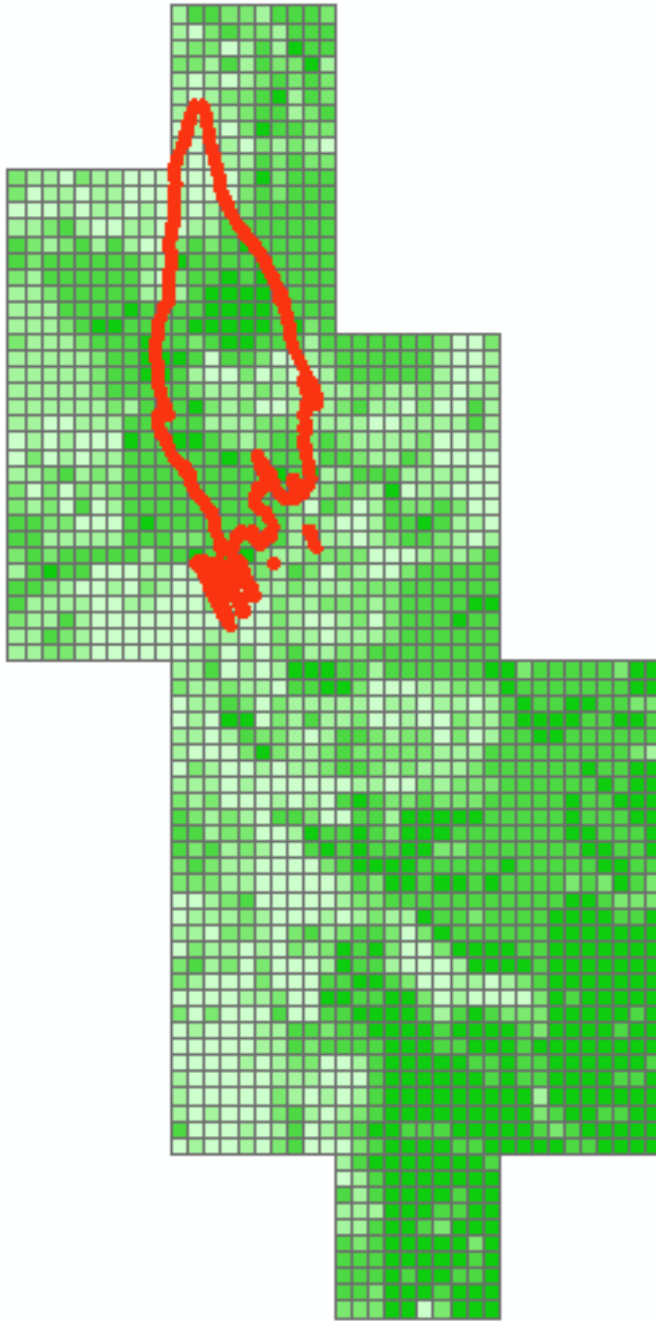
Figure 8. Data is retrieved in tiles of 10 x 10 Fire Grid cell as a fire spreads in the landscape. Red polygons show the fire perimeter and the varying shades of green indicate fuel loading with darker green representing more fuel. Additional cells are shown in this illustration because they have been impacted in some way (perhaps by embers).

4 INPUTS
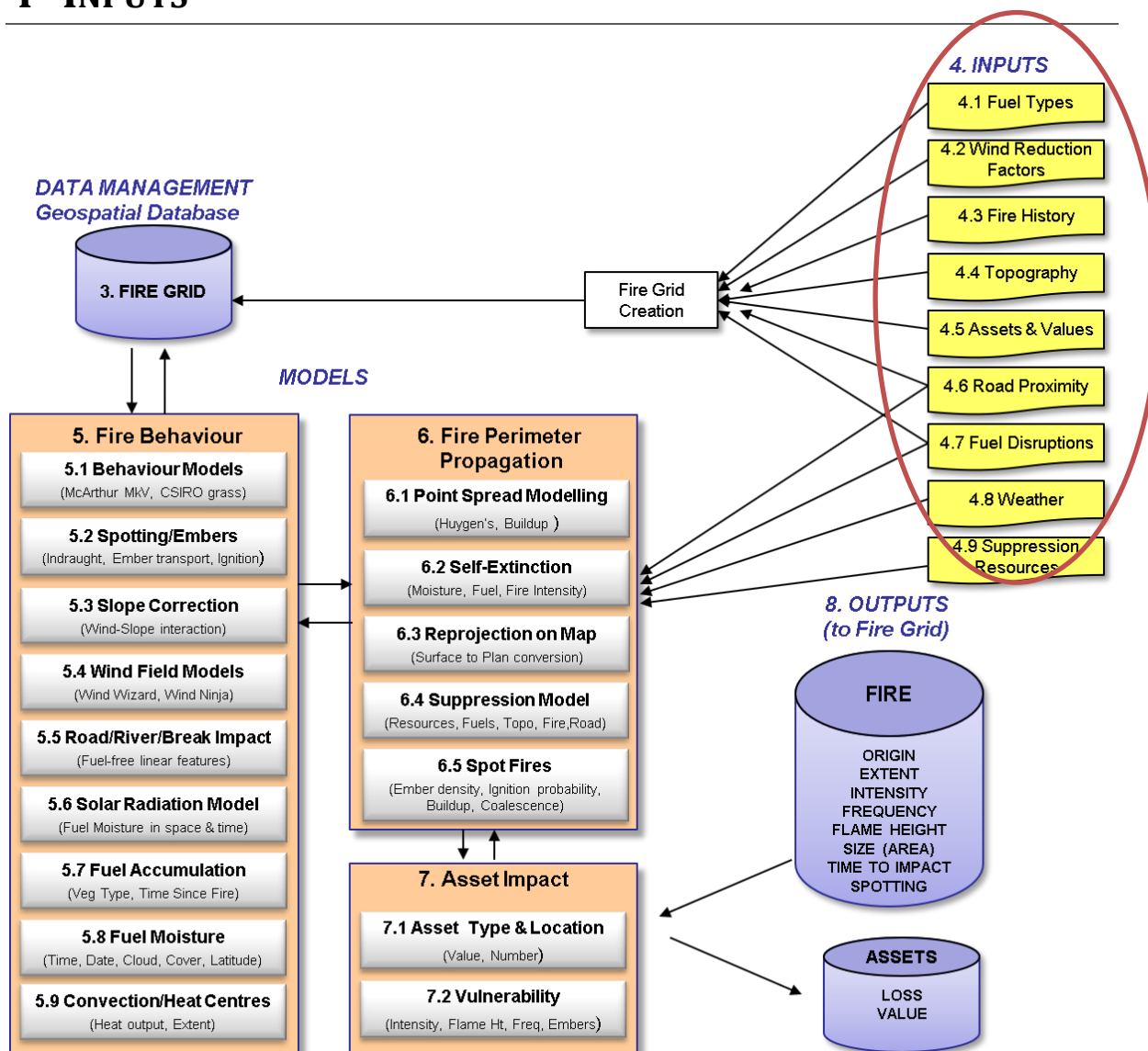
Input data to the model must be prepared in a GIS such as ESRI's ArcGIS or MapInfo. This base data is then converted into a format read by PHOENIX which is an ASCII grid broken into data tiles. Tiling can be achieved manually, but is better achieved using ancillary support tools provided as part of PHOENIX, installed as part of the ArcGIS Toolbox.

In some cases an Input to the model is produced by taking several data files provided to PHOENIX (as configuration or spatial data sets) and performing some pre-processing. The relationship between inputs and file names used by PHOENIX as described in Appendix 2. For detailed instructions on preparing data for PHOENIX (including descriptions of preparing individual input layers), please refer to the *PHOENIX Input Data Guide.*

Generally, PHOENIX input data has the following requirements:

1. All data layers must be in the same coordinate system, and this must be a map grid projection (grid reference in metres) not a geographic one (latitude and longitude in degrees). In Victoria, using 'VicGrid 94' is recommended, which is a Lambert Conformal Conic Projection with a GDA 94 reference Datum. Across Australia, using 'Geoscience

Australia Lambert 94' projection is recommended, which is also a Lambert Conformal Conic Projection with a GDA 94 reference Datum.

2. The only data layer that must be provided is fuel types. However, other layers are required for realistic simulations. If there is no fuel types file location specified, then the input value defaults to zero (no fuel, or bare area).

3. As all data layers must be in the same coordinate system only one GIS spatial projection file is required.

4. Layers are broken into 'tiles' and packaged as zip files, to decrease the size and number of files that have to be copied and transported. The zipped files are unzipped on the first run of a simulation session.

4.1 FUEL TYPES
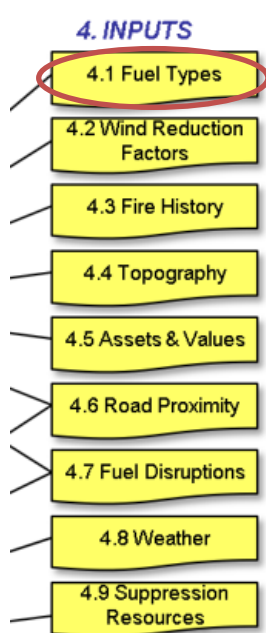
4.1.1 Purpose
Fuel types is a mandatory input layer required by PHOENIX to generate fine fuel levels for each fuel stratum (surface, elevated and bark – see Hines *et al*. 2010 for details).

4.1.2 Basis
Fuel type is built upon spatial vegetation type data.

In Victoria, 900 or so vegetation types (EVCs) were manually assigned to one of about 40 fuel types by Kevin Tolhurst on the basis of his knowledge and experience. This was initially done to enable a proof-of-concept run of the PHOENIX simulation. However, this initial classification is largely still being used. In some areas, there have been efforts to improve/correct this classification. In NSW, a significant effort was made to map the fuel types and their accumulation rates after fire, as part of a separate research program. South Australia, Western Australia, Tasmania and Queensland have undertaken similar processes to what has occurred in Victoria.

4.1.3 Assumptions and limitations
Vegetation type is used because it is assumed that vegetation type is the most likely layer to be kept up-to-date by government agencies. The mapping must cover the whole area. Areas with no fuel type mapped will be assumed to not carry fire.

Fuel types with no elevated or bark fuel are assumed to be grasslands.

4.1.4 User interactions
Due to varying vegetation classification standards in different jurisdictions, vegetation types must be converted/aggregated to fuel types by the user. The user prepares the input layer by assigning each vegetation type to a user-defined fuel type for use in PHOENIX. The maximum fine fuel levels for each fuel stratum (surface, elevated and bark) and the rate of reaccumulation in each stratum after burning must be specified for each fuel type defined.

4.1.5 Description
Management agencies commonly spatially classify landscapes into distinct vegetation types suitable for use in modelling (Sun *et al.* 1998). It is acknowledged that there are several vegetation type classifications and a range of mapping detail and quality within some states and between states.

Therefore, in the creation of the PHOENIX fuel layer, each vegetation type must be classified into a fuel type and assigned an integer code ('FuelCode') by the user. An example of a fuel type classification is shown in Table 3. The fuel mapping must cover the whole area being simulated. Areas with no fuel type mapped will be assumed to carry no fuel (e.g. a water body) and therefore will not carry fire.

A lookup table of fine fuel parameters must then be defined and conform to the PHOENIX convention. This lookup table is typically called 'Fueltype.xml' and joins to the fuel type layer via the FuelCode. Section 5.7: Fuel Accumulation has more information.

Fine fuel hazard levels are converted to an equivalent fine fuel load (t/ha). While coarser fuels are consumed during a fire, the combustion of fine fuels is the process that predominantly determines spread rates. Fuels are considered as three separate strata; surface (which includes near-surface fuels), elevated fuel and bark, in accordance with forest fuel measurement standards in Southern Australia (McCarthy *et al.* 1999; *Hines et al.* 2010). Fuel classes that have no elevated or bark fuels are considered by PHOENIX as grasslands and are processed using functions derived from the CSIRO grassland fire spread model (Cheney *et al.* 1998).

Table 3. PHOENIX fuel types currently recognised in southern Australia.

Veg Type	Code	FuelCode	Description	Fuel Characteristics
Forest	F01	15	Rainforest	dense vegetation with little dead material, epiphytes, vines, ferns, rarely dry
	F02	32	Wet Forest with rainforest understory	wet sclerophyll forest with a mesic understorey
	F03	13	Riparian Forest shrub	dense vegetation but with a small proportion of dead material
	F04	11	Wet Forest shrub & wiregrass	high biomass forest, but with little dead suspended material unless wiregrass present
	F05	12	Damp Forest shrub	dense understorey and potentially high bark hazard (karri)
	F06	40	Semi-mesic Sclerophyll forest	forest with semi-mesic shrubs and flammable grasses, sedge understorey
	F07	33	Swamp Forest	dense Melaleuca forest with little understorey
	F08	6	Forest with shrub	potentially high bark hazard, shrubs moderate flammability (mixed jarrah/karri)
	F09	7	Forest herb-rich	potentially high bark hazard, little elevated fuel
	F10	45	Dry Forest shrubs	dry forest with continuous understorey, (southern jarrah)
	F11	8	Dry Open Forest shrub/herbs	dry forest with open understorey (northern jarrah)
Grass/sedges	G01	16	High Elevation Grassland	dense sward of tussock grasses or herbs, high cover
	G02	4	Moist Sedgeland / Grassland	dense sward, potentially high dead component, button grass
	G03	29	Ephemeral grass/sedge/herbs	dense grass and sedges with potentially high levels of dead suspended material
	G04	20	Temperate Grassland / Sedgeland	grasses and sedges widespread, but varying in biomass
	G05	44	Hummock grassland	hummock grassland, discontinuous surface fuels
Herbs	H01	30	Moorland / Feldmarks	low flammability cushion plants
	H02	36	Alpine herbland	dense, upright, low flammability herbs
	H03	34	Wet herbland	freshwater herbs on mud flats

	H03	37	Wet herbland	low herbs in seasonally inundated lakebeds or wetlands
Mallee	M01	27	Mallee chenopod	low flammability except after exceptional rain bringing grasses
	M02	42	Mallee grass	mallee woodland with predominantly grass understorey
	M03	25	Mallee shrub/heath	continuous shrub layer but amount of dead material depending on species present
	M04	26	Mallee spinifex	discontinuous fuels, very flammable under windy conditions
Bare	NIL	0	Water, sand, no vegetation	fuel absent
Plantations	P01	98	Softwood Plantation	dense canopy with continuous surface fuels
	P02	99	Hardwood Plantation	uniform canopy with continuous surface fuels
Shrubs	S01	17	High Elevation Shrubland/Heath	dense cover of shrubs with surface fuel largely under plants
	S02	14	Riparian shrubland	dense vegetation with little dead material
	S03	35	Wet Scrub	flammable shrubland with high level of dead elevated fuels
	S04	1	Moist Shrubland	dense shrubland, salt affected
	S05	31	Dry Closed Shrubland	tea-tree or paperbark thickets, little understorey
	S06	21	Broombush / Shrubland / Tea-tree	dense shrubland, but with relatively low level of dead material
	S07	10	Sparse shrubland	sparse shrubby vegetation with discontinuous surface fuels
	S08	3	Low flammable Shrubs	low flammability except after exceptional rain bringing grasses
	S09	38	Mangroves / Aquatic Herbs	trees, shrubs and herbs in permanent water, unburnable
Heaths	S10	23	Wet Heath	dense heath possibly with dense sedgy undergrowth
	S11	24	Dry Heath	dense heath with significant amounts of dead material
Woodland	W01	18	High Elevation Woodland shrub	wooded area with shrubby understorey
	W02	19	High Elevation Woodland grass	wooded area with continuous grass tussocks
	W03	97	Orchard / Vineyard	orchard or vineyard
	W04	2	Moist Woodland	low trees, shrubby, sedgy understorey, bark hazard
	W05	22	Woodland bracken/shrubby	wooded area with varying understorey, but not heathy
	W06	9	Woodland Grass/Herb-rich	surface fuels dominated by grass and herbs
	W07	5	Woodland Heath	flammable shrubs and high bark hazard
	W08	41	Gum Woodland heath/shrub	gum woodland with moderate bark hazard, heath/shrub understorey
	W09	43	Gum Woodland grass/herbs	gum woodland with moderate bark hazard, herbaceous understorey
	W10	39	Savanna grasslands	tall flammable grasses in an open woodland
	W11	28	Woodland Callitris/Belah	low flammability except after exceptional rain bringing grasses

4.2 WIND REDUCTION FACTORS
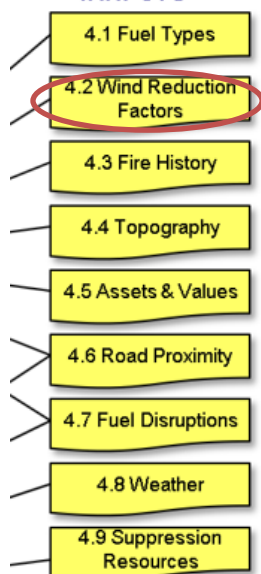
4.2.1 Purpose

Bureau of Meteorology forecast wind data is provided at 10 m above ground. PHOENIX takes this data and converts it to wind speeds at 1.5 m above ground for use by various PHOENIX models.

4.2.2 Basis

Wind reduction factors are specified by the user for each defined fuel type in the Fueltype.xml file (See Section 5.7: Fuel Accumulation).

4.2.3 Assumptions and limitations

It is assumed that the wind at 1.5 m is the 'mid-flame height' wind speed which is clearly untrue for very low-intensity fires and very high-intensity fires. It also assumes that the wind reduction factor is a constant, but it is known to vary from day to night and with the magnitude of the wind speed in the open.

4.2.4 User interactions

Wind reduction factors can only be changed by the user by redefining the fuel type characteristics in the Fueltype.xml file.

4.2.5 Description

Wind reduction factors are assigned to each fuel type in the fueltype.xml file. Values for the wind reduction factors are not well studied and so many will have to be estimated by an experienced fire behaviour scientist. Some guidance on the values of wind reduction factors can be gained from the Western Australian 'Red Book' (Sneeuwjagt and Peet 1998 p.30). The wind reduction factor is used to estimate the mid-flame height wind speed within the vegetation based on the observed or forecast wind speed measured at 10 m in the open. In 18 m high open eucalypt forest, McArthur assumed that the wind reduction factor at 1.5 m above the ground was a factor of 3. In Jarrah forest in Western Australia, Project Vesta found that the wind reduction factor at 5 m above the ground was also a factor of 3. In grassland, there is no wind reduction factor assumed so the value is set to 1. In grassy woodland in northern Australia, Cheney *et al.* (1998) found the wind reduction factor to be a factor of 2. Since flame height varies from low-intensity surface fires to high-intensity crown fires, the reality is that the wind reduction factor is not constant even for a single fuel type, but a single typical value is used. Work by Kangmin Moon (2016) developed a model of estimating the wind reduction factor in different fuel types at different heights which would enable the use of a dynamic wind reduction factor, but this has not yet been incorporated into PHOENIX.

The cell wind reduction factor is also used to estimate an approximate leaf area index (LAI) used to calculate shading based on Beer's law (Silberstein, Sivapalan *et al.* 2003). Refer to Section 5.6: Solar Radiation Model for further information on how shading is used.

4.3 FIRE HISTORY
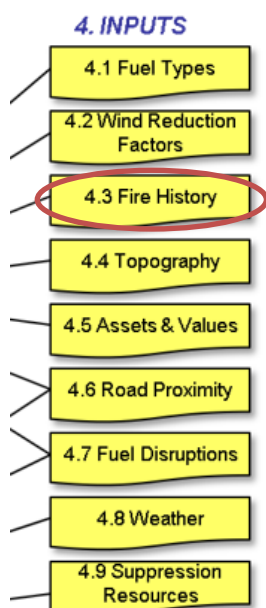
4.3.1 Purpose

Fuel types are used in conjunction with the fire history layer to generate fuel levels at the time of the simulation. Based on the time of ignition specified by the user, fuel levels are calculated through the combination of fuel type and the time since the last fire using fuel accumulation curves defined in the fuel type conversion file.

4.3.2 Basis

This layer is based upon fire history provided by the user.

4.3.3 Assumptions and limitations

In the case of overlapping fire histories, PHOENIX only uses the most recent fire occurrence.

4.3.4 User interactions

PHOENIX uses the fuel accumulation model (see Section 5.7: Fuel Accumulation) to calculate fine fuel hazard classes which are then converted to an equivalent fuel load (t/ha) for surface, elevated and bark fuels. The accumulation curves are part of the fuel type conversion file.

The user can upload a supplementary fire history layer to PHOENIX to capture recent fire events or to explore the effect of hypothetical fires in the landscape.

4.3.5 Description

Fuel types are used in conjunction with a user-provided fire history layer to create fuel layer information used in PHOENIX simulations and stored in the Fire Grid. The time since the most recent fire is used to estimate fuel levels using negative exponential accumulation curves (discussed in Section 5.7: Fuel Accumulation). As data is retained for only the most recent fires (see Figure 9), where historic fires are being simulated, the fire history layer must be adjusted to be representative of the appropriate conditions.

Figure 9. Diagram of how PHOENIX treats overlapping fire history. On the left, two fires have been mapped, one in 1972 and the other in 1985. On the right, a new fire in 2008 has overlapped these earlier fires and has replaced their fire history in the overlapping areas.

ESRI Shapefiles can be used to supplement the baseline fire history layer for particular simulation runs. This provision is made to account for fires that have occurred since the baseline fire history was processed or to enable hypothetical prescribed burning scenarios to be quickly evaluated. The supplementary fire history is added to any existing fire history layer and processed in the same manner as the fire history stored in the Fire Grid.

4.4 TOPOGRAPHY
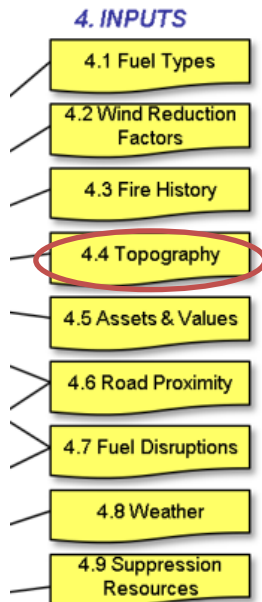
4.4.1 Purpose
A digital elevation model (DEM) is required by PHOENIX to support various models, such as slope correction, wind field models and map reprojection.

4.4.2 Basis
An ASCII grid DEM provided by the user with values represented as heights above sea level.

4.4.3 Assumptions and limitations
That the DEM is accurate.

4.4.4 User interactions
Preparation and provision of input data.

4.4.5 Description
From the DEM, elevation, slope and aspect are determined using bilinear interpolation with neighbouring cell values during a simulation. Bilinear interpolation is a common texture mapping technique.

4.5 ASSETS AND VALUES
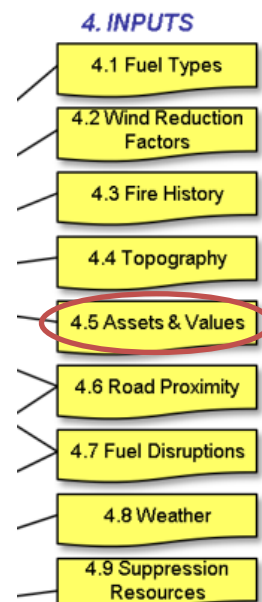
4.5.1 Purpose
The user can provide data about asset locations, type, value and vulnerability in order to support the Asset Impact PHOENIX model (see Chapter 7: Asset Impact).

4.5.2 Basis
The asset and values layer can be built by the user using one or more spatial datasets that represent assets and values (such as houses, infrastructure, catchments, plantations or biodiversity values).

4.5.3 Assumptions and limitations
A limitation of using an ASCII grid for primary input data is that only one asset can be recorded against an input data cell (e.g. 30 x 30 m), although this might correspond to 30 or more asset types for each Fire Grid cell (e.g. 180 x 180m). All spatial data must be converted to density per square metre for consistency in using different Fire Grid cell sizes. Impacts can be calculated for up to 99 asset types and evaluated against up to 99 loss functions. Asset values are limited to a maximum of 4 digits and 4 decimal places giving an effective range of 0.0001 to 9999.

4.5.4   User interactions

The user prepares an asset data code in an ASCII grid. The asset code includes the asset type, and impact type, an asset priority and an asset value for that cell in units per square metre.

4.5.5   Description

Users can draw on a range of spatial data layers in order to build a composite asset and values input layer. Examples include state and federal government data for property addresses, critical infrastructure or biodiversity values. For example, Tolhurst *et al.* (2017), in Appendix C, contains a review of potentially suitable data layers in Victoria, and Appendix A described the process of creating the composite asset layer in detail (using point, line and polygon data sources).

Against each cell of the input asset layer (e.g. 30 m raster) the user assigns an asset type, asset priority, an impact type and asset value per square metre, to build an asset code. Assets are sampled by the Fire Grid for use in the PHOENIX asset impact model. Chapter 7: Asset Impacts, has more information.

4.6   ROAD PROXIMITY
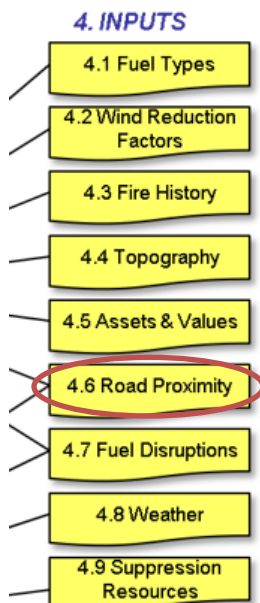
4.6.1   Purpose

Roads play an integral role in fire suppression, providing access and acting as anchors for suppression, backburning and burning out (Arienti *et al.* 2006). PHOENIX uses the road proximity layer to assess how much, if any, roads will assist in suppression efforts.

4.6.2   Basis

Road proximity is gridded data created from a road GIS layer provided by the user.

4.6.3   Assumptions and limitations

It is recommended that maximum values are truncated at 1,000 m as beyond this distance roads are assumed to have minimal influence. It is recommended that proximity is calculated to the nearest 50 m.

4.6.4   User interactions

Creating a road proximity raster data layer from road polylines for the development of a 'road proximity' ASCII grid data layer for PHOENIX.

4.6.5   Description

PHOENIX incorporates the effect of roads on suppression rates by calculating the average distance (in metres) from the nearest road for each Fire Grid cell from a data input layer typically called 'Road_Prox' (see Section 6.4: Suppression Model for more information).

A road proximity input data layer is created by the user from a 'polyline' feature road layer. GIS software is used to create the Road_Prox input data layer at the typical data resolution (e.g. 25 or 30 m). This analysis records the proximity to the nearest road to the nearest 50 m for a maximum distance of 1,000 m. Please refer to the *PHOENIX Input Data Guide* for instructions.

4.7 FUEL DISRUPTION

4. INPTUS

- 4.1 Fuel Types
- 4.2 Wind Reduction Factors
- 4.3 Fire History
- 4.4 Topography
- 4.5 Assets & Values
- 4.6 Road Proximity
- **4.7 Fuel Disruptions**
- 4.8 Weather
- 4.9 Suppression Resources
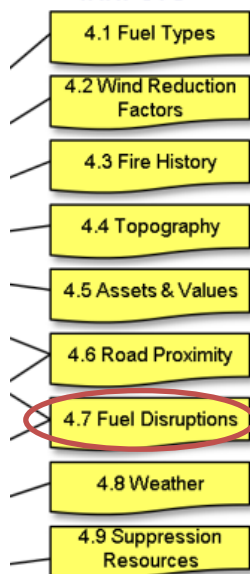
4.7.1 Purpose

The Fuel Disruption Layer defines the location and width of linear features such as roads, streams, firebreaks and railway lines that are generally devoid of fuel and may act as barriers to the progress of a fire.

4.7.2 Basis

Created from vector linear data prepared by the user in a program such as ESRI ArcGIS.

4.7.3 Assumptions and limitations

It is assumed that there will be little or no fuel on these linear disruptions.

4.7.4 User interactions

The user must prepare linear GIS layers with a field called 'width' for each linear feature that describes the effective width of the fuel-free area along the length of the linear feature. This is then converted into a raster data grid (usually 30 m or 25 m resolution) using GIS software.

4.7.5 Description

There is likely to be a number of GIS layers needed to describe all the linear fuel disruptions in the landscape, however, each of these GIS layers must be prepared to contain a field called 'Width' which describes the effective width of the fuel-free area along the length of the linear feature (polyline).

The various layers are combined by the user to create a single ASCII fuel disruption file which represents the combined widths of various disruptive features occurring at each point. The resultant raster input data file is typically called 'Disruption.zip'.

The width of the disruption will be used in PHOENIX to determine the effect of the disruptions on the local fire intensity and will determine if the local fire intensity is sufficient to breach the disruption. This is discussed in Section 5.5: Road / River / Break Impact.

4.8 WEATHER

4. INPUTS
- 4.1 Fuel Types
- 4.2 Wind Reduction Factors
- 4.3 Fire History
- 4.4 Topography
- 4.5 Assets & Values
- 4.6 Road Proximity
- 4.7 Fuel Disruptions
- 4.8 Weather
- 4.9 Suppression Resources
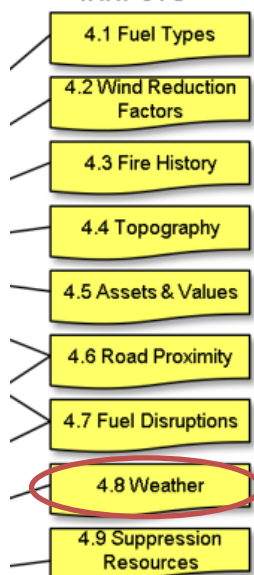
4.8.1 Purpose
PHOENIX requires weather data to support its fire spread models.

4.8.2 Basis
PHOENIX can incorporate spatially gridded weather data, in NetCDF format, as produced by the Bureau of Meteorology. Alternatively, the user can provide a stream of weather data for a particular point in the landscape and at known intervals of time.

4.8.3 Assumptions and limitations
Where weather data is provided as a stream of point data, the same weather conditions are assumed to apply for the entire fire. PHOENIX does not discriminate between forecast and observed data.

4.8.4 User interactions
The user can download gridded weather from the Bureau of Meteorology. A downloading tool has been developed to assist and automate this process. Alternatively, the user inputs a stream of weather data at specified time intervals. Grass curing can input into PHOENIX simulations as part of a point weather stream, gridded weather input or as a separate spatial data layer.

In the case of the passage of a cold front, additional entries may be added to the dataset immediately before and after the front's impact if a sudden change is wanted. Excluding this will result in a gradual shift in conditions from weather conditions input at the time step before the change and the time step after the change.

4.8.5 Description
To initialise PHOENIX to process fires on a particular day, the appropriate daily values for Drought Factor (Finkele *et al.* 2006) and grass curing (McArthur 1966) are required. The Drought Factor, an index of fine fuel availability developed specifically for the McArthur forest fire spread model, is derived from the number of days since rain and the Keetch-Byram drought index (Keetch and Byram 1968). When using PHOENIX to make future predictions, forecast rain may need to be considered to estimate Drought Factor.

PHOENIX provides a tool to download NetCDF data provided by BoM. NetCDF data is an open data standard used internationally to create and share data. Currently, only spatially gridded weather data compatible with the Australian Bureau of Meteorology's Gridded Forecast Editor (GFE) tool are supported.

The NetCDF files produced by the Bureau of Meteorology and used by PHOENIX are:

- Surface Temperature (°C);
- Surface (10m) Wind Speed (km/h);
- Cloud Cover %;
- Surface Relative Humidity (%);
- Surface (10m) Wind Direction (deg.);
- Drought Factor (0-10);
- Grass Curing (0-100%); and

- KBDI – Keetch-Byram Drought Index (0-200).

In Victoria and Tasmania, the resolution of the gridded weather forecast data is currently about 3 km, but in Queensland, NSW, WA, and South Australia, the NetCDF weather data has about a 6 km spatial resolution. All NetCDF data used currently has a one-hour temporal resolution.
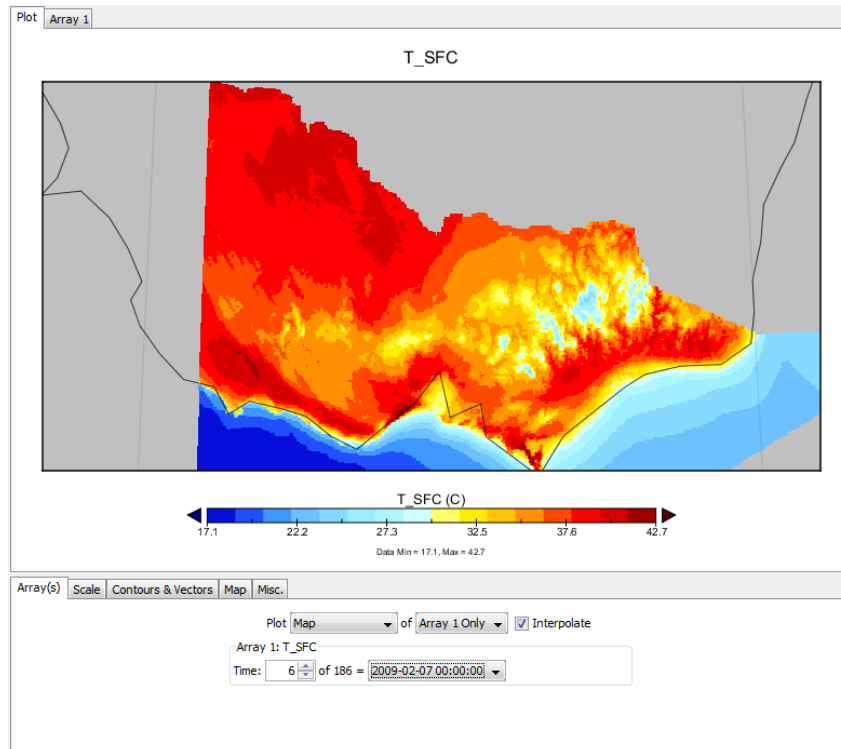
Figure 10. Victorian gridded Temperature data for 11 am 7 February 2009.

Alternatively, a string of weather data can be specified. Values for the air temperature (°C), relative humidity (%), wind direction (deg), wind speed (km/h), drought factor (0-10), degree of grass curing (%) and cloud cover (%) for specified times must be provided as specified in Table 4. An example is provided in Table 5.

Table 4. Standard weather attributes

Attribute	Comments
Date/Time	Date and time of weather condition
Temperature	10 minute average in °C measured at 1.5 metres in a screen
Relative Humidity	10 minute average as a %, measured at 1.5 metres in a screen
Wind Direction	10 minute average in degrees, measured at 10 metres in the open
Wind Speed	10 minute average in km/h, measured at 10 metres in the open
Drought Factor	Fine fuel availability 0-10
Curing	Grass curing level as a % (0-100)
Cloud	Cloud cover as a % (0-100)

Table 5. An example of user-provided point stream weather inputs that are time-stamped

Time	Temp (C)	RH (%)	Wind Dir	Wind (km/h)	Drought Factor	Curing %	Cloud %
07 Feb 2009 09:00	28.5	30.8...	10	42.618...	10	100	0
07 Feb 2009 09:12	28.7...	29.9...	10	42.618...	10	100	0
07 Feb 2009 09:30	29.2...	29.8...	10	46.325...	10	100	0
07 Feb 2009 10:00	30.7...	27.9...	10	46.325...	10	100	0
07 Feb 2009 10:11	31.6...	26.8...	10	44.472...	10	100	0
07 Feb 2009 10:30	32.7...	22.8...	10	51.883...	10	100	0
07 Feb 2009 10:40	34.2...	21.8...	10	44.472...	10	100	0
07 Feb 2009 11:00	34.0...	20.0...	360	55.590...	10	100	0
07 Feb 2009 11:08	34.2...	19.8...	360	61.148...	10	100	0
07 Feb 2009 11:30	35.7...	17.0...	360	51.883...	10	100	0
07 Feb 2009 11:34	36.0...	16.9...	360	50.030...	10	100	0
07 Feb 2009 12:00	36.5...	14.9...	360	55.590...	10	100	0
07 Feb 2009 12:09	37.7...	13.9...	360	53.736...	10	100	0
07 Feb 2009 12:30	39.4...	11.9...	350	48.178...	10	100	0
07 Feb 2009 13:00	39.5...	10.9...	350	68.560...	10	100	0
07 Feb 2009 13:04	40.2...	10.9...	350	63.001...	10	100	0

4.8.5.1 Upper-level winds

For simulations, PHOENIX either uses forecast wind data at 10 m above ground or otherwise converts this data to wind speeds at 1.5 m above ground (refer to Section 4.2: Wind Reduction Factors).

During its development, PHOENIX was modified to incorporate multi-level wind data, however, the forecast data had an uncorrected bias that resulted in incorrect ember transport modelling results. The lack of systematic, high resolution and comprehensive upper-wind observations makes bias correction and fire model testing impossible at the current time. It was therefore not possible to develop an improved ember transport model for PHOENIX using multi-level wind data (Chong *et al.* 2012a).

The option of including a single layer of upper-level wind was incorporated into PHOENIX for theoretical testing purposes. However, it is not available in the operational version of PHOENIX (Chong *et al.* 2012a).

For a discussion on the evaluation of upper-level winds on ember transport within PHOENIX, refer to the *Incorporating Vertical Winds into PHOENIX RapidFire's Ember Dispersal Model* (Chong *et al.* 2012a) Bushfire CRC and University of Melbourne technical report.

4.8.5.2 Interpolating weather data

Spot forecast, gridded forecast and automatic weather station data are often temporally quite coarse. If used in this raw form, weather data would result in instantaneous condition changes at the supplied date and time, which (apart from a frontal system) would not be realistic. To emulate real-world weather behaviour, weather conditions are linearly interpolated between entries.

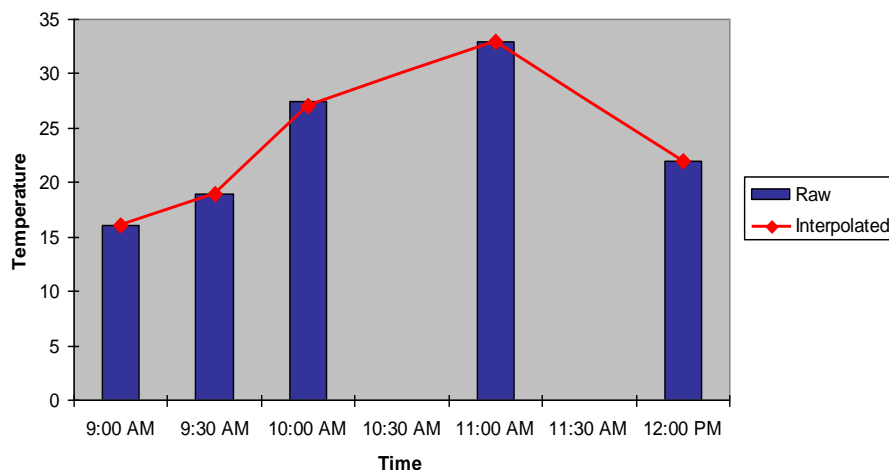*Figure 11. Raw versus interpolated temperature values (in degrees Celsius).*

A simple linear interpolation is used to derive continuous weather conditions for:

- Temperature;
- Relative humidity;
- Wind speed; and
- Wind direction.

BoM Gridded weather data is produced twice a day and provides forecasts for each hourly interval. However, for point stream data, time intervals can be specified down to 1-minute resolution.

Specifying intervals shorter than an hour does not necessarily improve the accuracy of PHOENIX. In the Bushfire CRC and University of Melbourne Technical Paper *Evaluation of weather data at different spatial and temporal scales on fire behaviour prediction using PHOENIX RapidFire 4.0 - Kilmore Case Study* (Chong *et al.* 2012c), it was found that course level inputs performed better than very fine time-scale inputs and that 30 minute intervals were optimal (though more testing is needed, Chong *et al.* 2012c).

That being said, in the case of a frontal system, extra entries immediately before and after the front's impact may be necessary to accurately model changing conditions. The span of time between the 'before' and 'after' the passage of a cold front needs to reflect actually expected period of the transition.

4.8.5.3   Grass curing

Grass curing level is used in the grass rate of spread function. It can be inputted as part of a point weather stream, gridded weather input or as a separate spatial data layer. Providing curing as a separate spatial data layer allows for a higher resolution input, which can be important where curing levels are highly variable. If a separate curing data layer is provided, it will take precedence over values in weather inputs.

4.9   SUPPRESSION RESOURCES

4.9.1   Purpose

To provide the data necessary to run the PHOENIX suppression simulation model. Suppression details only need to be specified when a simulation of suppression is desired.

4.9.2   Basis

The user is required to enter specific resources available during the course of the fire. Resource availability is characterised by the resource type, quantity, the time available at the fire perimeter, and in the case of aircraft, their turnaround time between drops.

4.9.3   Assumptions and limitations

Construction rate limiting factors have been identified for each of the suppression methods (McCarthy *et al.* 2003) including fire intensity, terrain, fuel density and turnaround time. In contrast to limiting factors, some elements, such as road proximity, augment construction rates.

4.9.4   User interactions

The user provides the suppression agent types, quantities, start time and turnaround times (if applicable). The user also provides data on the effect of limiting or augmenting factors on construction rates.

Suppression types and productivity rates can also be added or altered in the 'Suppression.xml', but this is an advanced user function and should not be undertaken without careful consideration and knowledge.

4.9.5 Description

Suppression operations are defined by the activities of individual suppression agents (Hu and Sun 2007). The model allows for construction rates to be defined for specific suppression methods. Suppression methods currently supported are:

- Hand Trail / Slip-ons (light tanker- 400 litre);
- D4 Dozer;
- D6+ Dozer;
- Tanker (4000 litre);
- Fixed Wing Bombers (Single Engine Air Tanker - 2500 litres);
- Medium Helicopter (1400 litres);
- Large helicopter (Erickson Air Crane) (5600 litres);
- Road Grader; and
- Mallee Roller/Clearing Chain.

Other types of suppression methods can be included if the user adds them to the suppression definition file 'Suppression.xml'. This is an advanced user task.

For a discussion on how suppression resource inputs are used in simulations see Section 6.4: Suppression Model.

4.9.5.1 *Construction rate limiting factors*

Construction rate limiting factors have been identified for each of the suppression methods (McCarthy *et al.* 2003) including fire intensity, terrain, fuel density and in the case of aircraft, turnaround time. The effect of each factor on the suppression method's construction rate is expressed as a series of tabular data points. A sufficient number of points are required to accurately capture the relationship. A simple linear interpolation is then performed to calculate the exact construction rate given a limiting factor value.

This data point-based method for expressing relationships has been chosen over inbuilt functions because of its transparency and ease of modification.
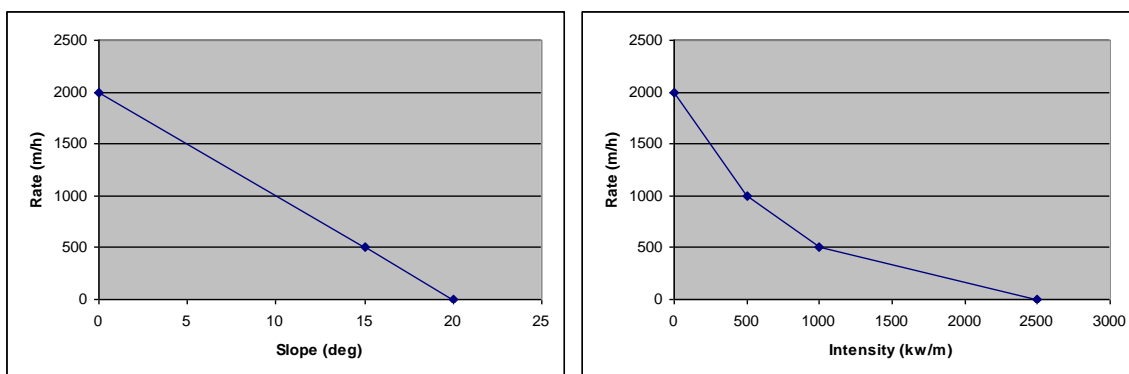
Figure 12. The effect of slope and intensity on fireline construction and holding rates of large tankers (4,000 litres).

The effect of each limiting factor is multiplicative. To calculate the resultant construction rate, the proportion of the maximum construction rate is calculated for each limiting factor then multiplied together. The resulting proportion is then multiplied by the maximum construction rate to calculate the resultant rate.

For example, a suppression type with a maximum construction rate of 2000 m/h with two limiting factors that result in a proportion of the maximum of 0.7 and 0.6 respectively, results in an 840 m/h construction rate.

> Resultant Rate = 0.7 x 0.6 x 2000 = 840 m/h

4.9.5.2   Construction rate augmentation based on road proximity

In contrast to limiting factors, road proximity augments construction rates. The distance from the Fire Grid cell centroid to the closest road is calculated and stored against each cell in the Fire Grid (see Section 4.6: Road Proximity).

PHOENIX incorporates an inbuilt basic road proximity modifier for land-based suppression methods that increases the previously calculated suppression rate based on the proximity of the fire to a road. The effect of road proximity is expressed as an increase in the maximum construction rate. The relationship between road proximity and construction rate increase varies between suppression methods.
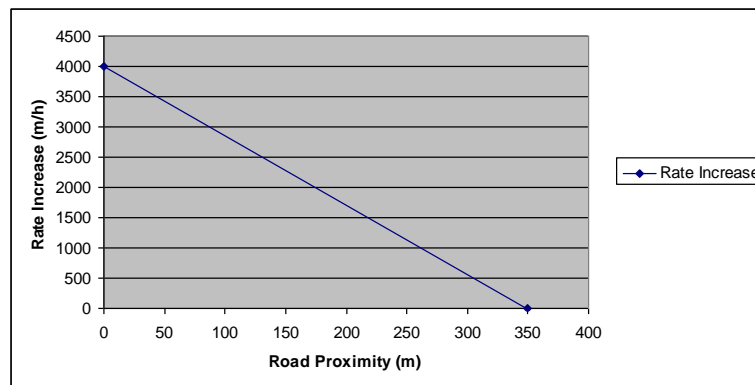
Figure 13. Increase in construction rate by large tankers (4000 litres) based on road proximity.

To calculate the modified construction rate, the percentage increase is calculated for the suppression type then applied to the previously calculated value.

For example, based on the graph in Figure 13, a road proximity of 200 m would result in a construction rate increase of 1714 m/h. Given an unrestricted maximum construction rate of 2000 m/h this would result in a 185.7% increase in the previously calculated construction rate.

> Percentage Increase = (2000 + 1714)/ 2000 = 185.7%

Given a limiting factor affected construction rate of 840 m/h the road proximity effect would augment the construction rate by 185.7% to 1559 m/h.

> New Rate = 840 * 1.857

5 FIRE BEHAVIOUR
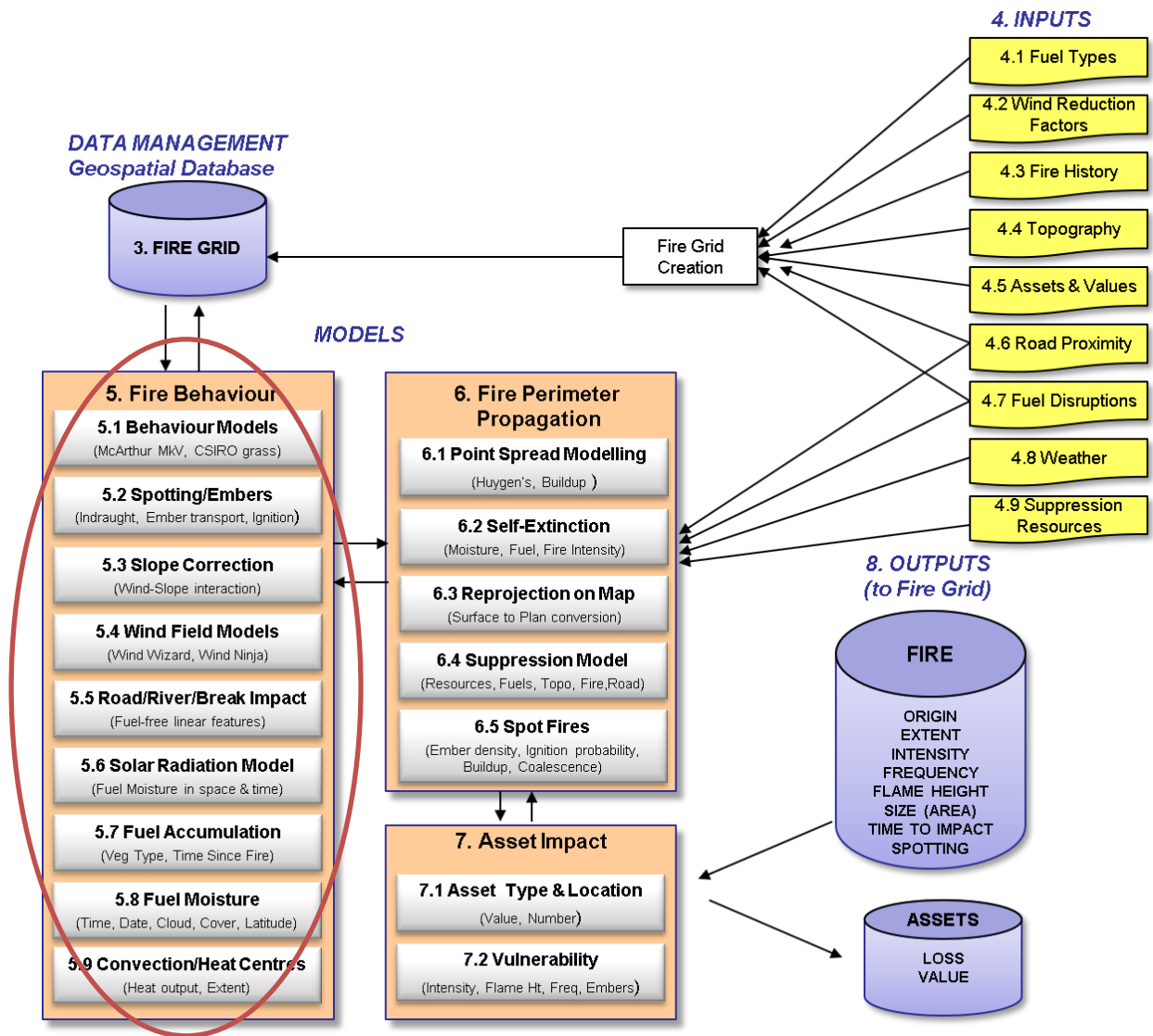
This chapter addresses the various models that drive underlying fire behaviour, including fire behaviour models, slope correction, convection, ember generation, fuel moisture and breaks in fuel.

5.1 BEHAVIOUR MODELS

5.1.1 Purpose
Fire behaviour models form the basis of simulations of fire spread and other fire characteristics within PHOENIX.

5.1.2 Inputs
- Fuel type;
- Fire history;
- Wind reduction factors;
- Topography; and
- Weather.

5.1.3 Basis
Elements of McArthur Mk 5 (Noble *et al.* 1980), McArthur prescribed burning guide (McArthur 1962), the Dry Eucalypt Forest Fire Model (Cheney *et al.* 2012), and CSIRO Grassland (Cheney *et al.* 1998) have been used. However, many novel fire behaviour functions have also been developed as part of PHOENIX.

5.1.4 Assumptions and limitations
Many of the parameters used in PHOENIX are 'best-estimates' based on a wide range of comparisons between observed fire behaviour and modelled fire behaviour.

FFDI calculations within PHOENIX limit wind speed to 70 km/hr.

5.1.5 User interactions
None.

5.1.6 Description
PHOENIX is a novel fire behaviour simulator utilising some existing published relationships and some conceptual models based on bushfire science and experience. One of the unique features of PHOENIX is how the convective strength of the fire is used to dynamically affect the spread of the fire. Rather than being just a 2-D model or a 3-D model, PHOENIX is somewhere in between (2.5-D). This is a compromise between computational efficiency and producing realistic results.

The development objective was to have a single, universal fire simulator based on a generic description of fine fuels. This was not achieved as there was insufficient information on fuel fineness and fuel strata heights to achieve this, but effectively only two fire models were required in PHOENIX – one for grassy fuel types and one for woody fuel types.

Elements of McArthur Mk 5 (Noble 1980), McArthur prescribed burning guide (McArthur 1962), the Dry Eucalypt Forest Fire Model (Cheney *et al.* 2012), and CSIRO Grassland (Cheney *et al*. 1998) have been used. None of these models have been used without modification and all have been used with the addition of some novel components and methods of interaction. As such, PHOENIX should be seen as a new and distinct fire behaviour model.

PHOENIX is mechanistic which means that if all inputs remain the same, the outputs for each run of the simulation will also remain the same. There are no stochastic elements involved. However, distributions of expected outcomes have been used for such things as ember spread, ignition probability and ember release. Many of the parameters used in PHOENIX are 'best-estimates' based

on a wide range of comparisons between observed fire behaviour and modelled fire behaviour. Stochasticity can be introduced to the simulations by way of varying the inputs such as has been done in Queensland with SABRE and was done in the Bushfire CRC with FIRE-DST (*Cechet et al.* 2014).

PHOENIX is dynamic in that there are several forms of feedback that drive the nature of fire behaviour. One of the best examples of this is how the size of the fire and the convective strength drives the spotting process and in turn drives the spread rate of the fire. Another example is how the fine fuel strata are conditionally included in fire behaviour calculations based on the flame height estimated from just the surface fine fuel burning. If flame heights are calculated to meet particular thresholds, the elevated and bark fuels will be added to the fuel being burnt and consequent calculations. If the flame height is less than 1 m, then only the combined surface and near-surface fuels are used in the calculation, and if the flame height is greater than 2 m, then all the combined surface, elevate and bark fine fuels are used in the fire behaviour calculations. For flame heights between 1 and 2 m, the elevated and bark fuels used are calculated proportionally, e.g. if the flame height is 1.8 m, then 80% of the elevated and bark fuels are used in the fire behaviour calculations.

The woody fuel fire spread function uses temperature and humidity values which are from two hours prior to the time step being simulated to account for the time taken for fine fuels to reach equilibrium moisture content under changing conditions (Cohen and Deeming 1985; Matthews 2006). Grass fuels reach equilibria more rapidly due to the higher surface area to volume ratios, so in the grass models, the temperature and humidity corresponding with the time step are used.

Terrain modified winds are used for all perimeter spread calculations and winds in forests are reduced by wind reduction factors specific to the fuel type. Wind reduction factors are only used in grassy type fuels if they are in grassy woodlands.

Fine fuel moisture estimation for woody fuel types is downscaled across the landscape to capture the local effects of canopy shading, incident solar radiation, wind, temperature and relative humidity. This significantly improves the fire spread modelling across the landscape even when the spatial scale of the weather inputs may be several kilometres apart.

To allow the spread functions to be used at any time of day or any time of year, a number of modifications were required. For example, McArthur's model is intended to estimate fire potential at the driest part of the day (between one and four pm) (McArthur 1967). As PHOENIX is intended to be applicable at any time, a solar radiation coefficient is calculated using the digital elevation model (Bird and Riordan 1986) and this is used to incorporate dynamic non-equilibrium diurnal changes in fuel moisture as described by McArthur (1967) (See Section 5.6: Solar Radiation Model).

At FFDIs below 12, PHOENIX uses a fire spread function that grades from the McArthur Mk5 surface fire spread prediction to one more aligned with the McArthur Leaflet 80 surface fire spread prediction. This was an empirically fitted adjustment that accounted for the effects of a reduced exposure of the flames to wind and reduced fine fuel availability at lower intensity fires which together reduced the effective surface fire spread rates. This is unique to the PHOENIX fire spread algorithm.

5.2 SPOTTING / EMBERS

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┌─────────────────────────────────┐
│        5. Fire Behaviour        │
│  ┌───────────────────────────┐  │
│  │   5.1 Behaviour Models    │  │
│  │ (McArthur MkV, CSIRO grass)│  │
│  ├───────────────────────────┤  │
│  │   5.2 Spotting/Embers     │  │
│  │(Indraught, Ember transport,│  │
│  │         Ignition)          │  │
│  ├───────────────────────────┤  │
│  │   5.3 Slope Correction    │  │
│  │  (Wind-Slope interaction)  │  │
│  ├───────────────────────────┤  │
│  │   5.4 Wind Field Models   │  │
│  │  (Wind Wizard, Wind Ninja) │  │
│  ├───────────────────────────┤  │
│  │ 5.5 Road/River/Break Impact│  │
│  │ (Fuel-free linear features)│  │
│  ├───────────────────────────┤  │
│  │  5.6 Solar Radiation Model │  │
│  │(Fuel Moisture in space & time)│
│  ├───────────────────────────┤  │
│  │  5.7 Fuel Accumulation    │  │
│  │ (Veg Type, Time Since Fire)│  │
│  ├───────────────────────────┤  │
│  │    5.8 Fuel Moisture      │  │
│  │(Time, Date, Cloud, Cover, Latitude)│
│  ├───────────────────────────┤  │
│  │ 5.9 Convection/Heat Centres│  │
│  │   (Heat output, Extent)   │  │
│  └───────────────────────────┘  │
└─────────────────────────────────┘
```

5.2.1 Purpose
Simulates ember generation, lofting, transport and distribution.

5.2.2 Inputs
- Convection heat centre model;
- Fire perimeter propagation;
- Fuel type; and
- Weather.

5.2.3 Basis
In principle, the process is akin to that used in other spotting models where embers are assumed to be lofted via convection to a particular height, and then transported at the speed and directions of local winds until they fall to the ground (Albini 1983). However, the nature of Australian fuels means that there is an order of magnitude more embers and some types can stay alight for long periods and traverse long distances (Ellis 2000). Therefore, PHOENIX simulates the ember propagation process through a uniquely developed convection and surface wind model, where fire-driven convection plays a key role in lofting embers.

It was found that a Weibull/bimodal distribution provided the best fit to observed long-distance and local spotting patterns (Sardoy *et al.* 2008).

5.2.4 Assumptions and limitations
The ember module of PHOENIX is designed to simulate both embers lofted in the convection column of a fire and windblown embers. Embers falling less than 200 m ahead of the fire front are assumed to be accounted for in the underlying surface spread functions.

Ember launches are only performed for cells under the influence of a convective centre (see Section 5.9: Convection / Heat Centres). It is assumed that the proportion of available embers launched is dependent on the convective strength at the cell's centre.

Spotting is always run in a fixed 200 m fire grid, regardless of the fire grid size specified by the user. This ensures a consistent effect of spotting on the simulated fire behaviour.

It is assumed that the total number of viable embers reaching the ground is inversely proportional to the convective strength of the launching column and hence the time aloft or maximum ember hang-time.

5.2.5 User interactions
None.

5.2.6 Description
Windblown embers, which result from burning bark detaching from trees, are an important mechanism of fire spread in Australian forests (McArthur 1967, Wilson 1992). McArthur's forest model incorporates short distance ember ignitions as an inherent part of the fire propagation mechanism; however, long-distance convection-driven embers (Albini 1983; Sardoy *et al.* 2008) are only recognised as a 'maximum spotting distance'. The PHOENIX spotting model accounts for longer distance embers. When a large number of windblown embers start new fires at high densities under

extreme conditions, 'mass fire' effects can occur, where fire spread rates and intensities are greatly elevated (Koo *et al.* 2010; Sharples *et al.* 2012).

5.2.6.1 *Ember launch*

The ember module of PHOENIX is designed to emulate embers lofted in the convection column of a fire as well as wind-blown embers travelling more than 200 m; windblown embers travelling less than 200 m at surface level are assumed to be accounted for in the underlying surface spread functions.

When a point along a fire's perimeter impacts a cell, an ember launch event is triggered. Only cells that result in intensity values greater than the self-extinction intensity (120 kW/m) are processed (see Section 6.2: Self-Extinction).

The embers available from the cell is scaled between the arbitrary range of 0 and 60 embers/m² based on the cell's bark load (McCarthy *et al.* 1999).

$$Available\ Embers = \frac{1}{1 + 108 * e^{(-1.2 \times Bark\ Load)}}$$
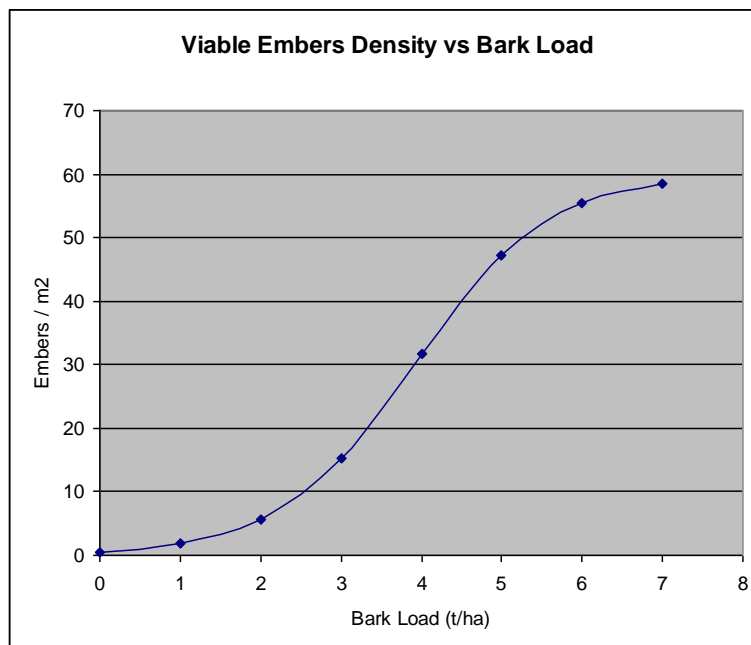
Figure 14. Graph showing the relationship between embers available and bark load

Ember launches are only performed for cells under the influence of a convective centre. It is assumed that the proportion of available embers launched is dependent on the convective strength at the cell's centre.

$$Ember\ Porportion\ Launched = 1.032 - e^{-.000045 \times Convective\ Strength}$$

A theoretical maximum ember 'hang-time' in minutes is calculated based on the influencing column's convective strength. This value is intended to represent the maximum time a viable ember can remain aloft, however, it is also used as a scaling mechanism that encapsulates an increased wind speed with altitude (as experienced in the vicinity of the major fires of the 7[th] February 2009 in Victoria). At these fires, the increased wind speed relative to surface was observed to a height of approximately 5,000 m.

$$Hang\ Time = 0.6\ \times Convective\ Strength \div 10000$$

Hang-time values increase linearly with convective strength with maximum modelled values achieved in the Kilmore and Murrindindi fires (7 Feb 2009 in Victoria) being 28 and 36 minutes respectively.

5.2.6.1.1 Ember Dispersal

The ember dispersal process can be conceptualised as a cloud of all the available embers from a cell launching simultaneously and being distributed by the prevailing winds. The embers are transported vertically by the convection column then horizontally by the prevailing winds.

Of all the embers launched, it is assumed that only a small proportion will reach the ground in a state that could result in a spot fire with the majority burning up before reaching the ground. It is assumed that the total number of viable embers reaching the ground is inversely proportional to the convective strength of the launching column and hence the time aloft or maximum ember hang-time.

$$Total\ Viable\ Embers = Embers\ Launched\ \times e^{-9\times(Hang\frac{Time}{35})}$$

The transport of viable embers is modelled using the reference weather stream rather than the local terrain affected wind as it is assumed to better match the winds aloft.

Without knowing the 'actual' lofting heights, descent rates or vertical wind profile, it is not possible to capture the 'real' transport winds experienced by the spotting material. Instead, an empirically fitted 'resultant' spatial ember density distribution is calculated for each launch event and distributed across the landscape. A Weibull/bimodal distribution provided the best fit to observed spotting patterns (Sardoy *et al.* 2008). The bimodal distribution captured the medium to long-distance spotting phenomenon better than a traditional exponential decay model which only addresses short distance spotting.
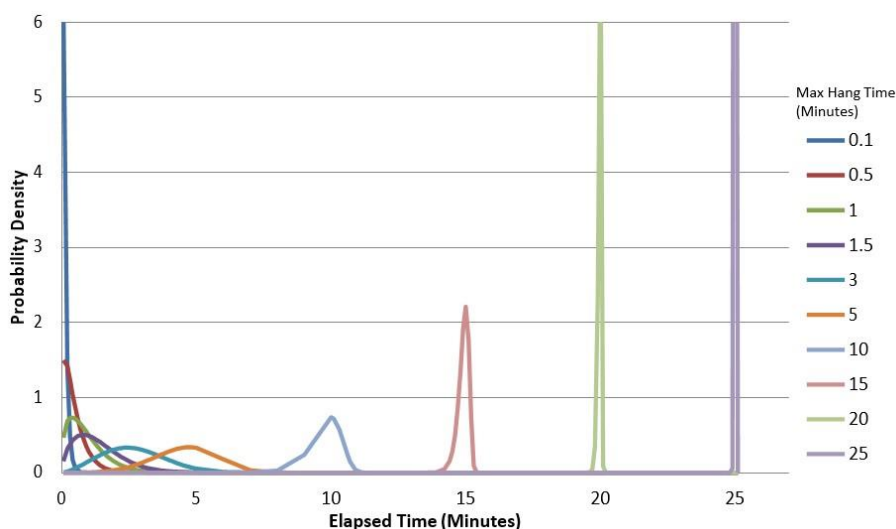
Figure 15. Bimodal ember impact pattern used in PHOENIX. Note, the cumulative probability version of the Weibull function is used to represent this pattern in Phoenix. This graph has been generated using the Weibull probability density function using the same shape and scale parameters as the cumulative function in order to show the change in ember impact pattern with increasing hang time.

In order to determine the proportion of ember impacts in the landscape from the launch cell as the ember cloud disperses, a cumulative Weibull distribution function is used. For small convective

values, the majority of embers impacting are assumed to fall within a short time of launch, however, as the hang-time increases, the majority of the viable embers impacting occur at a greater distance. The cumulative Weibull function used to describe the ember distribution takes the following form.

$$Cumulative\ Weibull = 1 - e^{-\left(\frac{Minutes\ Elapsed}{Max\ Hang\ Time}\right)^{e^{(0.3 \times Max\ Hang\ Time)}}}$$
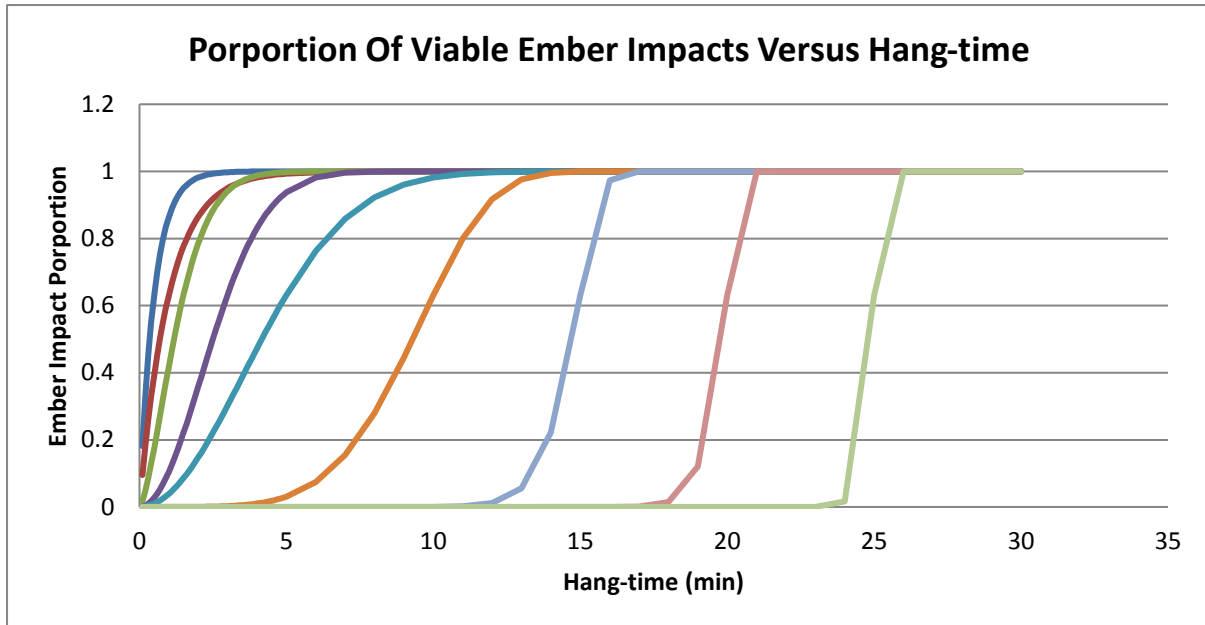
Figure 16. Cumulative Weibull distribution function generates the bimodal ember impact pattern observed as fires increased in convective on the 7th February 2009 and as described in Sardoy et al. 2008.

A Weibull function is also used to represent lateral ember distribution with ember hang-time. Reconstructions of Black Saturday fires show a general transition from a widening spot fire impact pattern with distance, which subsequently narrows for longer distance impacts. It is assumed that these longer distance ignitions are caused by heavier slower-burning spotting material which is less susceptible to turbulent flows in the plume which would widely distribute the smaller and lighter material.

Weibull function parameters were selected to produce an increasing lateral ember distribution for impacts up to seven minutes, which then narrows to the 15-minute mark where it asymptotes (increasingly approaching zero) in order to capture discrete viable long-distance ember impacts (Figure 17).

$$Lateral\ Spread_{std\ dev} = 1500 \times 0.275 \times (Hang\ Time \div 8)^{1.2} \times e^{-(Hang\ Time \div 8)^{2.2}}$$
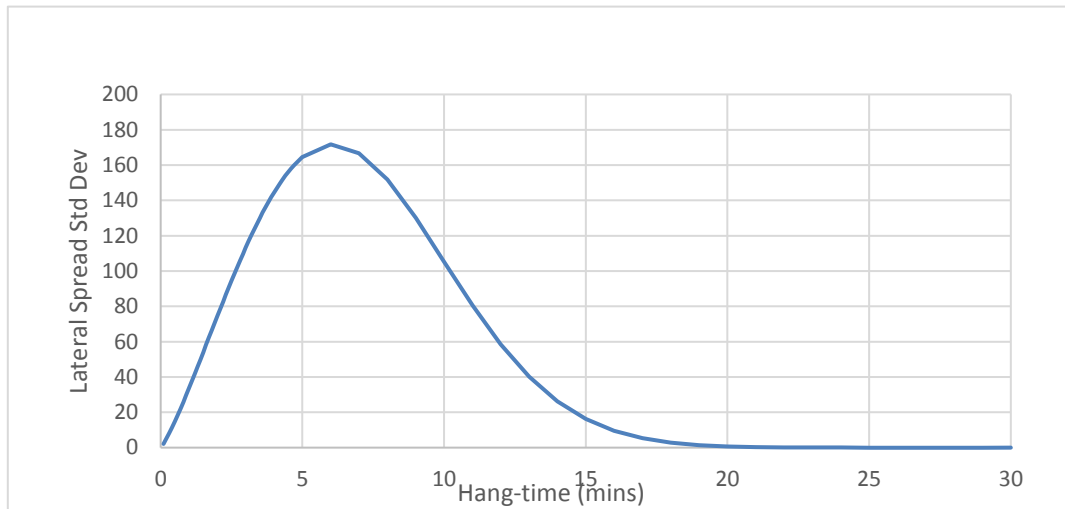
Figure 17. Lateral spread standard deviation showing that after an initial increasing spread period, the lateral spread decreases.

To ensure viable ember impacts along of the virtual ember cloud's trajectory are at a consistent scale to the Fire Grid, impacts are calculated at a set grid cell resolution interval of 200 m.
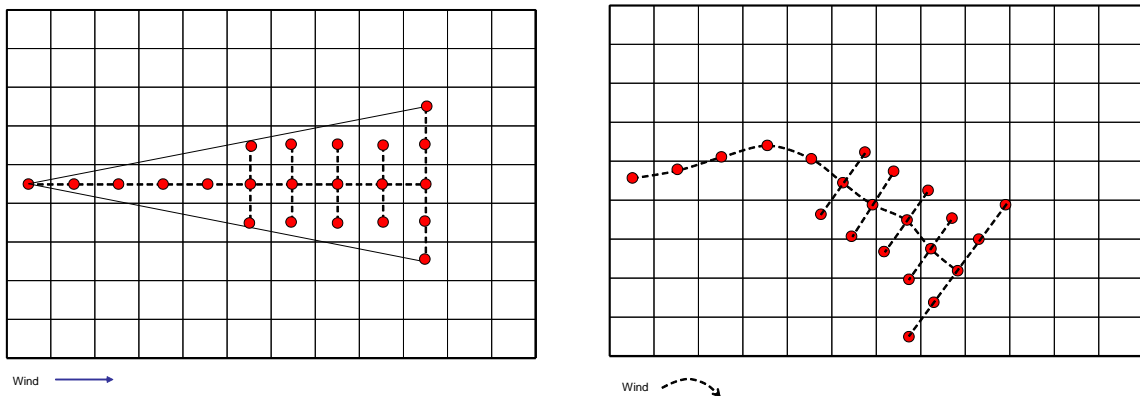
Figure 18. Ember impact patterns are shown matching grid resolution with a constant (left), and variable (right) wind direction.

Using the prevailing winds, the time to traverse a cell is calculated. Weather inputs are re-sampled at every cell traversal to capture any change to direction or speed. Each underlying Fire Grid cell is identified, and based on the elapsed time and the time interval, the number of viable embers impacting a cell calculated using the Cumulative Weibull distribution. The impacts are then distributed laterally assuming a normal distribution with a standard deviation derived from the lateral spread Weibull function.

5.3 SLOPE CORRECTION

5.3.1 Purpose
PHOENIX uses slope correction to modify the outcomes of fire behaviour models.

5.3.2 Inputs
Slope is derived by PHOENIX from the digital elevation model, and is used to modify the outcomes of fire behaviour models.

5.3.3 Basis
PHOENIX models the effect of slope on both the magnitude and direction of fire spread consistent with Sharples (2008). Slope effects are considered using the slope effect equation of McArthur (Noble *et al.* 1980) converted to a vector directed upslope perpendicular to the contour. This vector is added to the fire spread calculated with terrain modified winds, and the interaction between slope and wind, to give a final slope corrected result.

5.3.4 Assumptions and limitations
None.

5.3.5 User interactions
None.

5.3.6 Description
Fires will spread under the influence of three separate, but interacting factors including wind, slope and fuel continuity. Depending on fuel continuity and fire intensity, fires can spread in the absence of wind and slope. However, if wind or slope affects the fire, then the rate of spread of the fire will change. The effects of wind and slope are non-linear and in addition to the effect of wind and slope alone, there can be an interaction effect.

The spread vector in the direction of the wind (V_{ws}) is first calculated using the component of slope in the direction of the wind. A second 'Residual Slope' spread vector (V_{rs}) is then calculated using the component of the slope effect not already captured by V_{ws}. This is done by comparing the slope effect on rate of spread in the direction of the wind against the zero-wind slope effect using the following equation which limits maximum slope values to 30 degrees.

$$Mr = e^{0.069s}$$

- Where: Mr = rate of spread multiplier;
- And: s = slope relative to wind direction (capped at 30 degrees).

The two spread vectors V_{rs} and V_{ws} are then added together to produce the resultant slope affected spread vector V_r.

V_{ws} – Wind and relative slope effect vector (Blue)
V_{rs} – Residual slope effect vector (Red)
V_r – Resultant spread vector (Black)

Figure 19. The effect on slope on spread direction as well as rate due to upslope, cross slope and down slope winds.

In the case of the wind blowing directly up a slope, V_{rs} would be zero and have no effect on the resultant vector V_r, as the slope affect has already been fully captured by V_{ws}. However, in the case where the wind is blowing directly across the slope, V_{rs} would incorporate the full zero wind slope effect which would point the resultant vector V_r up slope.

5.4 WIND FIELD MODELS

5.4.1 Purpose
PHOENIX can incorporate a wind modification layer that represents the deviation in wind speed and direction caused by local topography, to modify the outcomes of fire behaviour models.

5.4.2 Inputs
- Topography (DEM); and
- Weather.

5.4.3 Basis
Wind Ninja 2.1.x (http://www.firemodels.org/index.php/windninja-software/windninja-downloads) is a tool available with PHOENIX that can be used to generate this layer from the DEM layer.

5.4.4 Assumptions and limitations
The wind field model works on the basis of mass conservation theory and not fluid dynamics theory and therefore does not model flow separation or lee slope eddies which occur at threshold wind speeds dependent on terrain.

Wind modifiers are generated at 100 m resolution and exclude areas where elevation varies by less than 10 m.

5.4.5 User interactions

None.

5.4.6 Description
Terrain can cause substantial deviations in wind speed and direction from prevailing winds (Forthofer 2007; Butler *et al.* 2004). These deviations are generally at too fine a scale to be represented in weather forecasts; however, can have large effects on fire behaviour. To compensate for this, PHOENIX can incorporate wind modification layers that represent the deviation in wind speed and direction caused by local topography for winds coming from a particular direction. This allows weather forecasts to be downscaled to a finer resolution.

Wind Ninja 2.1.x (http://www.firemodels.org/index.php/windninja-software/ windninja-downloads)
can be used to generate this layer from the DEM layer. It is a mass conservation model and captures
the wind speed acceleration up slope, deceleration down slope as well as channelling. It results in a
fixed proportional adjustment of speed and direction for a given input direction. It is not a fluid
dynamic model and therefore does not model flow separation or lee slope eddies which occur at
threshold wind speeds dependent on terrain. The mass conservation approach is computationally
simpler than a fluid dynamics approach and only requires terrain and open wind speed and direction
inputs to be run. Fluid dynamic wind models are computationally more complex and require a lot
more parameterisation of boundary layer conditions to be run. The mass conservation approach still
captures some important effects of terrain on wind speed and direction. Wind modifiers are
generated at 100 m resolution and exclude areas where elevation varies by less than 10 m.

Modifiers generated by Wind Ninja based on the DEM for each 100 m point across the landscape are
contained in a comma-delimited string made up of the paired direction, speed change factors for
each 30-degree point around the compass (Table 6) for a reference speed of 10 km/h. Zero or no
change values are left blank. Input/output wind speeds and directions are integer values at 10 m
above surface. The comma-delimited string for the point represented in Table 6 would be: '2,-2,-
3,,5,2,,, etc.' Figure 20 contains a visualisation.

Table 6. Wind modifier values at one point in the landscape using a reference wind speed of 10 km/h.

Input Direction in degrees	Topographically modified direction	Topographically modified speed	Paired direction, speed change
0	2	8	2,-2
30	27	10	-3,
60	65	12	5,2
90	90	10	,
etc			

To apply the modifiers to an input wind, the proportion change is calculated and applied. For
example, an input wind speed of 25 km/h at 0 degrees would result in:

$$Resulting\ speed = 25\left(\frac{-2 + 10}{10}\right) = 20\ km/h$$

$$Resulting\ direction = 0 + 2 = 2\ degrees$$

If the input wind direction falls between reference directions, then the resulting value is interpolated
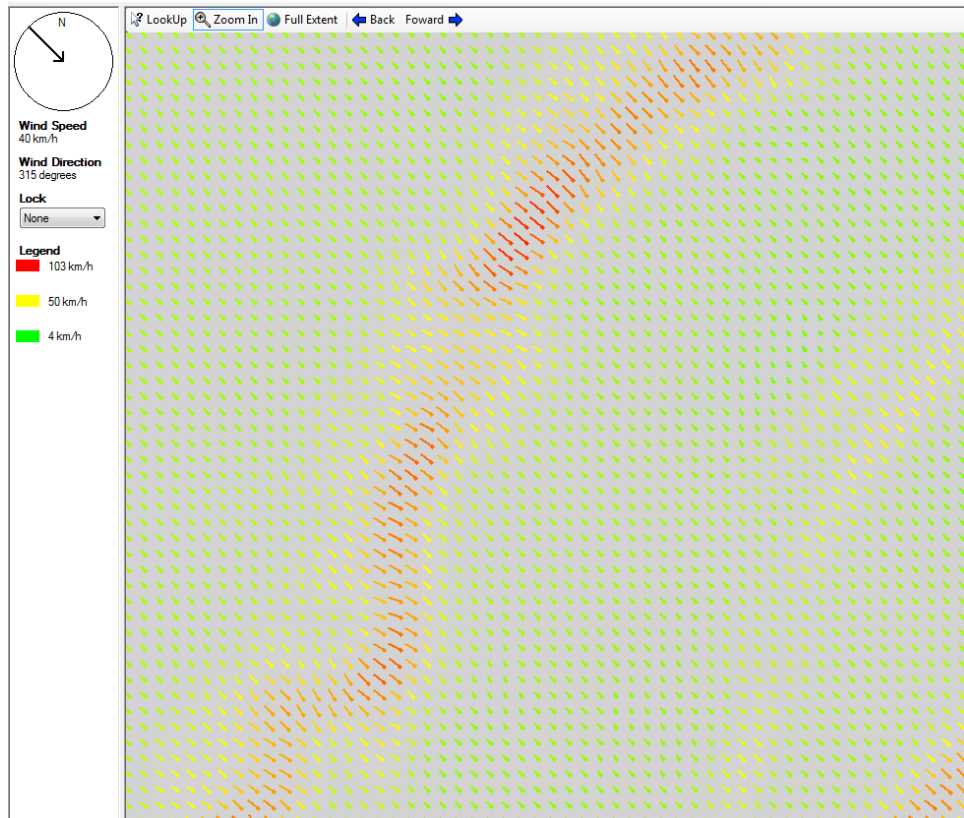based on the two adjacent values.

Figure 20. Visualisation of the effect of a mountain range on wind speed and direction as captured by the wind modifier layer for an input wind speed of 40 km/h at 315 degrees. The range is evident by the line of increased wind speeds shown in red stretching from the bottom left corner to the top right corner of the figure.

5.5 ROAD, RIVER AND BREAK IMPACT

5.5.1 Purpose

Linear fuel elements with no fuel such as roads and streams can be highly disruptive to fire spread, with their effect far exceeding the area they represent. PHOENIX implements a process that attempts to capture this effect.

5.5.2 Inputs

- Fuel disruption;
- Point spread model; and
- Spot fires model.

5.5.3 Basis

Discontinuities in the fuel, mapped as linear vector fuel disruptions, are analysed on a grid cell basis. Grid cell disruption values are calculated by sampling within the cell to determine the combined disruptive width for the cell. Following this, breaches of fuel disruptions are modelled for both embers and fire perimeters.

5.5.4   Assumptions and limitations
Although disruptions are stored as a linear feature with a north-south orientation in the centre of the cell, they are assumed to affect fire spread anywhere within the cell and be orientated perpendicular to the direction of fire spread.

5.5.5   User interactions
None, except to include/exclude disruption layer from input datasets.

5.5.6   Description
Discontinuities in the fuel, mapped as linear vector fuel disruptions are converted into a raster data grid (usually 30m or 25m resolution) using GIS software (see Section 4.7: Fuel Disruption). The resultant input data file is typically called 'Disruption.zip'. This disruption data layer is then analysed on a Fire Grid cell basis. For each cell, the effective area of disruptions is calculated by using an intersection function to find the total linear length of disruptions in each Fire Grid cell which is then multiplied by the length-weighted widths from the attributes of the disruption layer. This is transposed into a single polygon with a length equivalent to the grid cell resolution and a width based on the total area of disruptions within the cell.
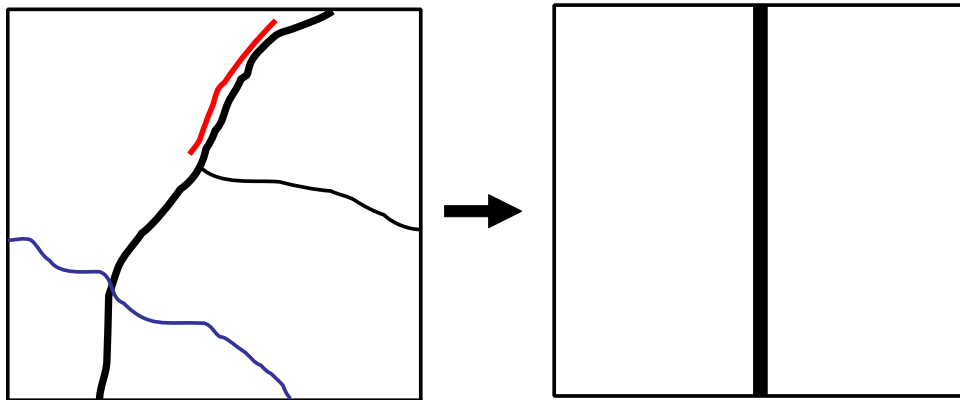
Figure 21. Fire Grid cell disruption values are calculated by sampling the Disruption input data cells within the Fire Grid cell to determine the combined disruptive width for that Fire Grid cell.

Fire Grid cell breaching is assessed in two ways; 'ember breaching' and 'flame breaching'.

5.5.6.1   Ember breaching
Firstly, the cell's spot fire ignition probability is checked. Then, to capture 'in-cell' or short distance spotting (< 200 m), the maximum spotting distance for the cell is calculated directly using the McArthur fire behaviour function including the subsequent spotting factor modification for bark load (McCarthy *et al.* 1999).

If either the cell's spot fire ignition probability is greater or equal to one ($p_c \geq 1$) or the maximum spotting distance exceeds the cells disruption width, then the disruptive elements are considered breached and the fire continues unhindered.

5.5.6.2   Flame breaching
The barrier will be breached via flame if the disruption width is less than a specified multiple of the simulated flame height (Mees *et al.* 1993).

5.6 SOLAR RADIATION MODEL

5. Fire Behaviour
5.1 Behaviour Models (McArthur MkV, CSIRO grass)
5.2 Spotting/Embers (Indraught, Ember transport, Ignition)
5.3 Slope Correction (Wind-Slope interaction)
5.4 Wind Field Models (Wind Wizard, Wind Ninja)
5.5 Road/River/Break Impact (Fuel-free linear features)
5.6 Solar Radiation Model (Fuel Moisture in space & time)
5.7 Fuel Accumulation (Veg Type, Time Since Fire)
5.8 Fuel Moisture (Time, Date, Cloud, Cover, Latitude)
5.9 Convection/Heat Centres (Heat output, Extent)

5.6.1 Purpose

PHOENIX incorporates a solar radiation model to determine the amount of solar radiation at each cell of the Fire Grid. Solar radiation is required as an input into the fuel moisture and suppression models.

5.6.2 Inputs

- Fuel type; and
- Topography (DEM).

5.6.3 Basis

The solar radiation model is based on the functions contained in the 'solrad.xls' Excel spreadsheet developed by Greg Pelletier of the Washington State Department of Ecology, Olympia, Washington. It is a part of the NOAA JavaScript implementation of the Bird and Hulstrom solar radiation model (Bird and Hulstrom 1981).

The cell wind reduction factor (see Section 4.2: Wind Reduction Factors) is used to determine leaf area index (LAI) used to calculate shading based on Beer's law (Silberstein, Sivapalan *et al.* 2003).

5.6.4 Assumptions and limitations

In the absence of cloud cover data, it is assumed that there is no cloud cover reducing the solar radiation reaching the ground, or if forecast cloud cover data is available, then it is assumed that the forecast is correct in time and space. The model incorporates slope and aspect, but not orographic shading from surrounding hills or ranges.

5.6.5 User interactions

None.

5.6.6 Description

The functions below describe the wind reduction factor to LAI conversion and the LAI to transmittance conversion.

$$LAI = 0.2333 Wrf^2 - 0.4333 Wrf + 0.2$$

Where: LAI = leaf area index

Wrf = wind reduction factor

$$t = e^{-LAI}$$

Where: t = transmittance (0-1)

LAI = leaf area index

5.7 FUEL ACCUMULATION

5. Fire Behaviour
5.1 Behaviour Models (McArthur MKV, CSIRO grass)
5.2 Spotting/Embers (Indraught, Ember transport, Ignition)
5.3 Slope Correction (Wind-Slope interaction)
5.4 Wind Field Models (Wind Wizard, Wind Ninja)
5.5 Road/River/Break Impact (Fuel-free linear features)
5.6 Solar Radiation Model (Fuel Moisture in space & time)
5.7 Fuel Accumulation (Veg Type, Time Since Fire)
5.8 Fuel Moisture (Time, Date, Cloud, Cover, Latitude)
5.9 Convection/Heat Centres (Heat output, Extent)

5.7.1 Purpose

Fuel levels are considered in a dynamic manner, using the time since the last fire to moderate total fuel levels for each stratum. These are then used in fire behaviour calculations.

5.7.2 Inputs

- Ignition;
- Fuel type;
- Fire history;
- Wind reduction factor;
- Solar radiation; and
- Weather.

5.7.3 Basis

Within PHOENIX, once a fuel type has been determined from the fuel input data grid, a lookup table ('FuelTypes.xml') is used to calculate the fuel levels for the 'combined surface', 'elevated' and 'bark' fuel strata. This calculation is based on the fuel type and the time since last fire. The fuel lookup table stores three parameters of a negative exponential fuel accumulation curve for each fuel type. These values are then combined and used in the Fire Grid for use by the PHOENIX simulation.

5.7.4 Assumptions and limitations

After a fire, the fuel level in each stratum (surface, elevated fuel and bark) is assumed to follow a modified Olson accumulation pattern (Olson 1963; Birk and Simpson 1980) with the modification that the value at time zero is not necessarily zero. That is to account for the fact that there is often some residual fine fuel after the passage of fire.

In Victoria, the peak fuel levels and the rate of accumulation after an understorey fire have been based on a lot of fuel sampling across the State over a 40 or so year period. However, the accumulation rates are very general and do not reflect all the variation in geographic conditions across the distribution of each fuel type and they do not reflect variation in accumulation rates due to the nature of the seasonal conditions following a fire event. Over time, some refinements of these accumulation rates have been made based on local observations.

In NSW, fuel accumulation rates in forested areas were specifically studied and incorporated into their fuel lookup table. However, non-forest fuel types have been treated more like the Victorian process. Fuel accumulation rates in other states have been derived in a similar way as they have been in Victoria. This has provided a good working base with the expectation that values in the fuel lookup tables will be refined and improved over time.

At present, there is no distinction made between fires of different intensities on fuel accumulation rates. The assumption currently used with fuel accumulation rates is that they are the rates expected after a surface or understorey type fire. Users should be aware that intense fires that have resulted in structural changes to the vegetation may result in fuel accumulation rates different to those generally used in PHOENIX.

5.7.5 User interactions

Users may modify the parameters for the fuel accumulation curves and the wind reduction factors in the fuel lookup table (FuelTypes.xml) using an editing tool in PHOENIX; however, it is not recommended to be done without careful consideration.

5.7.6 Description

Fuel loads are considered in a dynamic manner, using the time since the last fire (see Section 4.3: Fire History) to estimate the accumulated fuel load. After a fire, each stratum of fine fuel (surface, elevated fuel and bark) is assumed to follow a modified Olson curve accumulation pattern (Olson 1963; Birk and Simpson 1980). Fuel accumulation rates and the overall equilibrium levels are specified in the fuel description file (FuelTypes.XML) for each fuel stratum within each fuel type using a three-parameter negative exponential curve. Fuel types also include a Wind Reduction Factor (Wind RF), designed to capture the varying effect different fuels have on wind speed at 1.5 m above the ground (Figure 22, also see Section 4.2 Wind Reduction Factors).
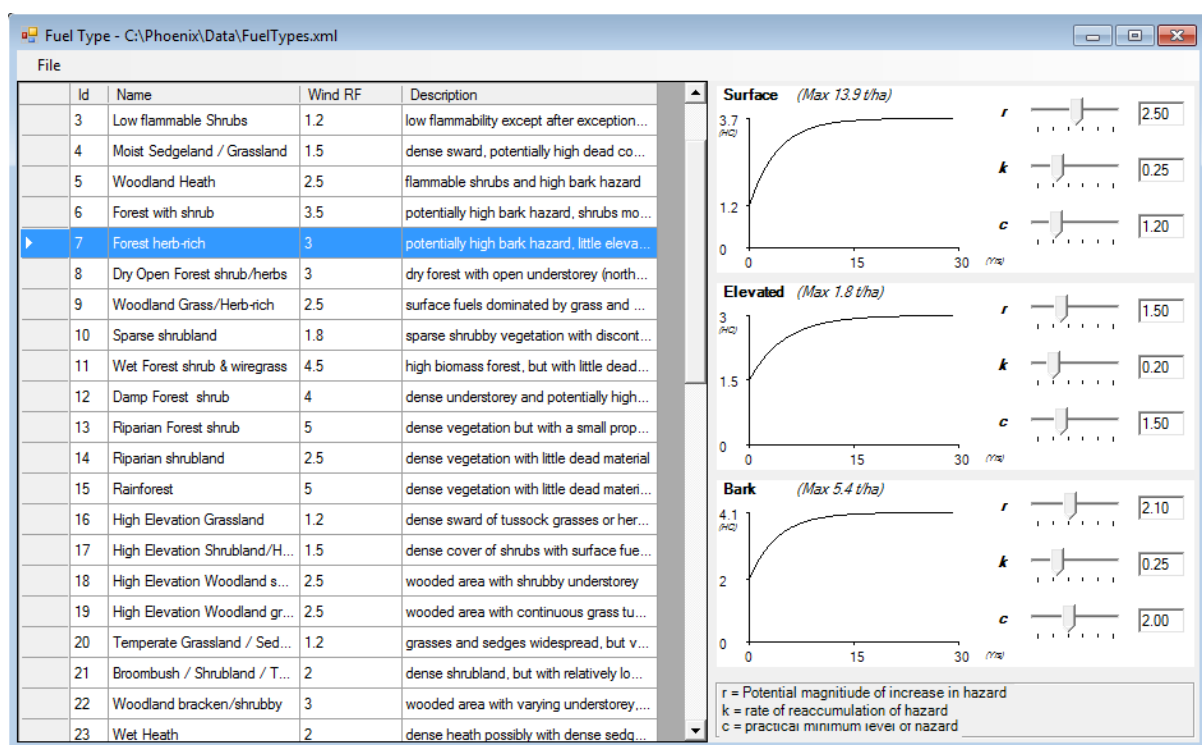
Figure 22. Fuel type lookup table showing surface, elevated and bark re accumulation rates for fuel type 7.

Fuel levels are expressed in hazard classes (HC) based on the *Overall Fire Fuel Hazard Guide* (McCarthy *et al.* 1999). Parameters r, k and c determine the current hazard class based on the equation below.

$$HC = r(1 - e^{-kt}) + c$$

Where: HC = hazard class (0-5)

r = range of change in hazard class

k = reaccumulation rate

t = years since last fire

c = post-fire hazard class (= effective minimum hazard class immediately after fire)

$r + c$ = equilibrium (maximum) hazard class

Internally, fuel hazard classes are converted to an equivalent fuel load (t/ha) using the following equations

$$ls = (-22.17HC)/(-9.605 + HC)$$

Where: ls = surface fuel or grass load in t/ha

HC = hazard class

$$le = 11.49/(1 + 1107.8e^{-1.78HC})$$

Where: le = elevated fuel load in t/ha

HC = hazard class

$$lb = 7.431/(1 + 937.8e^{-1.905HC})$$

Where: lb = bark fuel load in t/ha

HC = hazard class

5.8 FUEL MOISTURE

5. Fire Behaviour
5.1 Behaviour Models (McArthur MkV, CSIRO grass)
5.2 Spotting/Embers (Indraught, Ember transport, Ignition)
5.3 Slope Correction (Wind-Slope interaction)
5.4 Wind Field Models (Wind Wizard, Wind Ninja)
5.5 Road/River/Break Impact (Fuel-free linear features)
5.6 Solar Radiation Model (Fuel Moisture in space & time)
5.7 Fuel Accumulation (Veg Type, Time Since Fire)
5.8 Fuel Moisture (Time, Date, Cloud, Cover, Latitude)
5.9 Convection/Heat Centres (Heat output, Extent)

5.8.1 Purpose
Fine fuel moisture is an important component for fire behaviour calculations. PHOENIX incorporates a fine fuel moisture model.

5.8.2 Inputs
- Fuel;
- Wind reduction factor;
- Solar radiation; and
- Weather.

5.8.3 Basis
The PHOENIX fine fuel moisture model has been adapted from a Python script provided by Stuart Matthews of CSIRO (Matthews, Gould *et al.* 2010). It is a simplification of his multiple-layer process model, but more complex than the fuel moisture model used in Project VESTA. The PHOENIX adaption has not been published.

Grass fuel moisture is estimated with a grass specific function (Dimitrakopoulos *et al.* 2010).

5.8.4 Assumptions and limitations

Grass fuel moisture is assumed to react instantaneously to changes in temperature and relative humidity (Cheney and Sullivan 2008) and therefore does not directly include solar radiation affects.

Woody fuel moisture is assumed to have a two-hour lag time in response to changes in atmospheric temperature and relative humidity. Therefore, weather data two hours prior to the ignition time is used to run the simulation in wood fuels.

5.8.5 User interactions

None.

5.8.6 Description

The PHOENIX fine fuel moisture model uses screen (1.5m) weather (see Section 5.2: Wind Reduction Factors) and surface solar radiation (see Section 5.6: Solar Radiation) to determine fine fuel moisture content. Forest fine fuel moisture is calculated for each Fire Grid cell.

Forecast weather data does not incorporate the effect of the fire on the atmosphere. Large fires can entrain enormous amounts of air into the convection column and can heat cool air as it passes over the burning area, preventing or at least delaying the landscape downwind from experiencing forecast changes.

Fire behaviour lag time in response to fire weather conditions is addressed in PHOENIX by implementing a two-hour lag for temperature and relative humidity values. This two-hour lag attempts to capture the effect of the coupling between the fire and atmosphere on downwind weather conditions and the moisture diffusion rate in the fine fuels.

Grass fuel moisture is assumed to react instantaneously to changes in temperature and relative humidity (Cheney and Sullivan 2008) and does not directly include solar radiation. Grass fuel moisture is estimated with a grass specific function (Dimitrakopoulos *et al.* 2010):

$$Mf = -0.19625t + 0.1356r + 9.575$$

Where: Mf = grass fuel moisture (%odw)

t = air temperature in °C

r = relative humidity %

5.9 Convection / heat centres

5. Fire Behaviour
5.1 Behaviour Models
(McArthur MkV, CSIRO grass)
5.2 Spotting/Embers
(Indraught, Ember transport, Ignition)
5.3 Slope Correction
(Wind-Slope interaction)
5.4 Wind Field Models
(Wind Wizard, Wind Ninja)
5.5 Road/River/Break Impact
(Fuel-free linear features)
5.6 Solar Radiation Model
(Fuel Moisture in space & time)
5.7 Fuel Accumulation
(Veg Type, Time Since Fire)
5.8 Fuel Moisture
(Time, Date, Cloud, Cover, Latitude)
5.9 Convection/Heat Centres
(Heat output, Extent)

5.9.1 Purpose

The outputs of the convection model are used in conjunction with wind speed and direction to support the simulation of ember lofting and distribution. The resulting ember impacts are used to start spot fires (see Section 6.5: Spot Fires) as well as in asset impact calculations (see Chapter 7: Asset Impact).

5.9.2 Inputs

- Fire perimeter propagation model; and
- Weather.

5.9.3 Basis

PHOENIX has developed a simple, empirically derived representation of convection processes. There were no existing simple models for bushfire plumes that predict their convective strength or their effects on spotting, air quality or destructive potential. The PHOENIX model has made several advances in describing the convective elements of bushfires. Empirical validation of modelled convective centres, based on observed physical damage to trees and buildings, shows a good match between predicted location and extent and those observed in real bushfires.

5.9.4 Assumptions and limitations

The convection heat centres model assumes that convection columns will form over the hottest 25% of a fire perimeter.

Whilst the PHOENIX convection model shows promising results it is important to recognise its underlying functions are based on a simplified atmospheric boundary layer conditions and are fitted to events of a single day.

5.9.5 User interactions

None.

5.9.6 Description

With any fire, columns of convecting gases develop as a result of the heat being released. As fires become larger and more intense, these convection columns become substantial, reaching high into the atmosphere and affecting surface wind fields (Potter 2012).

The computation of fire-atmosphere interactions in fire models requires substantial processing due to the need to consider the interactions and feedbacks between fire, the landscape and the atmosphere in three dimensions (Coen *et al.* 2013). Currently, WRF-Fire and Access-FIRE have been developed to capture the full fluid dynamic effects of a coupled fire-atmosphere system, but the computational overheads of these models restrict their use to research (Chong *et al.* 2012bd). At the time of PHOENIX development, there were no simple models for bushfire plumes that predict their convective strength or their effects on spotting, air quality or destructive potential. Therefore, one was developed as part of PHOENIX. To keep processing times to within operational requirements, PHOENIX uses a simple, empirically derived representation of convection processes, and has made several advances in describing the convective elements of bushfires. In PHOENIX development, efforts to date have focused on identifying surface level, dominant heat centres (convective centres)

and using them as a predictor of plume locations and strength for ember dispersal. The algorithm performs a surface level aggregation of fire perimeter segments (heat centres) where they are deemed close enough to interact and act as one.

The model developed has been used to provide more realistic results in the PHOENIX ember dispersal and house loss probability model (Chong *et al.* 2012d). For details on the validation of this model, refer to *PHOENIX RapidFire 4.0's Convection Plume Model* (Chong *et al.* 2012d) University of Melbourne and Bushfire CRC technical report.

5.9.6.1 *Heat segments*

The first step in identifying potential convection columns or plumes is to locate relatively hot parts of a fire's perimeter (heat segments). This has been defined as the perimeter segments having an average intensity value in the top 25% of perimeter intensity values.

A PHOENIX fire perimeter consists of a series of ordered vertices, forming a polygon. A vertex intensity value for the identification of a heat segment is its average value for the preceding time step. Input and output data for PHOENIX are stored in the Fire Grid, the size of which is specified by the user. A vertex may traverse multiple grid cells, each resulting in a different rate of spread and resulting intensity value.

A heat segment's intensity value is smoothed out using a running average over 10 perimeter points or 10% of the total perimeter points, whichever is smaller. The heat segment begins when the intensity of the cell exceeds the 25% threshold and ends where a cell drops below this threshold.
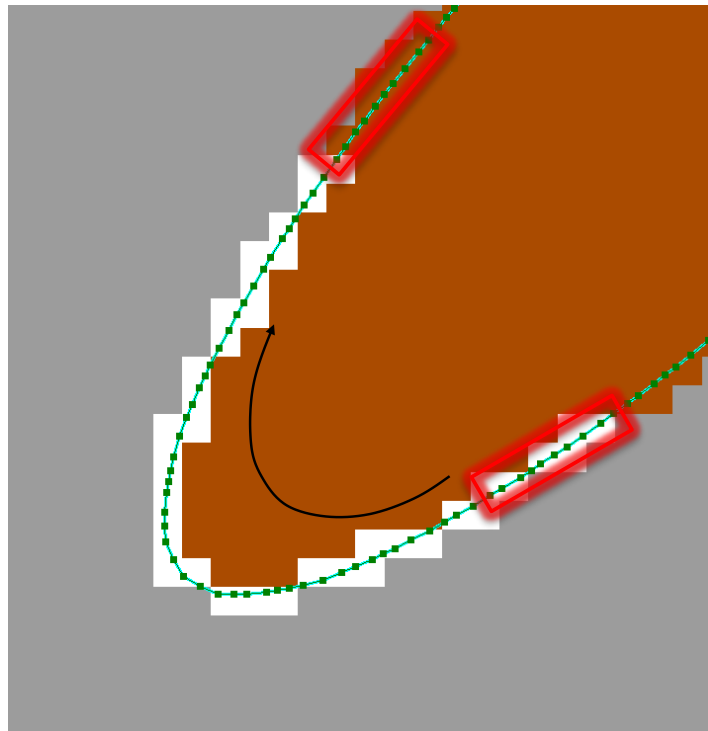
Figure 23. The fire perimeter is shown in green with dots representing vertices, white pixels indicate a section that has been identified as being in the top 25% of perimeter intensities. The running 10-point average in red is shown traversing the perimeter, entering and exiting the 25% threshold value.

Multiple ignitions, topography, varying fuel types and load and variable weather can generate complex fire perimeters, and these often generate more than one active convection column.

Figure 24. Early stages of the Bunyip Ridge fire on 7 Feb 2009 showing two distinct convective centres. Photo by Lex Wade.

The PHOENIX convection model allows for multiple distinct heat segments to be identified within a fire to reflect the multiple active fire fronts that can exist within a bushfire.
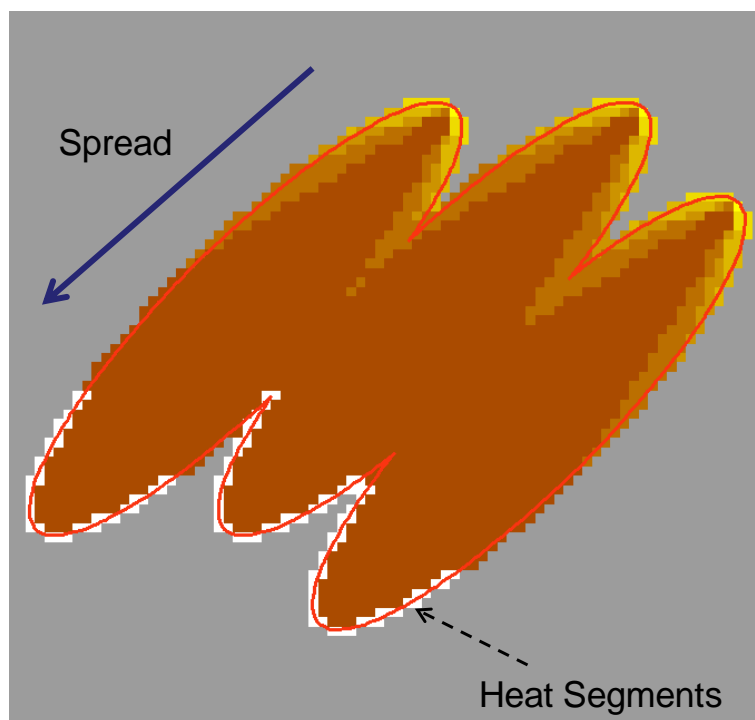

Figure 25. Results from three separate ignitions that have merged resulting in a complex perimeter shape with multiple active fronts, behaviour which regularly occurs in large bushfires where spotting and highly variable topography or fuel is prevalent.

5.9.6.2 Column merging

Heat segments individually do not necessarily reflect the size and strength of a fire's dominant convection columns. For a single regularly shaped elliptical fire this is expected to be the case, however regularly shaped fire perimeters are the exception rather than the rule in naturally occurring bushfires. A large fast-moving bushfire can have multiple active fronts and spot fires each with their own associated convection column. In these cases, any convection columns forming are likely to be an aggregate of multiple local heat sources merged to produce a locally dominant column. The PHOENIX convection model attempts to reproduce this phenomenon by aggregating heat segments where they are deemed to be close enough to interact.
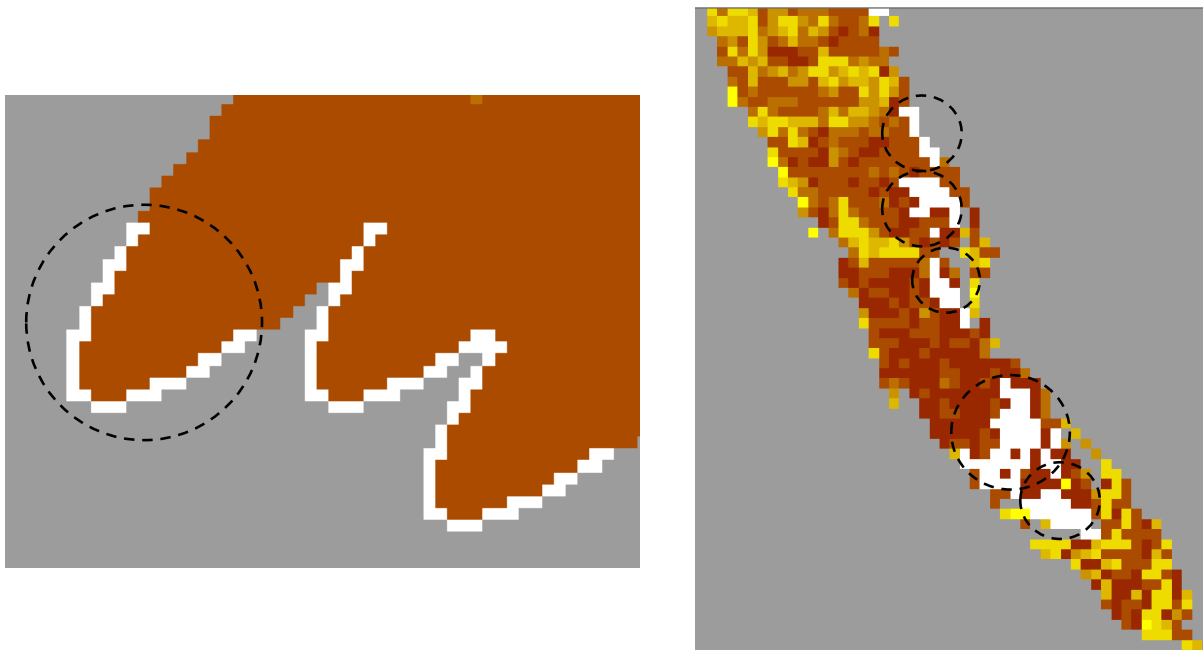

Figure 26. The image on the left shows heat segments identified after three regularly shaped elliptical fires have merged compared to the image on the right that shows heat segments identified in a fire modelled in a natural landscape with has resulted in significant spot fires. Note the irregular shape and spatial distribution of the heat segments in the right-hand image.

PHOENIX utilises a recursive merging algorithm that aggregates heat segments where they are deemed to interact. Each heat segment is first identified as a potential convection column whose heat output is that of the perimeter vertices it contains. Vertex point intensity (kW/m) is converted to total heat output in kilowatts (kW) by averaging the values between two vertices and multiplying by their distance apart. Column convective output is expressed in megawatts (MW).

A column's 'centre of gravity' is calculated using vertex locations weighted by their intensity. A minimum bounding box is determined for the heat segment. The single segment column's area of influence is expressed as its effective radius ($Column_{er}$) which is set as a function of its minimum binding boxes dimensions (E). This radius is inclusive of the area of convective indraught effect outside of the burning area which is assumed to be an additional 10% of the burning area radius.

$$Column_{er} = 1.1 \times \frac{E_h + E_w}{2}$$

Single heat segment columns are then sorted in descending order based on convective output. Starting with the strongest, each is tested against lesser columns and merged if within their effective radius.

When a heat segment is merged into a column, a new minimum bounding box is recalculated based on the vertices of the new heat segment, the additional heat output is added, and the column's location or centroid is adjusted to reflect the new heat source.

The merging process is recursive and continues until all merging is complete.

Figure 27. Series of images showing the development of three fires in a flat, homogenous landscape. Circles show estimated position of convection columns as they merge (darker circles indicate greater convective output). Columns are initially independent but as fires get progressively closer, they merge to form a single column.

All heat segments, including those from separate fires (spot fires or multiple ignitions), are processed in the same recursive algorithm to capture the heat distribution in the landscape (Figure 28).
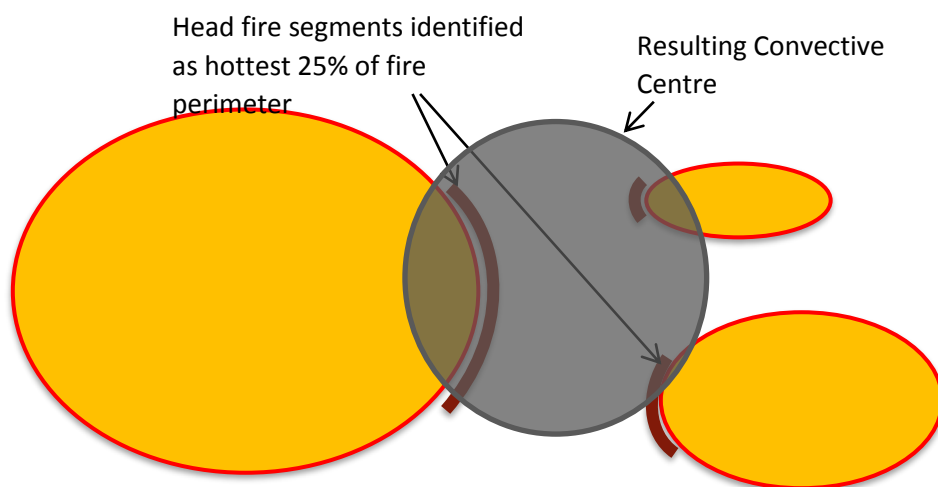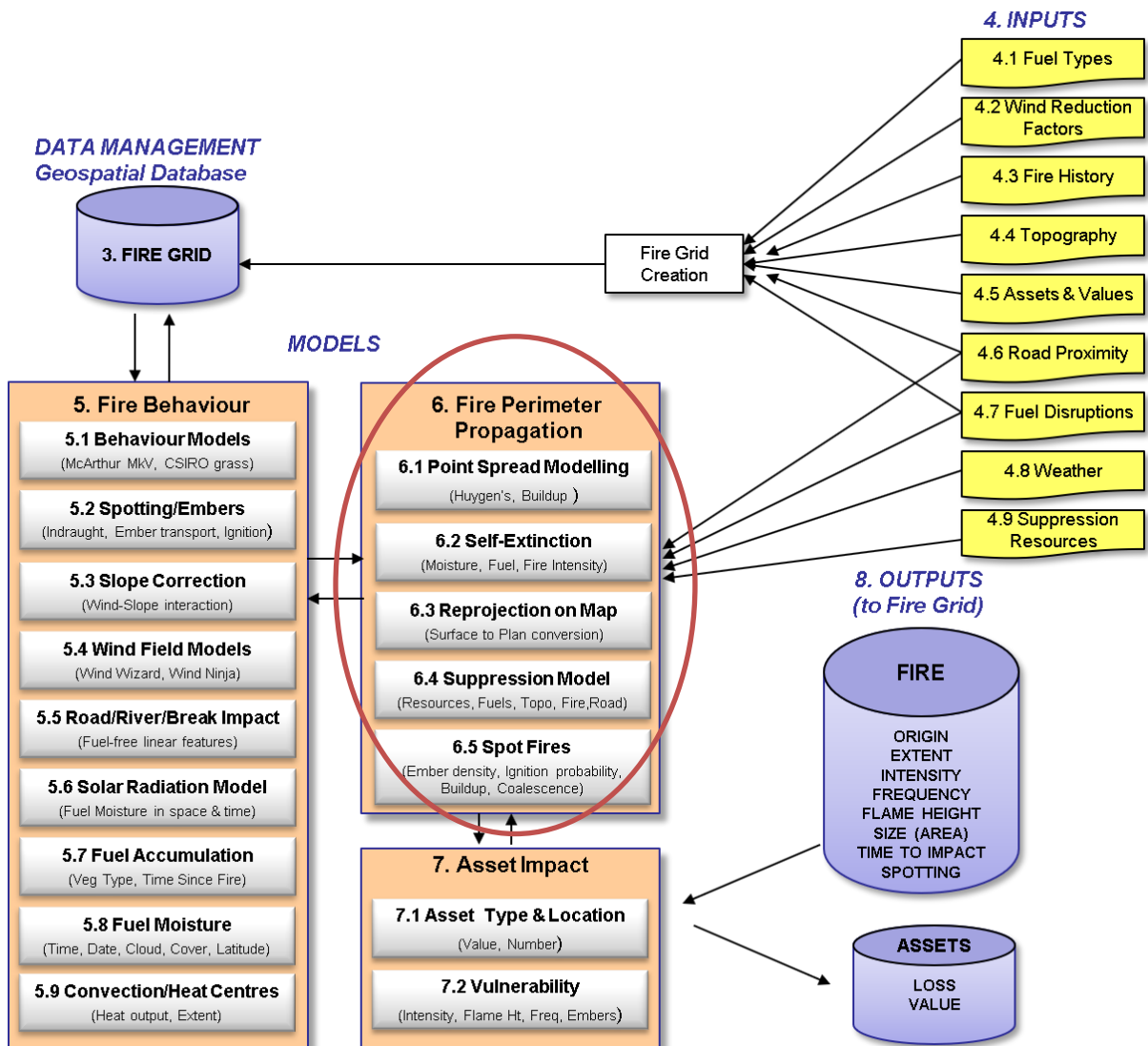

Figure 28. Diagram showing how the recursive merging algorithm processes heat segments from separate fires.
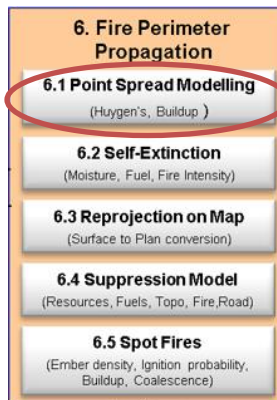
6 FIRE PERIMETER PROPAGATION

This chapter addresses models that deal with the spread of the fire perimeter. This includes perimeter expansion, spot fire generation and how fire spread is ameliorated through suppression efforts.

6.1 POINT SPREAD MODELING

6.1.1 Purpose
This model simulates the movement of the active fire perimeter.

6.1.2 Inputs
- Ignition point and time specified by the user;
- Fuel types;
- Fire history;
- Fuel Accumulation;
- Weather;
- Wind reduction factors;
- Wind field model;
- Slope correction;
- Fuel moisture;
- Solar radiation model;
- Road / River / Breaks;
- Self-extinction;
- Reprojection;
- Behaviour models; and
- Topography.

6.1.3 Basis
Each point on the perimeter is dealt with individually using Huygens's wavelet principle as solved by Andersen (Andersen *et al.* 1982). This mathematical solution to Huygen's principle was implemented in SiroFire (Coleman and Sullivan 1996). The implementation in SiroFire was used in PHOENIX with permission from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The model has similarity in structure to the operational models FARSITE (Finney 2004) and Prometheus (Tymstra *et al.* 2010), although it differs in the mathematical solution used.

6.1.4 Assumptions and limitations
There is no perfect solution for point-based fire spread in all circumstances; however, the Anderson solution has fewer artefacts ('tangles').

It is assumed that areas within the perimeter of a fire cannot burn more than once each simulation.

6.1.5 User interactions
The user must specify ignition location and time.

PHOENIX has a tool that can be used to automatically create a uniform ignition grid for doing scenario testing or risk analysis. This ignition grid can be created within the extent of a specified Shapefile, or within an area defined by coordinates and grid spacing.

6.1.6 Description
A fire simulation is started by igniting a fire at a particular place and time. Where point or line ignitions are specified, they are converted to polygons of nominal area. Perimeters are treated as vector (closed) polygons and are simulated to move through a landscape consisting of data at the simulation resolution. As with other Huygen's based models, fires are modelled as perimeters spreading in discrete time steps. At each time step, the locations of all points on the fire perimeter

are used to sample the underlying data grids, and weather is sourced for each point. Gridded weather is sampled for each perimeter point using a spatial intersection with the NetCDF weather grid with temporal interpolation used to select the weather for corresponding points in simulation time. Where a non-spatial weather stream is used, the same weather is applied to each vertex, albeit with locally specific wind modifiers computed.

Spread from each vertex is processed with the appropriate fire spread function (see Section 5.1: Behaviour Models) and contributing input vectors (e.g. wind speed, wind direction, slope) to determine point spread ellipses (Anderson *et al.* 1982). These are used to derive subsequent perimeter position for the initialisation of the next time step. If necessary, new vertices are added between existing perimeter points to ensure that the minimum resolution is equal to the simulation grid (Fire Grid) resolution. In PHOENIX, the dynamic time steps are defined by the time for the fastest spreading part of the fire to travel a specified distance, similar to that in Prometheus (Tymstra *et al.* 2010). This spread distance is a function of the Fire Grid size. The maximum duration of a time step is fixed, and is nominally 5 minutes.
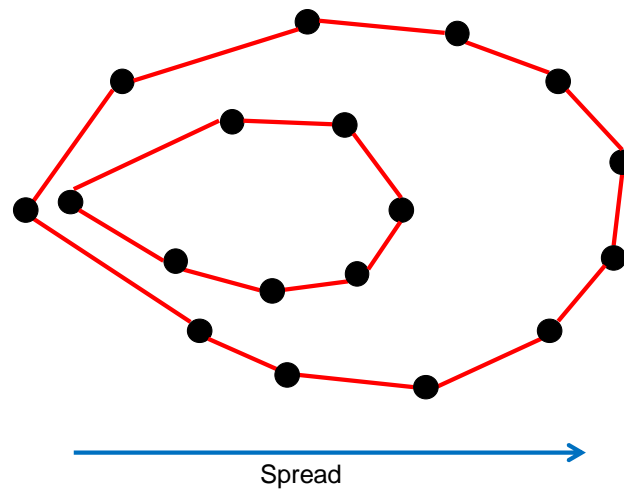
Spread

Figure 29. Perimeters are represented by a set of clockwise ordered points which are incrementally expanded based on a specified time step.

Cells can contain a mix of woody fuels, grassy fuels and, bare areas and the resulting spread rate is assumed to be the area-weighted average of all three.
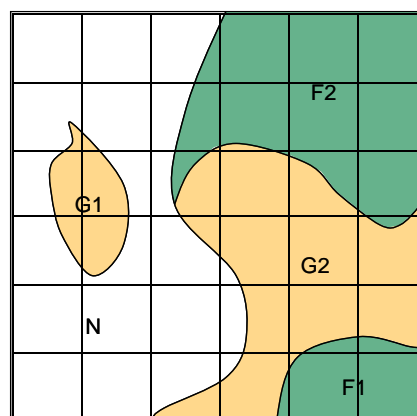
Key: F – Woody Fuel, G – Grassy Fuel, N – No Fuel

Figure 30. As cell size increases fuel types within a cell can become highly variable. An area-weighted average value for rate of spread will ensure some of this variability is captured compared to a centroid sampling approach.

Take for example a 180 m resolution Fire Grid cell (32,400 m²) that has a fine fuel load of 20 t/ha covering 15,300 m² and a grass load of 4 t/ha covering 9,900 m² with the remainder (7,200 m²) bare ground.

Woody fuel rate of spread @ 20 t/ha= 5 km/h

Grassy fuel rate of spread @ 4t/ha= 12 km/h

$$Average\ ROS = \frac{5 * 15300 + 12 * 9900 + 0 * 7200}{32400} = 6.03\ \text{km/h}$$

PHOENIX also incorporates a unique 'crawling' process to process perimeter changes between time steps. Between time steps, the movement vector of a perimeter point is recalculated each time it enters a new input grid cell. At the end of a time step, the position which results from the additive spread vectors through all cells crossed is reported. This process ensures that all fuel cells impacted by fire are processed and avoids the issue of rapidly spreading perimeters 'skipping over' cells that have extremely high or low fuel levels. In addition, computational efficiency is retained as points with slow spread rates are only calculated once each time step, and rapidly moving points are calculated more frequently. This reduces the number of calculations required for slow-moving parts of the fire without reducing overall simulation resolution, maximising computational efficiency. Fires spread as perimeters. Areas within the perimeter of the fire cannot burn more than once each simulation.
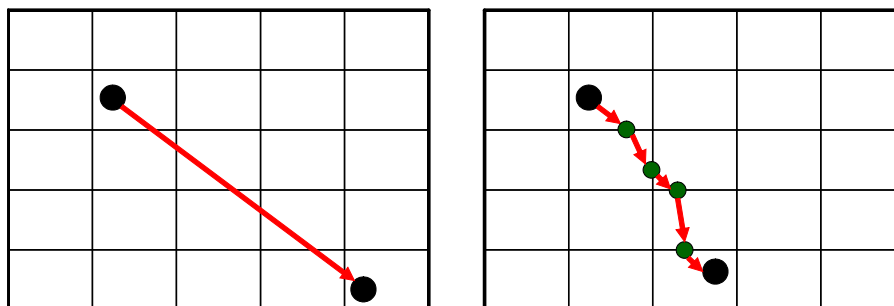

Figure 31. Unconstrained point spread on the left versus the 'grid crawling' approach on the right for a single time step. In the unconstrained approach, the resulting point has jumped over five cells based on the resulting distance and direction calculated at its original position, failing to capture the effects of five underlying cells. With the grid crawling approach spread rate and direction are recalculated at the intersected cell's boundary, indicated by the green dots. This ensures any changes in fuel types, loads, condition and topography are captured.

Small fires undergo a build-up phase until they reach a particular size where a steady-state rate of spread is achieved (McAlpine and Wakimoto 1991; Finney and McAllister 2011). PHOENIX incorporates this by assessing the conditions shortly after ignition and calculating the time required for an elliptical fire to reach a width of 100 m. This value was used as grassfires have reached equilibrium spread rates under most wind conditions by the time the headfire is 100 m wide (Cheney and Gould 1995). While PHOENIX can simulate multiple fires with a single run, surface (perimeter) spread is based entirely on Hugyen's system, and there are no dynamic interactions of surface fire perimeters (e.g. junction zones, Morvan *et al.* 2011). Where separate fires meet, they merge into a single fire and are subsequently treated as a single perimeter polygon. While there are no interactions in surface spread, the grid-based approach in the ember module allows the recognition of convective interactions between fires (see Section 5.9: Convection / Heat Centres). This affects ember transport and ignition. Multiple ignitions can be modelled in a single simulation, although for

processing efficiency where fires are far enough apart to be considered spatially independent, they should be modelled separately.

6.1.6.1 Perimeter expansion

Fire spread calculations start from the most windward point (the back of the fire) and progress clockwise until the perimeter is complete. Each vertex is initially treated as an ignition point with a resultant ellipse determined based on a head-fire rate of spread and time step incorporating any slope that may affect the ellipse orientation. Based on the neighbouring points three vectors are calculated to determine which section of the ellipse will best represent the resultant perimeter segment. Vp is the vector from the previous perimeter point to the current point, Vn is the vector from the current point to the next point and Vr is the resultant vector of Vp + Vn.
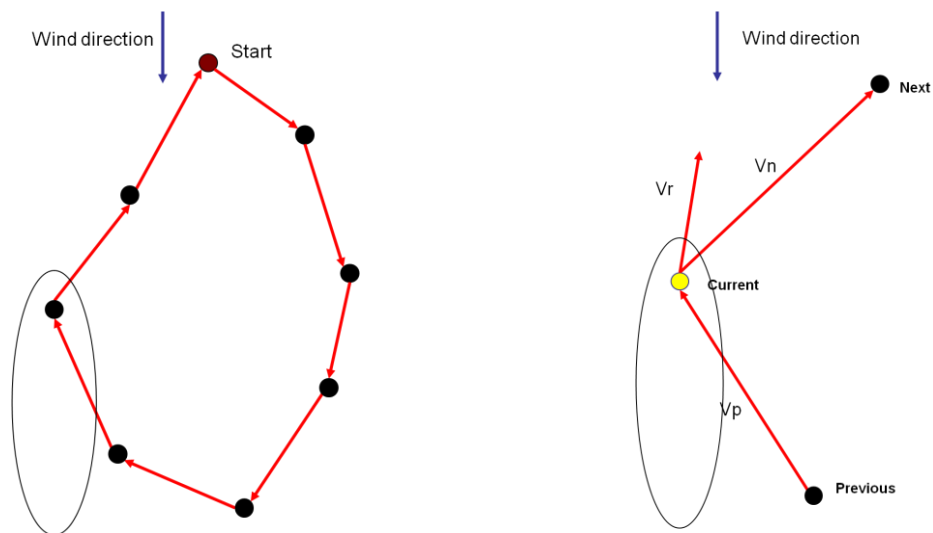
Figure 32. The image on the left shows the resultant ellipse for a perimeter point. On the right are the three vectors which will be used to determine which section of the ellipse will best represent the resulting perimeter segment.

The vectors Vp, Vn and Vr are then transposed as touch tangents on to the outside surface of the ellipse with the points at which they touch (Pp, Pr and Pn) being the resulting points on the new perimeter.
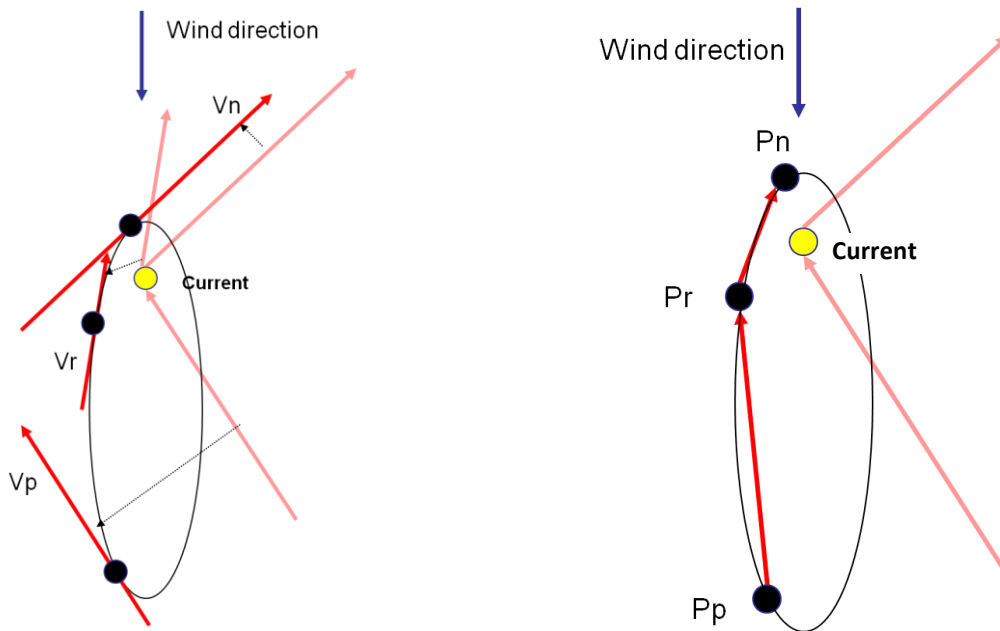
Figure 33. The image on the left showing vectors Vp, Vr and Vn being transposed on the outside of the point ellipse. On the right are the resulting new perimeter points Pp, Pr and Pn which are added as ordered points to the new perimeter.

Three points are created when the perimeter shape at the 'current' point is extremely convex as shown in the example above. When the perimeter shape at the 'current' point is relatively straight only the point at resultant vector (Vr) is used. In convex or concave situations, the two points resulting from Vp and Vn are used.

In concave situations, the resulting points Pp and Pn will often cross over (a 'tangle') resulting in a rotation. This rotation is removed in a later process and the two points are replaced by a single point where the crossing vectors intersect. The parallel vector Vr is not required as it would be eliminated when the rotation is resolved.

6.1.6.2   Perimeter vertex rate of spread

Generally, the term 'rate of spread' refers to the head-fire rate of spread; however, when modelling a perimeter, the rate of spread will generally vary significantly. To determine the rate of spread of each vertex its distance travelled is divided by the time step.

Figure 34. For the resulting perimeter point Pr, its rate of spread Rp the distance covered from the 'current' point divided the time step.

All subsequent fire characteristics are calculated from this rate of spread including intensity, flame height, depth, convection, etc.

6.2 SELF-EXTINCTION

6.2.1 Purpose
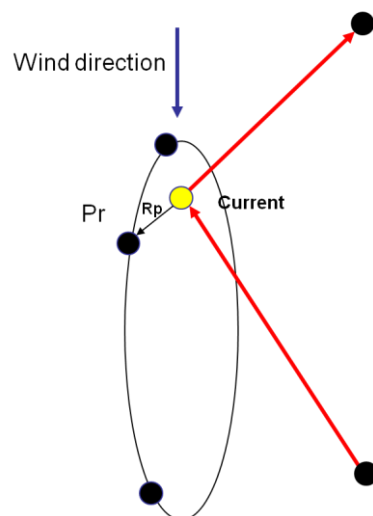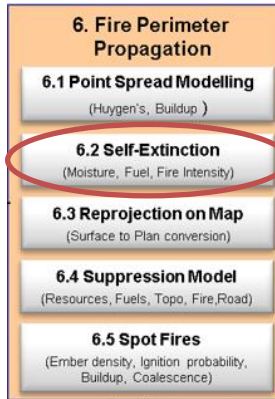A self-extinction process is incorporated into PHOENIX, in which parts of the perimeter are predicted to extinguish if heat output is less than a threshold, which in PHOENIX is nominally set at 120 kW/m.

6.2.2 Inputs
- Fire perimeter propagation.

6.2.3 Basis
It is acknowledged that the real fireline intensity that will result in extinction is closer to 40 kW/m, but it was found that this level for extinction resulted in too many active parts of a fire edge compared with what is observed. Therefore a fire intensity that was consistent with a surface fine fuel moisture content of about 18% was used and this was found to correspond to a fireline intensity of about 120 kW/m.

6.2.4 Assumptions and limitations
The threshold is set at 120 kW/m.

6.2.5 User interactions
The self-extinction threshold is coded into PHOENIX and cannot be altered by the user.

6.2.6 Description
When a perimeter point is moved to its new position, the resulting distance travelled is used to calculate the rate of spread in the direction the point travelled. This rate of spread value is used to calculate the intensity value used in the self-extinction function. Extinct cells cannot reignite. If the fire does not self-extinguish, it will continue to burn until the end of the specified simulation period.

6.3 REPROJECTION ON MAP

6.3.1 Purpose

6.3.2 During the perimeter modelling process, a surface-to-plan conversion of point spread is carried out to accurately capture the fire perimeter in three-dimensional space.

6.3.3 Inputs
- Topography (DEM).

6.3.4 Basis
The Cosine of the slope in the direction of fire travel is calculated and used to convert the distance a perimeter point travelled along the surface to the plan-view distance.

6.3.5 Assumptions and limitations
Uses basic geometric principles.

6.3.6 User interactions
None.

6.3.7 Description
Figure 35 illustrates the process of converting from the plan view representation of the perimeter on the Fire Grid, to a three-dimensional representation.
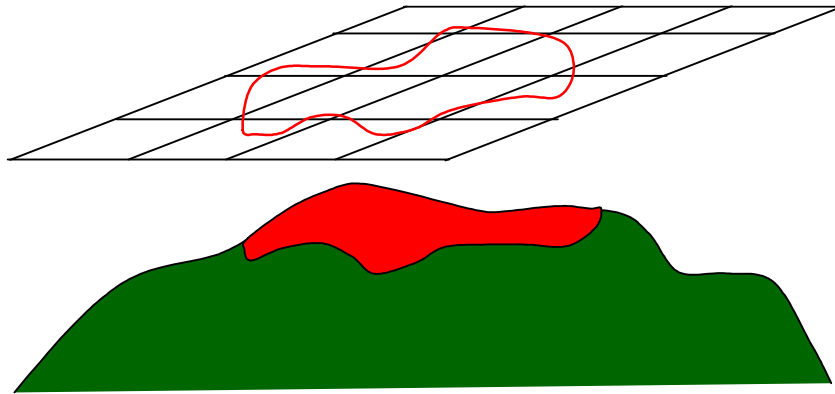
Figure 35. The Fire Grid and resulting fire perimeters are plan view representations, whereas fire spreads on the surface of a three-dimensional landscape. Therefore, a conversion is required.

6.4 SUPPRESSION MODEL

6.4.1 Purpose
The suppression model modulates fire spread based on suppression resources provided by the user.

6.4.2 Inputs
- Suppression resources;
- Topography;
- Point spread model;
- Fuel types;
- Weather;
- Disruptions; and
- Road proximity.

6.4.3 Basis
Suppression operations are simulated using an agent-based approach (Hu and Sun 2007) where agents construct an impermeable line around the fire (Smith 1986).

Construction rate limiting factors have been identified for each of the suppression methods (McCarthy *et al.* 2003) including: fire intensity, terrain, fuel density and in the case of aircraft, turnaround time. In contrast to limiting factors, some elements, such as road proximity, augment construction rates. This is based on field observations at real fires.

6.4.4 Assumptions and limitations
All of the resources are performing at their potential, so their suppression rates are added together.

Suppression rates are a sustained rate of production over at least an eight-hour work period. In reality, the rate would be greater earlier in the fire and lesser later in the fire.

Suppression starts at the first live fire perimeter vertex or point from the most windward (back) point of the fire, with the assumption that the back of the fire is the least intense and therefore most easily suppressed.

While going through a dead fire edge, there is no travel time or suppression effort consumed.

6.4.5   User interactions
Specifying the type and number of suppression resources and the time for them to start suppression work after ignition and the duration of their work in the suppression input data (see Section 4.9: Suppression Resources).

6.4.6   Description
Active agents simulate suppression by constructing a fireline beginning from the rear of the fire (as determined by the most windward point) and progressing forward along each flank, skipping over any previously extinguished points. The weighting of effort between flanks must be pre-specified in the project XML file. In South Eastern Australia, a weighting of 80% sinistral is typically used to account for expected wind changes (Huang and Mills 2006). The weighting of effort between flanks is continuous – hence the suppression approach is not a pure agent approach as suppression units are divisible between flanks.

Suppression rates are determined by evaluating the conditions under which each segment of the perimeter is being suppressed at each time step. The rates for each resource type are considered separately, multiplied by the resource quantity to determine resource-specific rates. The overall line construction rate is the sum of all resource type rates. Fireline construction rates for a resource type are determined by applying the piecewise linear functions specified in the suppression XML file. Examples of attributes that may affect line construction rates include fuel load, level of daylight, slope, proximity to roads and estimated flame cross-sectional area (Albini *et al.* 1978). Such attributes can add or decrease resource line construction rates (this was discussed in Section 4.9: Suppression Resources). If a suppression rate is calculated to be zero (which may result from extreme simulated fire behaviour), no suppression will occur in that cell.

Suppression is modelled between perimeter spread time steps. For each time step, available suppression agents are determined. The aggregate suppression rate for all active resources is calculated at each perimeter vertex and if suppressible, the fireline is 'built' along the perimeter to the next vertex at that rate. Line construction continues for a period which equates to the perimeter time step length. If a Fire Grid cell boundary occurs before the next point, the suppression rate is recalculated at the boundary. Once part of the fire is considered suppressed, all fire activity is assumed to cease and the fire will not re-ignite at that point.

If a fire perimeter vertex is found to have an intensity or other limiting factors too great to achieve any effective suppression, PHOENIX uses a 'look ahead' function to see if this is just a local aberration. If the local aberration is less than one grid cell ahead, then the suppression effort will 'jump ahead' and continue suppressing the fire perimeter with the aberrant vertices extinguished anyway. If the 'look ahead' indicates that the conditions are not conducive to effective suppression, the suppression progress around the perimeter will stall until conditions become controllable again.

Direct (fire suppression at the edge of the fire) and parallel (construction of fire line a short distance from the fire perimeter) attack are not simulated separately (National Wildfire Coordinating Group 1996). Differences in line construction rates of resulting from these methods can be considered when defining agent properties (see Section 4.9: Suppression Resources); the resolutions of PHOENIX simulations are typically not precise enough to discriminate between the two when creating maps. Indirect suppression methods, such as backburning, and strategic suppression of multiple fires are currently not supported.

6.5 SPOT FIRES

6.5.1 Purpose
Starts new fires outside of the fire perimeter where burning embers land in suitably flammable fuels. These fires are called 'spot fires' as opposed to the production and transport of the burning embers which is called 'spotting' (see 5.2: Spotting / Embers).

6.5.2 Inputs
- Spotting/embers;
- Fuel type;
- Fire history; and
- Fuel moisture content.

6.5.3 Basis
Spot fire ignition is a function of the cumulative number of embers to enter a cell and the ignition probability (based on fuel type, fuel load and fuel moisture content). When ignition occurs, a new fire polygon will be created at the cell centroid. This is then spread using the same functions as the primary simulation run fire. As with the initial fire, any new ignitions have a build-up phase. Where multiple fires intersect, they will join and become a single fire.

6.5.4 Assumptions and limitations
A separate fire grid is used for the spotting process. It is fixed at 200 x 200 m cell size, regardless of what the user specifies for the general fire simulation grid size. This has been done to maintain a consistent probability of spot fire generation, for a given set of fuel and weather conditions, regardless of the simulation cell size.

Grass fuels have increased flammability due to a high surface area to volume ratio and low bulk density (Hogenbirk and Sarrazin-Delay 1995), so for the determination of ignition potential, the effective fuel load of grass fuels is increased by a factor of four.

Only embers far enough downwind from a fire front (200 m) are processed, those closer are assumed to be subsumed by the main fire and their effect on rate of spread already captured in the surface fire spread rates.

6.5.5 User interactions
None directly, but the user could alter the bark hazard levels in the fuel type definitions to increase or decrease the number of embers being produced. This should only be considered if there is strong evidence to alter the fuel type definitions to better represent the true bark hazard levels.

6.5.6 Description

6.5.6.1 Spot fire ignition grid
Starting a spot fire on every cell that exceeds a spot fire count of one is problematic as the Fire Grid cell resolution can be varied by the user. Halving the resolution will result in up to four times the number of spot fire ignitions which can drastically affect the result. To allow grid cell resolution to change whilst maintaining a consistent spot fire ignition resolution, a 200 m spot fire ignition grid is used to control the density and locating of the resulting ignitions.

When a cell impact is logged, any intersecting ignition grid cells are identified. An area-weighted spot fire density is calculated for each of these ignition grid cells by summing the spot fire densities for each intersected fire cell. If a cell is partially intersected only the intersected area is used. When the resulting spot fire density is greater than or equal to one, the ignition grid cell is flagged as ignited and a spot fire added to the landscape at its centroid.

6.5.6.2 Spot fire ignition threshold
Fuel load is treated as a proxy for the proportion of the fuel bed which has suitable fuel for ember ignition. Grass fuels have increased flammability due to a high surface area to volume ratio and low bulk density (Hogenbirk and Sarrazin-Delay 1995), so for the determination of ignition potential, the effective fuel load of grass fuels is increased by a factor of four. Where more than one fuel type exists in a cell, the cell properties are area-weighted by fuel type.

Fuel moisture content (FMC) is an important factor in the ignition potential of fuel (Ganteaume *et al.* 2009). McArthur's equations are calibrated for predicting the equilibrium spread rates of 'going' fires; to determine ember ignition potential, forest fuel moisture is estimated using a recently developed formula that directly estimates fine fuel moisture by considering weather inputs and calculated solar radiation (Matthews 2006). Grass fuel moisture is estimated with a grass specific function (Dimitrakopoulos *et al.* 2010). The ignition of a cell is based on a dynamic threshold incorporating fuel load, fuel moisture and cumulative ember load. Parameters to define the ignition terms have been obtained through iterative adjustment guided by expert opinion.

The FMC ignition probability function is based on a model for line-fire ignitions in Mediterranean grass fuels (Dimitrakopoulos, Mitsopoulos *et al.* 2010), modified based on the assumption that ember ignitions and forest fuels having a lower surface area to volume ratio will be harder to ignite.

$$Ignition\ Probabilty_F = 0.9 \div \left(1 + e^{-(4.5 - 0.5 \times fmc)}\right)$$

Dead fuel moisture content for grass is determined using the fuel moisture function from the CSIRO grassland fire spread meter (Cheney, Gould *et al.* 1998, Cruz *et al.* 2015b). The grass FMC ignition probability is the product of a grass FMC ignition probability function and the grass curing coefficient, used to describe the percentage of cured grass. The grass FMC ignition probability function is similarly based on (Dimitrakopoulos, Mitsopoulos *et al.* 2010) and modified assuming ember based ignitions will be more difficult than direct flame from a drip torch.

$$Curing_{coeff} = 1.12 \div (1 + 59.2 \times e^{(-0.124 \times Curing - 50)})$$

$$Igniton\ Probability_{fmc} = 1 \div (1 + e^{-(6 - 0.263 \times fmc)})$$

$$Ignition\ Probability_G = Curing_{coeff} \times Igniton\ Probability_{fmc}$$

The effect of varying fuel loads in t/ha is captured by the following function, with grass loads supplied as a factor of four.

$$Ignition\ Probability_{FL} = 1 \div (1 + 350 \times e^{-0.55 \times Load})$$

7 ASSET IMPACT
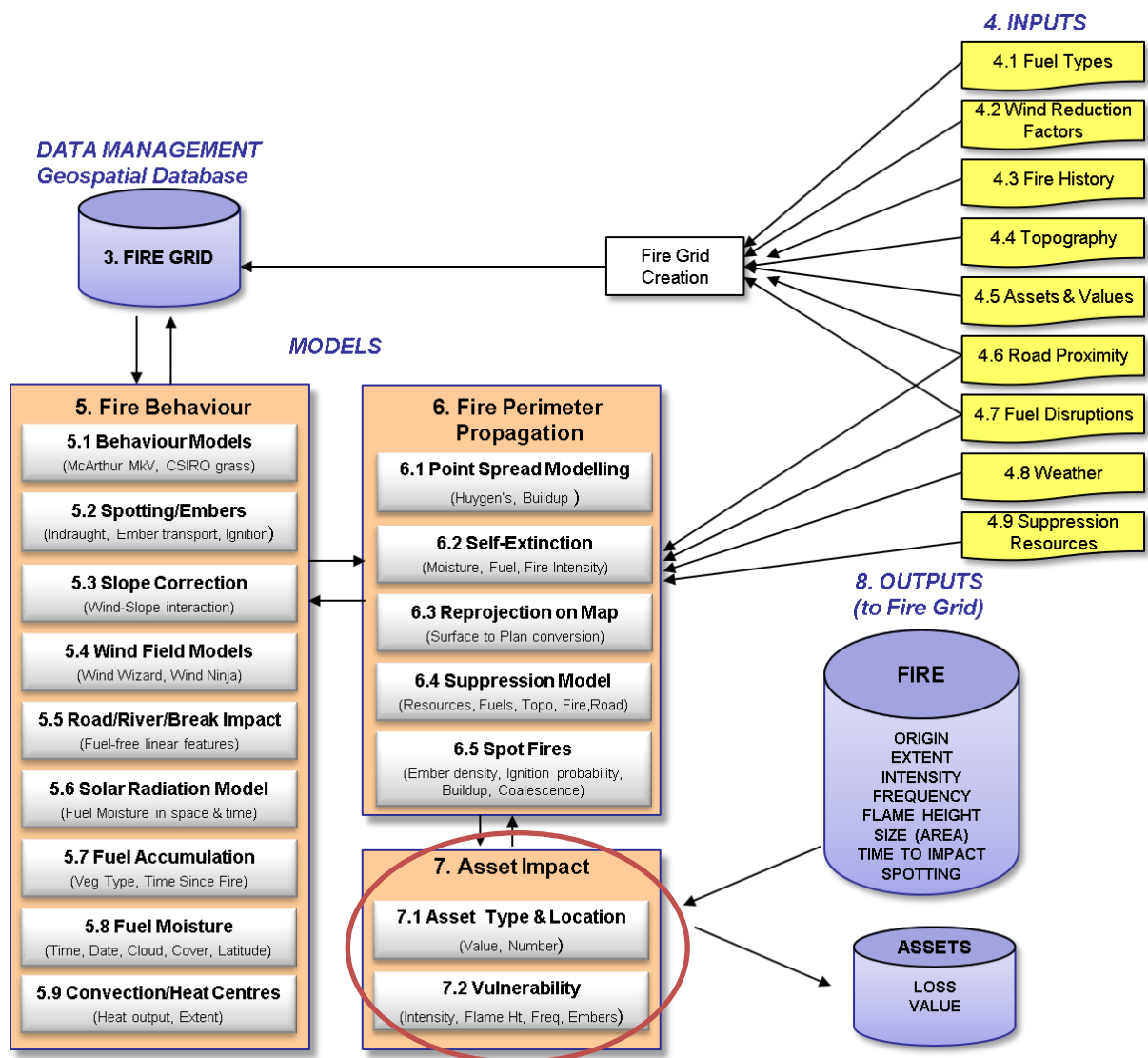
7.1 PURPOSE

PHOENIX provides for the intersection of fire attributes with maps of assets to allow estimates of fire damage. Characterising fires by asset impact provides an additional means of comparing fire management options.

7.2 INPUTS

- Asset layer;
- Fuel type;
- Fire history;
- Spotting/embers;
- Terrain (DEM); and
- Weather.

7.3 BASIS

Damage to assets is determined with the use of loss functions where outputs from the fire behaviour model (e.g. ember density, flame height and maximum intensity) are used as predictors. Impact is based on the interaction of the fire characteristics and the vulnerability of the asset to fire, such as fire intensity or ember density.

7.4 ASSUMPTIONS AND LIMITATIONS

Impacts can be calculated for up to 99 asset types and evaluated against up to 99 loss functions.

7.5 USER INTERACTIONS

None, other than preparing the asset and values layer (see Section 4.5: Assets and Values).

7.6 DESCRIPTION

Characterising fires by asset impact can be useful for prioritising fires in a tactical scenario or strategically for quantifying the effectiveness of a specific treatment. Asset impact can be a more meaningful measure than traditional characteristics like fire area, average intensity, perimeter length, etc.

Against each cell of the input asset layer (e.g. 30 m grid) the user assigns an asset type, asset priority, an impact type and asset value in metres squared. This is described below.

7.6.1 Asset type

One asset type is assigned per cell. The user can define up to 99 asset types and each is assigned an Asset ID. An example is provided in Table 7. Where more than one asset type occurs in an input data cell, a priority for asset types has to be defined so that the asset with the highest priority is stored in the input data raster file.

Only one asset ID can be stored per input data cell (e.g. 25 m or 30 m), but several asset IDs may be combined into a PHOENIX Fire Grid cell (e.g. 180 x 180 m).

Table 7. PHOENIX Asset ID (from Tolhurst et al. 2017)

Asset Id	Description	Priority	Impact Type
1	Housing	1	2
2	Infrastructure	2	5
3	Plantation	3	5
4	Catchment Tributaries	4	4
5	Catchment	5	3
6	Rainforest	6	5

7.6.2 Impact type and loss functions

Asset impacts are computed post-fire by applying the asset-specific impact functions. Asset impacts are recognised as the probability of loss weighted by asset density. Asset impacts can be tallied or used to produce impact maps (Tolhurst *et al.* 2013).

For each asset type, an impact type must be assigned. Some indicative functions have been developed to indicate impacts on the following asset types: housing, infrastructure, plantations, catchments and rainforest (see Table 7). Currently, only five impact types have been defined (Table 8) and can only be edited through the modification of the base PHOENIX code. Users can define

additional impact types and functions (up to 99 impact types). It is expected that these will be derived through empirical relationships. The impact type can be defined as a mathematical function (loss function), as with house loss. Alternatively, it can be defined as some fire characteristic threshold criteria such as an asset being exposed to a fire greater than a specified level of intensity (Table 8).

Table 8. PHOENIX asset impact type

Impact Type	Loss Description
1	Record loss if fire present
2	HouseLossProbability = see below
3	Intensity > 3,000 kW/m
4	Intensity > 10,000 kW/m
5	Intensity > 30, 000 kW/m

The house loss probability function used in PHOENIX is described in Tolhurst and Chong 2011, and is shown below. Users can also choose to use their own house loss function. For example DELWP uses: HouseLossProbability = Loss if Intensity > 10,000 kW/m or Ember Density > 2.5 embers/m2.

$$1 - EXP(0.2894 - 0.000487 * FlameXS - 0.02003 * EmberDensity - 0.0000157 * Convection) /$$
$$(1 + EXP(0.2894 - 0.000487 * FlameXS - 0.02003 * EmberDensity - 0.0000157 * Convection))$$

Where FlameXS is defined as FlameHeight * FlameDepth / 2

7.6.3   Asset value

The user prepares the data layer through geospatial analysis of source layers to derive density values for each cell.

Assets values are expressed as units per square metre; point assets such as houses must be converted by the user to their equivalent density in metres squared. Area-based assets such as catchments are given an asset value of 1, indicating a 1 to 1 relationship with burnt area i.e. 1 unit/m^2.

Asset values are limited to a maximum of 4 digits and 4 decimal places giving an effective range of .0001 to 9999. Care needs to be taken to ensure suitable units are selected for assets to accommodate this limited range.

7.6.4   Asset code description

Because each of the input data layers into PHOENIX are in ASCII format, only one value is possible from the input layer resolution cell (e.g. 30 x 30 m). To enable multiple pieces of information to be stored in a single integer value, a coding system is used (Figure 36). In Table 9, the integer value of 230312340 can be decoded as Asset ID 23, Impact Type 3, Asset Value of 1,234. The PHOENIX Integer Scientific Notation helps to interpret the 'asset value'. For example, when the scientific notation has a value of zero (0) as in this case, then the value is taken as is, i.e. 1,234, whereas for Asset ID 11 the Asset Value is 0.001234 because the scientific notation has a value of minus three (-3) which means x 10^{-3}.
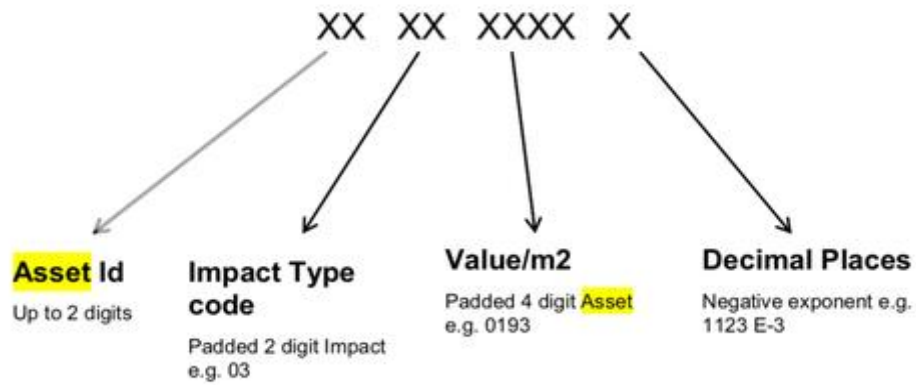
Figure 36. Asset code formulation.

Table 9. Worked examples of the PHOENIX asset code

Asset Id	Impact Type Code	Asset Value	PHOENIX Integer Scientific Notation	Asset Code
23	03	1234	**1234**E+0	230312340
11	02	1.234567	**1234**E-3	110212343
3	17	.0012345	**0012**E-4	_31700124
1	43	50	**0050**E+0	_14300500

8 OUTPUTS
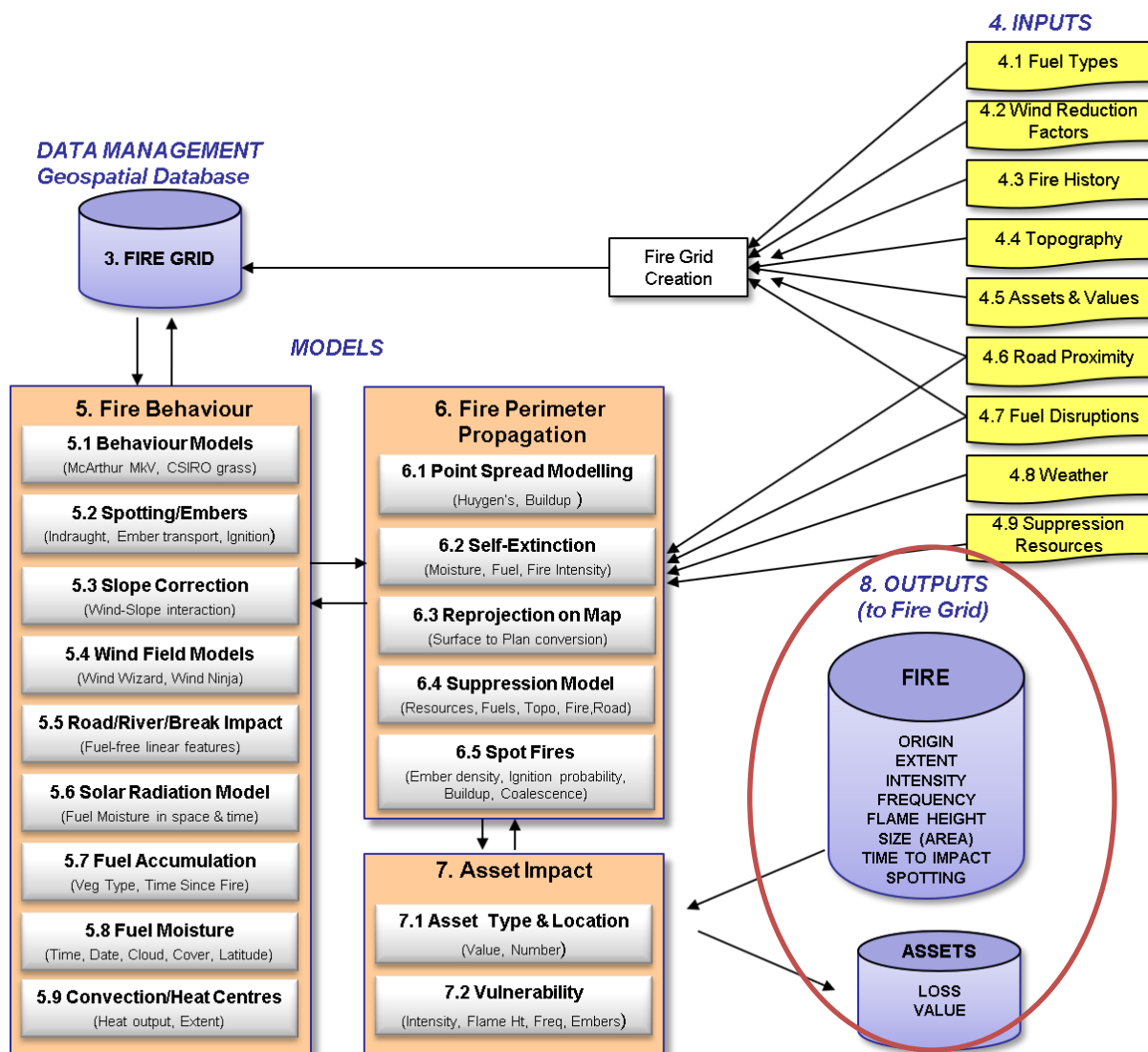
PHOENIX produces a wide range of outputs. Vector perimeter isochrones are a standard output, produced both as ESRI Shapefiles and Google Earth KMZ files. In addition, a wide range of gridded cell values about fire characteristics can be outputted in various formats. A sample is provided in Table 10. These can be presented as means, maximums or ranges for each Fire Grid cell. This information is provided over a range of file formats including:

- Shapefiles containing ignition points and incremental fire perimeter isochrones as well as StaticGrid;
- Image formats (PNG and PGW files) of fire perimeter;
- ASCII text files viewable in text editors and in GIS;
- XML files containing state-wide summary data viewable in MS-Excel or MS-Access; and
- CSV files containing gridded data viewable in MS-Excel or MS-Access.

Table 10. Gridded PHOENIX RapidFire outputs

Attribute	Definition
Time Burnt (hours since the fire started)	Time of first impact
Effective Rate of Spread	Rate of spread perpendicular to the fire perimeter
Effective Intensity (kW/m)	Intensity based on the Effective Rate of Spread
FDI	Fire Danger Index
Spotting Distance (m)	Spotting distance travelled
Spotting Time (hours since the fire started)	Time that spot fire was initiated
Time Suppressed (hours since the fire started)	Time the fire in the cell was suppressed
Suppression Rate (m/h)	Suppression rate
Suppression Efficiency (%)	Suppression efficiency achieved
Went Out (hours since the fire started)	Time the fire in the cell went out

The input variables relating to each grid cell (i.e. fuel load, weather at the time of burning, slope, aspect) are also provided as standard gridded outputs. KMZ files are time-stamped, providing for progression animation within Google Earth. In addition, an animated visualisation of the fire plume is generated in KMZ format, with values derived from the ember convection module. All outputs are spatially referenced and can be displayed in standards software packages. Alternative run modes of PHOENIX produce additional outputs not described here.

Refer to the PHOENIX user guide for more information.

There are five (5) simulation types (Figure 37): General, Batch, Grid Analysis, Batch All Cells and Batch Ascii Grids. There is also a Static Grid mode where every cell is assumed to burn simultaneously, but this does not include aspects of dynamic fire behaviour, such as ember density and convective strength, included in the simulations. The outputs from each simulation type differ.
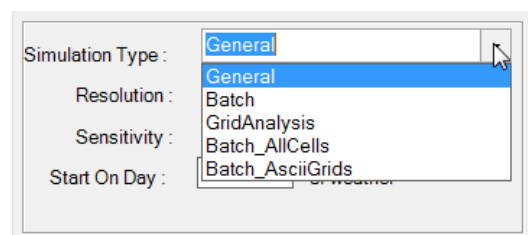
Figure 37. Simulation types

- **General**: run a single fire or multiple fires at the same time
- **Batch**: is designed to run combinations of a set of fires, under a set of fire histories, with a set of fire suppression scenarios and a set of road and firebreak scenarios. These conditions are specified in the '**Advanced**' > '**Batch Parameters**' table.
- **Grid Analysis**: is used to do an asset impact analysis of a single or grid of fires in the landscape. Only cells with an asset impact are saved for further analysis outside PHOENIX and only summary statistics are saved.
- **Batch_All Cells**: is similar to the Grid Analysis process except all cells from all fires are saved in CSV files for further analysis (can be massive amounts of data).

- **Batch_AsciiGrids**: as for Grid Analysis except ASCII grids for flame height and intensity are produced for each fire (can be massive amounts of data).
- **Static Grid**: fire, fuel, weather and terrain characteristics for each cell within a specified area are calculated without including the dynamic aspects of fire behaviour. This mode is similar to a lot of older bushfire risk analyses undertaken with GIS analysis.

Broadly speaking, PHOENIX provides four types of output:

- Perimeter information as isochrones (isochrones are representations of the fire perimeter at a specified time);
- Grid cell values (provided in various file formats) recorded against the Fire Grid for a single fire event ('General' and 'Batch' simulation types);
- Grid cell values recorded against the Fire Grid resulting from a grid of ignition points; and
- 'Fire Impact' values recorded against each unique ignition point and time.

General simulation outputs for each Fire Grid cell are:

- Cell ID;
- Slope (degrees);
- Elevation (m);
- Aspect (degrees);
- Grassland equivalent fuel load (t/ha);
- Combined equivalent surface fine fuel load (t/ha);
- Equivalent bark fine fuel load (t/ha);
- Equivalent elevated fine fuel load (t/ha);
- Total equivalent fine fuel load (t/ha);
- Road Proximity (m);
- Effective disruption width (m);
- Time burnt relative to ignition time (hrs);
- Fire rate of spread (m/h);
- Fireline intensity (kW/m);
- Time when spotting occurred in cell relative to ignition time (hrs);
- Maximum potential distance of spotting from cell (m);
- Ember density ($\#/m^2$);
- Time from ignition before fire was suppressed in this cell (hrs);
- Time fire self-extinguished in this cell relative to ignition time (hrs);
- Average flame length in cell (m);
- Average flame depth in cell (m);
- Maximum convective strength in cell (MW);
- Fine Fuel Moisture Content (% ODW);
- Drought Factor (equivalent to fine fuel availability factor) (0-10);
- Maximum Forest Fire Danger Index when fire in cell (0-200+);
- Highest value asset type in cell (1-99);
- Wind speed while fire was in cell (km/h);
- Wind direction while fire was in cell (degrees);
- Direction of fire spread in cell as it impacted assets (degrees);
- Theoretical house loss probability in cell (0-1); and

- X and Y map coordinate of cell centre.

Grid Analysis outputs for each Fire Grid cell are:

- Cell ID;
- Times Burnt;
- Times Impacted;
- Average Fire Intensity (kW/m);
- Average Flame Height (m);
- Times Impacted by Embers;
- Times Impacted by Convection;
- Average Convective Strength (MW);
- Average House Loss Probability;
- Asset Type 1 loss;
- Asset Type 2 loss;
- Asset Type 3 loss;
- Asset Type x loss (depending on the number of different asset types impacted); and
- X and Y map coordinate of cell centroid.

Grid Analysis outputs for each Fire are:

- Fire ID;
- Fire Scenario ID;
- Start Time (ignition);
- End Time (extinction or end of simulation);
- Self-Extinction time;
- Peak FFDI (Forest Fire Danger Index);
- Fire Area (ha);
- Data Extent Exceeded (True/False);
- Cumulative Asset Type 1 loss;
- Cumulative Asset Type 2 loss;
- Cumulative Asset Type 3 loss; and
- Cumulative Asset Type x loss (depending on the number of different asset types impacted by the fire up to 99).

Static Grid outputs for Fire Grid cells are:

- Cell ID;
- Slope (degrees);
- Elevation (m);
- Aspect (degrees);
- Grassland equivalent fuel load (t/ha);
- Combined equivalent surface fine fuel load (t/ha);
- Equivalent bark fine fuel load (t/ha);
- Equivalent elevated fine fuel load (t/ha);
- Total equivalent fine fuel load (t/ha);
- Road Proximity (m);
- Fire rate of spread (m/h);
- Fireline intensity (kW/m);

- Maximum potential distance of spotting from cell (m);
- Average flame length in cell (m);
- Average flame depth in cell (m);
- Fine Fuel Moisture Content (% ODW);
- Drought Factor (equivalent to fine fuel availability factor) (0-10);
- Maximum Forest Fire Danger Index when fire in cell (0-200+);
- Highest value asset type in cell (1-99);
- Wind speed while fire was in cell (km/h);
- Wind direction while fire was in cell (degrees);
- Direction of fire spread in cell as it impacted assets (degrees) = wind direction in Static Grid;
- Theoretical house loss probability in cell (0-1) (excludes the effect of ember density and convective strength in Static Grid); and
- Time of modelled fire.

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APPENDIX 1.
VERSIONS OF PHOENIX

Date	Version	Comments
May 2005	PHOENIX 0.0.0.0	Development begins. Spatial data handled by ESRI ArcGIS engine. Works within Microsoft's .NET Framework
October 2006	Workshop	First formal training for PHOENIX users. 2 days. 16 attendees.
March 2007	PHOENIX 0.0.0.0	Incorporated a Cellular Automata module for spotfire growth. Huygen's and CA working together.
February 2008	PHOENIX 0.0.1.0	Designed to run without need for ESRI's ArcGIS engine. General domain spatial software embedded in PHOENIX.
September 2008	PHOENIX RapidFire 1.0.0.0	Risk assessment functionality. Includes Batch runs and Multi-scenario run options.
April 2009	PHOENIX RapidFire 1.0.0.7	Gridded weather. Incorporated facility to read gridded forecast weather (GFE) for the Bureau of Meteorology.
July 2009	PHOENIX RapidFire 1.0.4.0	Isochrone smoothing. Introduced isochrone smoothing so that hourly or half hourly fire perimeters could be displayed.
November 2009	PHOENIX RapidFire	Zipped ASCII input files used. Zipped ASCII files used directly by PHOENIX to make it easier to copy input data layers from one computer to another - a lot fewer files to handle.
January 2010	PHOENIX RapidFire 2.0.0.1	XML Project format. Allows for simulations instructions to be captured in a single XML file thus enabling the easier management of multiple parallel processors.
February 2010	PHOENIX RapidFire 2.0.0.2	Multi-core computing. Cluster computation facility setup (Super Computer). PHOENIXWorker manages allocation of tasks to be processed in parallel.
May 2010	PHOENIX RapidFire 2.0.0.3	Auto-ignition for Batch runs. Automated function to ignite fires once specified or peak FDI is reached.
July 2010	PHOENIX RapidFire 2.0.0.4	Statewide Fire Danger Rating. Automated 7-day daily risk analysis process using the gridded forecast weather.
October 2010	PHOENIX RapidFire 3.0.0.0	Convective Strength output. A heat segment model implemented which identifies hottest parts of a fire perimeter, used in Version 2.x spotting model, to determine onground impact pattern.
October 2010	PHOENIX RapidFire 3.0.0.0	Fuel inputs in separate XML. Suppression now based on relative time to ignition. Gridded weather offset changed. Heat centres and convective strength calculated and displayed. Spotting driven by convection. Stuart Matthews' fuel moisture model used for spotting and FDI limits.
February 2011	PHOENIX RapidFire 3.0.0.1	Facility to incorporate a grass curing data layer if available. Removed all references to external APIs and any dependencies on .Net Framework to make it more compatible with Linux/Mono.

August 2011	PHOENIX RapidFire 3.0.0.6	WindNinja embedded rather than being a standalone process.
August 2011	PHOENIX RapidFire 3.0.0.7	Added convection value to grid output in "CONVECT" field, value in MW
November 2011	PHOENIX RapidFire 3.0.0.8	First iteration of convection column model implemented (bubbles). For visualization and comment. Only shows top 10% of columns in order of convective output.
November 2011	PHOENIX RapidFire 3.0.0.8	Added weather input sensitivity test option to simulation project file and interface.
December 2011	PHOENIX RapidFire 3.9	New splash screen interface. Full license text with "Accept" question. Further enhancements to assist in parallel processing.
January 2012	PHOENIX RapidFire 3.9	Added logistic house loss algorithm to code. HL_PROB in the grid shape file, 'HouseLossProb' in gridded outputs.
January 2012	PHOENIX RapidFire 3.9	Fixed bug in code that was not properly accounting for upslope component of fire spread when wind blows across slope.
February 2012	PHOENIX RapidFire 3.9	Rationalized Asset Impact calculation. Impacts are now only being calculated on a cell and aggregated up to the Landscape/Fire level.
March 2012	PHOENIX RapidFire 3.9	Changed cooling rate of bubbles to dry adiabatic lapse rate of 1 degree/100m and removed density adjustment to decelerate bubbles when entrainment cooling reaches ambient temperature.
April 2012	PHOENIX RapidFire 3.9	Changed approach to calculating convection column footprint radius. Previously, radius was determined by convective strength alone and did not directly incorporate the burning areas included. This approach overestimated column footprints for small fires.
May 2012	PHOENIX RapidFire 4.0	Open source GIS functions replaced with more generic versions
August 2012	PHOENIX RapidFire 4.0	Ember distribution algorithm updated to better capture medium to long-distance spotting observed on Black Saturday.
August 2013	PHOENIX RapidFire 4.0	Facility to incorporate Drought Factor as a dataset to override gridded weather or weather stream input.
September 2018	PHOENIX RapidFire 4.1	Rebranding of Phoenix by Fire Prediction Services. Small bug fixes and improvements based on recommendations by the TRG, the focus of which was stability of the user interface and supporting 'Cruz' for grass curing.

APPENDIX 2.
PHOENIX FILES USED FOR INPUTS

For more information on these, refer to the *PHOENIX Input Data Guide.*

Chapter /section	CHAPTER NAME	Input name	Relationship to PHOENIX files
4	INPUTS		
4.1		Fuel Types	Fuel types is stored as a compressed 'Fuel.asc' file inside the 'fuel' folder. Fuel parameters are stored in the 'fueltypes.xml' file.
4.2		Wind Reduction Factors	Wind reduction factors are specified alongside each defined fuel type in the 'Fuel Types' XML file.
4.3		Fire History	Stored as a primary layer and a secondary layer. The primary layer is Fire History. The secondary layer is called Sup History and is a supplementary fire history layer to capture recent fire events.
4.4		Topography	An ASCII grid DEM with values representing heights above sea level. Provided to PHOENIX as 'Dem' data.
4.5		Asset and Values	Stored as a gridded data layer with values representing assets and values (such as houses, infrastructure, catchments, plantations or biodiversity values). Provided to PHOENIX as 'Asset' data.
4.6		Road Proximity	A gridded data layer containing proximity to roads, usually created from a Road GIS layer. Provided to PHOENIX as 'Road Prox' data.
4.7		Fuel Disruptions	A linear vector data layer containing features that disrupt fire spread. Provided to PHOENIX as 'Disruption' data.
4.8		Weather	Either user-specified data entered as a series of predictions over time and provided to PHOENIX as 'weather', or as a weather grid provided as a set of NetCFD files each containing the forecast of a single weather variable which are provided to PHOENIX in a single 'Weather Dir'. In either circumstance, data layers can be provided for 'Curing' and 'Drought Factor' (DF) which override the above data for those parameters.
4.9		Suppression Resources	Provided to PHOENIX as 'Suppression' data.

APPENDIX 3.
THE SIMULATION PROCESS

PHOENIX is implemented as a deterministic (non-random) computer model that:

- Is designed to run on Windows based computers;
- Models large scale bushfires in a time frame suitable for operational use (<10 minutes);
- Is focused primarily at extreme fire events; and
- Grows fire perimeters using a Huygens' Wavelet Propagation based algorithm (Knight and Coleman 1993).

PHOENIX is a standalone executable program designed to run on Windows based computers. It has a graphical user interface (GUI) but can also be controlled via command line to allow integration with operating systems other than Windows.

PHOENIX broken down to its simplest components includes, *inputs*, *model processes* and *outputs* with data being managed in a spatial grid (*Fire Grid*). Below is a description of how the various components come together to form a simulation process. The general simulation process used in PHOENIX RapidFire is shown in Figure 38. Each step of the figure is then described.
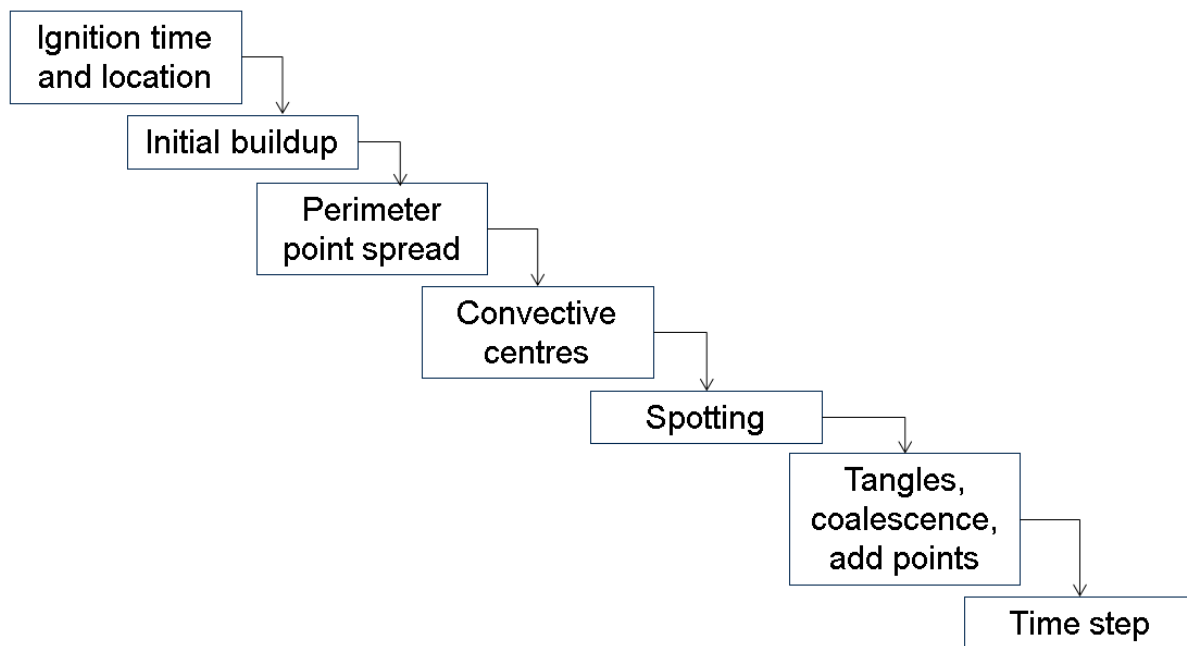

Figure 38.Simulation process used in PHOENIX RapidFire

IGNITION TIME AND LOCATION

To trigger a simulation the user specifies an ignition time and location. This is used to then access the relevant fuel, terrain and weather data to start the fire behaviour calculations.

PHOENIX accepts both point (new fires) and perimeter (existing fires) ignitions as inputs. Start times are assumed to be the time of ignition as opposed to the time the fire is reported. Start times are to

the nearest minute and multiple simultaneous fires with different start times can be modelled. A common end time is required, and fires are modelled to that time or until completely extinguished.

INITIAL BUILD-UP

Each new fire (including spotfires) has an initial build-up phase where the spread rate is less than its quasi steady-state rate. The duration of the buildup phase depends on the calculated length to breadth (L:B) ratio of the fire, where the lateral rate of spread is calculated in the same way as the head-fire, except that the effective wind speed affecting the lateral spread is assumed to be zero. An empirically derived relationship used in PHOENIX RapidFire is that the build-up time in minutes is 3.5 times the L:B ratio, so that if the L:B ratio is calculated to be 6 then the build-up time is taken to be 21 minutes. The rate of build-up is based on the conceptual model described by Cheney (1981) and shown in the equation below, and Figure 39. An addition is that the proportion of the available fine fuel and the wind speed affecting the build-up rate of spread is related to the proportion of the build-up phase completed. This approach results in fires developing to a width of about 100 m during the build-up phase.

$$R = R_{ss}e^{-a/t} \dots\dots\dots\dots\dots\dots\dots(1)$$

where:
R = rate of spread
R_{ss} = quasi-steady state rate of spread
t = time since
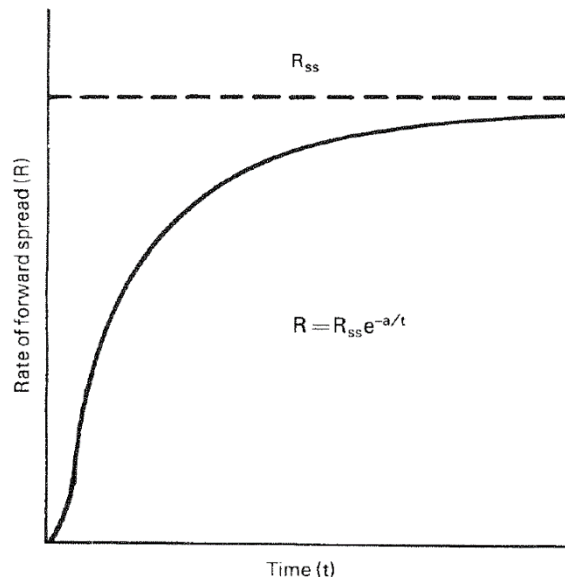a = variable determining the rate of change

Figure 39.   *Theoretical fire build-up rate (Source: Cheney 1981)*

PERIMETER POINT SPREAD

Each point on the perimeter is dealt with individually using Huygen's spread principle (Andersen *et al.* 1982). The simulation starts with the most windward point on the perimeter which is assumed to be the back of the fire. At this point, the weather, fuel and terrain conditions are used to calculate a flame height. If the flame height is less than 1 m, then only the combined surface and near-surface fuels are used in the calculation, and if the flame height is greater than 2 m, then all the combined

surface, elevated and bark fine fuels are used in the fire behaviour calculations. For flame heights between 1 and 2 m, the elevated and bark fuels used is calculated proportionally, e.g. if the flame height is 1.8 m, then 80% of the elevated and bark fuels are used in the fire behaviour calculations. Fire behaviour attributes for each point are then based on a modified McArthur model (McArthur 1967) if fuels where trees and/or elevated fuels are present and a modified CSIRO grassland model (Cheney *et al*. 1998) for all grasslands and sedgelands. The grassland model is modified to continuously vary fuels rather than use just three fuel condition classes.

Because PHOENIX RapidFire is a dynamic simulation, the extent of the fire can be very sensitive to the specified initial ignition time and location. The main cause of this sensitivity is due to how PHOENIX incorporates the spotting process into fire spread. A small change in the ignition time and/or location may have a significant impact on the spotting process and spread and therefore the fire spread. A second cause of sensitivity is the impact of local fuel conditions on the initial buildup phase of a fire. For example, an ignition location just upwind of a road, may result in a fire self-extinguishing, but by shifting the ignition location 100 m may see the fire spread rapidly.

CONVECTION CENTRES

The convection model is based on the assumption that convection columns will form over the hottest areas of a fire. PHOENIX uses this information, in conjunction with wind speed and direction to determine potential ember impact patterns resulting from these columns. Ember impacts are used to potentially initiate spotfires, and are also used in asset loss calculations.

The first step in identifying potential convection columns or plumes is to locate relatively hot parts of a fire's perimeter (heat segments). This has been defined as the perimeter segments having an average intensity value in the top 25% of perimeter intensity values. The PHOENIX convection model allows for multiple distinct heat segments to be identified within a fire to reflect the multiple active fire fronts that can exist within a bushfire. In these cases, any convection columns forming are likely to be an aggregate of multiple local heat sources merged to produce a locally dominant column. The PHOENIX convection model attempts to reproduce this phenomenon by aggregating heat segments where they are deemed to be close enough to interact.

SPOTTING

The convective strength and amount of bark fuel of each heat centre are used to determine the quantity of embers launched and the expected travel time for the embers once aloft. Embers are transported with the speed and direction of the 10 m winds. A Weibull/bimodal distribution is used to determine distribution distance from the fire front, and for distribution perpendicular to the travel path, a normal distribution is used. Only embers travelling more than 200 m are considered, as those that fall less than that are assumed to be subsumed quickly into the main fire front and have already been accounted for in the empirical fire spread models used. PHOENIX then calculates the probability of embers igniting a spotfire. Any spotfires are run as independent fires that start again with the build-up phase.

TANGLES AND COALESCENCE

Perimeter expansion is modelled in discreet time steps. At the end of each time step, the fire perimeter is checked for any 'tangles' or coalescence with another fire such as a spotfire. If there is an intersection of fires, the larger of the two will persist and the smaller fire is subsumed.

As a perimeter grows additional vertices are added to the perimeter to ensure there are enough points to represent the fire's shape and sample the landscape it is passing over.

TIME STEP

The computational sequence is now repeated for the new time step with fuels, weather and terrain conditions reassessed to find current conditions.