Review of Fire Growth Simulation Models for Application in New Zealand

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EXECUTIVE SUMMARY

New Zealand fire managers have expressed a desire for a spatial fire growth simulation tool to support operational and strategic fire management decision-making.

Fire growth simulation models combine spatial data on fuel types and terrain influences, and temporal data on changing weather and fire danger conditions, with fire behaviour prediction models to simulate the spread and development of fires across the landscape. A wide array of fire growth simulators are available from around the world, that utilise a range of different modelling approaches and underlying fire behaviour prediction systems to simulate fire spread. These differences are the result of the models having been developed to operate in contrasting fire environments and for a wide range of different applications. Few, if any, of these fire growth models are capable of being transferred to another country without some form of modification, due to differences in vegetation and associated fuel type classification, fire danger rating systems and fire behaviour prediction models.

As part of the proposed development of a New Zealand fire growth model, the objective of this report was to review the suitability of available fire growth models for modification and use in New Zealand. Nine models were identified for detailed review: the USDA Forest Service’s Farsite model; Prometheus, the Canadian wildland fire growth model; the Portable Fire Growth Model of Shamir; Networked Fire Chief, La Trobe University’s incident management fire scenario simulator; the University of Western Australia’s Fire Simulation Model under development within the Bushfire CRC; SiroFire, Australia’s first fire growth model developed by CSIRO; Phoenix, the successor to SiroFire also being developed within the Bushfire CRC; Wildfire, a New Zealand fire growth modelled developed by Dr Gavin Wallace in the early 1990s; and Pyrocart, a fire growth model developed for New Zealand vegetation types by Dr George Perry (now at Auckland University). The latter model was included as an example of numerous international cell-based fire growth models, and more appropriate or advanced models that utilise this approach are probably available. Several other New Zealand fire growth modelling applications were also considered, but were discounted due their incomplete nature, limited scientific basis and lack of operational application/evaluation.

In addition to determining the required data inputs (for fuels, weather, topography and fire behaviour) and operating requirements (i.e. computing and GIS compatibility), evaluation of the available models included reviewing the simulation and fire behaviour modelling approaches employed and their ‘robustness’ (scientific validity, operational implementation). The capacity for, and ease and likely cost of modification of each model for use in New Zealand was also considered. Other important factors also included each model’s intended purpose, and range of applications to which it had or could be applied, and the availability of ongoing model support. The nine models were then qualitatively ranked on the basis of these factors.
Of the nine models that were compared, the *Prometheus* model ranked highest in terms of the required features. However, this was closely followed by the *Phoenix* and *Farsite* models, with all three being developed and accepted models that offer a wide range of applications and ongoing support. *Prometheus* was favoured on the basis that it already contains the weather, Fire Weather Index inputs and fire behaviour prediction approach used in New Zealand, and only minor changes would be required to these modules (as demonstrated at a workshop in 2006) compared with the need to fully add these components to the *Farsite* and *Phoenix* models. Despite very similar rankings, *Phoenix* is also probably favoured over *Farsite* due to its simplicity and therefore likely easier adaptation, and the perceived desire for commonality across Australasia. The existing New Zealand models, *Wildfire* and *Pyrocart* (or similar), offer some potential for updating and upgrading, but major and potentially costly modifications would be required and ongoing support questionable. The remaining models were not considered suitable for adaptation or widespread use in New Zealand due to a lack of ongoing technical support, limited range of applications, and incompatibility with input fuel, terrain and fire behaviour data used in New Zealand.

Modification of the *Prometheus* model therefore appears to present the best pathway forward for development of a fire growth simulation model for use in New Zealand. However, this evaluation was undertaken from a research perspective and based on the perceived needs of end-users. For example, geographical and political links between New Zealand and Australian fire management agencies and research institutions provide some rationale for adopting a common tool in both countries to support fire management decision-making for operations and planning. The *Phoenix* model, which is being developed through the Bushfire CRC and is likely to become the model of choice in Australia, may therefore warrant further, more detailed investigation to determine whether it should provide the basis for the New Zealand fire growth simulation model. An end-user project team therefore needs to be established to clearly establish the model requirements and intended applications, as well as the project terms of reference and budget. The latter, in particular, may dictate which of these suggested approaches (i.e. *Prometheus* vs. *Phoenix*) is feasible, and whether end-user expectations can be met within the funding available.

**Recommendations**

- Establish a project team of end-users and scientists to guide the development of the New Zealand fire growth model and ensure that end-user's needs are met. This project team will provide the essential perspectives on operational needs and play a key role in establishing the pathway for development of a New Zealand model.

- Develop a detailed Project Plan and project team Terms of Reference, complete with project budget, to clarify the project scope and objectives. This should include identification of the known applications the model will be used for, as well as required and preferred model components (e.g. fire suppression, gridded wind, etc.).
• Undertake a more detailed review of the top ranking models (i.e. *Prometheus* and *Phoenix*) to better determine the advantages and disadvantages of each model for modification. This should include preparation of detailed costings for the modification of each model.

• Identify a key end-user organisation to participate in the development and pilot implementation of a beta-version of a New Zealand fire growth simulation model. This includes securing the necessary agency support, budget and personnel resources (i.e. fire management staff and GIS specialists) to conduct this work.

• Undertake a pilot trial to test and validate a beta-version of the developed model in an operational setting with at least one key end-user.

• Develop a technology transfer programme to assist delivery and operational implementation of the New Zealand fire growth model, and the ongoing need for technical support.
# TABLE OF CONTENTS

EXECUTIVE SUMMARY ........................................................................................................... i
Recommendations .................................................................................................................... ii

INTRODUCTION ......................................................................................................................... 1
Report scope .............................................................................................................................. 1

BACKGROUND .......................................................................................................................... 2
Terminology and modelling techniques ................................................................................. 2
Potential uses of fire growth models ...................................................................................... 5
Fire growth modelling in Australasia ....................................................................................... 6

REVIEW OF AVAILABLE MODELS ...................................................................................... 8
Farsite – Fire Area Simulator ................................................................................................. 8
Prometheus – the Canadian Wildland Fire Growth Model ....................................................... 9
Portable Fire Growth Model ................................................................................................. 11
Networked Fire Chief ............................................................................................................ 12
UWA Fire Simulation Model ................................................................................................. 13
SiroFire ..................................................................................................................................... 14
Phoenix .................................................................................................................................. 14
Wildfire ................................................................................................................................. 15
Other models .......................................................................................................................... 16

INPUT REQUIREMENTS FOR FIRE GROWTH MODELLING .............................................. 19
Topography ............................................................................................................................. 19
Fuels ....................................................................................................................................... 19
Weather ................................................................................................................................ 20
Fire behaviour models .......................................................................................................... 21
Fire suppression models ........................................................................................................ 22

RESULTS AND DISCUSSION ............................................................................................. 22
Ranking of reviewed fire growth models .............................................................................. 22
Pathway for development of a N.Z. fire growth model ......................................................... 26

CONCLUSION AND RECOMMENDATIONS ..................................................................... 28
Recommendations .................................................................................................................... 28

ACKNOWLEDGMENTS ........................................................................................................... 29

REFERENCES ....................................................................................................................... 30
Information for Scion abstracting:

<table>
<thead>
<tr>
<th>Contract number</th>
<th>FRST C04X0403</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client Report No.</td>
<td>16246</td>
</tr>
<tr>
<td>Products investigated</td>
<td>Fire growth simulation software</td>
</tr>
<tr>
<td>Wood species worked on</td>
<td></td>
</tr>
<tr>
<td>Other materials used</td>
<td>Geographical Information Systems (GIS)</td>
</tr>
<tr>
<td>Location</td>
<td>International</td>
</tr>
</tbody>
</table>

INTRODUCTION

Fire growth models combine spatial data on fuel types and terrain influences, and temporal data on changing weather and fire danger conditions, with fire behaviour prediction models to simulate the spread and development of fires across the landscape.

New Zealand fire managers require a GIS-based New Zealand fire growth simulation model that can be used to predict the development and spread of fires in the New Zealand environment. The resulting fire growth model will be used by fire managers as a decision-support tool, including:

- aiding development of suppression strategies during wildfire events that consider public and firefighter safety (e.g., evacuations, location of fire crews) and values at risk;
- as a planning tool prior to fire events to assess the potential risk of fire spread, and for use in “what if” scenarios such as assessing fuel management effects; and
- as a post-fire assessment tool to determine the effectiveness of fire suppression operations and values saved.

A number of fire growth simulation models have already been developed and are in use around the world. The adaptation of an existing model to New Zealand conditions and fire behaviour models is therefore seen as the most appropriate way forward, rather than developing a new model.

The project to develop a New Zealand fire growth model therefore aims to identify the most appropriate model from currently available international fire simulation models, and then to adapt this model for the New Zealand fire environment to create a New Zealand-specific model. All international simulation models require modification and reprogramming for use in New Zealand, since each model has been developed for use in its country of origin, and therefore relies on the vegetation types, fire behaviour models and fire danger rating system used in that country. The result will be a fire growth simulation model for use in New Zealand that is based on sound science, and combines local fire behaviour prediction capabilities with the best-available international computer modelling platform for simulating wildfire growth.

Report Scope

Development of a New Zealand fire growth simulation model is therefore seen as initially consisting of two main steps:

1) Fire growth model review
   Evaluation of available fire simulation models for predicting the spatial growth of wildfires for use in New Zealand; and

2) New Zealand fire growth model development
   Development of a beta version of a fire growth simulation model for predicting the spatial growth of wildfires in the New Zealand fire
environment and, in conjunction with at least one Rural Fire Authority, testing of the model in an operational setting.

This report aims to complete the first step in this process, by evaluating the suitability of available fire growth simulation models for use in New Zealand and making recommendations on the most appropriate pathway forward for development of a New Zealand fire growth simulation model. In particular, this includes reviewing:

- the capability of existing international fire growth simulators to incorporate New Zealand’s current (and future) fire behaviour models (based largely on the FWI System), and terrain and meteorological information; and

- the computing requirements to run each fire growth model, and fit with common GIS systems and computer hardware used by New Zealand rural fire authorities.

Internationally available fire growth simulation models include *Prometheus* from Canada, *Farsite* from the U.S.A., *Phoenix* (and its predecessor, *SiroFire*) from Australia, New Zealand’s own *Wildfire* model, and a number of other models in varying stages of development.

**BACKGROUND**

*Terminology and modelling techniques*

*Fire growth simulators* are “systems that combine different fire behaviour models with multi-dimensional mathematical models to predict rates of spread in complex environmental conditions varying spatially and temporally” (Bushfire CRC 2006). Fire growth simulators “estimate where a fire is likely to spread over certain time intervals based on fire behaviour models for the vegetation being burnt that include fuels, weather, fuel moisture and topography to predict spread rate, flame height and intensity” (Bushfire CRC 2006). Wildland fire growth simulators therefore combine spatial and temporal representations of fuels, weather, and topography with appropriate fire spread models to propagate point, line or polygon ignitions (Opperman et al. 2006).

As they require complex environmental information on fuels, weather and topography, which vary both spatially and temporally, fire growth simulation modelling is usually undertaken within a computer-based *Geographic Information System* (GIS). GIS systems include mapping and spatial analysis tools that allow combination of the large number of disparate factors required to predict the spread and growth of fires across the landscape.

Fire simulators are not new fire behaviour models. Calculations depend on the underlying mathematical expressions representing what are commonly referred to as *fire behaviour models*. Fire behaviour models include the equations for predicting rates of fire spread, fuel load or consumption, and fireline intensity using empirical models developed, for example, as part of the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), the Australian McArthur forest and grassland
models (Noble et al. 1980) and the semi-empirical Behave fire modelling system (Andrews 1986) used in the U.S. These fire behaviour models are contained in field manuals (e.g. Taylor et al. 1997, Pearce and Anderson 2008), and tools such as the NZ Fire Behaviour Toolkit calculator software (Scion 2008, Anderson et al. 2008) and Wildfire Threat Analysis (WTA) systems (e.g. Pearce and Majorhazi 2003, Briggs et al. 2005, Majorhazi 2006).

Fire growth simulation models combine the underlying fire behaviour prediction models with a fire simulation technique, of which there are a range of techniques available for representing both the landscape and the fire spread process (Albright and Meisner 1999). These broadly fall into two categories:

- “raster” approaches, where the landscape is represented using regular or irregular shaped cells (or lattices), and the fire spreads from one cell to the next using specific rules (e.g. fire spread equations) (cellular automaton) or a probability of occurrence (bond percolation) (Figure 1a); or
- “vector” approaches, where the landscape is assumed to be a continuous medium, and fire spread is determined by spread equations and fire shape from mathematical functions (elliptical wave propagation) (Figure 1b).

To date, the most commonly used technique has been the raster or “cellular” approach (Finney 2004), where fire growth is simulated as a discrete process of ignitions across a regularly spaced landscape grid. In the cellular method, each cell has a state (burning, burnt or unburnt), and rules are defined to determine how fire spreads from burning to unburnt cells based on cell states and cell properties (fuel slope, weather, etc.). Cellular fire growth simulation models are generally simpler to implement because there is no need to consider the geometry of the fireline (Johnston et al. 2005). However, the major problem in implementing cell-based models is in obtaining realistic fire shapes because cellular methods are strongly influenced by the geometry of the grid. While use of cells of varying shapes and sizes can partly overcome this problem, cell-based models still struggle to handle non-uniform environments (e.g. due to fuel types or topography) and temporal changes (e.g., changing wind speed and direction, or fuel moisture).
The vector approach, which is employed in the most commonly-used simulation models (e.g. *Farsite*, *Prometheus*), avoids these problems. It utilises the assumption that fires burning in continuous uniform fuels under constant conditions of slope, wind velocity and fuel moisture spread in an elliptical shape (Van Wagner 1969, Anderson 1983, Alexander 1985, Richards 1990). Based on Huygens’ wave propagation principle (after Anderson *et al.* 1982) (see Figure 1b), points (or vertices) along the fire perimeter are considered as new ignition points for small fires which grow elliptically outward, with their size and shape determined by local conditions. The fire perimeter at each succeeding time step is the envelope that encompasses all of the small ellipses burned.

This wave propagation technique does require some numerical adjustments to ensure that the small fires do not overlap or burn previously burnt areas and that the simulated ignition points on the perimeter remain evenly spaced. These adjustments can be implemented using a mathematical solution to the fire simulation equations that can generally be run on a personal computer (PC), and does not require the greater computer power (of networked processors or a supercomputer) that high-resolution cellular models require due to the very high number of cells required to describe the fire shape accurately. The elliptical wave technique also requires no local tuning, assuming that the fuels, weather, and topography in the area of interest are sufficiently similar to those for which the underlying parameters (i.e. fire behaviour models) were recorded. However, this technique should not be used under conditions for which representative parameters are not available (Albright and Meisner 1999). The attractiveness of using the cellular techniques to simulate fire spread lies in the fundamental simplicity of their components for producing an overall fire behaviour that can be extremely complex. These cellular techniques also yield reasonable estimates of fire spread when the physical determinants are unknown (Albright and Meisner 1999).

A further set of fire simulation models have also been developed over the last decade that are becoming increasing prominent. Termed *coupled fire-atmosphere* models, these simulators solve the equations for the transport of heat and convective gases above the fire as well as the motion of the fire front (Johnston *et al.* 2005). Prominent examples are the *Firetech/Higrad* model of Linn *et al.* (2002) and the NCAR coupled fire-atmosphere model of Clark *et al.* (1996, 2004). However, as these simulators require powerful supercomputers to model the high resolution, 3-dimensional movement of heat and moisture, they are currently unsuitable for use in operational fire spread prediction and day-to-day fire management planning (Johnston *et al.* 2005).

The choice of whether to use the raster (cellular) or vector (wave propagation) simulation techniques for operational applications therefore depends on the kind of mathematical model being simulated, and on the technical criteria regarding precision, calculation speed and programming complexity (French 1992). In general, cellular techniques have faster calculation speeds and lower programming complexity, but produce less precise fire shapes than vector-based methods (Pastor *et al.* 2003). A more detailed description of the
two approaches and their respective advantages and disadvantages is contained in the review by Sullivan (submitted).

In recent years, with advances in computer speed and modelling, storage capacity and graphical capabilities, fire behaviour models have been implemented into a number of different spatial fire growth simulation models. Internationally, more than 20 spatial fire growth simulators have been developed for operations, planning and research (Pastor et al. 2003). While the majority of these are raster (cell) based, the vector-based models would seem to be favoured for operational applications, especially in North America (in the Prometheus and Farsite models) and Australia (in SiroFire and Phoenix).

**Potential uses and requirements of fire growth models**

Fire growth simulation models have a wide range of potential uses. The most obvious application of fire simulation modelling is the prediction of fire growth for use in supporting operational decision-making during wildfire events. This includes:

- projecting fire growth for use in determining appropriate suppression strategies and resource requirements;
- supporting incident management options analysis through prediction of likely fire spread under different scenarios;
- assessing values-at-risk based on the predicted spread direction;
- determining evacuation needs based on predicted rate of fire spread; and
- conducting escape fire analysis to predict the likelihood and locations of fire break-outs.

Fire growth simulation models also have a useful role in prescribed burning, where they can be used to predict fire behaviour and effects, particularly spatial variability across a burn area based on differences in fuels (fuel loads and moisture contents, as well as fuel types), topography (slope, aspect) and microclimate (temperature, humidity, wind speed).

Other important uses of spatial fire growth models relate to their use in support of strategic fire management planning. Such applications include (after Finney 2003, Tymstra 2006):

- evaluating threats to values-at-risk – conducting “what-if” scenarios in a planning mode to determine the threat of potential wildfires to important values (e.g. communities, recreation areas, conservation values, etc.);
- fuels management – assessing the effectiveness of alternative fuel management strategies (e.g., harvest scheduling, cut block design, silviculture, stand density management) at reducing the threat of large fires (e.g. Finney 2001);
- evaluating burn probabilities across a landscape – use of stochastic modelling (e.g. Burn-P3; Parisien et al. 2005) to produce a burn
probability map for all points on the landscape under different fuel and weather conditions;
- spatial and temporal variation in fire behaviour – determining spatial and temporal (diurnal, seasonal) differences in predicted fire behaviour for areas of interest based on various combinations of fuels, weather and topography (e.g. FlamMap, Finney 2006);
- fire severity mapping – evaluation of likely fire severity based on predicted fire behaviour (fire intensity, fuel consumption, crown fire occurrence) for various fire weather scenarios;
- budget justification – evaluation of the impact of escaped fires on area burned based on various budget scenarios;
- function of fire as a landscape disturbance – use of a process-based fire growth model to investigate the role of fire in establishing and maintaining landscape patterns;
- post-fire analysis – cost/benefit analyses evaluating suppression effectiveness (area/values saved); and
- forensic support – evaluation of probable ignition times and/or fire locations to support fire investigations.

In addition to supporting fire management decision-making, fire simulation models can also be used as training tools to enhance fire management skills. Fire simulation systems can also be useful in displaying and explaining fire behaviour and management strategies to those unfamiliar with fire, particularly to the public, media and government officials (Albright and Meisner 1999).

Fire simulation systems must therefore address the different requirements of these specific applications Andrews (1989). For wildfire suppression, for example, users may require information on fireline location, flame length or fire intensity, or crowning potential. They might also require a system that can accommodate a fire suppression component that determines the probability of containment and subsequent impact on fire spread. In the case of prescribed burning, users might require information on fire intensity, flame lengths, burn severity or fuel consumption (Albright and Meisner 1999). For strategic planning applications, the model may need to be capable of predicting growth for multiple as well as single fire ignitions. Fire managers therefore need to ensure they consider the intended use, required inputs and associated outputs along with the modelling and simulation techniques when choosing a fire growth simulation system (Albright and Meisner 1999).

**Fire growth modelling in Australasia**

Both New Zealand and Australia have a history of interest in fire growth simulation model development. In Australia, the CSIRO Bushfire Research group developed the *SiroFire* model in the early 1990s (Beer 1990, Coleman and Sullivan 1996) while at a similar time in New Zealand, Dr Gavin Wallace developed his *Wildfire* model (Wallace 1993). However, neither was widely adopted or used operationally as both models were DOS-based and had limited linking capabilities to GIS.
Interest in fire growth simulation models has increased more recently as a result of the more widespread use of GIS and availability of international simulation models (such as Farsite and Prometheus), as well as recognition of the potential uses of fire simulation models to support fire management planning (e.g. fuels management, suppression effectiveness) and wildfire suppression operations. The establishment of the Australian Bushfire Cooperative Research Centre (CRC) in 2003 presented an opportunity to consolidate this growing interest, and the CRC contains several projects investigating the development of fire growth simulators including the Phoenix fire growth model, the University of Western Australia’s fire growth simulator, and the Networked Fire Chief incident management fire simulation tool (Bushfire CRC 2006).

In 2006, the Ensis\textsuperscript{1} Bushfire Research group and the Bushfire CRC hosted an international workshop\textsuperscript{2} on fire growth modelling (16-20 January 2006, in Christchurch), involving researchers from Canada, the U.S.A., Australia and New Zealand. In addition to sharing information on modelling techniques and approaches, participants applied a number of the available fire growth simulation models to several New Zealand and Australian wildfires with the aim of evaluating the applicability of the different models for use in New Zealand and Australia. At the end of the workshop, modelling results were presented to an end-user forum, and a series of “white papers” (see Appendices in Gould 2007) prepared describing the development status, application and technical requirements for each of the models presented. Workshop outcomes and modelling results were also summarised in an international conference paper (Opperman \textit{et al.} 2006) and briefing paper to the Australasian Fire Authorities Council (AFAC) (Gould 2007), in the latter case as an input into decisions regarding the fire simulation modelling research being undertaken within the Bushfire CRC (Bushfire CRC 2006).

As a follow on to this workshop, in New Zealand it was decided to undertake a more detailed review of the available fire growth simulation models to determine the best approach for developing a New Zealand-specific model that incorporates local fuel types, fire danger rating and fire behaviour prediction requirements. New Zealand researchers have continued to monitor developments in fire growth simulation modelling, both within the Bushfire CRC and internationally. As part of this process, a workshop on the Australian Phoenix fire growth model, which had not been fully developed at the time of the 2006 workshop, was held in August 2008 (in association with the FRFANZ annual conference in Palmerston North) for interested end-users.

\textsuperscript{1} Ensis was the joint venture between Scion (the New Zealand Forest Research Institute Ltd) and Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) Forestry and Forest Products division, which ceased in December 2007.

\textsuperscript{2} Titled the 1st International Fire Spread Modelling Workshop. A second international workshop has since been held at the USDA Forest Service’s Intermountain Research Station in Missoula, Montana, during June 2007 (Finney, \textit{pers. comm.}). Although New Zealand was not represented at this 2\textsuperscript{nd} workshop, linkages with the developers of all the major international wildfire growth simulation models have been maintained.
REVIEW OF AVAILABLE MODELS

Due to the advent of GIS, remote sensing, improved landscape information, and more powerful computers, a wide array of different types of fire simulation models have been developed, and more than 20 have been implemented around the world. Over the years, these models have been the focus of detailed reviews of fire behaviour calculation methods, fire simulation modelling approaches and model availability (Perry 1998, Albright and Meisner 1999, Pastor et al. 2003, Morvan et al. 2004, Johnston et al. 2005, Sullivan, submitted). Detailed overviews and technical documentation for individual models are also available in many cases and, where relevant, these have been referenced within the model synopses that follow. This documentation should be consulted where more detailed information is required on a specific model or modelling approach.

Due to a preference in New Zealand to utilise an established simulation model that has been implemented operationally and tested on a number of actual wildfires, the review that follows has been restricted to the models presented at the 2006 fire growth modelling workshop (Prometheus, Farsite, Portable Fire Growth Model), the models being progressed through the Bushfire CRC (UWA fire simulation model, Networked Fire Chief, Phoenix and its predecessor, SiroFire), and to known models developed or tested in New Zealand (Wildfire, Pyrocart, Firesim and the GNS dynamic fire-spread model). It is likely that one of these models will offer the best pathway for development of a New Zealand-specific fire growth model. However, more comprehensive lists of available models, together with references and brief descriptions of their characteristics, can be found in Albright and Meisner (1999), Pastor et al. (2003) and Sullivan (submitted).

FARSITE – Fire Area Simulator

Farsite is perhaps the best known and most widely used fire growth simulation modelling package. Developed in the U.S., it has been in use since the early 1990s (Finney 1994) and continues to be nationally supported by the USDA Forest Service (Finney 2004).

Farsite is a two-dimensional deterministic fire growth model (USDA Forest Service 2006) that uses the wave-front expansion technique based on Huygens’ principle to achieve two-dimensional elliptical fire growth (Anderson 1983, Richards 1990). It is a PC/Windows-based application that requires GIS data from ESRI (i.e. ARC/Info, ARCView) or GRASS programs. It applies existing one-dimensional models of fire behaviour (based primarily on Rothermel 1972) to information on fuels, weather and topography that vary both spatially and temporally. This fuel and topographic information needs to be input as GIS-generated ASCII raster data. The basic data themes required include elevation, slope, aspect, canopy cover, and fire behaviour fuel model. Weather information is required as streams of data in a text file with a particular format, and data from remote automatic weather stations (RAWS) cannot be directly input without user intervention. Although normally non-spatial, Farsite can use gridded wind fields such as those provided by a model.
like WindWizard (Butler et al. 2004). The user can control the space and time resolutions of the calculations made by *Farsite*.

Fire behaviour support in *Farsite* includes surface fire spread (Rothermel 1972, Albini 1976), crown fire behaviour (Van Wagner 1977, Rothermel 1991), spotting from torching trees (Albini 1979) and post-frontal combustion (Albini and Reinhardt 1995). However, the system is currently limited to use of those fuel models contained in the American fire behaviour prediction system (Anderson 1982, Scott and Burgan 2005), although custom fuel models can be developed as long as they are formatted and contain the required attributes for use with the underlying Rothermel (1972) fire spread model.

*Farsite* generates vector and raster maps of fire growth and behaviour which can be exported as ASCII grids (time of arrival, rate of spread, fireline intensity, flame length and fire type) or shapefiles (final, as well as intermediate, fire perimeters). Fire behaviour maps can be used for analyses of fire effects or for estimating suppression options. Fire suppression can be simulated in *Farsite* using ground and aerial attack resources. Ground tactics include direct, indirect, and parallel attack (Finney and Andrews 1999). A variety of fire environment maps can also be produced that display fuel moisture and weather conditions across the landscape at a particular time (e.g. Finney 2003). *Farsite* inputs may also be used with the FlamMap application, which computes fire behaviour for every landscape cell using a single wind and weather scenario. A recent innovation also includes the determination of fire spread using the alternative Minimum Travel Time method (Finney 2002).

The principle users of the *Farsite* software are typically fire managers within natural resource management agencies; however, the program is also increasingly being used by researchers. It is primarily used by fire behaviour analysts to make short-range projections on wildfire events and for medium to long-range projections on wildland fire use events. *Farsite* has also been used for reconstruction of past fire events, and for use in planning scenarios including examining the effectiveness of fuel treatments (e.g. Finney 2001).

*Farsite* is extremely well-supported through its documentation (Finney 2004), online help\(^3\) and a national (U.S.) fire applications helpdesk. A national, interagency training course is also offered annually, and other special purpose workshops are also taught.

**Prometheus – the Canadian Wildland Fire Growth Model**

*Prometheus* is the national Canadian wildland fire growth simulation model, coordinated and supported by the Alberta Department of Sustainable Development, Forest Protection Division (Tymstra and Bryce 2007). It is a spatially explicit, deterministic fire growth model written as a stand-alone PC-based fire management application in Visual C++. A key feature of *Prometheus* is its Microsoft component (COM) software architecture which

\(^3\) http://fire.org
allows application developers to build, update, distribute and integrate software applications more easily (Tymstra 2006). Prometheus is built on five separate low-level COMs (FuelCOM, FireEngineCOM, FWICom, WeatherCom and GridCom), with the high-level PrometheusCOM providing a user-friendly programming interface for accessing the low-level COMs.

Like Farsite, Prometheus uses Huygens’ principle of wave propagation, and incorporates two sets of elliptical growth equations to mathematically expand the elliptical wave front: the two-dimensional differential equations of Richards (1990) for flat ground, and the three-dimensional equations defined by Richards (1999) to simulate fire growth where terrain effects are present. The underlying template used to shape fire growth is the simple ellipse model of Van Wagner (1969).

The foundations of the Prometheus model are the Fire Weather Index (FWI) (Van Wagner 1987) and the Fire Behaviour Prediction (FBP) (Forestry Canada Fire Danger Group 1992) sub-systems of the Canadian Forest Fire Danger Rating System (CFFDRS). FBP System fuel types are input into the Prometheus model as ASCII grids, and are usually obtained from forest or vegetation inventory. Users can also edit fuel type parameters to modify existing fuel types or create new fuel types. Fuel polygon “patches” can also be created, and imported or exported. Slope, slope azimuth (direction) and elevation ASCII grids are used to integrate terrain effects. Weather data can vary daily or hourly, and can be added manually or imported directly from a weather station file (such as WeatherPro). Users also have the option to import hourly gridded wind speed and direction data, which can be stacked and used along with the “weather stream”.

Like Farsite, the Prometheus model can handle single or multiple point, line or polygon ignitions that can be run in a single scenario. These ignitions can be added manually or imported as a file. Fuelbreaks or firebreaks can also be included as non-burnable fuel types as part of the underlying fuel type grid or manually input as fuel patches. A methodology for incorporating firebreak breaching and spotting considerations within Prometheus is also being developed (Alexander et al. 2004). Prometheus does not currently include a suppression component. The Prometheus model produces maps of fire perimeters that can be exported as graphics or shapefile formats. A variety of FBP System outputs (fire intensity, rate of spread, surface fuel consumption, crown fuel consumption, and total fuel consumption) can also be exported from Prometheus as ASCII grids.

The primary use of Prometheus is to provide operational decision support, including the prediction of wildfire behaviour during escape fire situations for both single and multiple fires. It has successfully been used on a number of major wildfire events. However, the model is being used for many other applications and, in particular, to support strategic management planning initiatives (Tymstra 2006). Primary users therefore include operational fire behaviour analysts and agency fire technical and GIS specialists, as well as fire researchers, graduate students and consultants.
Software engineering of *Prometheus* began in 2000, and updates and enhancements have continued since that time. The Microsoft COM architecture of the model provides for the reusability and extension of its components. As examples, burn probability mapping applications such as Burn-P3 (Parisien et al. 2005) and batch routine applications for simulating multiple ignitions such as Pandora re-use *Prometheus* functionality. The PrometheusCOM has also been successfully integrated with the Canadian Forest Service’s Spatial Fire Management System (sFMS). Support is provided through a user manual and the inbuilt help file, and further information is also available on the *Prometheus* website\(^4\). Formal training courses are also held in most years.

**Portable Fire Growth Model**

The *Portable Fire Growth Model* is a partially developed fire growth simulation model developed by Ron Shamir, a spatial modeller and volunteer firefighter with the Country Fire Authority of Victoria, Australia (as a personal project). The model is designed for operational use by fire suppression personnel and management personnel, with the ultimate aim of increasing firefighter safety and effectiveness (Shamir 2006). The model is relatively new, has had limited validation, and has yet to be published.

The model is intended to provide a safety tool to firefighters and to assist with planning at the incident management level. It has therefore been designed with simplicity and computer processing/projection speed as primary requirements, and prediction accuracy as a secondary but still important factor; i.e. to provide a “quick and dirty” projection of potential fire spread. The model is intended to run on a laptop computer or hand-held device, and does not operate within a GIS environment. However, it is intended to utilise standard GIS data layers for fuel and elevation, and currently imports from and exports to a range of GIS interchange formats.

The model utilises an alternative vector-based vertex dispersion algorithm that implements a tear-drop fire shape (as opposed to the more traditional ellipse). Fuel and terrain data are input in grid format, with 5 fuel classes currently recognised. Variable temporal resolution weather data is utilised, whereby the weather stream may contain observations at irregular intervals, potentially better reflecting the variable nature of weather influences compared to regular (e.g. hourly) observations.

The model aims to be most applicable for fast moving grass and intense dry-eucalypt forest fires, and currently utilises the McArthur forest and grassland fire behaviour models (Noble et al. 1980). However, in the developer's view, these fuel and fire behaviour models can be easily modified, and the system has been developed to utilise a number of different fire behaviour models (Shamir 2006).

\(^4\) [http://www.firegrowthmodel.com](http://www.firegrowthmodel.com)
The *Portable Fire Growth Model* does not currently include a suppression simulation component, or a spotting component, although both are planned in future modifications of the model (Shamir 2006). The model has been successfully tested using a limited number of historical fire perimeters, including during the 2006 fire spread modelling workshop (Opperman *et al.* 2006), although is yet to be used operationally. Therefore, despite a number of promising characteristics, the model’s incomplete development and potential lack of ongoing support mean that it is not likely to provide a suitable pathway for development of a New Zealand version.

**Networked Fire Chief**

*Networked Fire Chief* is a flexible, portable graphic research and training tool designed for use in complex decision-making environments (Omodei 2006). As such, it is a *fire scenario simulator*, more akin to the Kiwi Fire Training Simulator or Vector Command, and not a fire growth simulation model as required for fire management applications. It is included here for comparative purposes and because it was one of the simulation models presented at the 2006 New Zealand fire spread modelling workshop. It has been developed by researchers at the School of Psychological Science at La Trobe University, Melbourne, in conjunction with the Bushfire CRC (Omodei *et al.* 2004).

Within *Networked Fire Chief*, a map is made up of a rectangular array of cells. Each cell consists of a particular landscape type with its own flammability and fuel load characteristics. *Networked Fire Chief’s* fire spread model approximates real world fire behaviour, in that fires graphically depicted within the model generally spread in the direction the wind is heading and with spread rates that are dependent on wind speed. Fire spread is also affected by terrain, with fires spreading faster upslope and slower downslope, and also by fuel load, with heavier fuels taking longer to burn. Fire intensity also varies according to these fire environment factors. The model is flexible, and allows the user to define a virtually unlimited number of different fuel types although, to retain validity, users need to have a reasonable knowledge of the relative fire behaviour associated with different fuel types.

However, Omodei (2006) stresses that as the fire model has only been developed to provide sufficiently plausible fire spread behaviour to support the primary interest on fire suppression decision-making, its use is not recommended in situations where the focus of interest is on fire behaviour. *Networked Fire Chief* also does not presently support GIS application linkages, although future developments plan to allow this.

As the primary aim of *Networked Fire Chief* (and its precursor, Fire Chief) was to generate scenarios that allow for maximum realism in firefighting decision-making, considerable attention is given to implementation of fire suppression models. A range of ground and aerial suppression resources and techniques can be employed and depicted within the model, and programmed to consume resources such as water supplies, foam or retardant, and fuel.
Networked Fire Chief is therefore not a fire growth simulation model, but is still a useful research and training tool for investigating and practising the processes involved in fire suppression decision-making for either single user or team environments.

UWA Fire Simulation Model

The University of Western Australia (UWA) initially commenced development of a new fire simulation model as a project within the Bushfire CRC (Project A5) (Bushfire CRC 2006).

The UWA model uses the cellular automata approach together with heat transfer equations to simulate fire spread and growth. It is particularly innovative in that it utilises irregular shaped polygons in an effort to overcome the problems with accurately reproducing fire shapes typically encountered with this raster approach when square cells are used. The model simulates the spread of fire on a landscape with spatial variation in fuels and slope, and time variation in wind and weather. However, as the initial version of the model did not utilise underlying fire spread relationships for specific fuel types (but used the physical processes of heat transfer to spread the fire from polygon to polygon), the model required tuning based on actual fire spread rates in different fuel types. The version 1 model was tested on at least one wildfire, the 2005 Wangary fire (Bushfire CRC 2006, Johnston et al. 2006), and also used to replicate the sensitivity of fire spread to fuel moisture, the ability of fires to breach firebreaks, and different spread rates for line fires versus point ignitions (Gould 2007).

Following criticism of the need to tune the simulation model based on actual spread observations for different fuel types, a revised version was developed (known as Mk2). This kept the irregular shaped cells but, instead of the heat transfer method, adopted the more tradition fire spread model approach (utilising the McArthur spread models) to simulate the spread of the fire. The simulator has also been re-implemented using the Java programming language, and is computationally extremely fast, completing simulations that previously took several minutes to run in less than a second (Milne and Johnston 2007).

However, development of the UWA simulator is not complete, and its validity across a range of vegetation types, fuel models, and weather and fire danger conditions remains largely untested. The advent of the Phoenix fire growth model (see below), which is the preferred option of the majority of Australian end-users for operational use, has resulted in a shift in the focus of the UWA work to investigating improved methods for modelling fire growth and faster computational processing of fire spread calculations for use within the next generation of fire simulation models. As a result, the UWA simulation model is unlikely to be far enough advanced for application in New Zealand within the timeframe required of this project (i.e. 6-12 months).
**SiroFire**

*SiroFire* was developed by the CSIRO Bushfire Behaviour and Management Group during the 1990s (Beer 1990). Like *Farsite* and *Prometheus*, the spread of the fire front was modelled using Huygens’ wave propagation method for elliptical fire growth based on local fuel, slope and weather conditions (Knight and Coleman 1993). A PC-based application, *SiroFire* used GIS-derived geographic maps and digital elevation information as the basis for determining fire spread and growth for the two main Australian fuel types – forest and grass (Coleman and Sullivan 1996). The software operates within the old MS-DOS environment, and a major effort would be required to upgrade it to work within the Microsoft Windows operating environment and to integrate it with GIS data (Gould 2007). Recently, the *SiroFire* programming code was adopted as part of the Bushfire CRC’s Bushfire Risk Management Model project (Project A4) as the basis for the *Phoenix* fire growth simulation model.

**Phoenix**

*Phoenix* is a dynamic fire behaviour characterisation model that has been developed by the University of Melbourne’s School of Forest and Ecosystem Science under the auspices of the Bushfire CRC’s Bushfire Risk Management project (Project A4), where it forms one of the elements of a broader bushfire risk management model (Tolhurst *et al.* 2006, 2008b).

The *Phoenix* model utilises the wave propagation algorithm of Huygens (Richards 1995) and the computational implementation employed by *SiroFire* (Knight and Coleman 1993). It is underpinned by two fire behaviour models, the CSIRO southern grassland fire spread model (Cheney and Sullivan 1997, Cheney *et al.* 1998) and the McArthur (Mk5) forest fire behaviour model (McArthur 1967, Noble *et al.* 1980). The fire behaviour models are used to calculate the point rate of spread, flame height and fireline intensity.

The spatial input data required to run *Phoenix* includes contour data to build a Digital Elevation Model of the landscape, and fuel data based on vegetation types across the landscape and fire history information. Input data are entered as shapefiles. Weather data are typically entered as temporally varying point data, but it is hoped that gridded weather data will eventually become available (Tolhurst *et al.* 2006). An option is already available for utilising gridded data for wind speed and direction from, for example, WindWizard (a computation fluid dynamics (CFD) model, Butler *et al.* 2004) or Wind Ninja (a mass conservation model) (Tolhurst *et al.* 2008a).

To run the model, the fuel and topography information are converted into gridded data, with the size of the grid selected by the user. For single fires, a grid size of 200 m has been found to be adequate, and at this resolution a 20,000 ha fire can be run in about 30 seconds on a standard laptop computer (Tolhurst *et al.* 2006). *Phoenix* can be used for a single fire or for multiple fires. The outputs for each cell for single fires include fire intensity, cell burn time (from time of ignition), fire size, location of fire origin, time of spotfire
impact and weather conditions at the time of burning. For multiple fires, the fire frequency is also included, as well as summary statistics for the various fire characteristics.

The model incorporates the influence of fuel discontinuities such as firebreaks, roads and other barriers on restricting fire spread, and also includes a spotting component that captures the effects of spotfires ahead of the main fire front on increasing the rate of spread of the fire or starting new ignitions (Tolhurst et al. 2008b). The Phoenix model also includes a fire suppression component in which fire suppression resources are specified and the fire can be suppressed at the same time as the perimeter is generated to give a realistic final shape and size. The rate of fireline suppression and control is based on the average production rates described by McCarthy et al. (2003). Only one suppression strategy is assumed, that being direct attack from the back of the fire, and the rate of suppression is reduced due to impediments such as fire intensity, topographic steepness, fuel density and degree of spotting. Conversely, the rate of suppression is enhanced if the fire perimeter is near a road (Tolhurst et al. 2008a).

While some elements of the Phoenix model are still under development, the overall application development is well advanced. A series of training workshops have already been run across Australasia, including one in New Zealand in August 20085. It is likely that the model will become the accepted fire growth simulation (and risk management) application in use in Australia, and receive considerable operational testing and validation over the next few years. If this is the case, it will also likely undergo further improvements, and provide ongoing support and training for end-users.

**Wildfire**

Wildfire is a simple fire growth model developed in New Zealand by Dr Gavin Wallace6. Its basis and application are described in Wallace (1993).

Developed to run on a PC in an MS-DOS environment, the model in its present format is not GIS-compatible. Fuel cover and terrain, entered through a graphical user interface, appear in the system as a grid of points (Albright and Meisner 1999). Maps need to be drawn using a mouse, but can be stored and retrieved from file. The system permits variation in slope over the fire area, with the effects of slope on fire spread rates being determined by calculating gradients based on the contour array of map heights. Spatial resolution can be as small as 1 m, and features and conditions can be changed as a fire is being simulated. Up to three fuel types can be represented at any one time, and users can also specify non-combustible barriers to fire spread such as roads and water-bodies. Weather conditions are assumed to be spatially uniform, but the wind velocity may be changed

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5 Held in conjunction with the Forest and Rural Fire Association of New Zealand (FRFANZ) annual conference in Palmerston North.

6 Dr Gavin Wallace is a scientist with the Institute of Geological and Nuclear Sciences (GNS) and a volunteer rural firefighter with the Wainuiomata Bushfire Force.
over time. Output consists of maps of fire perimeters at user-defined time steps and a final fireline intensity.

The *Wildfire* model is vector-based, and utilises Huygens’ principle for an expanding fire perimeter of point ignitions producing small ellipses. The numerical calculation methodology has also been programmed to detect and remove loops in the perimeter (Wallace 1993). In its current form, the model incorporates rate of spread equations and elliptical length-to-breadth ratios for the 14 fuel types originally contained in the Canadian FBP System (Alexander *et al.* 1984, Forestry Canada Fire Danger Group 1992), of which several are already utilised in New Zealand (e.g. O-1 grass, C-6 mature pine plantation, and S-1 logging slash models). Adjustments of fire spread rates for slope are made using the Canadian slope correction factor from Van Wagner (1977)\(^7\). Similarly, fuel consumption and fireline intensity (after Byram 1959) are also calculated using the Canadian FBP approach. The model can readily be run on a basic PC or laptop, with individual fire perimeter evaluation runs typically taking just a few seconds.

Due to the lack of GIS-compatibility and MS-DOS format, the *Wildfire* model has not been widely adopted by New Zealand fire managers and has not been operationally, apart from by the developer. However, consideration has been given to integrating the model with digital terrain information within GIS and the Windows operating environment, and to updating it to incorporate the broader range of fuel types and associated fire behaviour models being used in New Zealand\(^8\). The inclusion of new fire behaviour equations into the model is a relatively easy process, and Wallace (1993) suggested the model could also be extended to include determination of other useful fire behaviour considerations such as crown fire development and firebreak effectiveness. A module incorporating the influence of suppression actions on fire growth could potentially also be added to the model (Wallace 1993).

**Other models**

A large number of other fire growth simulation models are also available, and these are referenced in the reviews by Albright and Meisner (1999) and Pastor *et al.* (2003). The majority of these models are raster-based (i.e. cellular) (e.g. Firemap, Ball and Guertin 1992, Vasconcelos *et al.* 1992; Geofogo, Vasconcelos *et al.* 1998; Firestation, Lopes *et al.* 1998) and are therefore not considered in any detail here due to the perceived preference to stick to the more mainstream vector approach (as used in Farsite, Prometheus and Phoenix) in New Zealand.

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\(^7\) It is uncertain whether the model includes adjustments for downslope fire spread, but this is believed unlikely as the Canadian FBP System is currently limited to upslope spread only despite some work having been done on downslope spread adjustments (Alexander *et al.* 1984, Van Wagner 1988).

\(^8\) Such an update was proposed as part of a previous funding bid to the Foundation for Research Science and Technology (FRST) in 1996/97; however, this part of the proposal was not supported. Related research to evaluate windflow models for interpolation of wind speed and direction in complex terrain for integrating with GIS and fire growth models was also proposed to FRST, but was again not successful in receiving funding support.
Raster-based simulation models have previously been tried in New Zealand by Perry et al. (1999), who developed the Pyrocart model using this cellular approach and fire behaviour models for 11 local fuel types derived from the U.S. (Rothermel 1972) fire spread model. They then tested this Pyrocart model against the spread of the 1995 Mt Horrible wildfire in inland Canterbury, and reported that fuel class and slope angle had the most influence on prediction accuracy. Interestingly, Perry et al. (1999) utilised Van Wagner’s (1988) relationships for downslope fire spread adjustment (in addition, it is assumed, to those for upslope spread from Rothermel 1983). Barker (1998) also attempted unsuccessfully to test the Fire Demo model, a cellular-based model developed by ESRI that appears not to be based on any specific fire behaviour models and utilises a probabilistic approach for determining spread from cell to cell based on a designated flammability (fire susceptibility) for each vegetation type.

Perry et al. (1999) demonstrated that, with inclusion of appropriate fire behaviour prediction equations for local fuel types and topography, the raster (cell-based) approach could still have some applicability in New Zealand.

The only other known applications of spatial fire growth modelling in New Zealand are the elliptical fire growth package (Firesim) developed by the Hastings District Council and the GIS-based urban fire-spread model developed by Geological and Nuclear Sciences.

The Firesim model developed by Hastings District Council (HDC 1999, Robertson 1999) overlays a fire ignition point and predicted elliptical fire perimeters on a topographic map. Fire behaviour, in the form of predicted spread distances and elliptical length-to-breadth ratios (after Alexander 1985), are determined from weather inputs and calculated FWI values using the models contained within the New Zealand Fire Danger Rating System (NZFDRS). However, the number of fuel types currently included is unknown, although it is believed the model can only work in one fuel type at a time. Similarly, the model only predicts fire behaviour on flat ground, and does not include adjustments for the effect of slope. In addition to projected elliptical fire perimeters, the model produces a table showing the rate of fire spread, perimeter growth, head fire intensity and resources required (presumably based on Alexander’s (1992) table of fire suppression effectiveness with fire intensity) for each fire interval. The model was originally developed for operational use on wildfires to assist tactical planning, but has also been promoted as an aid for strategic fire management planning, for post-fire analyses (such as debriefs), and as a training tool (Robertson 1999). Firesim runs as an application of the Genamap GIS software, which is not widely used by other New Zealand fire authorities, and it is believed the software company may have since gone out of business.

The urban fire spread model developed by Geological and Nuclear Sciences (GNS) was originally developed for fire spread in urban areas following earthquakes (Heron et al. 2003). The main focus of the model is therefore on fire spread between buildings, based on building characteristics, construction materials and separation distances. However, the more recent version of the
model (Heron et al. 2003) includes a rural fire component for predicting the spread of fire in vegetation between houses and suburbs. The dynamic fire-spread model (Cousins et al. 2002) uses the cellular automata technique to model fire spread over time. ARC/INFO GIS is used to represent the environment as a regular lattice of cells, and spread of fire from cell to cell determined from the attributes of the cell (e.g. vegetation type and flammability) and spread rules. After considering a range of options for modelling fire spread from cell to cell, the inbuilt PATHDISTANCE function within ARC/INFO was used within the model. This function calculates for each cell the least-accumulative-cost distance over a cost surface from a source factor while accounting for surface distance. In this case, the cost being accumulated was time (Heron et al. 2003). Rules for fire spread included spread through direct flame contact and close-range spotting (within a pre-set maximum distance), and spread rates from existing New Zealand fire behaviour models for a limited number of fuel types (assumed to be forest and grass, and based on model spread rates with ISI). The model was tested for a range of hypothetical situations, and also with some success against the 1991 Tikokino grassfire (Rasmussen and Fogarty 1997). However, Heron et al. (2003) noted the inability of the cell-based technique employed to accurately model the effect of wind or slope when the spread direction was not equal to one of the eight sub-cardinal directions (i.e. N, NE, E, SE, etc.). This limited the usefulness of this approach and they considered replacing this with vector-based methods utilising the expanding ellipse approach (e.g. as employed in Farsite).

Figure 2. Examples of fire growth simulation model output for the Craigieburn Fire (after Opperman et al. 2006), from (left) Farsite, with simulated fire perimeters in white against the final fire perimeter in red; and (right) Prometheus, with simulated perimeters in black against the actual fire perimeter in red. According to Opperman et al. (2006), both simulations are reasonable, especially when the effects of suppression are considered.
INPUT REQUIREMENTS FOR FIRE GROWTH MODELLING

The successful use of fire simulation models depends on the quality of the input data as much, if not more, than the accuracy and applicability of the underlying fire behaviour prediction relationships and simulation technique (Bushfire CRC 2006). Accurate information on the spatial and temporal variation in fuel types, topography and weather conditions are essential to the accurate prediction of fire spread and other fire behaviour, and fire shape. Similarly, tried and tested fire behaviour models for local fuel types, and information on fire suppression capability for local resource types, are required to support the wider range of fire simulation modelling applications that can be used with confidence by fire managers.

Topography

To accurately predict the rate of spread and shape of fires, fire behaviour models require information on slope steepness. While this can be input manually (e.g. as is currently done in Wildfire), it is more preferable for this to be automated using data derived from a Digital Terrain Model (DTM)\(^9\), usually contained within a GIS. Digital contour information can also be used to classify aspects, for example, for use in determining differences in the receipt of solar radiation and impacts on fine fuel moisture content for use in fire hazard assessment (e.g. within Farsite and FlamMap, Finney 2003). Topography also has a significant influence on wind flow, so that terrain information from a DTM is an essential requirement for production of more detailed gridded wind flow information for use in fire growth simulation modelling (e.g. Butler et al. 2004, 2006; see below). It is therefore important that fire growth models have links to GIS containing a DTM wherever possible.

Fuels

Accurate information on fuel types is also an essential input into fire behaviour prediction and fire growth simulation modelling. Fuels information is obtained from data on vegetated land cover which is then classified into a series of fuel models or fuel types for use in predicting fire spread and growth. In New Zealand, the Land Cover Database version 2 (LCDB2; Thompson et al. 2004) currently provides the most up-to-date information on national vegetation cover; however, it is understood that an upgrade is being planned (K. Majorhazi, Ministry of Agriculture and Forestry, pers. comm.). This local vegetation information is not compatible with the fuel models contained within international fire behaviour prediction systems and associated simulation models, where often detailed physical parameters of the vegetation are required to determine fuel moisture, fuel loads and other fire behaviour (e.g. crowning).

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\(^9\) Sometimes referred to as a Digital Elevation Model (DEM).
Some research has been undertaken on translating New Zealand vegetation cover classes into fuel types for use with local fire behaviour models (Opperman and Coquerel 2005), which are based in some cases on similar Canadian fuel types. These “crosswalks” (defining the appropriate fuel type and associated fire behaviour model for each vegetation type) were successfully used to implement fuel type maps within Prometheus for the New Zealand (and Australian) wildfires modelled during the 2006 spread modelling workshop (Opperman et al. 2006), although these were for the most part relatively simple fuel conditions (predominantly grass). Significant effort would be required to translate all New Zealand vegetation types into corresponding fuel models used within other international simulators such as Farsite and cellular models utilising Rothermel’s (1972) spread equation (which now recognises some 40 fuel models; Scott and Burgan 2005), and it is likely that new fuel models would still need to be developed for many unique New Zealand vegetation types.

**Weather**

Weather data requirements for each fire growth model are different depending on the variables used to determine fire behaviour (fuel moisture, rate of fire spread and fuel consumption) in the underlying fire behaviour models. Weather station records often need to be manually reformatted into the unique input files (weather ‘streams’) required by each application. Opperman et al. (2006) noted, for example, that it was not possible to readily input weather streams into Farsite spanning different calendar years; however, it is believed that this problem may have been rectified.

Other changes are also necessary to modify many of the models for use in the southern hemisphere due to the majority having been developed in the northern hemisphere. For example, Opperman et al. (2006) reported that six months needed to be added to dates in Prometheus to account for the difference in seasons on day length factors within the FWI System calculations. However, modifications to solar radiation effects within Farsite could be accomplished directly by entering a negative latitude which changes the sun angle and day length.

Opperman et al. (2006) also stated that adjustments needed to be made to recorded wind directions to more accurately reproduce the actual fire perimeters and predominant spread directions observed for several of the wildfires they tested. This was partly due to differences in conditions resulting from the distance of the nearest weather station away from the fire sites. However, it was also associated with the models applying a constant wind flow across the entire modelling area, due to a lack of more detailed ‘gridded’ wind information describing the variation in wind speed and direction across the landscape from the interaction of the prevailing wind flow with the terrain.

A number of wind flow models are available that use computational fluid dynamics (CFD) or other models of atmospheric processes to simulate the effects of topography on wind, and output wind velocity and direction in raster
or vector formats that can be input into fire growth simulation models. For example, *Farsite* can utilise output from the WindWizard model (Butler *et al.* 2004) as well as gridded wind data from other wind flow models, as can *Prometheus* and the *FireStation* cellular model (Lopes *et al.* 1998). A considerable amount of research has been done on reviewing the applicability of wind flow models for use in New Zealand’s complex terrain, for example, for predicting wind risk to forestry (Wilson 1995) and for identification of wind-power generation sites (Reid *et al.* 1998). The ability of fire simulation models to incorporate more detailed gridded wind information is an obvious advantage that can result in improved predictions of spatial fire growth and behaviour, particularly at finer scales (Butler *et al.* 2004, 2006).

**Fire behaviour models**

In addition to a fire simulation modelling technique, all fire growth simulators also use an underlying fire behaviour prediction model to project the spread of fire across the landscape. However, a feature of the various fire growth simulation models described in the literature is that they are often built around different underlying fire behaviour models. In the case of the vector models, for example, *Farsite* implements the U.S. fire behaviour models based on Rothermel (1972), and *Prometheus* (and also the N.Z. *Wildfire* model) the Canadian models contained within the FBP System (Forestry Canada Fire Danger Group 1992), while *Phoenix* (and also *SiroFire*) is based around the McArthur forest and grassland fire behaviour models used in Australia (Noble *et al.* 1980). The majority of raster-based simulation models that contain fire behaviour models for determining spread from cell to cell (as opposed to probabilistic or statistical methods) have been developed around standard or customised fuel models based on Rothermel’s (1972) spread equation (including the N.Z. *Pyrocart* model) (Pastor *et al.* 2003).

While fire spread equation coefficients within these underlying fire behaviour models can be user-manipulated to some degree (Opperman *et al.* 2006), few (if any) simulation models support the entry of fully customised fire spread equations with varying parameters (i.e. give the user the option to change spread equation parameters at the start of a simulation run). Fire behaviour calculations are done in the background using a prescribed set of models for defined fuel types. As a result, all of the available simulation models would need to be modified to incorporate the fire behaviour prediction models (and fuel types) currently used in New Zealand (Pearce and Anderson 2008, Scion 2008). However, as outlined above, some initial work has been done on this in the case of the *Prometheus* model for the 2006 simulation workshop.

In addition to models for surface fire behaviour, some simulators also incorporate additional models to calculate crown fire behaviour and spotting (Pastor *et al.* 2003). These additional fire behaviour elements are not formally part of the current New Zealand FBP System despite relationships being available within the Canadian system for both crowning (Forestry Canada Fire Danger Group 1992, after Van Wagner 1977) and spotting (after Albini 1979). Both crown fire behaviour and spotting are included within *Farsite* using these
Fire suppression models

To accurately model fire growth, simulation models also need to capture the impacts of fire suppression on fire spread. To do this they require a fire suppression module that can capture (and display) rates of perimeter containment (based on fireline construction rates for different types of resources, including ground and air), and potentially even a probability of containment model to predict whether suppression efforts will be successful (based on the number and types of resources relative to fire intensity).

Many fire simulation models include a method for inserting firebreaks (or fuel breaks) of non-combustible cover types that act to prevent fire spread. These can be used to simulate the effects of fire suppression activities around the fire perimeter to restrict fire growth. In some cases, they are also linked to a model for firebreak effectiveness that allows the probability of breaching to be determined, sometimes for a range of mechanisms (flame contact, radiant heat transfer or spotting), based on calculated fire behaviour (fire intensity, flame length, spotting distance).

While guidance on firebreak breaching (based on Byram 1959 and Wilson 1988) is provided within the New Zealand FBP System (Pearce and Anderson 2008), there is very little information currently available on local fire suppression resource productivity that could be incorporated within a New Zealand fire growth model. Data collection is underway in an effort to develop guidelines for ground resources (Parker et al. 2007, 2008). In the interim, however, overseas information, of which some is already included within the available fire growth simulation models (e.g. Phoenix), may adequately model suppression effects.

RESULTS AND DISCUSSION

Ranking of reviewed fire growth models

As highlighted in the previous section, the successful use of fire simulation models lies in the quality of the data inputs and the accuracy and applicability of the underlying fire behaviour prediction relationships (Bushfire CRC 2006). Johnston et al. (2005) note that for a fire growth simulator to be useful to fire managers, it must not only be accurate, but it must also be “easy to use (i.e. easy to enter data, easy to modify input data), have good presentation of output (i.e. easy to understand) and [be computationally] fast (results of a simulation available in minutes)”. Opperman et al. (2006) also concluded that it was important to choose an application compatible with current data availability and fire management systems, and that can be modified to use unique and varied fire spread equations. Albright and Meisner (1999) further
suggest that when choosing a fire growth simulation system, fire managers should also consider other factors such as the intended use, required inputs, associated outputs, and required hardware platform and software, in addition to modelling and simulation techniques to be employed. Hence, there are a range of factors that need to be considered when selecting (or developing) the most appropriate fire simulation model.

With these factors in mind, nine of the available models were compared and qualitatively ranked based on the required simulation characteristics, computing requirements, model capabilities, and compatibility with local data and fire behaviour modelling inputs (Table 1). As previously stated, these nine models evaluated included those investigated during the 2006 spread modelling workshop (Opperman et al. 2006, Gould 2007), models being developed within the Bushfire CRC (Bushfire CRC 2006, Gould 2007), and additional models developed in New Zealand with further development potential (i.e. Wildfire and Pyrocart). The Pyrocart model (after Perry et al. 1999) is also included as an example of the raster (cell-based) approach with fire spread from fuel model prediction equations (and not statistical or probabilistic methods). The other New Zealand models identified (the HDC Firesim, and GNS urban fire-spread models) were not included in this ranking analysis due to their incomplete nature, limited scientific basis and operational application/evaluation.

Within Table 1, the ‘Simulation technique’ refers to the simulation modelling approach employed, which has been classed as either vector (perimeter ellipse wave propagation utilising Huygens’ principle) or raster (cellular or polygon) based, with the ranking favouring the vector approaches over raster methods. The ‘Operating environment’ describes the computer operating system environment required by the modelling software, with Windows being ranked above MS-DOS based applications. ‘Computing requirement’ describes the computer processing requirements and likely hardware platform required to run the simulation models, and has been classified as either typical PC/laptop compatible with low to moderate processing requirements or as requiring higher processing power such as provided by multiple processors. Obviously this processing requirement will depend on the input data complexity and modelling resolution. GIS-based applications involving high resolution inputs (such as gridded wind information) require higher processing power, and are ranked as a disadvantage over a model such as the Portable Fire Growth Model, designed to run on a handheld device. ‘GIS compatibility’ refers to the capability of the models to link directly with Geographic Information Systems (GIS), and is classed as either “full” integration, “limited” with some input/output compatibility, or “none” where there is no apparent GIS capability.

Similarly, in the case of the fire environment factors assessed within Table 1, ‘DTM topography’ refers to the ability of the model to incorporate digital contour information, ‘NZ vege/ fuel models’ to their compatibility with New Zealand fuel models and/or vegetation types, ‘Variable weather’ to their ability to incorporate variable (i.e. hourly or more frequent) weather and also ‘Gridded wind’ data. In all these cases, this is described as a simple “yes” or
Table 1. Review and ranking of available fire growth simulation model characteristics and capacity for modification for use in New Zealand.

<table>
<thead>
<tr>
<th>Simulation modelling characteristic or capability/ compatibility</th>
<th>Farsite</th>
<th>Prometheus</th>
<th>Portable Fire Growth Model</th>
<th>Networked Fire Chief</th>
<th>UWA Fire Simulation Model</th>
<th>SiroFire</th>
<th>Phoenix</th>
<th>Wildfire</th>
<th>Pyrocart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation technique</td>
<td>vector</td>
<td>vector</td>
<td>vector</td>
<td>cell</td>
<td>vector</td>
<td>vector</td>
<td>vector</td>
<td>vector</td>
<td>cell</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Windows</td>
<td>Windows</td>
<td>??</td>
<td>Windows</td>
<td>??</td>
<td>MS-DOS</td>
<td>Windows</td>
<td>MS-DOS</td>
<td>??</td>
</tr>
<tr>
<td>Computing requirement</td>
<td>PC (mod)</td>
<td>PC (mod)</td>
<td>PC / handheld</td>
<td>PC</td>
<td>multi-proc (high)</td>
<td>PC (low)</td>
<td>PC (mod)</td>
<td>PC (low)</td>
<td>PC</td>
</tr>
<tr>
<td>GIS compatibility</td>
<td>full</td>
<td>full</td>
<td>limited</td>
<td>none</td>
<td>none</td>
<td>?</td>
<td>limited</td>
<td>yes</td>
<td>none</td>
</tr>
<tr>
<td>DTM topography</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no ??</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>NZ vege/ fuel models</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Variable weather</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Gridded wind</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>??</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>FWI/FDRS</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>NZ fire beh. models</td>
<td>unlikely</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Crowning</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Spotting</td>
<td>yes</td>
<td>coming</td>
<td>no</td>
<td>yes</td>
<td>??</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Firebreak breaching</td>
<td>yes</td>
<td>coming</td>
<td>no</td>
<td>yes</td>
<td>??</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Suppression module</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>??</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Range of applications</td>
<td>many</td>
<td>many</td>
<td>few (ops)</td>
<td>few (training)</td>
<td>few research</td>
<td>few (ops)</td>
<td>many</td>
<td>some (ops)</td>
<td>few (plan)</td>
</tr>
<tr>
<td>Tech support availability</td>
<td>yes</td>
<td>yes</td>
<td>unlikely</td>
<td>may be</td>
<td>unlikely</td>
<td>no</td>
<td>yes</td>
<td>unlikely</td>
<td>no</td>
</tr>
<tr>
<td>Development cost</td>
<td>high</td>
<td>mod/high</td>
<td>v. high</td>
<td>na</td>
<td>v. high</td>
<td>na</td>
<td>high</td>
<td>high</td>
<td>v. high</td>
</tr>
</tbody>
</table>

"no", with the positive contributing to a better ranking than a negative response. ‘FWI/FDRS’ refers to the compatibility of the various simulation models with the existing New Zealand Fire Danger Rating System, including FWI calculations and inputs, and FBP System ‘fire behaviour models’ and modelling approach (i.e. utilising equations based around FWI System components). ‘Crowning’ and ‘Spotting’ refer to the inclusion of these additional fire behaviour considerations within the models, and ‘Firebreak
breaching’ and ‘Suppression module’ to their capacity to include firebreak breaching and/or suppression (i.e. fireline construction and/or suppression effectiveness) considerations.

For the final group of ranking characteristics included in Table 1, ‘Range of applications’ refers to the capability of the model to link with other applications as well as to the diversity of uses of model outputs, and ‘Tech support availability’ to the provision of training and availability of ongoing support for model use, including the likelihood of further model developments or upgrades and provision of help with software use or model application. Lastly, ‘Development cost’ refers to the estimated cost to develop a New Zealand version, qualitatively assessed on the basis of the preceding categories as either moderate to high (“mod/high”), “high”, very high (“v. high”) or, in the case of those models where modification is not possible or not warranted, as not applicable (“na”).

An overall assessment of the capabilities of the selected fire growth simulation models was then gained by determining the total number of positive responses achieved by each model. These were used to obtain an overall rank for each model from 1 - 9, with the best ranked model (1) being that which achieved the greatest number of positive responses, and the worst ranked model (9) being that which achieved the least number of positive responses (and greatest number of negatives).

Of the nine models that were compared, the Prometheus model ranked highest (1) in terms of the required features. However, this was closely followed by the Phoenix (2) and Farsite (3) models, with all three being developed and accepted models that offer a wide range of applications and ongoing support. Prometheus was favoured on the basis that it already contains the weather and FWI inputs and fire behaviour prediction approach used in New Zealand, and only minor changes would be required to these modules compared with the need to fully add these components to the Farsite and Phoenix models. The inclusion of many of the New Zealand fire behaviour models and vegetation cover data within Prometheus demonstrated during the 2006 modelling workshop with only limited development time shows that this can be successfully achieved. However, a possible drawback to use of the Prometheus model could be the need to purchase access rights to use the PrometheusCOM (at a cost of approx. C$10,000).

Despite very similar rankings, Phoenix is also probably favoured over Farsite due to its simplicity and therefore likely easier adaptation, and perceived desire for commonality across Australasia (and through the Bushfire CRC). The existing New Zealand models, Wildfire and Pyrocart (or similar), which ranked 4th and 5th, offer some potential for updating and upgrading, but major and potentially costly modifications would be required and ongoing support questionable. The remaining models are not considered suitable for adaptation or widespread use in New Zealand due to a lack of ongoing technical support, limited range of applications, and incompatibility with input fuel, terrain and fire behaviour data used in New Zealand.
Although the scale of wildland fire in New Zealand versus Australia differs significantly, their fire management and research institutions are geographically and politically linked. There is therefore some rationale for adopting a common tool in both countries to support decision-making for operations and planning, especially with regard to reconstructing fire events to measure the success of suppression operations or investigate potential fire behaviour. The Phoenix model, which is being developed through the Bushfire CRC and is likely to become the model of choice in Australia, therefore may warrant further, more detailed investigation to determine whether it should provide the basis for the New Zealand fire growth simulation model.

However, the above assessment suggests that modification of the Prometheus model presents the best pathway forward for development of a fire growth simulation model for use in New Zealand. However, this evaluation was undertaken from the research perspective and is based on the perceived needs of end-users. An end-user project team therefore needs to be established to clearly establish the model requirements and intended applications, as well as the project terms of reference and budget. The latter, in particular, may dictate which of the approaches suggested above is feasible, and whether end-user expectations can be met within the funding available.

Pathway for development of a N.Z. fire growth model

Key steps in the development of a New Zealand fire growth simulation model (most likely from modification of either Prometheus or Phoenix) therefore include:

- Establishment of a project team to guide the development of the fire growth model and ensure that end-user’s needs are met. The project team will provide the essential perspectives on operational needs and play a key role in establishing the pathway for development of a New Zealand fire growth simulation model;

- Identification (by research) of the New Zealand-specific requirements (such as fuel types, terrain effects, weather and FWI System fire danger ratings, and fire behaviour prediction models) that need to be adapted within the chosen model, and gathering of the data needed to support the modification;

- Development of a beta-version of the New Zealand fire growth simulation model;

- Testing and validation of the beta-version of the model in an operational setting by conducting a pilot implementation trial with at least one key end-user;

- Production of a technical report to accompany the beta-version. This report should outline the technical basis of the simulator, including its underlying assumptions and limitations, and general instructions on how to use the simulation model. A more detailed User Guide and technology transfer plan should also be produced later, following a period of operational
testing of the beta-version, to accompany the widespread release and implementation of the final operational version of the model; and

- Development of a technology transfer programme to assist delivery and operational implementation of the New Zealand fire growth model. In addition to initial workshops and/or training courses, this will need to include provision for ongoing support to users.

Key to the success of any New Zealand fire growth model development will be the securing of the resources required. These include:

- Fire research scientist(s) – to lead the project, including initial review of available fire growth models, and model development including fire behaviour modelling technical input;
- GIS specialist – to assist with initial model review by advising on GIS requirements, and provide technical advice and input into GIS aspects of model development and the implementation pilot trial;
- Programmer – to modify fire growth simulation algorithms within the selected model, and refine the beta-version of the model following pilot trial testing; and
- End-user agency – to participate in and provide the necessary support and resources to complete the implementation pilot trial.

Potential risks or issues facing the development of a New Zealand fire growth model through adaptation of an existing model therefore include:

- the lack of a suitable international model for modification due to model incompatibilities or, more likely, excessive costs of modification;
- a lack of GIS and/or programmer support to participate in the project;
- inability to obtain the support of an end-user agency (with sufficient budget and resources) to undertake the pilot implementation trial;
- inadequate project budget to obtain the required resources to undertake the necessary model modification and development, including a possible need to purchase usage rights to one of the preferred models for modification (e.g. the PrometheusCOM at a cost of approx. $10,000).

Production of a detailed project plan, including clear identification of the project scope and expectations, and budget and personnel requirements, would go some way to alleviating many of these potential issues.
CONCLUSION AND RECOMMENDATIONS

A wide range of fire growth simulation models are available internationally that utilise different simulation and fire behaviour modelling approaches, data inputs and operating requirements, and that can be used in a vast array of different fire management applications. However, few if any of these models can be implemented in another country without some need for modification.

Despite this, rather than developing a new model, adaptation of an existing model to New Zealand conditions and fire behaviour models still represents the most efficient and cost-effective way to develop a New Zealand fire growth simulation model. As a result of building in local fire behaviour prediction requirements (fuel types, slope effects, weather and fire danger ratings, and fire spread models), the fire growth model that will be developed as a result will be specific to the New Zealand environment. This modification of the model to New Zealand conditions will mean that it can be more confidently employed by New Zealand fire managers as decision support tool to provide accurate estimates of fire growth for use in a range of fire management activities. These include: aiding development of suppression strategies during wildfire events; as a strategic planning tool prior to fire events to assess the potential risk of fire spread, and for use in “what if” scenarios such as assessing fuel management effects; and as a post-fire assessment tool to determine the effectiveness of fire suppression operations and values saved.

Review of available models has indicated that the Canadian Prometheus model and/or Australian Phoenix model provide the best opportunities for adaptation to local requirements. However, identification of the most appropriate model for modification from the currently available international fire simulation models represents just the first step in a project to develop a New Zealand fire growth model. More work is required from both researchers and end-users to decide on the most appropriate pathway for model development, and to secure the necessary funding and resources to enable this.

Recommended

As outcomes from the evaluation of available fire growth simulation models, it is therefore recommended that:

- Establish a project team of end-users (with research input) to guide the development of the New Zealand fire growth model and ensure that end-user’s needs are met. This project team will provide the essential perspectives on operational needs and play a key role in establishing the pathway for development of a New Zealand model.

- Develop a detailed Project Plan and project team Terms of Reference, complete with project budget, to clarify the project scope and objectives. This should include identification of the known applications the model will be used for, as well as required and preferred model components (e.g. fire suppression, gridded wind, etc.).
• Undertake more detailed review of the top ranking models (i.e. Prometheus and Phoenix) to better determine the advantages and disadvantages of each model for modification. This should include preparation of detailed costings for the modification of each model.

• Identify a key end-user organisation to participate in the development and pilot implementation of a beta-version of a New Zealand fire growth simulation model. This includes securing the necessary agency support, budget and personnel resources (i.e. fire management staff and GIS specialists) to conduct this work.

• Undertake a pilot trial to test and validate a beta-version of the developed model in an operational setting with at least one key end-user.

• Develop a technology transfer programme to assist delivery and operational implementation of the New Zealand fire growth model. This should include appropriate technical documentation (e.g. user guide), workshops and training to accompany release of the model, and provision of ongoing technical support for users.

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