

# Fire activity modelling for use in smoke predictions

## Final Report



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## Document summary

This report summarises the work undertaken by the University of Melbourne in 2014/2015 to link fire activity modelling and smoke emissions modelling, as part of a project coordinated by CSIRO to develop predictions of smoke emissions and impacts from bushfires and prescribed burns in Victoria.

The report provides an overview of the research tasks and presents key findings. It also describes some of the key challenges in smoke emission prediction, documents the chosen fire modelling approach and associated software, and presents the results of some case studies of fires in Victoria.

The report includes a discussion of model limitations and uncertainties, and recommendations are made for further development. Note that this edition of the report describes software enhancements provided in 2016 at the request of CSIRO.

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## Further information

This research was undertaken in accordance with a CSIRO Collaborator Agreement (CSIRO and University of Melbourne 2013), and University of Melbourne Research Agreement LEX #22050 (University of Melbourne 2013).

Technical details can be found in the project plan (Walsh and Duff 2014), the progress report (Walsh, Duff, and Tolhurst 2015), CRC publications (BCRC 2013; BNHCRC 2014) and CSIRO publications (Cope et al. 2014; Lee and Cope 2014).

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## Abbreviations

BCO = Burn Coverage Objective (defined in a burn prescription)

CSV = Comma Separated Values

DELWP = Victorian Department of Environment, Land, Water and Planning

FFDI = Forest Fire Danger Index

FFMC = Fine Fuel Moisture Content

GPS = Global Positioning System

NPI = National Pollutant Inventory

UTC = Coordinated Universal Time (international time reference)

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# Contents

<b>1. Objectives and scope</b> .....	5
<b>2. Background</b> .....	6
<b>3. Integration of fire prediction and smoke modelling</b> .....	8
3.1 Fire prediction and fuel consumption.....	8
3.2 Application to smoke modelling .....	9
<b>4. Model development</b> .....	11
4.1 Bushfire emissions model .....	11
4.1.1 Overview .....	11
4.1.2 Fuel loads and fuel consumption.....	13
4.1.3 Carbon and heat emissions.....	14
4.1.4 Model outputs .....	15
4.1.5 Example results.....	15
4.2 Planned burn emissions model .....	18
4.2.1 Overview .....	18
4.2.2 Flame height and fireline intensity .....	22
4.2.3 Example results.....	23
4.3 Software implementation .....	29
4.3.1 Supported operating systems.....	29
4.3.2 Running the model – operation, inputs and outputs .....	30
4.3.3 Software ownership.....	30
<b>5. Prediction uncertainty and model limitations</b> .....	31
5.1 Underlying system components and data .....	31
5.2 Bushfire model .....	31
5.3 Prescribed burn model.....	33
5.4 Model verification – issues and challenges.....	34
<b>6. Conclusions and recommendations</b> .....	35
6.1 Key outcomes and findings .....	35
6.2 Recommendations for further development.....	35
<b>7. References</b> .....	37
<b>8. Appendix A – Software user interface</b> .....	41
8.1 Bushfire Model (LINUX version).....	41
8.2 Planned Burn Model (LINUX version) .....	43
8.3 Operating the Windows 7 version .....	45

# 1. Objectives and scope

This report summarises the work undertaken by the University of Melbourne as part of the collaborative project *'Smoke Transportation Modelling and Emission Modelling for Victoria'*, involving several research partners and managed by CSIRO.

The University of Melbourne was contracted to predict information about smoke and heat emissions from bushfires and planned burns. This information is intended as input data for a CSIRO-developed atmospheric modelling system designed to predict smoke transport and exposure resulting from fires in Victoria. A simplified outline of the prediction system is shown in Figure 1.

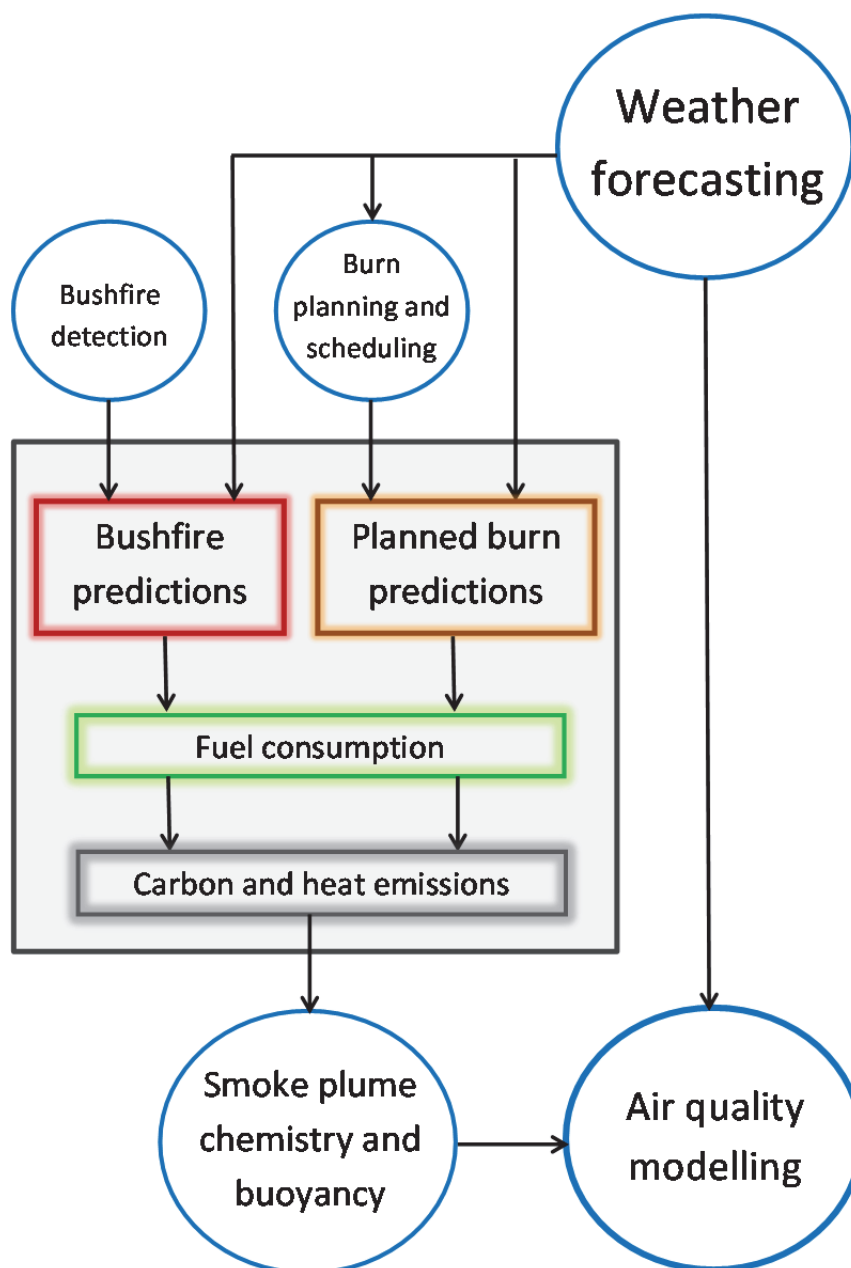


Figure 1. Simplified diagram of the smoke forecasting system. The shaded square indicates the scope of the work described in this report.

## 2. Background

Smoke from large fires can affect human health (Tham et al. 2009; Youssouf et al. 2014), visibility (McMeeking et al. 2006) and vineyard crops (Kennison et al. 2009), as well as having negative effects on recreation, tourism and general amenity.

During major bushfires, intense smoke plumes may impact on major population centres, potentially affecting millions of people. The movement of these plumes can be complex; for example, on the 11<sup>th</sup> Feb 2014, smoke from far-east Victoria reached the surf coast and Geelong before it reached eastern Melbourne, because part of the plume was transported quickly over water, where wind speeds are higher (Figure 2).

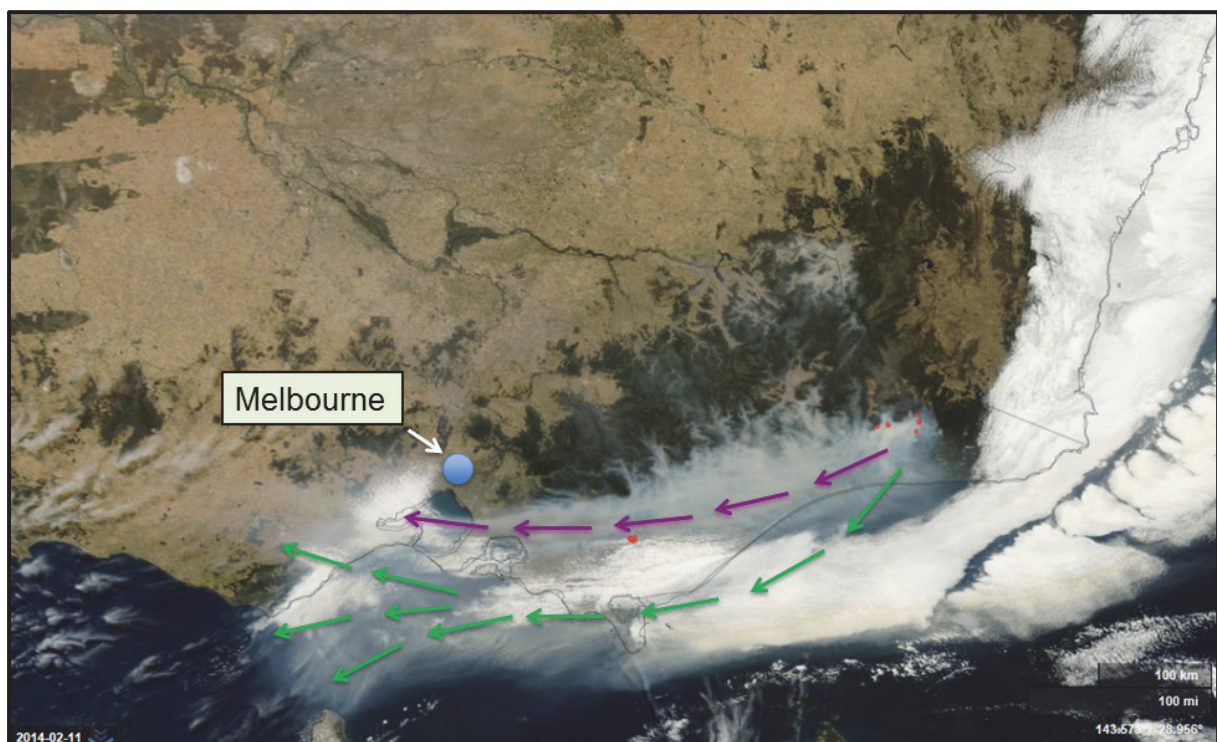


Figure 2. Bushfire smoke affecting Victoria (MODIS, 11<sup>th</sup> Feb 2014). Purple arrows show smoke transport over land; green arrows show transport over water.

The impacts of smoke on sensitive people (which includes the elderly and those with chronic respiratory disease) can be reduced if protective actions are taken, such as staying indoors and closing windows (DoH 2013). However, public health authorities will only issue advice if an extended period of smoke at high concentrations is expected. For this to work effectively, an accurate forecasting system is needed, and a key input into such a system is the rate of smoke emissions.

Planned burns can also result in significant smoke emissions (Figure 3). Smoke concentrations are usually lower than those seen during major bushfires, but smoke exposure can occur over longer periods, as burning is typically done during calm weather, and often extends over several weeks, increasing the amount of time that smoke remains within the affected area.

Burns will inevitably generate some smoke impacts, but through careful management, these impacts can be minimised whilst still achieving the intended burn outcomes. A system that could accurately forecast smoke emissions and impacts could form part of this process of keeping impacts to a minimum, by providing information to assist burn planning and scheduling.



Figure 3. Planned burn at St. Andrews, Victoria, 30<sup>th</sup> March 2015.

For both bushfires and planned burns, it is important to predict the rate of heat release as well as the rate of smoke emissions. Heat release is needed because this affects the rate at which the plume rises vertically, which has a significant effect on smoke concentrations downwind of the fire (Lee and Cope 2014).

Current practice for forecasting smoke in Victoria includes a combination of manual methods (Walsh 2014) and automated tools (Wain and Mills 2006). However, these systems do not include quantitative calculations of the smoke emission rate, which depends on the rate of progress of the fire and the rate at which fuel is consumed.

This problem is addressed in the current project by using fire behaviour modelling to estimate the rate of fuel consumption, and consequently the rates of smoke and heat release. This approach can be applied to fires that have ignited but not finished burning, as well as fires that have not yet been ignited. It can also be adapted to support the prediction of different scenarios, for example by using a range of different weather forecasts to drive the fire prediction model. The following section provides further detail on the application of fire behaviour modelling to smoke emissions.

## 3. Integration of fire prediction and smoke modelling

### 3.1 Fire prediction and fuel consumption

A number of smoke forecasting systems have been developed in Europe, the USA and Canada (Meyer et al. 2013). Many of these systems rely on detection of active fires and simple assumptions about fire growth. These systems also rely on locally developed fuel models that cannot be directly applied to Australian forest fuels. Therefore such models are of little direct use for operational smoke predictions in Victoria, although some components are useful, for example the USA-developed *BlueSky* system (Larkin et al. 2009), which has been employed by CSIRO to provide a framework for smoke modelling (CSIRO 2014).

For modelling bushfires, this project has used an established Australian fire propagation system, PHOENIX RapidFire<sup>1</sup> (Tolhurst, Shields, and Chong 2008). This software system predicts the future development of a bushfire given a weather forecast and ignition details, plus spatial datasets describing vegetation fuels, topography, barriers to fire propagation (such as roads) and fire history.

To track the rate at which fuel is consumed in a fire, the PHOENIX software was extended to record details of the incremental area burnt after each time step of the model (Figure 4). Within that area, the consumed fuel is counted and assigned a time and location. This generates a sequence of data on fuel consumption throughout the duration of the simulated fire.

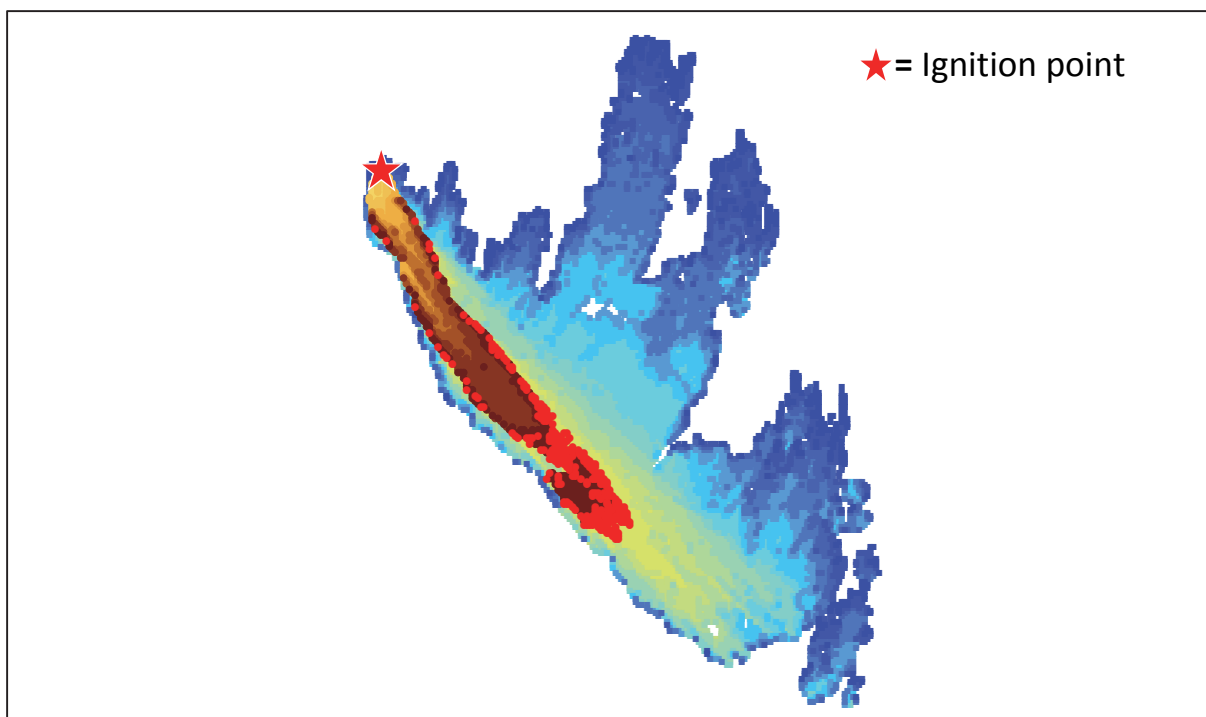


Figure 4. PHOENIX simulation of the Kilmore East Fire on 7<sup>th</sup> Feb 2009 (Walsh, Duff, and Tolhurst 2015). Fire activity to 4:05 pm is shown in brown, and fire activity from 4:05 to 4:14 pm (one time step) shown in red.

<sup>1</sup> Hereafter this will be referred to simply as PHOENIX.



For planned burns, there are no established models that can perform an equivalent prediction. PHOENIX was designed and calibrated for high intensity, fast-moving bushfires, and has not been evaluated for low intensity planned fires, which typically involve a complex ignition process and a patchwork of many slow moving fires under mild weather conditions.

More fundamentally, the ignition pattern for planned burns is usually determined by the burn controller on the day of the burn (Tolhurst and Cheney 1999). Emulating the detailed judgements of an experienced burn controller would require extensive research into the decision-making process as well as accurate prediction of fine-scale weather and fuel conditions. These significant research tasks are beyond the scope of the current work.

Consequently, fire propagation modelling is not yet suitable for predicting smoke emissions from future burn. For this reason, a specialised simulator for planned burns was developed (Walsh et al. 2015), described in detail in section 4.2 of this report. Fuel consumption information (including location, amount of fuel burnt and time of consumption) is recorded in the same way as described above for bushfires.

## **3.2 Application to smoke modelling**

This project component quantifies the burning of fine fuels in flaming phase combustion. After flaming combustion has finished, there is usually an extended period of smouldering combustion with significant amounts of coarse fuel being consumed (Figure 5). It is beyond the scope of the current work to quantify emissions from coarse fuel consumption. Similarly, no attempt has been made here to quantify the smouldering combustion of fine fuels, which can occur in the lower (wetter) layers of forest litter.

The objectives set by CSIRO for this project component were to compute the carbon and heat emissions rates from fires. The next section of this report describes the development of models for estimating carbon and heat emissions from bushfires and planned burns. Fire behaviour results are also output by these models to assist with future research into the links between fire behaviour and smoke emissions.

Note that although this project component has established links between fire behaviour and smoke emission rates, a full linkage of fire behaviour, smoke emission and atmospheric models is not attempted here. Significant work is underway in other project components to develop methods to convert carbon emissions into chemical smoke profiles (Meyer, Sullivan, and Surawski 2013), and to find suitable techniques for using heat emissions to model the buoyant rise of smoke plumes (Lee and Cope 2014).



Figure 5. Coarse fuel combustion at the St. Andrews burn, 30<sup>th</sup> March 2015.

## 4. Model development

### 4.1 Bushfire emissions model

#### 4.1.1 Overview

The PHOENIX bushfire simulator, currently used by the Victorian Department of Environment, Land, Water and Planning (DELWP), was used as the basis for building a model of carbon and heat emissions from active fires. As the operational version of PHOENIX does not output the necessary information needed to compute a time sequence of fire emissions, some extensions and modifications were made to the software.

A fire simulation is initiated by specifying a number of ignition events, either as points or as established fire perimeters. Using forecast weather, and landscape information including topography, vegetation fuels and fire history, PHOENIX then simulates the likely progress of the fire. The simulation proceeds using variable-length time steps (up to a maximum of 20 minutes), and continues until user-specified end time, which is typically several hours from the first ignition.

For this project, the PHOENIX software was modified so that at the end of each model time step, all the area burnt during that time step is identified (Figure 6), and the total amount of fuel consumed in this area is calculated. The amount of fuel consumed is then converted into carbon and heat emissions data, and assigned a location and time.

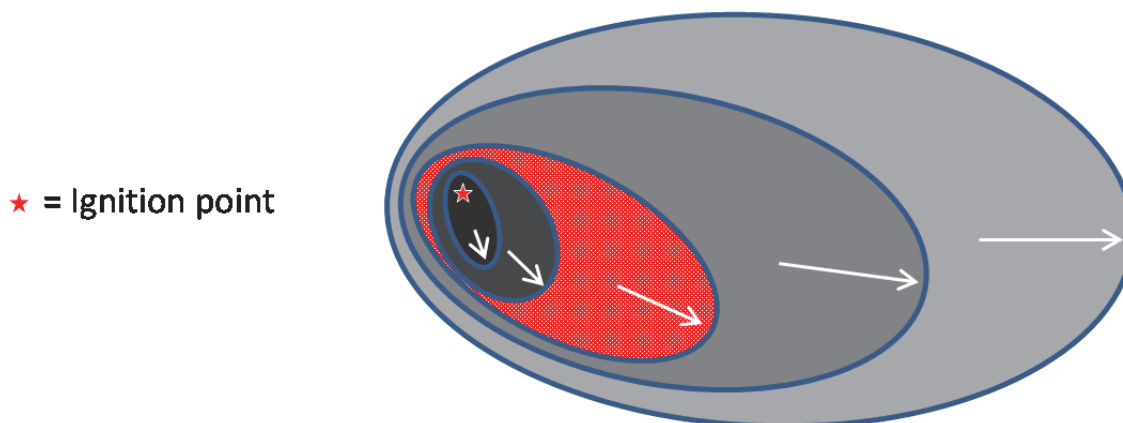


Figure 6. Time steps in a PHOENIX fire simulation. The highlighted area (in red) represents the area burnt during one time step.

Emissions for one model time step are assigned a point location by calculating a weighted centroid of all the model grid cells that were burnt during that time step. The weighting function is constructed so that areas of higher fuel load are given greater weight, as these will have the most effect on carbon and heat emissions.

All emissions data, including locations and times, are recorded throughout the fire simulation. At the end of the simulation the data are summarised and written to result files. The process is described in the flowchart in Figure 7.

For details of how to operate the model, please refer to Appendix A. Limitations of the model and prediction uncertainties are discussed in section 5.2.

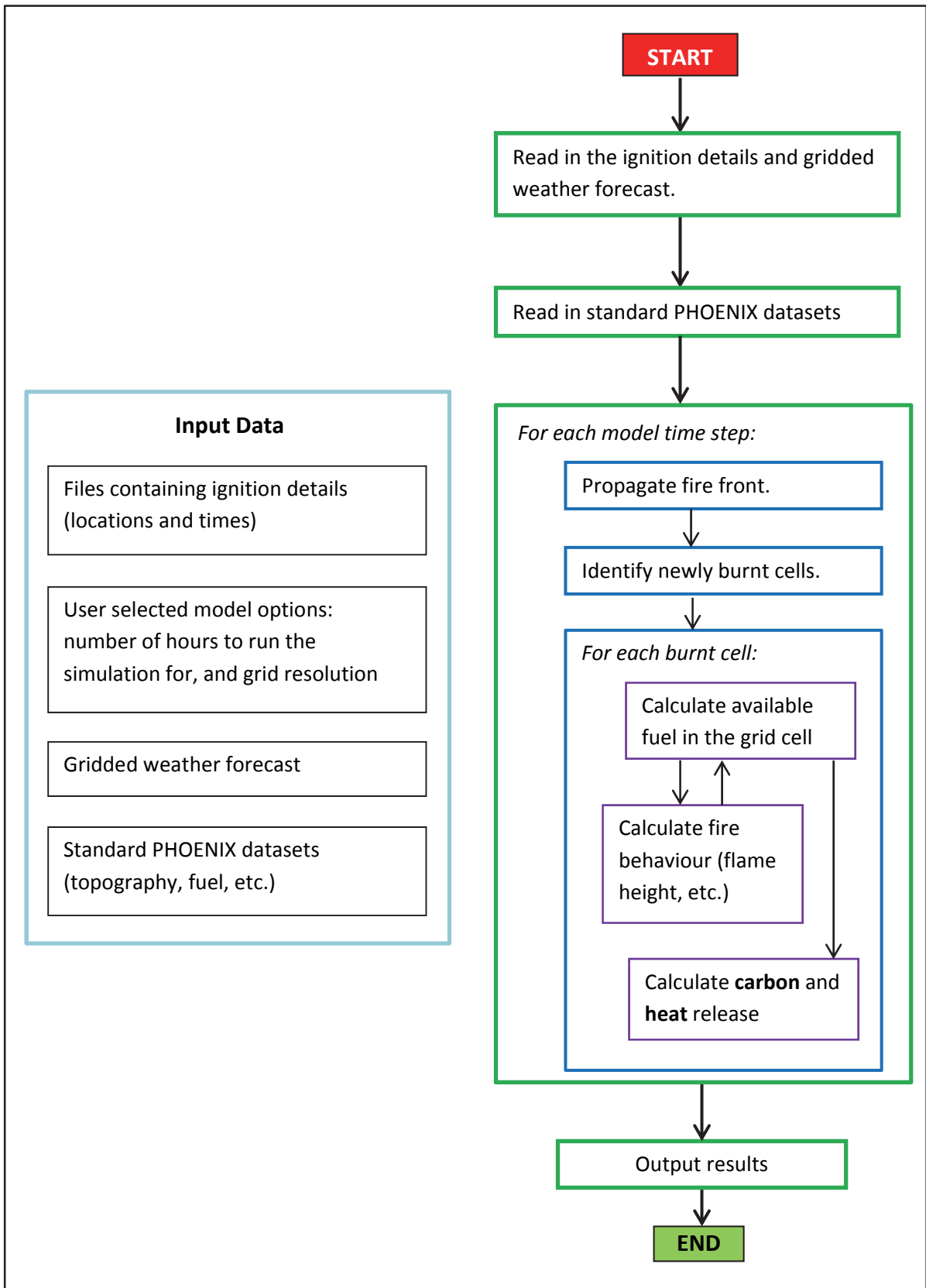


Figure 7. Overview of the system for modelling bushfire emissions.

#### 4.1.2 Fuel loads and fuel consumption

The main factor affecting emissions from a bushfire is the rate at which fuel is consumed by the fire. Only 'fine' fuel is considered here, which includes dead fuels less than 6 mm thick and live fuels less than 2 mm thick (Tolhurst and Cheney 1999). This section explains how vegetation fuel is handled within the fire simulation.

In the PHOENIX model, vegetation fuel is represented by two broad classes – forest and grassland. Sub-classes ("fuel types") are used to distinguish different levels of fine fuel load. Fuel types are derived by combining information on native vegetation, commercial plantations, land use patterns and urban areas (Tolhurst et al. 2012). Fine fuel load refers to the mass of fine vegetation fuel per unit area, usually expressed in tonnes per hectare (t/ha).

Fine fuel is further classified into 'strata' (Figure 8). For grasslands, all fuel is assigned to a single stratum (*grass*), whilst for forests, three strata are used (*surface*, *bark* and *elevated*, with *surface* including both surface litter fuels and near-surface fuels). Note that canopy fuels are not included in the PHOENIX model.

For each of these strata, fine fuel load is mapped across Victoria at 30 m resolution, using vegetation type and the time since the last fire at each location (Tolhurst, Chong, and Pitts 2007). The PHOENIX fire history input data file is used in the calculation of time since fire at each point in the landscape, which is simply the time difference between the most recent fire at that location, and the time of the fire simulation.

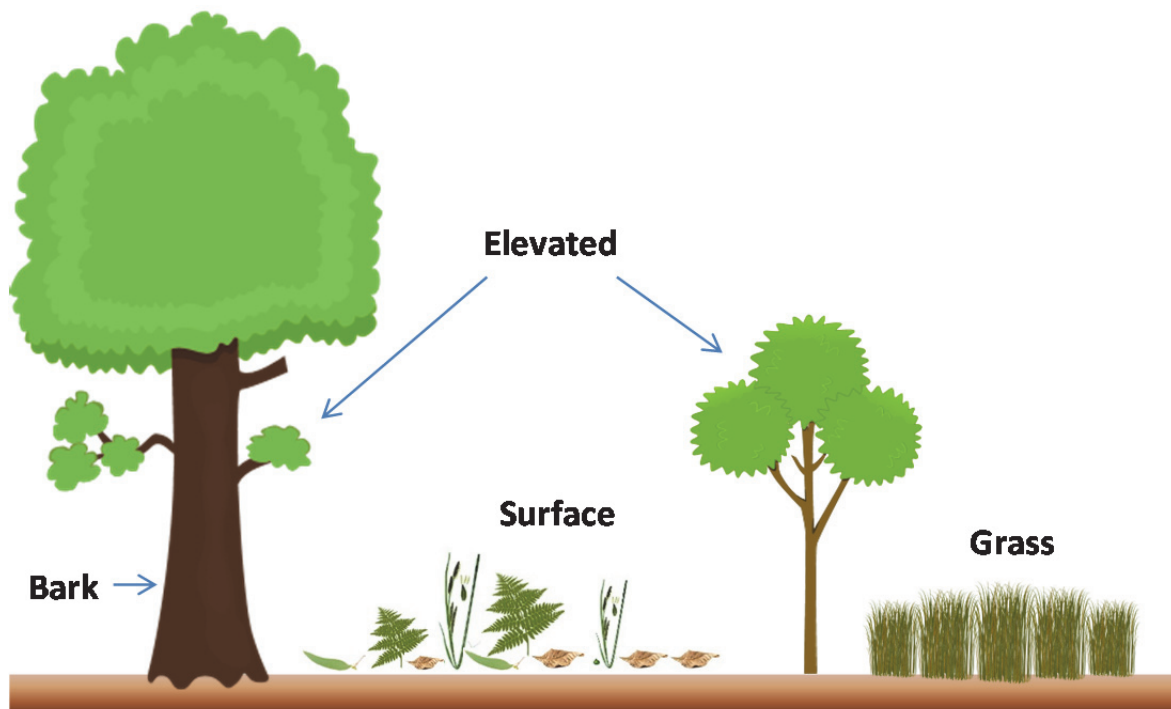


Figure 8. Fine fuel strata in the PHOENIX model. Canopy fuel loads are excluded.

A further step is needed to calculate the amount of fuel that is 'available' to be burnt by fire. In general, when fire passes over a section of the landscape, only some of the total fuel will be dry enough to burn. This is accounted for by applying a fuel availability factor; with different factors used for grass fuels and forest surface fuels.

For grass fuels, fuel availability is determined by the fraction of grass that has reached a 'cured' state, expressed as a percentage from 0-100% (Martin et al. 2009; Anderson et al. 2011). For forest surface fuels, availability is determined by a 'drought factor', a value from 0-10, with 10 indicating that all fine fuel is available (McArthur 1967; Finkele et al. 2006).

Both the level of curing and the drought factor are provided by the Bureau of Meteorology in daily gridded weather forecasts. Within the PHOENIX model, the drought factor is modified to account for the effects of slope and aspect, as north to north-west facing slopes tend to be drier due to increased solar radiation.

The amounts of elevated and bark fuels consumed by fire are not adjusted by fuel availability factors, but are dynamically adjusted using a function of modelled flame height. As flame heights increase, a greater proportion of the elevated (shrub) and bark fuels are included in the fire simulation.

Thus the total amount of fuel consumed at a point in the landscape is a dynamic calculation, dependent not only on the fuel load (a function vegetation type and time since last fire), but also on weather forecasts (curing and drought factor) and fire behaviour (flame height).

#### **4.1.3 Carbon and heat emissions**

The amount of carbon released to the atmosphere is calculated by multiplying the fuel consumed in each stratum by a carbon mass fraction. The literature on carbon mass fractions in vegetation was reviewed, and suitable values for Australian fuels were chosen: 47.7% carbon for surface, elevated and bark fuels (Thomas and Martin 2012) and 31.0% carbon for grass fuels (Eslemont et al. 2007). Further details can be found in (Walsh, Duff, and Tolhurst 2015).

The amount of heat released is determined by the amount of fuel consumed multiplied by a Heat Yield value (H). A generic value of  $H=18,700$  kJ/kg is used here (Alexander 1982), consistent with values reported elsewhere (Sullivan, Knight, and Cheney 2002; Morandini et al. 2013).

Heat yields are typically measured by calorimetry, and describe the average heat release over flaming and smouldering combustion, with an adjustment to subtract the latent heat from vaporisation of water in the fuel. There is some evidence to suggest that heat release during smouldering is higher than during flaming (Ohlemiller and Corley 1994), indicating that flaming-phase heat yields should be lower than the average value. However, due to a lack of studies confirming this effect in Australian fires, no correction has been made to the H value.

A further factor relates to the direction of released heat. It is expected that whilst most of the emitted heat will be released upwards and will influence plume rise, some will be lost downwards to the soil. Using an average of published data (Burrows 1999), the total heat release was reduced by 6.5% to account for downward heat loss.

#### **4.1.4 Model outputs**

To simplify the interface between this software and atmospheric models, emission results are converted to hourly data. For carbon and heat emissions, this is a simple total over all time steps within each hour. To determine an emission location, a weighted centroid is computed over all model grid cells burnt in each time step during the hour.

If a time step is split over two hours (e.g. 2:58 pm to 3:11 pm), the results are partitioned and allocated to both hours according to the number of minutes falling within each hour. Hourly results are written to a CSV (comma separated values) file.

Version 1.0.0.2 of the software also generates two additional files, one which provides a summary of fire behaviour, emissions and cumulative burnt area for each model time step, and another which provides spatial details of all the model grid cells that were burnt during each time step. For further details refer to section 4.3.2.

#### **4.1.6 Example results**

The following figures illustrate how carbon and heat emissions are generated for the simulation of the Kilmore East fire, a severe event which occurred on Black Saturday (7<sup>th</sup> Feb 2009). The fire simulation begins at 11:45 am and runs to 10:00 pm, burning 44,049 ha. (Note that the actual Kilmore East fire was significantly larger than this, partly because of pyrocumulus cloud development and consequent lightning ignitions which are not represented in the model). More details about this case study can be found in the project progress report (Walsh, Duff, and Tolhurst 2015) and in a study prepared for the 2009 Victorian Bushfires Royal Commission (Tolhurst 2009).

Progress of the simulation up to 4:14 pm, highlighting fire activity during one time step (4:04 pm to 4:14 pm), is shown earlier in this report (Figure 4). The weighted centroid corresponding to this time step is shown in Figure 9. Weighted centroids for the entire fire simulation are shown in Figure 10, which shows how the path of emission locations follows the progression of the fire front.

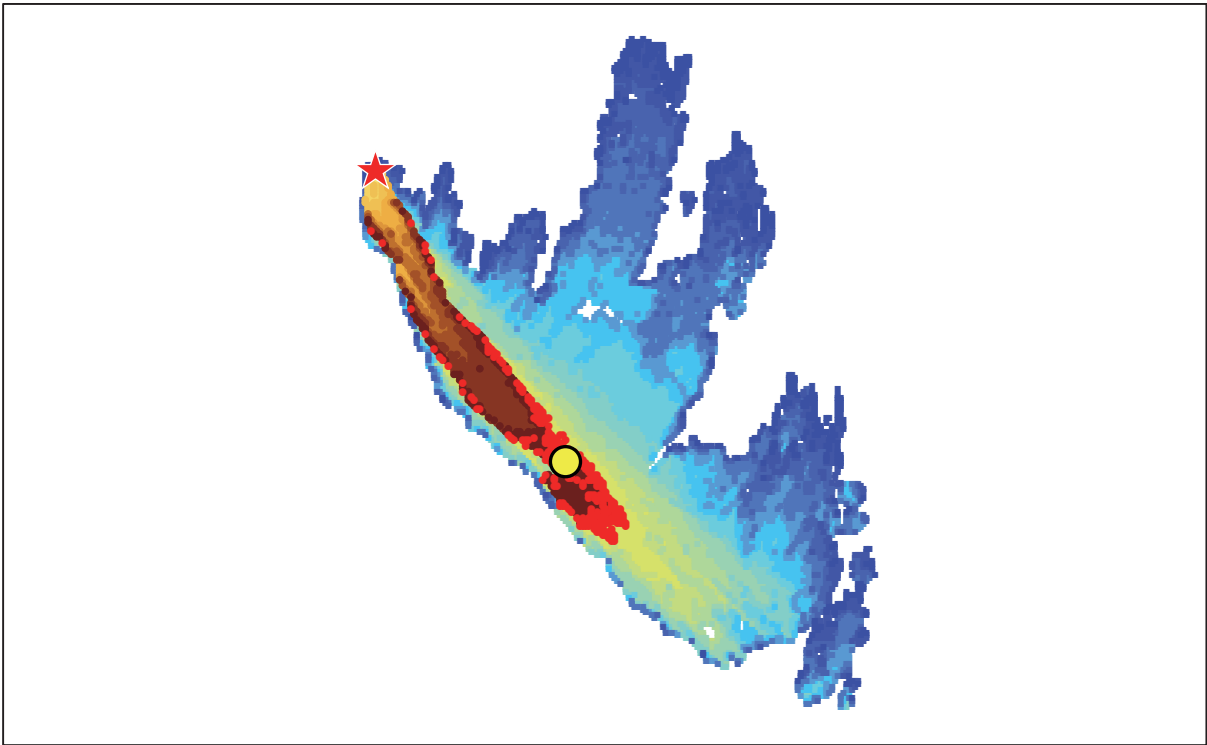


Figure 9. Example of a centroid (shown as a large yellow circle) used to represent one time step of the Kilmore East fire simulation (see Figure 4).

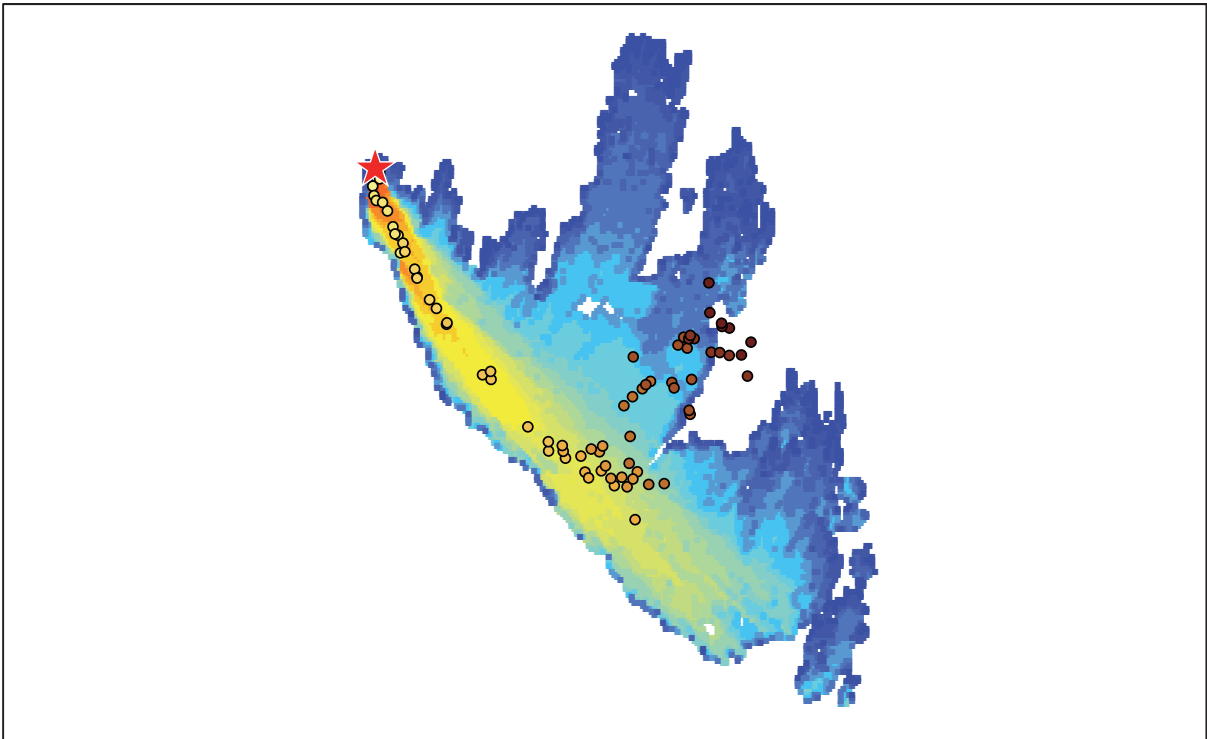


Figure 10: Path of weighted centroids over the duration of the fire simulation (the colour of circles indicates time progression).



Figure 11 shows the rate of fuel consumption during the Kilmore East fire simulation, expressed on a per-minute basis. Figure 12 shows the corresponding carbon and heat emission rates. Note that total heat release from the Kilmore East fire was extremely large (in this simulation, 20000 TJ).

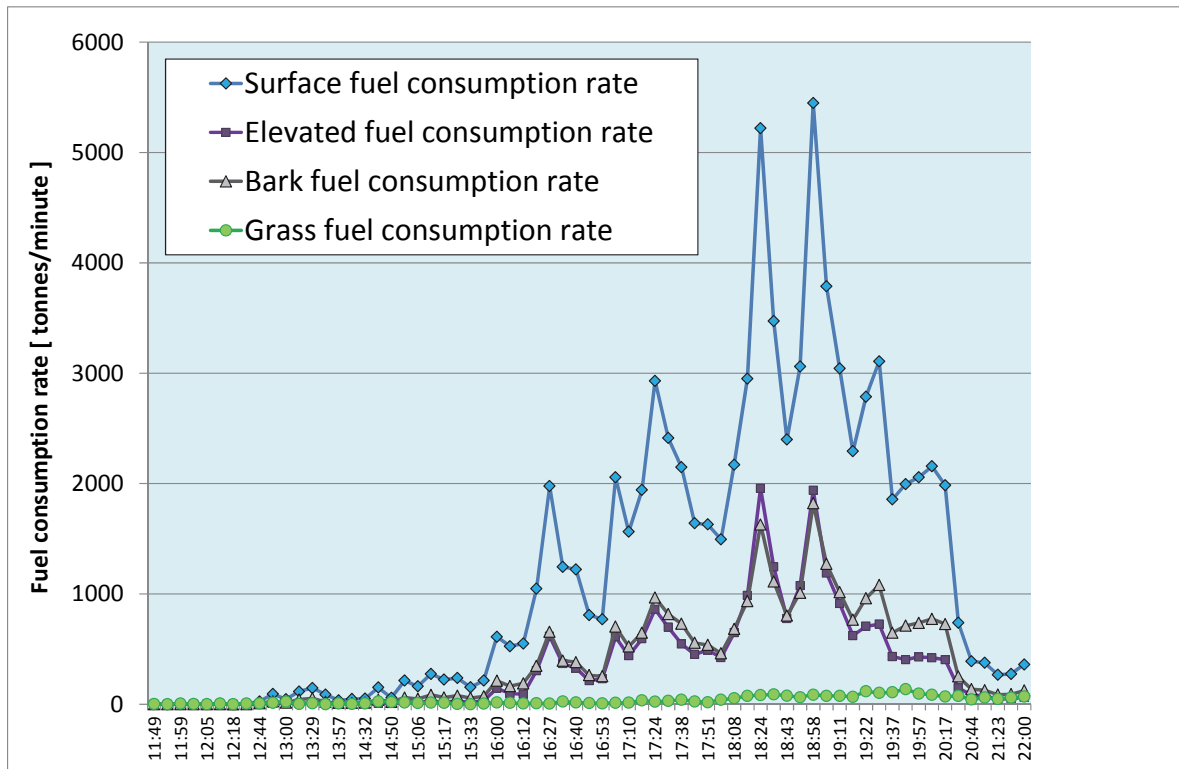


Figure 11: Predicted time series of fuel consumption (Kilmore East fire).

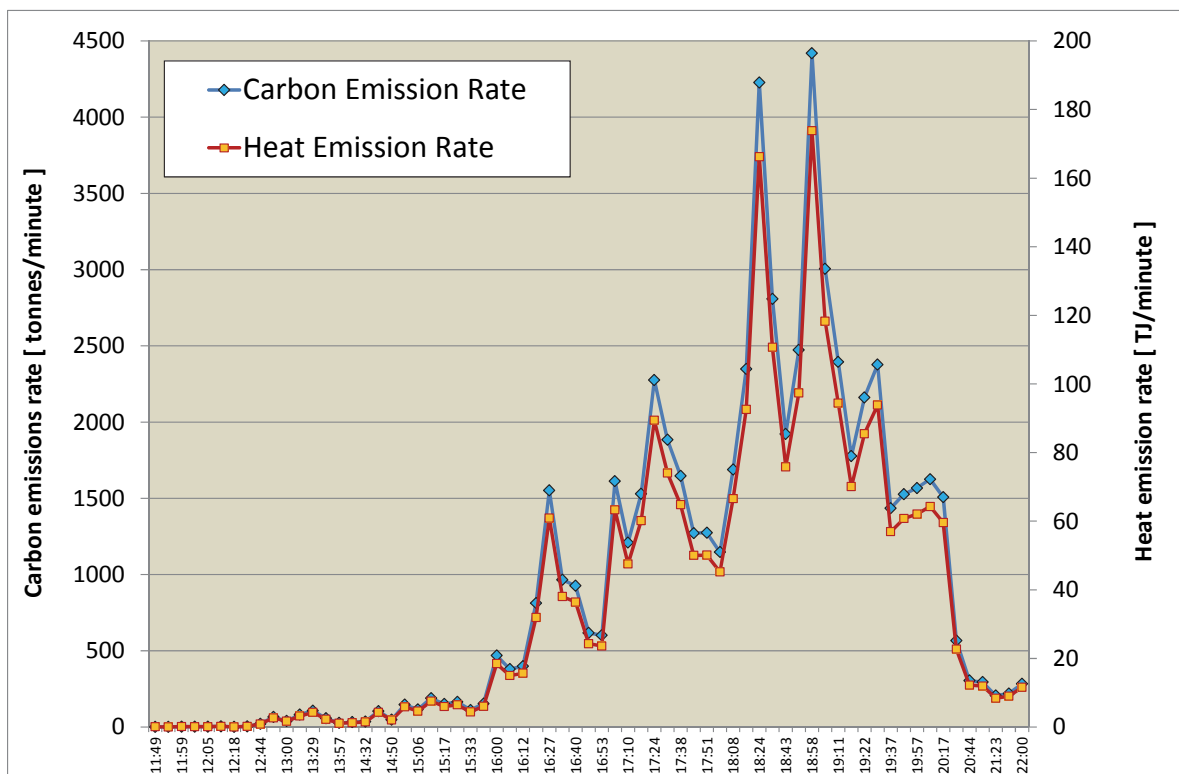


Figure 12: Predicted time series of carbon and heat emissions (Kilmore East fire).

## 4.2 Planned burn emissions model

### 4.2.1 Overview

The science of bushfire simulation is reasonably well established, with a number of models developed and in operation internationally. In contrast, very few models have been developed for simulating planned burns in a manner that would allow the calculation of fuel consumption and smoke emission rates during the burn.

One important study used a fire propagation model to drive an emissions model, achieving good results when compared with experimental fuel consumption rates (Ferguson, Peterson, and Acheson 2001). However, as mentioned earlier, fire propagation modelling is not a suitable method due to the problems associated with determining an ignition pattern in advance of the burn.



Figure 13: Hand ignition at the McMahon's Creek burn (13-14 March 2015). The ignition pattern for a burn is typically decided on the day of the burn by the burn controller, with verbal instructions issued to ground and aerial ignition crews.

In Australia, the National Pollutant Inventory provides a simple technique which uses an average forest fuel load, the expected burn area and emission factors to estimate total emissions for specific pollutants (EA 1999). This provides an estimate of the total fuel consumption and emissions, but not the rate of fuel consumption or emissions during the burn. Also, in this method, no account is taken of the effect of different weather conditions on fuel availability.

Given the lack of suitable models, a custom planned burn simulator was developed for this project. Some key components of the PHOENIX software (including fuel, topography, and weather) were used as the starting point for this development. In the process, a number of specific issues were identified and addressed, which are listed in Table 1.

Table 1. Development of the planned burn model – issues and solutions.

Model development issues	Approach / solution
<p>The area within the burn boundary that is actually burnt is a key input for estimating emissions from fires (Ottmar, Miranda, and Sandberg 2008). In a typical burn, not all of the area within the boundary is treated with fire. Burn prescriptions usually include a target percentage of area to burn, the “Burn Coverage Objective”, which can vary from 30-100%. Because the fuel load varies significantly within the boundary, the amount of fuel consumed depends critically on which areas actually burn. This is difficult to determine without a full fire simulation.</p>	<p>This problem is addressed by assuming that the Burn Coverage Objective will be achieved, and using an “ignition strategy” to decide the order in which areas within the boundary are burnt. In the current version of the simulator, a map of predicted fuel moisture is prepared using a simplified physical model (Matthews, Gould, and McCaw 2010), and the software burns from ‘dry’ areas to ‘wet’ areas, until the coverage objective is reached. This ignition strategy is based on safe burning practice - dry areas need to be burnt early in the day when fire danger values are lower.</p>
<p>The number of days it takes to complete a burn and the timing of fire activity on each day are not known before the burn is conducted. A large burn may take several days to complete, and the timing often depends on a range of factors including local fuel and weather conditions, and external issues such as smoke complaints, which are difficult to predict in advance.</p>	<p>The burn model prepared for this study is designed to simulate a single day burn. This effectively assumes that a multi-day burn can be partitioned by the model operator into several blocks to be simulated separately on different days. It is also assumed that the model operator will be able to specify a start and end time for each single-day simulation.</p>
<p>The fuel availability at each location within the burn boundary needs to be estimated. This determines the fraction of surface fuel that is combustible, given the weather conditions at the time that fire reaches that location. Forecast weather and drought factor values from the Bureau of Meteorology are provided as hourly data, but only on a coarse grid (~2.3 km x 2.3 km, or about 530 ha per grid cell). This scale is not able to represent the variation in fuel availability in forested ridges and gullies.</p>	<p>This is addressed by using a recently developed feature of PHOENIX - an algorithm to downscale the forecast drought factor to account for canopy density, slope and aspect. As each part of the landscape is burnt in the simulation, the downscaled drought factor is calculated for the time of day that the location is burnt, thus making use of the hourly detail provided in the forecast, and the spatial detail provided by the downscaling algorithm.</p>

<p>The relative amounts of fuel consumed in each fuel stratum (Figure 8) is difficult to predict in a low intensity fire. This is likely to depend upon the burn prescription and on the ignition pattern decided by the burn controller.</p>	<p>The current model requires the software user to specify which fuel strata to include in the fire. It is assumed that this selection applies across the entire burn.</p>
<p>Forecast wind speed and direction are provided by the Bureau of Meteorology on a coarse grid, and do not account for the effects of local topography and vegetation. Wind speed is a key input into fuel moisture and fire behaviour calculations.</p>	<p>The existing PHOENIX approach is used, which involves two adjustments to the standard 10 m open-terrain wind forecast. The first adjustment involves the use of the <i>WindNinja</i> system, which is a mass-balance method to adjust wind vectors for the effect of hills and gullies on airflow (Forthofer, Shannon, and Butler 2010). The second adjustment (Wind Reduction Factor) is dependent on the vegetation type, and is used to estimate wind speed under the forest canopy at a height of 1.5 m. No corrections are made for local thermal effects such as anabatic or katabatic winds.</p>
<p>The rate of fuel consumption during the burn needs to be determined. The amount of area subject to flaming fire activity clearly begins at zero and ends at zero, but the time profile in between is unknown, and will depend heavily on the ignition process.</p>	<p>This is addressed by assuming a piecewise linear time profile for flaming fire activity (Sandberg and Peterson 1984; Ng and Walsh 2002). The profile consists of three phases – a rapid ignition phase in which the flaming area increases linearly, a steady state phase in which flaming area remains roughly constant, and an extinction phase represented by a linear decrease in flaming area (see Figure 21 for an example profile).</p>

With these issues addressed, the burn simulator was coded and tested. An overview of the simulator is shown in Figure 14. A burn simulation is able to generate estimates of total fuel consumption and hourly rates of carbon and heat release, as well as maps of the predicted burnt area. Carbon and heat emissions are calculated from fuel consumption in the same way as for bushfires. Limitations of the model and prediction uncertainties are discussed in section 5.3 of this report.

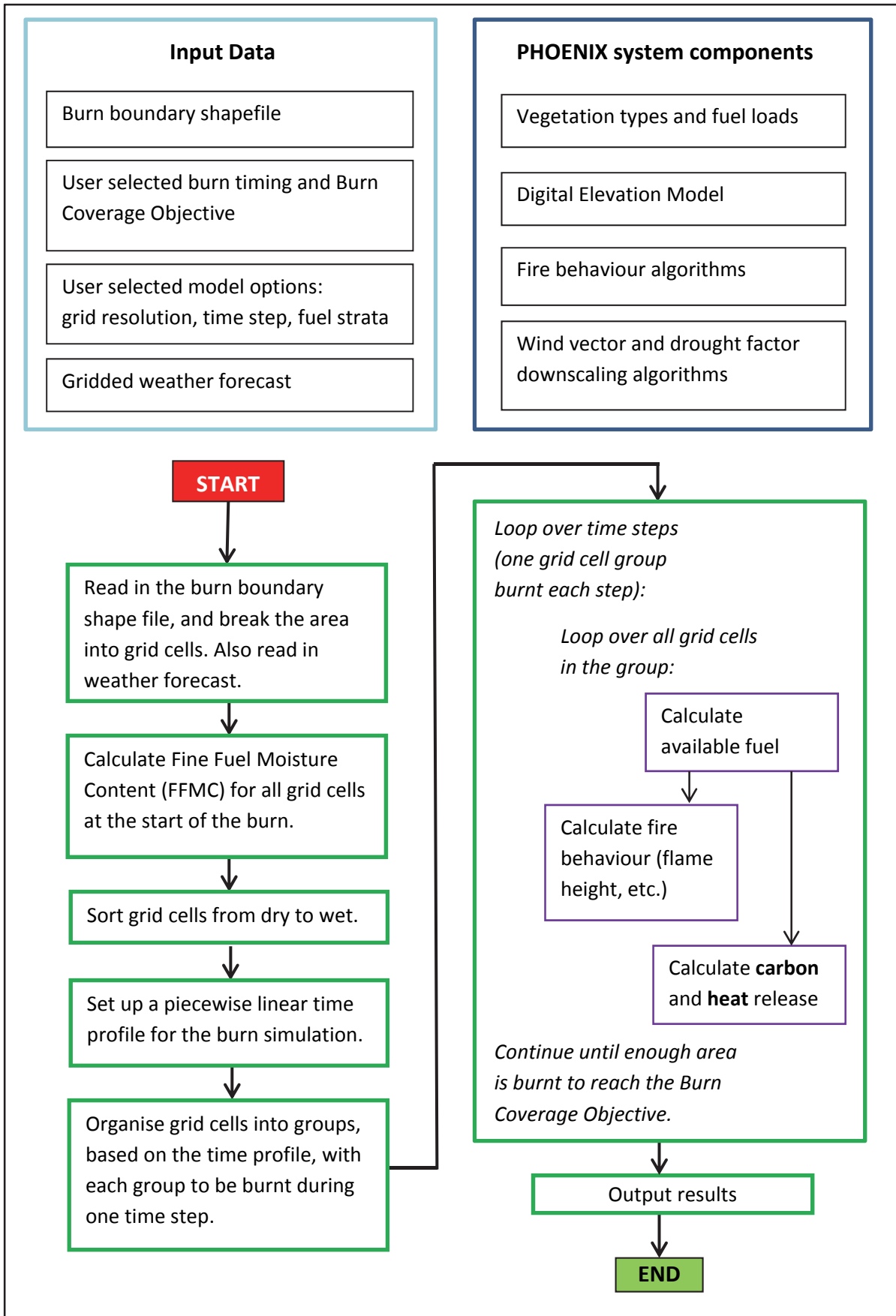


Figure 14: Overview of the system for modelling planned burn emissions.

## 4.2.2 Flame height and fireline intensity

As the burn simulator does not use fire propagation, fire behaviour calculations such as rate of spread, flame height and fireline intensity (Byram 1959) are not required in order to run the simulation. However, in order to provide information to assist with future research into fire behaviour and smoke emissions, estimates of flame height and fireline intensity are calculated and output along with carbon and heat emissions data.

In a PHOENIX bushfire simulation, flame height and fireline intensity are calculated using an adaptation of the McArthur Mk5 fire danger calculator (McArthur 1967). The calculations account for the interaction of slope and wind, and also allow for dynamic inclusion of elevated and bark fuels according to flame height.

This approach is not suitable for planned burns, which typically involve much lower fireline intensities, outside the range of applicability of the Mk5 fire danger system. Therefore, for the burn simulator, the Mk5 calculator was replaced with McArthur Leaflet 80 controlled burning guide (McArthur 1962). This guide is available in equation form (Gould 1994), making it suitable for use in simulation systems. Leaflet80 equations were integrated into the burn simulator, with some minor modifications:

- The simple fuel moisture model in Leaflet 80 was retained to ensure compatibility with the fire behaviour calculations, except for the addition of a smoothing function applied between the hours of 11 am and 1 pm, to avoid unrealistic discontinuities in the transition between the desorption phase (6 am - midday) and absorption phase (after midday); and
- For determining the wind speed at 1.5 m above ground, the simple wind reduction relationship in Leaflet80 was replaced with the PHOENIX Wind Reduction Factor, allowing the under-canopy wind speed to vary with different vegetation types.

Flame height and fireline intensity results are calculated for each model grid cell as it is burnt in the simulation, with average results determined for each time step. These values are then converted into hourly averages, which are output along with carbon and heat release data.

### 4.2.3 Example results

The burn simulator was tested against a case study (Henderson Creek, Otway Ranges, Victoria) for which detailed ground-based and satellite observations have been made (Loschiavo 2012). The burn boundary covered an area of 408 ha, within which a 343 ha study area was established. A ground-based GPS survey of the burnt edge was conducted, and RapidEye 5 m satellite imagery was obtained (Tyc et al. 2005) and processed by DEWLP staff to determine burn severity. The study area, observed burnt edge and burn severity data are shown in Figure 15.



Figure 15: Henderson Creek study area (yellow b), ground-observed burnt edge (black lines), and satellite-derived burn severity (grey=unburnt, green=surface burnt with minimal or no canopy scorch, brown=extensive canopy scorch).

Except for one section towards the south-east of the study area, there is good spatial agreement between the burnt area as observed by the ground survey and the severity assessment, which were conducted independently. Based on the ground survey data, 49.5% of the study area was found to be burnt.

Figure 16 shows estimated fine fuel loads (surface + near-surface) before the burn, using the PHOENIX fuel model. The majority of the area was burnt in the 1983 Ash Wednesday fires, with no recorded fire activity in the 29 years from 1983 to 2012, resulting in significant fuel accumulation. There are two vegetation (fuel) types in the study area, “*Wet forest with shrub & wiregrass*” (wet forest) and “*Forest herb-rich*” (foothills forest), with estimated fuel loads of 24 t/ha and 14 t/ha respectively.

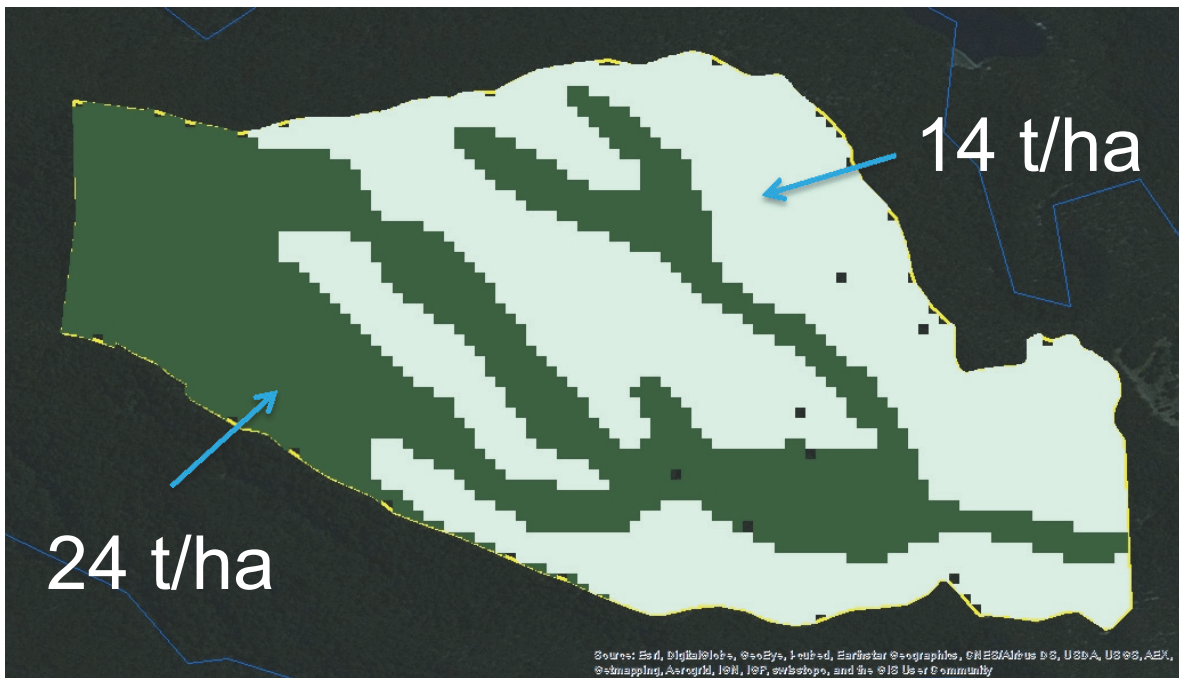


Figure 16. Model predicted surface + near-surface fine fuel loads.

The site includes a number of ridges and gullies, which can be seen in the topographic data used in PHOENIX (Figure 17). This data is used to derive slope and aspect, which are key inputs into fuel moisture and fire behaviour calculations.

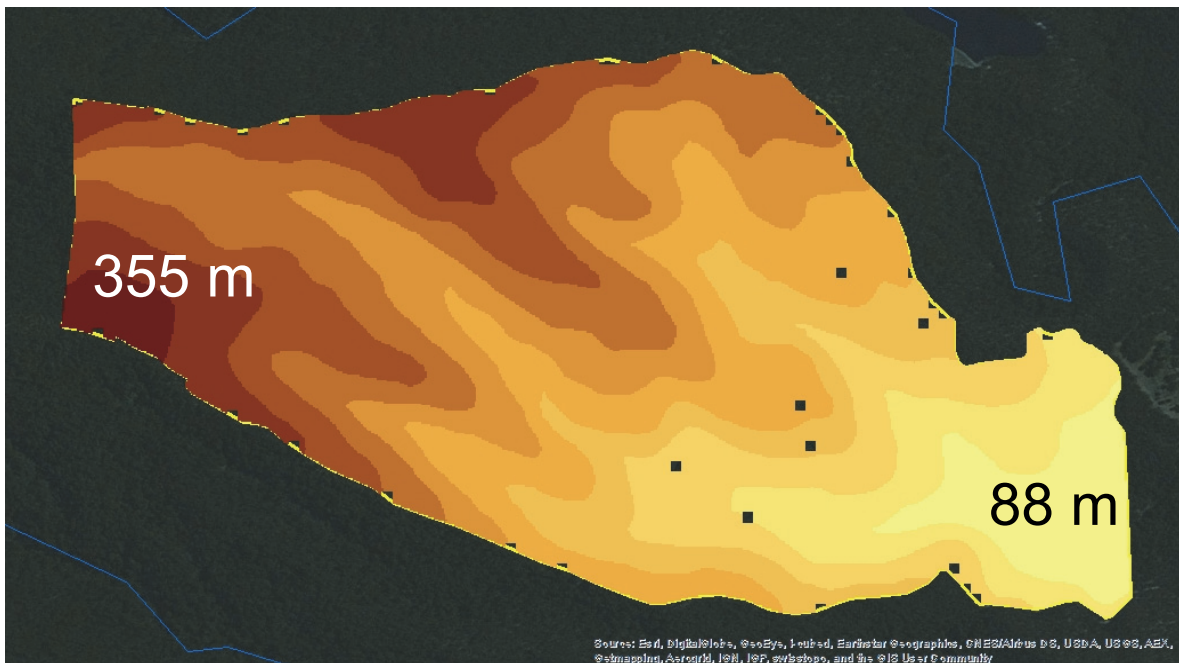


Figure 17. Digital elevation model.



Fuel availability was predicted to be highly variable across the site. Figure 18 shows the downscaled drought factor (0-10) at the start of the burn, with the highest values on north-facing slopes in the foothills forest type, and lowest values on south-facing slopes in the wet forest type.

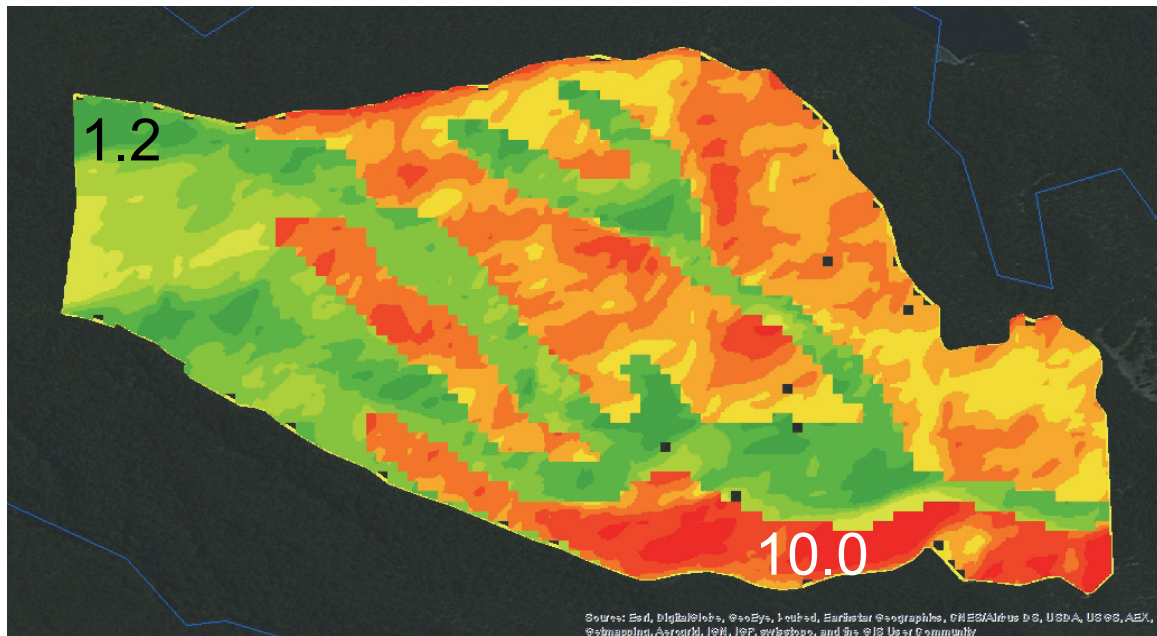


Figure 18. Predicted drought factor at the start of the burn.

Predicted fine fuel moisture content at the start of the burn is shown in Figure 19. The north-facing slopes towards the south of the site are predicted to be relatively dry, whereas the gullies within denser vegetation towards the west of the site are expected to be much wetter. The vertical artefact seen towards the middle-left of the image is actually the boundary of a grid cell from the gridded weather forecast, which supplies wind speed, temperature and humidity. Wind speed is downscaled in the model, but temperature and humidity are not, resulting in some minor discontinuities.

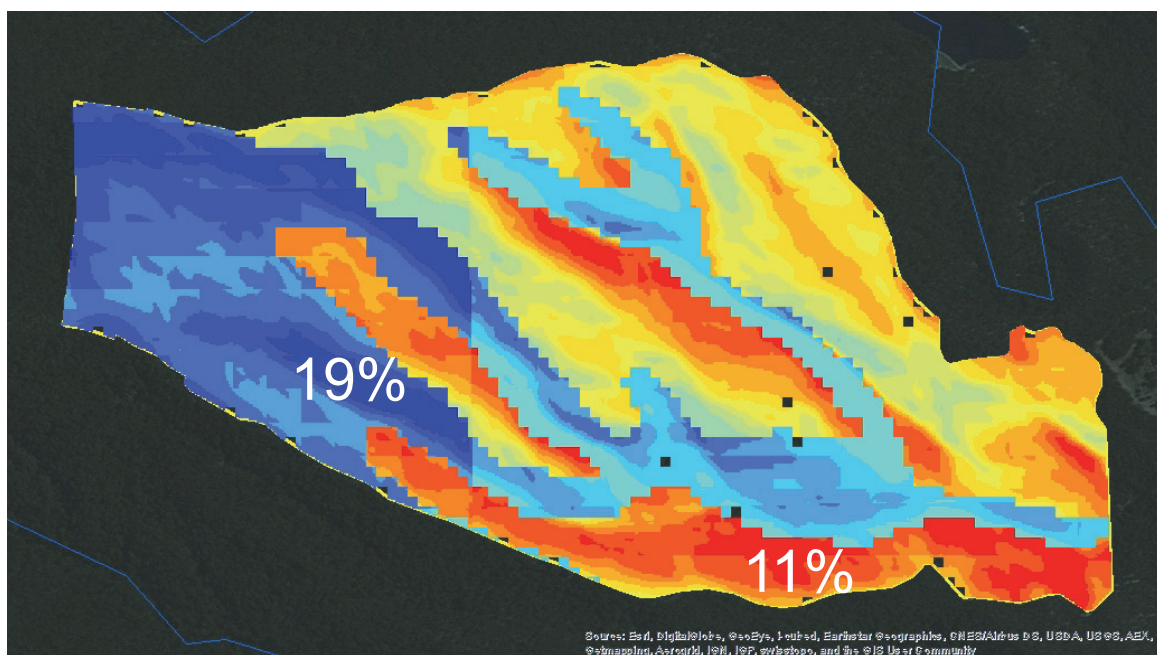


Figure 19. Predicted fine fuel moisture content (FFMC) at the start of the burn.

The first ignition for the 404 ha burn occurred at 11:55 am, but within the study area, the first ignition occurred at 1:00 pm, so the simulation was started at this time. This was actually a 2-day burn, but as the model is currently configured for single day burns only, the simulation was set up by assuming that all fuel was consumed on the first day (30<sup>th</sup> March 2012). This enables comparison of the model's spatial predictions with observed burn outcomes, although the predicted emission rates are likely to be higher than actual emission rates on the first day of the burn.

The simulation was set to run for 12 hours from 1:00 pm. Burn Coverage Objective (BCO) was set to 50% (the observed burnt fraction within the study area), with the intention of testing the model's spatial performance. The original burn coverage objective (specified in the burn prescription) was not suitable as input in this case, as it relates to the original 408 ha boundary, which is larger than the study area. A more comprehensive test of the model would involve checking predictions against burn outcomes for a range of burns under different conditions, using the original coverage objective values, but this has not been attempted here.

The default time step of 15 minutes was used, and default values were also used for the ignition time fraction (30%) and extinction time fraction (50%). The fuel strata selection was set to "S", so that only surface fuel would be burnt. The spatial resolution of the model was set to 5 m, to match the resolution of satellite imagery available for the site (Figure 15). Weather forecast files were chosen as the most recent predictions available prior to the burn, dated 29<sup>th</sup> March 2012 18:18 (UTC).

Figure 20 shows the burn boundary prediction, after running the model to completion, overlaid on the observed burnt area determined from the ground survey.

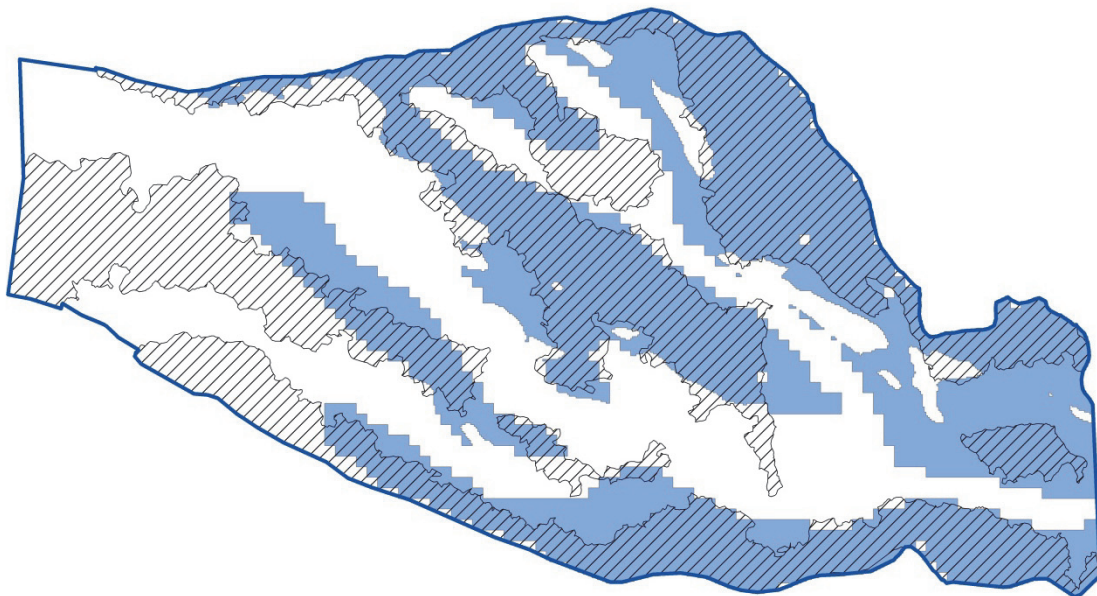


Figure 20. Predicted pattern of burnt area (blue), compared with ground-mapped burnt area (black lines).

The results show good agreement between the predicted boundary and the ground survey, except for the western area of the site, which was considered to have high fuel moistures in the model. Further investigation showed that this was because the vegetation in this area is a dense/wet forest type, and the shading factor assigned to this vegetation type is probably too high, particularly in north-facing areas<sup>2</sup>.

Figure 21 shows the model predicted time profile of flaming area and carbon emissions for the Henderson Creek simulation. The area of flaming activity (blue curve) is assumed in the model to follow a piecewise linear profile, with the breakpoints of the profile being user adjustable (defaults are 30% of time spent in the 'Ignition Phase', and 50% of time spent in the 'Extinction Phase').

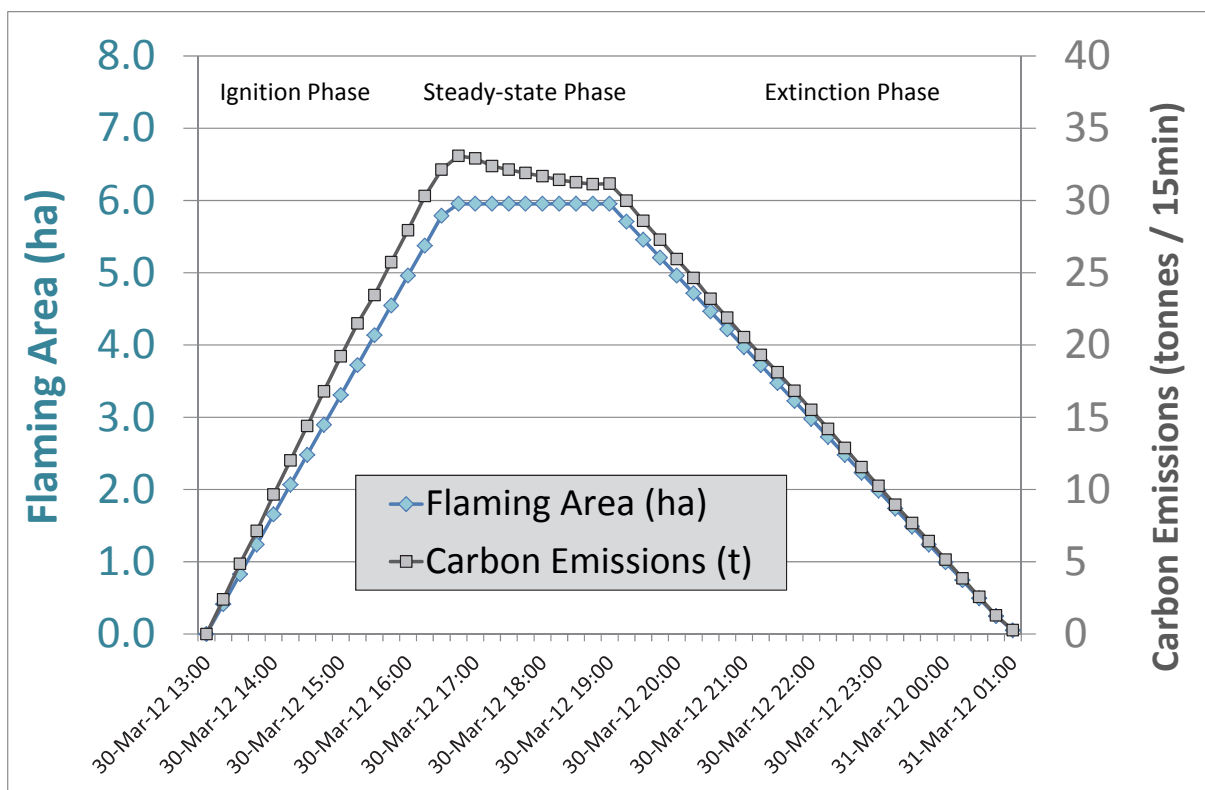


Figure 21: Henderson Creek burn - predicted time sequence of fire activity.

Because the fire simulation begins with dry areas and progresses to wet areas, the fire moves through areas of different fuel load and fuel availability. In this simulation (undertaken with a Burn Coverage Objective of 50%), the dry areas tend to have higher fuel availability (drought factor). This is why the rate of carbon emissions (grey curve) is higher during the early stages of the simulation.

Carbon and heat emissions results for each time step were then converted to hourly emission values (Figure 22).

<sup>2</sup> Further research is currently underway to improve the canopy shading algorithm. Early results indicate a significant improvement can be achieved in the spatial prediction for this case study.

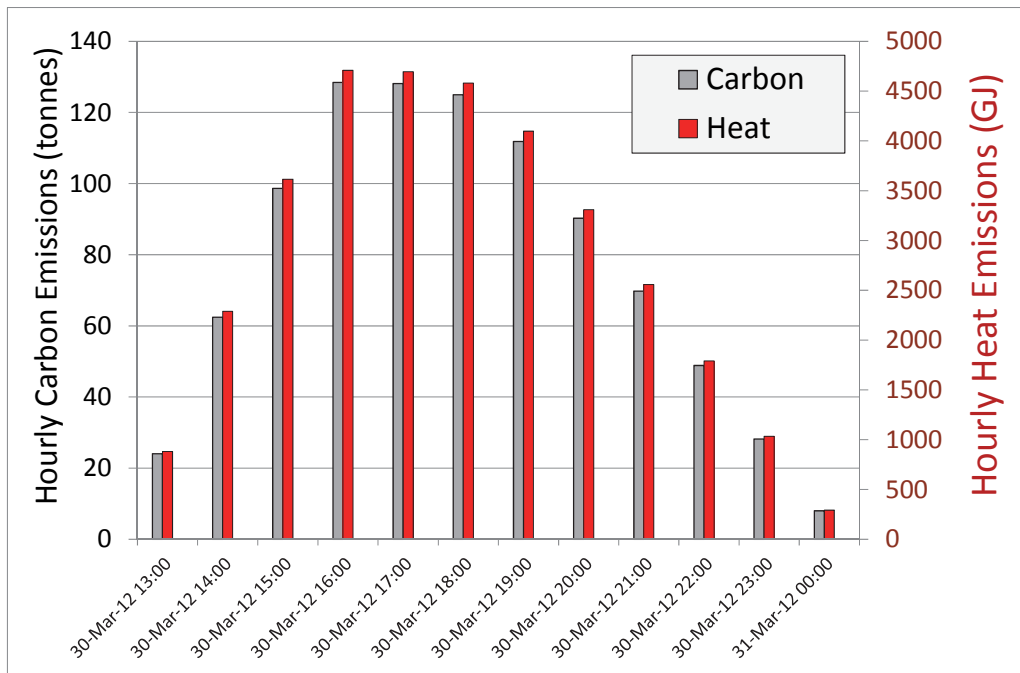


Figure 22: Henderson Creek burn - predicted hourly carbon & heat emissions.

No Australian data could be found to enable testing of the time profiles of carbon and heat emissions. In theory the total fuel consumption can be evaluated from field measurements of pre- and post-burn fuel loads, but this requires an exact consistency between the field method and the model definition of fuel, which is difficult to achieve in practice. For example, in the Henderson’s Creek study, litter fuel loads were carefully measured but near-surface fuel loads were not, thus complicating the comparison of measured fuel loads with the combined surface and near-surface data within PHOENIX.

Table 2 shows the total carbon and heat emissions predicted for the Henderson Creek burn. For comparison, results are also derived using the default fuel loading for forests in Victoria (7.22 t/ha) in the National Pollutant Inventory (NPI) Emissions Estimation Manual (EA 1999). For the NPI-based calculation, a 50% burn coverage was assumed, and commonly used values were chosen for carbon fraction (0.5) and heat yield (18,700 kJ/kg), with no correction for downward heat loss.

Table 2. Comparison of predictions with a simple NPI-based method

	PHOENIX FireFlux	NPI Emissions Estimation Manual
Total carbon emissions (tonnes)	924	618
Total heat emissions (TJ)	33.9	23.1

In this case, the prescribed burn simulator gives higher results than the NPI method because the total available surface fuel load within the simulated burnt area (after accounting for the drought factor) is estimated at 11.3 t/ha, which is higher than the NPI default fuel loading of 7.22 t/ha. Clearly, the burn simulator provides much greater flexibility in dealing with different vegetation types, although verification is needed to test predictions of total and available fuel across a range of forest types and weather conditions. Further work is currently being undertaken to identify suitable data from Victorian burns that will allow model verification.

## 4.3 Software implementation

### 4.3.1 Supported operating systems

The bushfire model and planned burn model have been combined together into a software package called **PHOENIX FireFlux** (v1.0.0.2, 4<sup>th</sup> May 2016). This software is available on Microsoft Windows 7 and LINUX, in the form of an executable file and a set of standard input data files. PHOENIX FireFlux operates via a command-line interface only, and does not contain a graphical user interface.

The LINUX version is available with scripts providing a simpler command-line interface. This version makes use of template XML files, which are edited automatically by the script to insert key details such as the user's chosen spatial resolution and weather forecast file. It also generates a log file which records the progress of the simulation, including diagnostic messages where necessary.

To make the code more portable across different platforms, some code changes were made, mainly to deal with different file pathname conventions (e.g. "/" is used in LINUX whereas "\" is used in Microsoft systems). However, these changes were not sufficient to make the software accessible on other platforms, because the code is written in .NET, a Microsoft-specific framework.

The problem of converting the software to LINUX was solved by using the "Mono" open-source .NET implementation, which supports LINUX, Android and other non-Microsoft systems (Easton and King 2004; Mamone 2005). Mono must be installed before the software will operate on a LINUX platform.

The model has been successfully implemented on the NCI (National Computational Infrastructure) *Raijin* supercomputer, and the University of Melbourne *Edward* supercomputer. These systems run CentOS LINUX.

### 4.3.2 Running the model – operation, inputs and outputs

Appendix A describes the command-line arguments used to control the two models provided in the software. The bushfire model can be operated by simply specifying a set of ignition points and a fire duration, but the planned burn model requires somewhat more detailed information, including a burn boundary and the expected timing, duration and area coverage of the burn.

As with the operational version of PHOENIX, the software also expects a number of key data files to be present to provide details of vegetation fuel, topography, barriers to fire propagation (such as roads) and fire history. The software makes use of standard gridded weather forecast files for Victoria which are available on a daily basis from the Bureau of Meteorology (BoM 2015).

The bushfire model outputs the following data:

- A CSV file containing carbon and heat emissions, fire activity centroid locations and fire behaviour parameters, aggregated over each hour (\*\_fire\_activity\_HOURLY.csv)
- A CSV file containing carbon and heat emissions, fire activity centroid locations, fire behaviour parameters and cumulative burnt area, aggregated over each model time step (\*\_fire\_activity\_TIMESTEPS.csv)
- A CSV file detailing the location of all the grid cells burnt during each model time step (\*\_fire\_activity\_BURNTCELLS.csv)
- Standard PHOENIX outputs indicating the spatial results of the prediction:
  - A Google Earth file (\*.kmz)
  - A static image of the fire prediction (\*\_img.png, \*\_img.pgw, and \*\_img.png.aux.xml)
  - If required, spatial output files (see SHPOPT setting in *run\_bushfire\_model.bash*):
    - Shapefiles containing the model predictions as grid cells (\*\_grid.shp, \*\_grid.shx, etc)
    - Shapefiles containing the model predictions as points (\*\_pts.shp, \*\_pts.shx, etc)

The planned burn model outputs the following data:

- The same three “fire activity” files described above (\*\_fire\_activity\_HOURLY.csv, \*\_fire\_activity\_TIMESTEPS.csv and \*\_fire\_activity\_BURNTCELLS.csv)
- Shapefiles representing the spatial model predictions (\*\_burn.shp, \*\_burn.shx, etc). These files summarise fire behaviour and landscape parameters for the burnt area. To see spatial information over the entire burn polygon, set the burn coverage objective to 100%.

### 4.3.3 Software ownership

The PHOENIX model and its derivatives are jointly owned by the Department of Environment, Land, Water and Planning (50%), the University of Melbourne (25%) and the Bushfire & Natural Hazards CRC (25%). This software is copyright and must not be copied or distributed without permission from the owners.

## 5. Prediction uncertainty and model limitations

### 5.1 Underlying system components and data

The emissions models presented in this study rely on an adequate representation of vegetation fuels, and on assumptions about which vegetation elements are consumed by fire and converted to carbon and heat.

Vegetation types in PHOENIX are represented by broad fuel types (Tolhurst et al. 2012), but there may be significant variation in the extent of live and dead fuels due to local micrometeorology, and extended interface zones (ecotones) between vegetation types. Apart from the downscaling of drought factor (fuel availability) using slope and aspect, very little of this fine-scale variation is represented in the model. Vegetation types are mapped at 30m resolution across Victoria, which should be adequate for most applications.

The fuel accumulation curves used in PHOENIX require accurate information on time since the last fire. This is coded in the “Fire History” input file, which needs to be kept up to date by the software operator. The time since last fire is used in separate fuel accumulation calculations for surface fuel (which includes near surface), elevated fuel and bark fuel.

The models also rely on a gridded weather forecast, in the Australian Digital Forecast Database format (BoM 2015). A standard forecast includes temperature, relative humidity, wind speed and direction, cloud cover, grass curing, drought factor (fuel availability) and the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968). Due to the nature of numerical weather forecasting, uncertainty in some parameters (such as KBDI and drought factor, which are dependent on rainfall) may be higher than for other parameters.

Within PHOENIX, forecast wind vectors are downscaled to account for the effect of hills and gullies on airflow, using a mass-balance method (Forthofer, Shannon, and Butler 2010). The forecast drought factor is downscaled using a function of vegetation type, KBDI, slope and aspect, in order to represent the increased fuel availability on dry north-facing and north-west-facing slopes. No attempt is made to downscale cloud cover, grass curing, KBDI or temperature.

More details about the input data and assumptions used in the PHOENIX model can be found in a Bushfire CRC report (Tolhurst, Chong, and Pitts 2007). These limitations must be kept in mind when using the PHOENIX FireFlux system for predictions of carbon and heat emissions from fires.

### 5.2 Bushfire model

Modelling the future development of a bushfire contains inherent uncertainties. This is partly due to uncertainties in the input data (such as weather forecasts and fuel loads), but also due to the highly non-linear nature of fire propagation, which can make simulations sensitive to initial conditions (Dunn 2007).

In a fire model, the internal representation of key processes can also affect model uncertainty. For example, in a severe bushfire where the seeding of spot fires is a major factor, the development of the fire will be sensitive to the rate of ember production (Rochoux et al. 2014) and the probability of an ember igniting a spot fire, which is affected by fuel moisture and local wind speed (Ellis 2015). Simulations will therefore be sensitive to the internal parameterisation of these processes.

A common source of uncertainty in bushfire simulation is the initial fire location. For example, an observer who is travelling on a road may see a smoke plume, but be unable to estimate the actual fire location. In this situation it is common for the fire location to be recorded as occurring on the road, or at a nearby intersection. If such a location is used directly as the ignition point for a simulation, then depending on the accuracy of the location record, it may result in a fire being started very close to the road but on the upwind side, causing the fire to spread a short distance before being extinguished by the road barrier. This and other problems are addressed in operational fire forecasting by employing specialist Fire Behaviour Analyst (FBAN) staff, who review inputs to simulations, and verify and approve forecast outputs before they are used in decision making.

The accuracy of weather forecasts can significantly affect fire predictions, and one approach is the use of an automatically generated weather ensemble (Finney et al. 2011). However, the full range of uncertainty in a fire prediction will be larger than that associated with weather variations (Salvador et al. 2001; Bachmann and Allgöwer 2002; Jones, Garvey, and Hunter 2004; Cruz and Alexander 2013). Some work has been undertaken to examine the sensitivity of PHOENIX fire predictions to factors such as ignition location, ignition time, model resolution, fuel load and weather, showing complex interactions between wind and slope in forest fire simulations (Chong et al. 2013).

The bushfire model assumes that once flame heights reach 1 m, elevated and bark fuels will be accessible to the fire, and that for flame heights above 2 m, all elevated and bark fuels will be consumed. This assumption is likely to be reasonable for many forest types, except for heathlands with very low canopy heights, and wet forests with a very tall shrub layer. Also, in a bushfire that has developed into a crown fire, some or all of the canopy biomass will be consumed, but as canopy fuel loads are not represented in the model, this component will be missing from the emission estimates.

The model of emissions presented here considers only flaming phase fuel consumption, and only includes fine fuel (Tolhurst and Cheney 1999). In severe bushfires, the greatest level of fire activity will occur on a small number of days during which fire weather is extreme, which is often only a single day. Therefore, in terms of the overall smoke emission rate, it is likely that emissions based on the flaming phase consumption of fine fuel should provide a good approximation to the highest smoke emission rates during a rapidly developing bushfire. Predictions are likely to be less accurate for prolonged fire events involving significant coarse fuel consumption.

Note that the perimeter-ignition feature in version 1.0.0.2 of the software is based on a rarely-used feature of PHOENIX RapidFire, and as such needs to be used with some care. So long as input perimeters are clockwise polygons, fire propagation will always be outward from the perimeter. However, there is a known limitation with PHOENIX perimeter ignitions, which can result in a small number of embers being generated from backing fire, which subsequently land within the perimeter causing a small amount of fire activity in already burnt ground. The net contribution to carbon and heat emissions is generally very small. For long running fires, ignition from an observed perimeter is likely to generate much more accurate predictions than starting from a point some days prior.



A further important consideration is that bushfires are often subject to active fire suppression. Whilst PHOENIX includes features to enable simulation of suppression, the current configuration of the model assumes that no suppression will be applied. This should be a reasonable approximation for very large and severe fires, for which suppression is often ineffective. For less intense fires where suppression is more successful, the model may generate an overestimate of flaming phase fine fuel consumption and smoke emissions.

### 5.3 Prescribed burn model

The burn simulator uses a simplification of the original Matthews fuel moisture model (Matthews, Gould, and McCaw 2010) which does not accept rainfall as input, but instead calculates the dynamic exchange of moisture between the fuel and the atmosphere. This means the absolute values of predicted fuel moisture content may be too low (dry) in the days after recent rain. However, fuel moisture predictions are only used here in a relative spatial sense to decide on a burn sequence, so there is likely to be little impact on burn model predictions.

The simulator is best suited to medium to large sized burns, where the ignition process is likely to follow a broad strategy. For small burns which are intensively managed because they are close to residential areas or other sensitive land uses, the model is unlikely to be able to predict the pattern of burnt area (unless the Burn Coverage Objective is very high). Intensively managed burns can include special interventions including highly customised ignition patterns, and sprinklers to protect specific areas. For these burns, a conservative (upper) estimate of carbon and heat emissions can be obtained by using a Burn Coverage Objective of 100%.

As the simulator does not attempt to predict which way a fire will propagate (for example, down or up a particular slope in the landscape), flame height and fireline intensity data need to be treated with caution. These results are best used in a relative rather than absolute sense. For example, the spatial pattern of predicted fireline intensity will reflect variations in fuel load and fuel availability, but will not be able to represent the effect of the burn controller's decisions about the type of fire to use (backing, flanking or head fire), or ignition point spacing. Similarly, temporal variations in weather will be represented in changes in predicted fire behaviour during the burn, but the results will not reflect variations in how fire has been applied over this time.

A further limitation is that the sequence of the burn is determined only by an initial map of fuel moisture at the start of the burn. During the progress of a burn, some areas that were initially 'wet' may become 'dry', resulting in differences between the model representation and the true pattern of fuel moisture. This can be overcome to some extent by adjusting the scan time, which is one of the command-line arguments available in the model (see Appendix A).

As the burn model uses a simple piecewise linear function to represent fire activity, and assumes that the user can specify the burn start and end time, there is likely to be some uncertainty associated with the timing of the burn, and the rate of fuel consumption. This aspect of model operation will require significant expert judgement. The two breakpoints in the piecewise linear function (Figure 21) can be adjusted through command-line arguments, which may be useful in representing differences between burns in terms of the intensity of ignition effort.

Finally, a fundamental assumption of the burn simulator is that the Burn Coverage Objective (specified in advance of the burn) will accurately reflect the proportion of area burnt within the boundary. Often this objective is specified in the burn prescription as a range of values, reflecting the difficulty of achieving a precise level of coverage. The uncertainty associated with the coverage objective can be represented by running an ensemble of simulations with different BCO values specified via the command-line interface.

## 5.4 Model verification – issues and challenges

The bushfire and prescribed burn emission models presented here are to be considered preliminary and approximate in nature, with significant future work required to determine model accuracy against experimental data.

A number of Australian studies have measured and characterised smoke downwind from bushfires (Meyer et al. 2012; Walsh 2004) and planned burns (Ross et al. 1980; Reisen, Meyer, and Keywood 2013; Reisen et al. 2011). Direct plume samples can also be taken from the edge of low intensity fires (Hansen et al. 2007). However, very few estimates are available for the smoke emission rates from an entire fire.

As direct measurement of the total fire emission rate is not practical, indirect estimation methods are needed. One costly but effective approach is to use aircraft-based measurements to sample a plume cross-section, which can be combined with wind measurements to estimate a pollutant flux. Assuming no chemical loss, conservation of mass can be used to derive the rate at which the pollutant is emitted from the ground (Ward and Radke 1993; Hurst et al. 1994).

Bushfire reconstructions may be useful for mapping the progress of a large fire front, enabling comparisons with model-predicted fuel consumption rates, although that has not been attempted here. Remote sensing data may also be useful for tracking bushfires, particularly a new geostationary satellite with 10-minute temporal resolution (JMA 2015).

For planned burns, aerial surveys during the burn would provide key information on the progress of fire activity. Ground-based surveys of pre- and post-burn fuel load would also provide critical information about the total amount of fuel consumed (and thus the amount of smoke emitted), but these need to be conducted in a manner that is consistent with the PHOENIX fuel data. In particular, near-surface fuel loads need to be included as well as surface (litter) fuels, and for more intense burns, elevated and bark fuel loads will also need to be quantified.

## 6. Conclusions and recommendations

### 6.1 Key outcomes and findings

This project component has achieved a number of outcomes:

- An established bushfire simulator has been used to generate information on carbon and heat emissions during the progress of a simulated forest fire or grass fire;
- A new model has been developed which uses fuel moisture calculations, forecast weather and end-user constraints to simulate the progress of a planned burn, allowing calculation of carbon and heat emission rates; and
- The software has been successfully converted to LINUX and implemented on the target platform (Raijin).

In the process a number of knowledge gaps have been identified:

- There is a need for more comprehensive experimental data on overall smoke emission rates from Australian bushfires and prescribed burns, to support model verification.
- The net heat yield from burning forest fuels is often assumed to be a constant, however there may be variations associated with fuel moisture content, differences between flaming and smouldering phases, and the dynamic effects of downward heat loss to soil and unburnt surface materials, which need further experimental and theoretical investigation.
- A number of studies have identified that flaming and smouldering combustion result in different smoke chemical profiles, however little information is available on the effect of variations *within* flaming fire activity (e.g. low intensity vs high intensity prescribed burns.)
- The ignition of a planned burn is a complex process involving the use of guidelines and expert judgement, but few records have been kept of the fine details of ignition locations and times, and it is unclear if the chosen ignition patterns vary from expert to expert (given the same conditions).

### 6.2 Recommendations for further development

The accuracy and range of applicability of the models presented in this project may be enhanced through further development.

For the bushfire model, it is suggested:

- that fire-weather interactions are considered, to the extent that they affect smoke production, heat release and plume buoyancy (Achte-meier, Goodrick, and Liu 2012; Kochanski et al. 2015);
- that research is undertaken to examine the effect of bushfire suppression on fire propagation, smoke emission rates and smoke chemistry (Kalabokidis 2000); and
- that the model be enhanced to run ensemble forecasts, where ensemble members are automatically generated to vary ignition location, key model parameters (such as spatial resolution) and weather (if external ensembles are not available).

For the planned burn model, it is suggested:

- that alternative ignition strategies are explored, including burning from high fuel availability to low fuel availability, and multi-stage strategies such as burning the perimeter followed by burning from high elevation to low elevation (a method commonly used on larger burns);
- that alternative sequencing approaches are considered, such as the use of FFDI instead of time for sequencing the burn (i.e. burn areas of low fuel moisture at times of lower FFDI, and areas of high fuel moisture at times of higher FFDI);
- that burn coverage objectives are verified against burn outcomes to determine the extent of variation from the target, or as an alternative approach, that the model is configured to burn until a threshold of fuel moisture is reached, which would avoid the need for a coverage objective, but would require significantly greater accuracy in FMC predictions;
- that research is undertaken to find methods for predicting whether head fire, flank fire or backing fire will be used at each location within the burn;
- that the model is extended to simulate multi-day burns, by repeating the fuel moisture scan at appropriate intervals during the simulation, and recreating the sequence for burning the remaining grid cells; and
- that the use of fire propagation simulation be explored, by including additional physics relevant to planned burns (such as the junction zone effect), and developing methods for automatically predicting a range of plausible ignition patterns for a specific burn.

For both models, it is suggested:

- that carbon and heat release rates are experimentally verified, using a range of methods including ground and satellite observations of smoke plumes, downwind measurements of smoke concentrations, and (where possible) direct measurement of plume composition;
- that fine fuel loads for each vegetation type are experimentally verified, considering both total fuel load and fuel availability under various weather and fuel moisture conditions;
- that models of coarse fuel load accumulation and coarse fuel availability are developed and verified in a range of forest types;
- that the dynamics of smouldering phase emissions be included (Ward and Hardy 1991; Ferguson and Hardy 1994; Urbanski 2014), with quantification of smouldering combustion rates for both coarse fuel and the wetter layers of fine fuel; and
- that current techniques for downscaling weather and fuel moisture be further refined, to examine fine-scale environmental and landscape factors such as:
  - Localised rainfall, runoff and throughfall, which affect the wetting of forest fuels;
  - Canopy height and density, which affect solar radiation reaching the ground, a key influence on the drying of forest fuels; and
  - Under-canopy temperature, humidity and wind speed at various heights, which affect fire behaviour and the moisture dynamics of surface, near-surface and elevated fuels.

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## 8. Appendix A – Software user interface

### 8.1 Bushfire Model (LINUX version)

#### Usage

```
run_bushfire_model.bash JOBNAME POINTCSV  
                        [PERIMETERCSV [RUNHOURS [RESOLUTION [WEATHERDIR]]]]
```

**JOBNAME** = Your chosen name for this run (no spaces or non-alphanumeric characters; underscores are OK). The main purpose of this is to give sensible names to the output files.

**POINTCSV** = Name of the CSV file containing point ignitions.

The file must have a header, and contain one file per ignition. Each location will be considered a separate ignition. If DateTime is not supplied, then the current computer system datetime will be used for the ignition.

If you want to run with a Perimeter ignition only, with no points, set this argument to "NONE".

Format of POINTCSV file:

```
HeaderLine (must be present, but content does not matter)  
Longitude,Latitude[,DateTime]  
Longitude,Latitude[,DateTime]  
Longitude,Latitude[,DateTime]  
...
```

**PERIMETERCSV** = (OPTIONAL) Name of a CSV file containing PERIMETER ignitions for the simulation.

This file must have a header, then describe each perimeter ignition, starting with the keyword "PERIMETER" and ending with the keyword "END".

The points in a perimeter must form a CLOCKWISE POLYGON, ideally a closed polygon. Each perimeter ignition should have a datetime, on the same line as the PERIMETER keyword, separated by a comma, but if this is missing, the current computer system date will be used.

If this parameter is left blank then the system will use the point ignition file only. If both point and perimeter ignitions are provided, then both sets of data will be used in the simulation. If you don't want to provide a perimeter file but want to use subsequent optional command line arguments, set this parameter to "NONE".

**NOTE** : For the simulation to work, there must be either a POINTCSV file, a PERIMETERCSV file, or both files provided.

Format of PERIMETERCSV file (each perimeter must run clockwise):

```
HeaderLine (must be present, but content does not matter)
PERIMETER[,DateTime]
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
END
PERIMETER[,DateTime]
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
Longitude,Latitude
END
...
```

**RUNHOURS** = (OPTIONAL) Number of hours to run the simulation for.  
This can be a fraction, e.g. 1.5 = 90 minutes. If this argument is not supplied, the model will run for 12 hours.

**RESOLUTION** = (OPTIONAL) Phoenix model grid resolution, defaults to 180m.

**WEATHERDIR** = (OPTIONAL) Override the default location for weather data. By default this script will set up the weather directory so that the latest GFE files are used (i.e. most up to date forecast).

### Example

```
run_bushfire_model.bash Mickleham.csv NONE 5.0 180 ~/WEATHER/2014-02-10
```

## 8.2 Planned Burn Model (LINUX version)

### Usage

```
run_planned_burn_model.bash JOBNAME BOUNDARY STARTDATE STARTTIME DURATION COVERAGE
                             [BURNSTRATA
                             [IGNITIONFRAC
                             [EXTINCTNFRAC
                             [RESOLUTION
                             [SCANTIME
                             [TIMESTEP
                             [WEATHERDIR]]]]]]]
```

**JOBNAME** = Your chosen name for this run (no spaces or non-alphanumeric characters; underscores are OK.) The main purpose of this is to give sensible names to the model output files.

**BOUNDARY** = Name of the set of ESRI SHAPE files that define the boundary of the target area. Must include the .shp extension.

**STARTDATE** = Date of first ignition, in the format dd-mmm-yyyy or dd/mm/yyyy

NOTE: This date can be anytime in the future, so long as you have a weather forecast available in the gridded weather (GFE) file.

**STARTTIME** = Time of first ignition, in the format hh:mm (24 hr clock) in LOCAL TIME

**DURATION** = Expected burn duration, as number of hours of flaming fire activity.

**COVERAGE** = Intended % of the target area to be burnt (Burn Coverage Objective). If the Burn Prescription involves a range of values (e.g. 40%-59%), use an average, or run the model more than once.

**BURNSTRATA** = (OPTIONAL) Fuel strata to include in the fire. Each type of fuel is represented by a single character, S=Surface,E=Elevated, B=Bark,G=Grass. Default is S (Surface fuel only). Examples:

```
SE = Surface + Elevated
SEB = Surface + Elevated + Bark
SB = Surface + Bark
SEBG = Surface + Elevated + Bark + Grass
```

**IGNITIONFRAC** = (OPTIONAL) Fraction of flaming hours in "ignition" phase (linear ramp-up). This should be a number between 0.0 to 0.95. Default 0.3 (30%)

**EXTINCTNFRAC** = (OPTIONAL) Fraction of flaming hours in "extinction" phase (linear ramp-down). This should be a number between 0.05 to 1.0. Default 0.5 (50%)

**RESOLUTION** = (OPTIONAL) Phoenix resolution, defaults to 30m. If you make this too small, you will run out of memory. If you make this too large, the burn profile algorithm will break down and you will see warnings and errors in the log file.

**NOTE:** To run at resolutions finer than 25m on Raijin, you need to clip the fuel layer to the burn boundary, to reduce memory usage. Clipping the fuel layer has to be done manually and requires editing of the XML file.

**SCANTIME** = (OPTIONAL) When to undertake the initial fuel moisture scan, in hours from the start of the burn. Used to decide what areas to burn first. Defaults to 0.0 hours (i.e. start of burn).

**TIMESTEP** = (OPTIONAL) Time step for burn simulation in minutes. Defaults to 15 minutes. Do not make this too small, or the burn profile algorithm will break down and you will see warnings and errors in the log file.

**WEATHERDIR** = (OPTIONAL) Override the default location for weather data. By default this script will set the weather directory so that the latest GFE files are used (most up to date forecast).

## Examples

**run\_planned\_burn\_model.bash MyBlock MyBoundary.shp 30-Mar-2015 11:55 12 59 SEB**

This will run a simulation starting at 11:55am on 30th March 2015, running for 12 hours with a burn coverage objective of 59%, and including surface, elevated & bark fuels.

**run\_planned\_burn\_model.bash SmallBlock Small.shp 15/4/2015 13:00 8 100**

This will run a simulation starting at 1:00pm on 15th April 2015, running for 8 hours, with a burn coverage objective of 100%, burning only surface fuel.

**run\_planned\_burn\_model.bash LargeBlock Big.shp 2-Apr-2014 13:30 16.5 35 SE 0.5 0.4**

This will run a simulation starting at 1:30pm on 2nd April 2014, running for 16 hours, with a burn coverage objective of 35%, burning surface & elevated fuel, and with the first 50% of the burn in ignition phase (linear ramp up of flaming area), and the last 40% of the burn in extinction phase (linear ramp down, fires gradually going out).

### 8.3 Operating the Windows 7 version

To operate the Windows 7 version, type the name of the executable file and you will be given a list of command-line options. Using the model this way is not straightforward as an XML file must be prepared with suitable settings (including weather, grid resolution, simulation date-times etc).

Also, for bushfire modelling, the point and perimeter ignition CSV files are not specified to the executable via command line arguments; instead the model looks for specific file names. These file names must be constructed by appending the strings `_POINT.csv` and `_PERIMETER.csv` to the stem of the project XML file name, e.g. `TEST.xml`, `TEST_POINT.csv` and `TEST_PERIMETER.csv`.

Please contact the University of Melbourne if further assistance is required.

```
*****
*
*      >>>>>>>>>      PHOENIX FireFlux v1.0.0.2      <<<<<<<<<<<<      *
*
*      Incorporating:      *
*
*          > PHOENIX RapidFire 4.0.0.8 bushfire simulator      *
*          > Prescribed burn simulator - beta version      *
*          > Carbon and Heat fluxes      *
*
*      (C) University of Melbourne, 2015,2016      *
*
*****

USAGE:

PH_FireFlux.EXE /FIRE CONTROL.XML [Duration_Hrs]

or :

PH_FireFlux.EXE /BURN CONTROL.XML Boundary.SHP StartDate
          StartTime Duration_Hrs Burn_Coverage_Objective_%

          [Strata to Burn(S[E][B][G])
          [Fraction of burn hours in ignition phase
          [Fraction of burn hours in extinction phase
          [Time of initial fuel moisture scan (hours from start)
          [Time Step in minutes
          [Fire Type for output files (B/F/H) ]]]]]]
```