CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF14047

Techniques for evaluating wildfire simulators via the simulation of historical fires using the AUSTRALIS simulator

Joel K. Kelso[A,B], *Drew Mellor*[A], *Mary E. Murphy*[A] *and George J. Milne*[A]

[A]School of Computer Science and Software Engineering, University of Western Australia, M002, 35 Stirling Highway, Crawley, WA 6009, Australia.
[B]Corresponding author. Email: joel.kelso@uwa.edu.au

Abstract. A methodology for validating fire spread simulation systems using historical fire data is presented. The key features of this methodology are (a) quantitative comparison between simulator-generated fire perimeters and fire perimeters from an independently produced fire reconstruction at multiple time points during the fire, and (b) extensive sensitivity analyses on simulation variables including simulation spatial resolution, weather, vegetation coverage and fire behaviour model selection to determine the effect of each simulation input on the simulation output. The methodology is demonstrated in a case study in which the ability of the AUSTRALIS high-performance wildfire simulator to replicate a large wildfire in Western Australia was examined. Simulation accuracy was found to be lower in extreme fire danger conditions and exhibited under-prediction of the head fire rate of spread. This was caused by inaccuracies in at least one of wind speed data, vegetation data or the fire behaviour model applied; however, the source of the inaccuracy could not be further diagnosed with the available data. The gathering of accurate data during and after active wildfires would facilitate more rigorous simulator and fire behaviour model validation studies as well as more accurate prediction of 'live' wildfires.

Additional keywords: Boorabbin Fire, fire spread simulation, Geographic Information System (GIS), validation.

Received 27 March 2014, accepted 15 March 2015, published online 11 June 2015

Introduction

Predicting wildfire behaviour is an essential component of the management of both planned and unplanned fires. In Australia and other countries, empirically derived fire behaviour models (FBMs) such as the McArthur forest fire model (McArthur 1966, 1967), Vesta (Gould *et al.* 2007) and Arid Heath models (Cruz *et al.* 2010) are used by fire managers to manually estimate fire front rate of spread and so predict the future fire perimeter. Fire agencies in the USA (Finney and Ryan 1995) and Canada (Tymstra *et al.* 2010) have increasingly used wildfire simulators to more rapidly predict fire spread. Rapid automated fire prediction permits the many variables that influence fire spread to be quickly examined by changing simulator input parameters, such as forecast wind speed and direction, to determine how such changes influence fire spread.

A survey of fire spread modelling and simulation (Sullivan 2009*a*, 2009*b*, 2009*c*) classified fire spread simulators into several groups. *Physical* FBMs subdivide the area or volume of the fire into small cells and fire spread is simulated by numerically solving equations governing heat transport, ignition, combustion and fluid flow occurring within and between cells (Sullivan 2009*a*). This type of simulator is exemplified by WFDS (Mell *et al.* 2007) and FIRETEC (Linn *et al.* 2002). *Quasi-physical* simulators also model physical processes, but use simpler and more computationally tractable sets of rules designed to reproduce the net effect of the physical processes at some desired level of detail (Sullivan 2009*a*). Examples of quasi-physical simulators are described in Sullivan and Knight (2004), Santoni *et al.* (2011) and Achtemeier (2013).

Other simulators make use of *empirical* FBMs that predict rates of fire spread based on observations of experimental fires (Sullivan 2009*b*). These models are one-dimensional in that they predict head fire rates of spread. In order to predict fire spread over a two-dimensional landscape, simulators using rate-of-spread models make additional assumptions about fire shapes, the most common being that fires form elliptical shapes in uniform fuel and under constant wind. Given head fire rates of spread and a fire shape assumption, there are two commonly used approaches to computing spread across the landscape (Sullivan 2009*c*). Simulators using the *Huygens*' *wavelet principle* represent the current fire perimeter as one or more curves that are updated by calculating spread of a small point fire at points along the curve and then calculating the new curve as the area enclosing each of these small fires. FARSITE (Finney 2004), PROMETHEUS (Tymstra *et al.* 2010) and SIROFIRE/PHOENIX (Coleman and Sullivan 1996) use this approach. In contrast, the *grid-based* approach subdivides the landscape into discrete cells, and the time taken for the fire to propagate from each burning cell to its neighbour is calculated using an empirical fire behaviour model, the distance between cells and the current wind speed and direction. The time taken for the fire to arrive at any cell in the landscape is then the shortest time for the fire to travel from the ignition cell(s) to the target cell along any possible path. The earliest simulator of this type was created by Kourtz and O'Regan (1971), who identified several important issues regarding the representation of the landscape as discrete cells. FSPro (Finney 2002), FireStation (Lopes *et al.* 2002) and the Australis simulator (Johnston *et al.* 2008) examined in this study make use of this method.

Although wildfire simulators allow fire spread to be rapidly predicted and made available to fire, the accuracy of such simulators needs to be validated. Validating a wildfire simulator poses significant challenges including a scarcity of accurate fire progression data for real wildfires; the large number of variables, parameters and modelling assumptions involved; and the cumulative effect of errors, particularly when simulating large-scale fires. As a result, validation exercises have generally been restricted to smaller fires, in the order of tens and hundreds of hectares (Finney 1994; Finney and Ryan 1995; Perry *et al.* 1999; Miller and Yool 2002; Arca *et al.* 2007; Filippi *et al.* 2014).

Fire spread simulators form the core of *fire simulator systems*, consisting of (a) input datasets describing weather at the fire front, topography, vegetation, fuel load data and other determinants of fire spread, (b) mathematical models of physical phenomena such as rates of spread, fire shapes and rates of fuel accumulation, and (c) simulation software algorithms that apply the FBMs to the input data. Any of these components may introduce error into the output predictions. First, input data are subject to inaccuracy. For example, spatial boundaries in vegetation maps have limited precision and may have changed since the map was generated; ignition times and locations are generally approximate; and the closest meteorological observations may have been taken tens of kilometres from the fire site. Second, mathematical models approximate real phenomena based on a limited range of experimental and observational data. Third, the simulation algorithm itself can potentially introduce inaccuracy. For example, the Australis simulator partitions the environment into discrete cells with homogeneous attributes such as vegetation, slope and aspect. If the spatial resolution of the cell grid is coarse relative to the features being modelled, the assumption of homogeneity is likely to be inaccurate for many cells. Given the need for *accurate wildfire spread prediction* these factors need to be quantified and overcome – the rationale for this study.

The primary outcome of a simulator validation exercise is an assessment of overall system accuracy; however, an important secondary outcome is an evaluation of sources of error. Validation exercises can thus indicate whether further dataset gathering, fire behaviour model improvement, or algorithmic development would most contribute to improved simulator accuracy.

Rigorous validation of fire spread simulators should include a quantitative geometric comparison of reconstructed and simulated fires at multiple time points during the fire. A study by Filippi *et al.* (2014) evaluates four different measures for comparing simulated and reconstructed fires. The time-dependent kappa measure used in the current study is more sophisticated than the final area kappa analysed in the Filippi study, with our measure being closer to their proposed 'Arrival Time'. Like the Arrival Time measure, our measure penalises differences in intermediate propagation speed even when the final burnt areas agree.

In this study, we demonstrate a validation technique for any fire spread simulator that predicts a fire front time of arrival across the landscape by application to datasets from well-documented historical fires. We give a detailed worked example of the validation method via the application of one particular simulator (Australis) to a large-scale historical fire that occurred near the Boorabbin National Park, Western Australia (WA) in December 2007. Issues related to the availability of suitable high-quality data from the fire front are discussed, together with suggestions as to how this 'data problem' may be overcome in the future.

Materials and methods

Validation of wildfire simulation

The validation technique presented in this paper proceeds as follows:

1. Obtain the best available topographic, meteorological and fuel data for a historical fire event; and reconstructed ignition locations, final fire perimeter and intermediate fire spread perimeters for as many time points during the fire as possible. If the fire is long running and/or large, the period of the fire can be broken into phases separated by periods of low fire spread (e.g. overnight) or major changes in weather conditions. This allows the accuracy of the simulator to be assessed under a wider range of conditions, and prevents error in some phases from propagating to later phases. Each phase should contain multiple intermediate reconstructed fire perimeters.
2. Determine a *baseline* set of simulation inputs and parameters that represents the best estimate of weather conditions and fuel parameters (e.g. type, load, location). The fire should then be simulated using the baseline settings to generate a progression of simulated fire spread perimeters.
3. Quantitatively compare the level of agreement between the simulated and reconstructed fire progression perimeters.
4. Conduct sensitivity analysis by repeating the baseline simulation using alternative but plausible values of input variables to gauge how each variable might contribute to simulation inaccuracy. Simulations should cover the entire range of plausible values (based on experience and observations). Values should be evenly spaced for simplicity. This approach provides qualitative information on the response to the variable, such as whether increasing or decreasing the parameter value increases or reduces simulation accuracy, and on the comparative magnitude of the response (e.g. wind speed causing a larger change than temperature). Sensitivity analyses should also be performed over internal tuneable simulation algorithm parameter settings such as cell sizes or simulation time steps.

An overview of the validation technique is shown in Fig. 1.

The Boorabbin Fire

The Boorabbin Fire (28 December 2007–8 January 2008) burnt ~39,634 ha in the vicinity of the Boorabbin National Park, adjacent to the Great Eastern Highway, WA (see Fig. 2). Government reports on the Boorabbin Fire provided (i) a

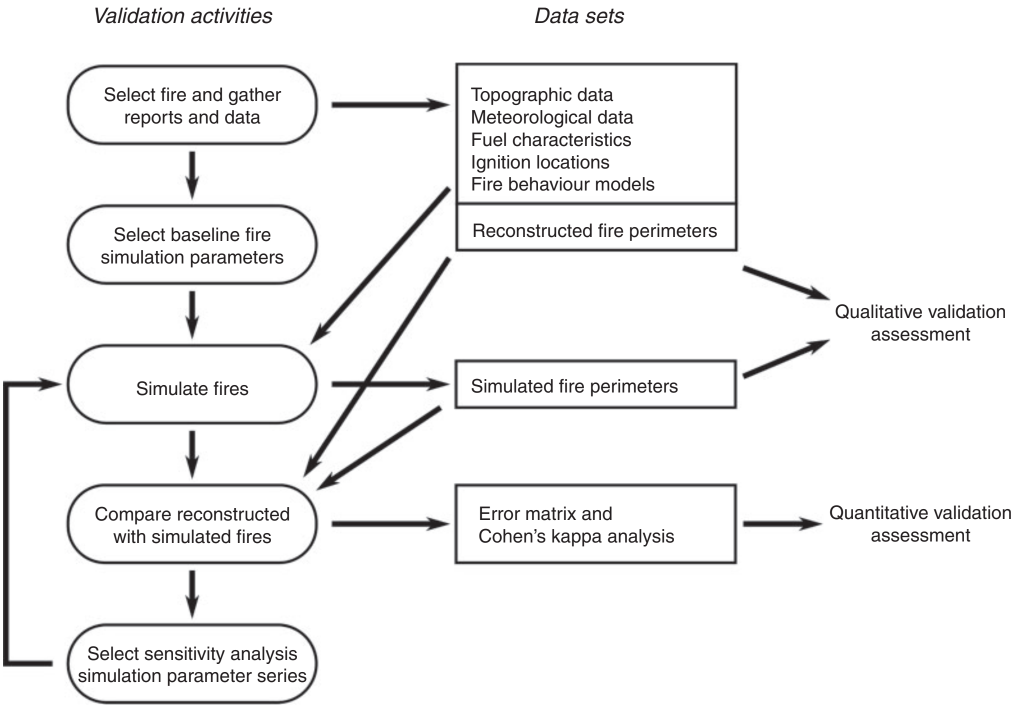

Fig. 1. Overview of fire spread simulator validation technique.

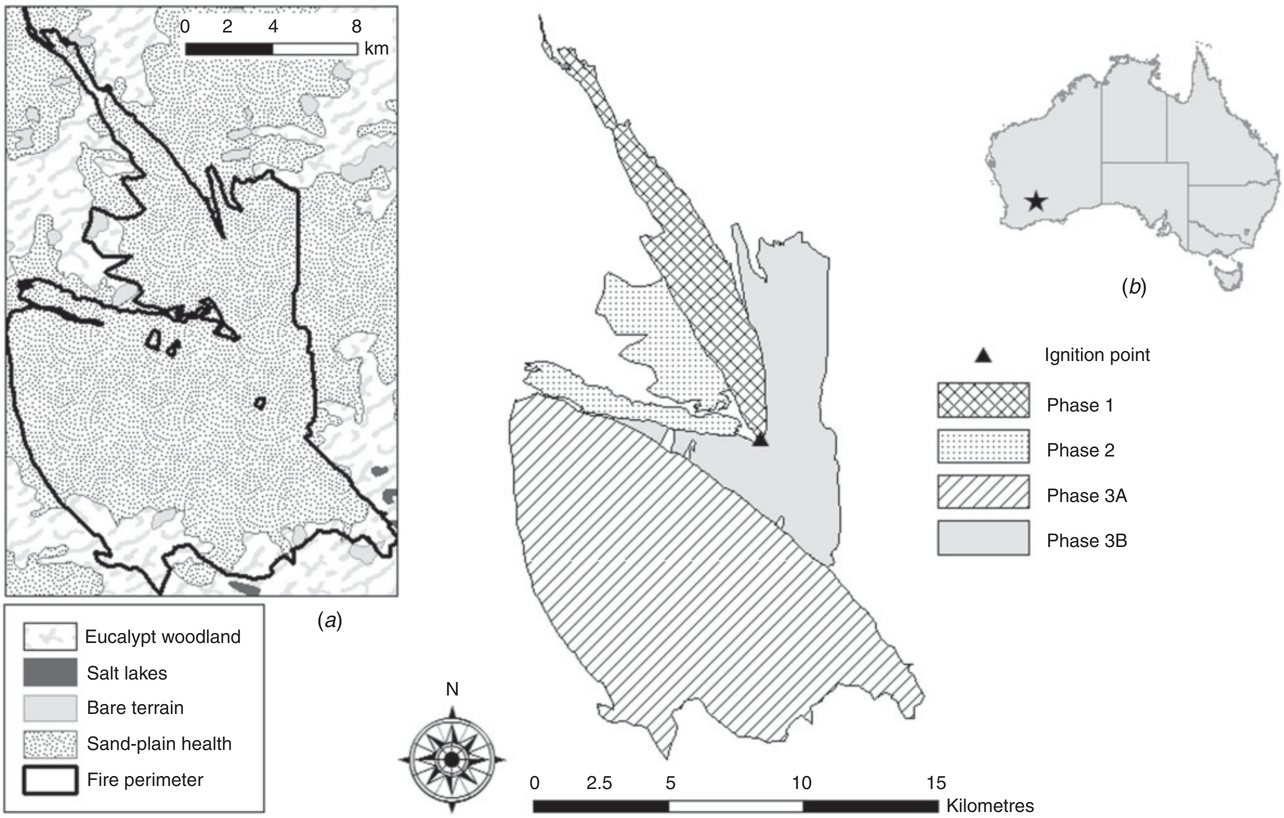

Fig. 2. The spatial extent of four phases of the Boorabbin Fire of 28–30 December 2007. Insets show: (*a*) the dominant vegetation communities occurring across the fire site, and (*b*) the location of the Boorabbin Fire in Western Australia.

Table 1. Summary of the four phases of the Boorabbin Fire simulated in this study

The date and time, total area burnt, meteorological conditions and indicators of fire weather severity are tabulated. Temperature, relative humidity and wind speed for each phase are given as a range (min–max) and mean (in parenthesis) from observations taken at the Southern Cross Airport AWS, the closest official automatic weather station to the fire site. The maximum Fire Danger Index (FDI) and Fire Danger Rating (FDR) for each phase are also listed; differences in the values of these indicators are solely due to variation in temperature, relative humidity and wind speed. WDT, Western Daylight Time; UTC, Coordinated Universal Time

	Phase 1	Phase 2	Phase 3A	Phase 3B
Time (WDT; UTC+9)	1200–2400 hours	1100–1900 hours	1100–2000 hours	2000–2400 hours
Date	28 Dec 2007	29 Dec 2007	30 Dec 2007	30 Dec 2007
Area burnt[A] (ha)	2200	1950	10 000	3700
Meteorological conditions[B]				
Temperature (°C)	19–37 (31)	25–35 (32)	38–43 (42)	20–38 (28)
Relative humidity (%)	19–58 (30)	18–36 (24)	4–11 (7)	9–68 (41)
Wind speed (km h^{-1})	18–39 (27)	19–24 (21)	22–44 (34)	26–48 (37)
Fire weather severity[B]				
FDI	28	20	104	47
FDR	Very high	High	Extreme+	Extreme

Source: [A]de Mar 2008; [B]Bureau of Meteorology 2008.

comprehensive assessment of the fuel and meteorological conditions (Bureau of Meteorology 2008; de Mar 2008) and (ii) a rigorous reconstruction of the fire perimeters by a fire behaviour expert at time steps ranging from 15 min to 3.5 h (de Mar 2008).

The climate of the fire site is semiarid with a mean annual rainfall of ~320 mm and a mean December rainfall of ~14 mm (Bureau of Meteorology 2008). At the time of the fire there was a substantial rainfall deficit, with a total of 202.6 mm recorded for 2007. The closest official weather observatory was the Southern Cross Airport Automatic Weather Station (AWS) (31°13′44″S, 119°21′12″E, elevation 347 m above sea level), located ~75 km west of the fire's ignition point.

The fire area was very flat with the majority of the whole area studied (~15 × 30 km) lying between 420 and 450 m above sea level. Apart from the variation in vegetation noted below, topography is believed to have little effect on the progress of the fire. The fire site contains two plant communities with markedly different fuel characteristics (de Mar 2008). The first is eucalypt woodland dominated by Salmon Gum (*Eucalyptus salmonophloia*), characterised by a sparse understorey layer and low fuel continuity. The second is the semiarid, sand-plain heath of the Goldfields region. This is distributed across the fire site area as a heterogeneous mosaic of two major sub-types: 'heath-scrub', containing shrub species of the genera *Acacea*, *Hakea*, *Grevillea* and *Callitris*, and several *Eucalyptus* species of the mallee form; and 'tamma scrub', dominated by species of the genera *Allocasuarina*, *Acacia* and *Melaleuca*. Where heath-scrub is characteristically open and patchy, tamma scrub is relatively dense and continuous. In general, it was not possible to identify which type of sand-plain heath community was present in a particular area as the different types are indistinguishable in satellite imagery and vegetation maps of the area combine the different heath communities into a single group. The density, size and structure of fuel in the eucalypt woodland are sparse, mostly coarse and arranged as dead branches and logs on the ground. In contrast, fuel in the sand-plain heath, although frequently discontinuous, is denser and arranged in a mature elevated fine fuel complex containing a high proportion of dead fine fuel. Due to these differences in fuel characteristics, the heathlands are more fire prone and support a faster rate of forward spread of fire than the woodland.

The first 3 days of the Boorabbin Fire were the most well documented (28–30 December 2007). For the purposes of this study, this period has been divided into four phases. An overview of each phase is given in Table 1 and the area burnt in each phase is shown in Fig. 2. Phases 2 and 3A begin when increasing temperatures and decreasing relative humidity had reduced fuel moisture values sufficiently to allow sustained fire spread.

In each of the four phases the burnt areas consisted predominantly of sand-plain heath (de Mar 2008). Comparison of pre- and post-fire Landsat satellite imagery (captured 21 August 2007 and 16 March 2008) confirmed this observation. The boundaries of the fire coincided well with the boundaries between the sand-plain heath and the eucalypt woodland, indicating that the spread of the fire was constrained by the eucalypt woodland, even under extreme fire weather conditions. Fire site inspection showed that the fire typically penetrated no more than 50 m into woodland areas (de Mar 2008), with some exceptions to this rule occurring in Phases 2 and 3A.

Fire spread simulations

Simulations of the Boorabbin Fire were generated using the Australis wildfire simulator, which implements the algorithm described in Johnston *et al.* (2008). Australis uses existing empirically derived rate-of-spread models that predict head fire rates of spread under constant weather and fuel conditions, and a geometric algorithm to derive two-dimensional fire spread over a heterogeneous landscape under time-varying weather conditions. The geometric algorithm uses the standard assumption that point ignition fires will develop into elliptical fire shapes. Australis employs a discrete event simulation technique (Zeigler *et al.* 2000) that is based on partitioning the landscape into a collection of two-dimensional cells and calculating the propagation delay between an 'ignited' cell and each of its 'unburnt' neighbours. Each cell contains state information ('unburnt', 'ignited', or 'burnt out') and several attributes relevant for calculating propagation delay, including location, elevation, slope and orientation, and fuel characteristics such as

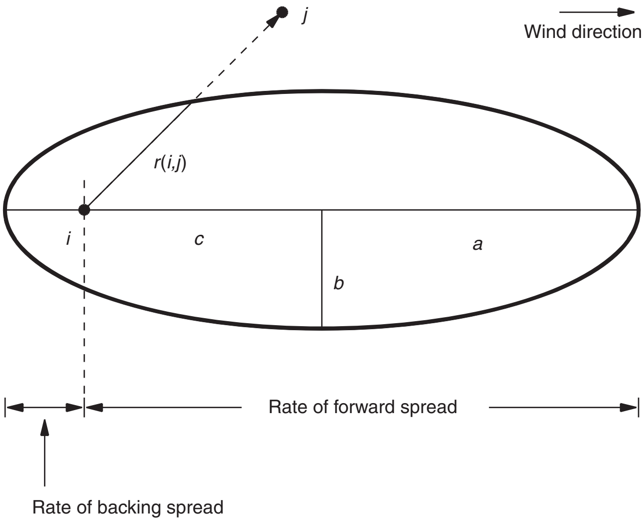

Fig. 3. The rate of spread $r(i,j)$ between the centroids of cells i and j is determined from the geometry of an ellipse, where the major axis of the ellipse is aligned in the direction of the wind. The ellipse is uniquely determined by specifying the parameters a (semi-major axis), b (semi-minor axis) and c as follows: $a + c$ is the predicted rate of forward spread; $a - c$ is the rate of backing spread (and can be zero); and b is determined from a length-to-breadth ratio. The rate of spread $r(i,j)$ is determined from the length of the line segment lying on the ray ij and bounded by i and the perimeter of the ellipse.

vegetation type and fuel load. In contrast to other cell-based approaches to wildfire simulation in which cells are distributed regularly, here the location of the cells is distributed semi-randomly across the landscape in order to avoid a form of fire shape distortion that results from using a regular partition, as described in Johnston *et al.* (2008). The cell centroids are generated according to the Poisson disk distribution (Lagae and Dutré 2008). The discrete cellular structure of the landscape model is a potential source of simulation error that we assess as part of this study.

To enable investigation of alternative fire spread shape assumptions, the version of AUSTRALIS used in this study utilises an algorithm where the fire shape is determined by the head fire rate of spread and an independent length-to-breadth ratio parameter, as shown in Fig. 3. Further, in this study each cell was connected to additional, more distant neighbours in addition to its immediate neighbouring cells, allowing arbitrary elliptical fire shapes to be reproduced more accurately (Schönfisch 1997). This approach has been applied previously in fire spread simulators using square (Lopes *et al.* 2002) and hexagonal (Hernández Encinas *et al.* 2007) grids. For all simulations in this study, cells were connected to neighbours up to eight 'network hops' away in the Delaunay triangulation (de Berg *et al.* 2008) induced by the cell centroids.

Baseline simulation input data

Table 2 lists the baseline simulation input data sources and simulation parameters. Hourly meteorological data input to the simulator were obtained from the closest official weather station (the Southern Cross Airport AWS). Elevation data were obtained from the Shuttle Radar Topography Mission digital elevation map of Australia, a raster with a spatial resolution of $\sim 90 \times 90\ m^2$ (Farr *et al.* 2007). Most of the fire site had not been cleared or otherwise altered for human use and the pre-European settlement vegetation database for WA was used. For each phase of the fire the initial ignition times and locations were determined from the fire reconstruction (de Mar 2008).

The FBMs used in the simulations are listed in Table 3. As no FBMs have been developed specifically for the type of sand-plain heath present in the study area, all rate-of-spread models that might be suitable for discontinuous heath vegetation in Australia were examined. These were a semiarid heath model, HE (the baseline setting) (Cruz *et al.* 2010); three mallee–heath models, MH1–3 (McCaw 1997; Cruz *et al.* 2010); a shrubland model, SH (Catchpole *et al.* 1998); and a spinifex model, HG (Burrows *et al.* 2009). With respect to fuel characteristics, the HE model is perhaps the best match for the two dominant types of sand-plain heath occurring at the fire site; before the development of HE the MH1 model was considered to be the most appropriate match (de Mar 2008). A hummock grass fire behaviour model, HG (spinifex), (Burrows *et al.* 2009) was also evaluated. As spinifex was not present at the fire site, this fire behaviour model was included not as a candidate model for the fire site vegetation, but rather to examine how another fire behaviour model developed for discontinuous fuels compared with the candidate models. All areas containing eucalypt woodland used McA, the McArthur Mk 5 forest fire equations (Noble *et al.* 1980; Sirakoff 1985).

Three FBMs (MH1, SH and HG) use 2-m wind speed values, which were calculated according to $U2 = d \times U10$, where d is a wind-reduction factor satisfying $d < 1$. The relevant wind-reduction factors were 0.8 for HG and SH, and 0.71 for MH1. The value $d = 0.8$ is an approximation used by convention for bare terrain and is appropriate for spinifex (N. Burrows, pers. comm.) and shrubland fuels less than 2 m high (R. Smith, pers. comm.); $d = 0.71$ is appropriate for mallee–heath (McCaw 1997).

Measurements of fuel moisture were not available, so fuel moisture was estimated from meteorological variables using predictive models. For MH1, the suspended dead fuel moisture M_s and the moisture of the deep litter layer M_{dl} were estimated from temperature and relative humidity using a model for the moisture content of the surface layer of a eucalypt litter bed (McArthur 1967; Viney 1991), which has been found to approximate M_s and M_{dl} (McCaw 1997). For MH2, MH3 and HE, suspended dead fuel moisture content M_s was estimated from solar radiation, temperature, relative humidity and wind speed using a tabular relationship developed for the meters (Cruz *et al.* 2010; Matthews *et al.* 2010). Clear sky solar radiation was estimated from the time of day and latitude and longitude of the fire site using the pysolar library.[1]

Other variables were set as follows. The heath-scrub vegetation present at the fire site was assessed from the photographs of unburnt vegetation in the vicinity of the fire site contained in de Mar (2008) for percentage cover score (PCS) and fuel hazard

[1]Pysolar release 0.43. Available at http://pysolar.org/ (accessed 3 April 2012).

Table 2. The simulation parameters, input variables and fire behaviour models for the Australis simulations performed in this study
Baseline values are indicated where relevant

Simulation parameters, input variables and models	Symbol	Baseline value/model
Cell grid		
Cell size (m)		50
Cell connectivity	k	8
Meteorological variables		
Wind speed measured at 2 m (km h^{-1})	U2	
Wind speed measured at 10 m (km h^{-1})	U10	Southern Cross AWS
Wind direction (°)	WD	As above
Temperature (°C)	T	As above
Relative humidity (%)	RH	As above
Drought factor	DF	10
Fuel variables		
Height of vegetation (m)	H_v	1
Height of overstorey (m)	H_o	2
Percentage cover score of elevated layer (0–4)	PCS	1.5
Fuel hazard score of elevated layer (0–4)	FHS	1.5
Suspended dead fuel moisture (%)	M_s	Table-based estimates from meteorological inputs (Cruz *et al.* 2010)
Fuel load of eucalypt woodland (t h^{-1})	FL_E	4
Fuel load of spinifex (t h^{-1})	FL_S	7
Spinifex profile moisture content (%)	M_p	14 (Phase 3A), 18 (other phases)
Fire behaviour and fuel moisture models		
Rate of forward spread	RoS	HE (scrub), McA (woodland)
Length-to-breadth ratio	L:B	12 : 1 (scrub), 6 : 1 (woodland)
Slope correction		(McArthur 1967; Noble *et al.* 1980)

Table 3. Fire behaviour models used to estimate rate of spread in Australis simulations of four phases of the Boorabbin Fire, WA 2007
Listed for each fire behaviour is the type of vegetation to which the model applies, the input variables to the model and their corresponding values. For an explanation of input variables, see Table 2

Symbol	Reference	Vegetation type	Input variables
HE	(Cruz *et al.* 2010)	Semiarid heath	U10, M_s, PCS
MH1	(McCaw 1997)	Mallee–heath	U2, M_{dl}, M_s
MH2	(Cruz *et al.* 2010)	Semiarid mallee–heath	U10, M_s, PCS, H_o
MH3	(Cruz *et al.* 2010)	Semiarid mallee–heath	U10, M_s, FHS, H_o
SH	(Catchpole *et al.* 1998)	Shrubland	U2, H_v
HG	(Burrows *et al.* 2009)	Spinifex	U2, M_p, FL_S
McA	(McArthur 1967; Noble *et al.* 1980; Sirakoff 1985)	Eucalypt forest/woodland	U10, T, RH, DF, FL_E

score (FHS): the PCS was 1.5 and the FHS was 1.5. Height values were also assessed from the photographs, giving shrub height $H_v = 1$ m and overstorey height $H_o = 2$ m. The spinifex fuel load variable FL_S was set to 7 t ha^{-1}, the mean fuel load over the HG model's sample data (Burrows *et al.* 2009); spinifex profile moisture content M_p was estimated to be 18% (for Phases 1, 2 and 3B) and 14% (Phase 3A) (N. Burrows, pers. comm.). The drought factor and grass-curing variables were set to 10 (the maximum value) and 100% to reflect the antecedent drought conditions at the time of the fire. Finally, the fuel load in eucalypt woodland FL_E was estimated as 4 t ha^{-1}, due to the very sparse understorey component.

Flank fire spread is related to fluctuation in the wind direction and the continuity of the fuel and can be modelled using an appropriate length-to-breadth ratio. For sand-plain heath, the length-to-breadth ratio was estimated as 12 : 1. This relatively high ratio reflects the discontinuous nature of the fuel, which inhibits flank spread. As far as the authors are aware, no length-to-breadth relationships have been published for discontinuous heathland fuels. The length-to-breadth ratio for eucalypt woodland was 6 : 1 (Cheney 2010).

Measuring simulation accuracy: predicted vs. reconstructed fire spread

The accuracy of the Australis simulator at predicting the fire spread progression of the Boorabbin Fire was measured as follows. At the conclusion of a simulation, Australis output the fire arrival time for each burnt cell in the cell grid. The duration of each fire phase was divided into discrete time periods

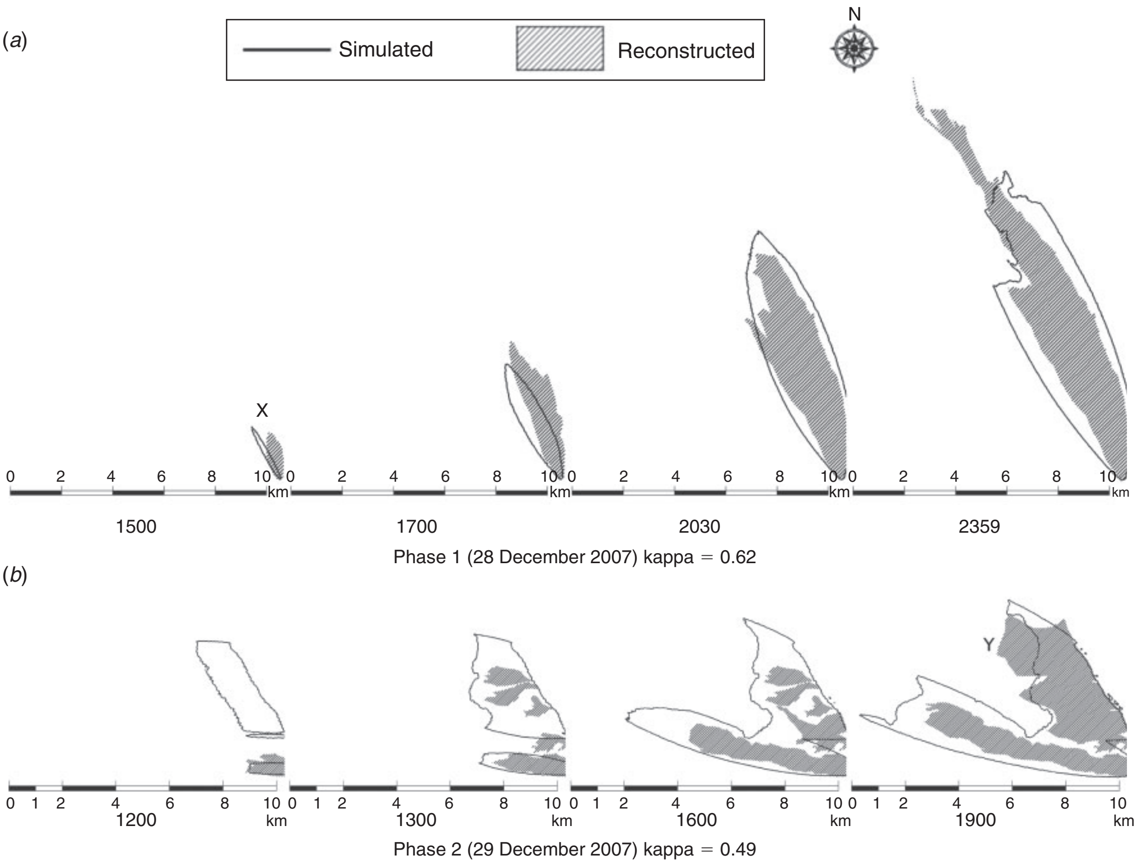

Fig. 4. The progression of the Boorabbin Fire, Western Australia, during Phases 1 and 2 (28–29 December 2007). Comparison between simulated and reconstructed fire perimeters for (*a*) Phase 1 at 1500, 1700, 2030 and 2359 hours, and (*b*) Phase 2 at 1200, 1300, 1600 and 1900 hours. Simulation parameters were the baseline values given in Table 2. The annotations 'X' and 'Y' are discussed in the text.

demarcated by the times of the reconstructed time perimeters, plus an additional 'unburnt' category. For example, if ignition occurred at time zero and three reconstructed perimeters were recorded at hourly intervals (the third representing the final perimeter), each cell would be classified as having burnt in hour 1, hour 2 or hour 3, or remained unburnt. Each simulation cell was then classified into these categories *twice*: once based on the fire reconstruction map, and once based on the simulated fire arrival time. Simulation accuracy was then determined using Cohen's kappa coefficient (K) (Congalton and Green 1999) – a statistical measure of agreement between two geo-spatial datasets that has been used previously for assessing the accuracy of fire spread simulation (Arca *et al.* 2007), given by:

$$K = \frac{N\sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k}(x_{i+} - x_{+i})}{N^2 - \sum_{i=1}^{k}(x_{i+} - x_{+i})}$$

where x is the error matrix: x_{ij} is the number of simulation cells where the simulated and reconstructed fires arrive in time period i and j respectively; x_{i+} and x_{+i} are the marginal totals of row i and column i respectively; and N is the total number of samples.

K varies over [–1,1], where $K = 1$ indicates perfect agreement, $K = 0$ indicates that agreement is due to chance alone and negative values indicate systematic disagreement. For this application, perfect agreement would be obtained if the simulated fire resulted in the same final fire perimeter *and* if each cell burnt in the same period determined from the reconstructed fire. The large sample variance for K was calculated using the delta method (Congalton and Green 1999) and this was used in the construction of confidence intervals for K values (see 'Confidence intervals for kappa agreement values' in the Results).

It is important to note that K as used here gives simulation accuracy with respect to the *reconstructed* rather than the *actual* behaviour of the fire. In order to minimise inaccuracies resulting from discrepancy between the actual and reconstructed behaviour of the fire, we simulated the phases of the fire that were reconstructed with the most rigour, which were Phases 1, 2, 3A and 3B described above. In these phases, fire progression was reconstructed at a temporal resolution of no less than one perimeter every 3.5 h.

Results

The reconstructed and simulated fire perimeters are shown for Phases 1 and 2 (Fig. 4) and Phases 3A and 3B (Fig. 5), at four

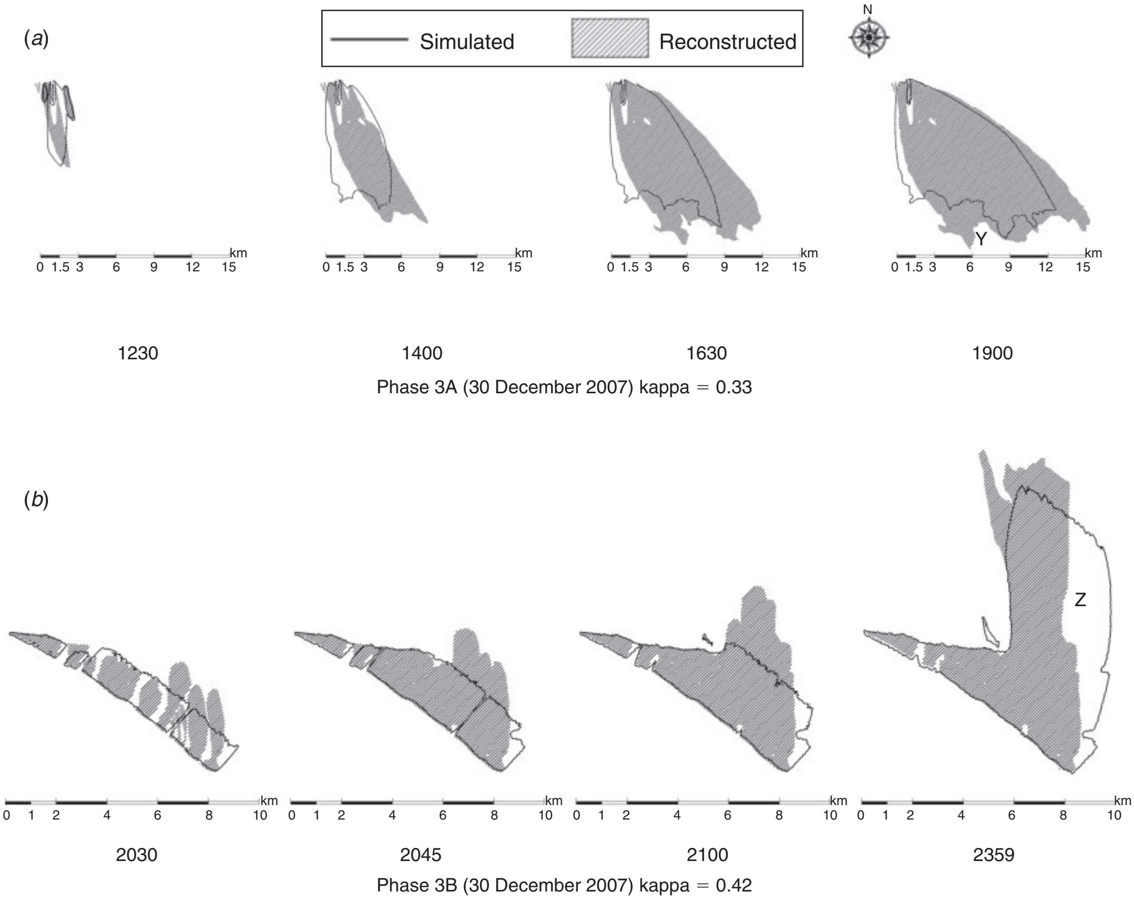

Fig. 5. The progression of the Boorabbin Fire, Western Australia, during Phases 3A and 3B (30 December 2007). Comparison between simulated and reconstructed fire perimeters for (*a*) Phase 3A at 1230, 1400, 1630 and 1900 hours, and (*b*) Phase 3B at 2030, 2045, 2100 and 2359 hours. The annotations 'Y' and 'Z' are discussed in the text.

time points during each phase. Examination of the baseline simulated *vs.* reconstructed fire perimeters permits the following qualitative assessment.

The distance of the Southern Cross AWS from the fire site (~75 km) led to some discrepancies in the wind direction. For example a discrepancy can be inferred from directional differences between the simulated and reconstructed perimeters for 1500 Phase 1, which represent fire spread unconstrained by fire-fighting activity (see mark X in Fig. 4). A discrepancy is also apparent at the beginning of Phase 3B, which led to substantial over-prediction in the extent of the final fire perimeter (see Z, Fig. 5). In this case the initial discrepancy was relatively small but was compounded over the duration of the simulation. A second source of inaccuracy, apparent at the beginning of Phase 2, is the initial fire positions. From the reconstruction report and the reconstructed fire perimeters for Phase 2 (de Mar 2008), it appears that only part of the fire line fully extinguished during the night and that there were 'ignitions' (i.e. fire picking up from smouldering) in several places between 1200 and 1900 hours the next day, and we assumed a continuous ignition line at the beginning of the phase. Note that for Phase 2, the *final* simulated fire perimeter was similar to the reconstruction; however, the agreement parameter *K* penalises the discrepancy at *intermediate* fire perimeters, which explains the lower Phase 2 *K* value compared with Phase 1.

A third source of inaccuracy was the resolution of the vegetation map. Inspection of the Landsat imagery of the area showed that some areas of the map marked as eucalypt woodland were interspersed with heath, and carried fire. Simulation in these areas under-predicted the extent of fire spread (see Y, Fig. 4 and 5).

Another major discrepancy between the simulated and reconstructed fire progression is apparent in Phase 3A and 3B, where the simulated fire significantly lags the reconstructed fire. As discussed below, there are multiple possible explanations for this discrepancy.

Cell size and confidence intervals for agreement statistic kappa

All the values for the agreement measure (*K*) given in these results have a 95% confidence interval of at most +/− 0.0170. This value includes variance contributions from two sources, the first being the large sample variance of *K* calculated using the delta method (Congalton and Green 1999). The largest sample standard deviation for any simulation was 0.00401. The second source of variance was due to the fact that as Australis uses a

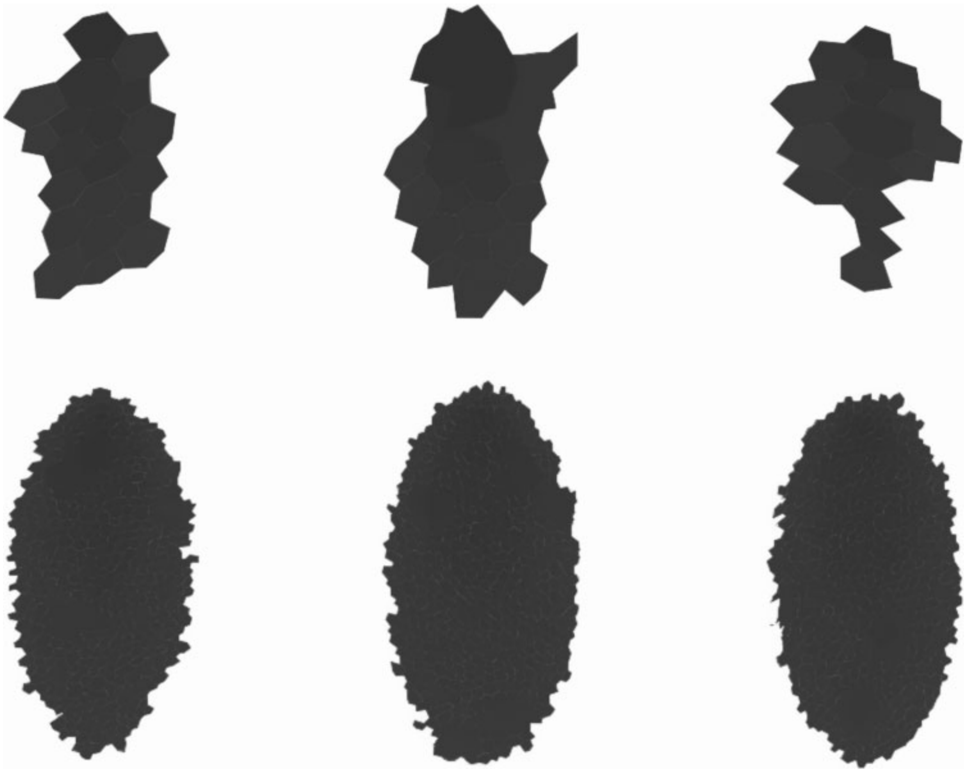

Fig. 6. The top row shows three simulations with identical parameters but that use different randomly generated cell grids. The bottom row uses the same simulation parameters but the cells are five times smaller, again with three different random grids.

Table 4. The effect of cell size on mean simulation accuracy (*K*) and standard deviation over *n* = 5 AUSTRALIS simulations

Cell size (m)	Phase 1	Phase 2	Phase 3A	Phase 3B
50	0.62 (0.006)	0.49 (0.002)	0.33 (0.001)	0.42 (0.008)
100	0.63 (0.007)	0.48 (0.011)	0.34 (0.002)	0.38 (0.004)
250	0.64 (0.006)	0.45 (0.026)	0.33 (0.010)	0.34 (0.008)
500	0.41 (0.061)	0.37 (0.060)	0.31 (0.017)	0.29 (0.027)
750	0.22 (0.069)	0.28 (0.049)	0.29 (0.016)	0.26 (0.014)

Table 5. Meteorological input sensitivity analysis simulation parameters

Meteorological variable	Baseline	Adjusted meteorological series
Wind speed (km h^{-1})	U10	U10 ± 5, U10 ± 10, U10 ± 15, U10 ± 20
Wind direction (°)	WD	WD ± 5, WD ± 10, WD ± 15
Temperature (°C)	T	T ± 5, T ± 10, T ± 15
Relative humidity (%)	RH	RH ± 5, RH ± 10, RH ± 15

randomly generated rather than a fixed cell grid, which means that two simulations made with identical input data may have varying output (Fig. 6 illustrates this simulation artefact at two different cell sizes). Variance due to the random cell grids was estimated by repeating simulations for each fire phase using five random cell grids (see Table 4); for the standard 50-m cell size the largest standard deviation was 0.00748. Rather than report confidence intervals for every tabulated *K* value, we indicate values in each table that are not significantly different (at the 95% confidence level) from the highest *K* value for each phase.

Influence of meteorological variables on simulation accuracy

The influence of the weather on simulation accuracy was achieved by systematically varying each meteorological variable from its baseline value (i.e. the observations obtained from the Southern Cross AWS). The full set of weather variations are given in Table 5. The effect of each meteorological input series on simulation accuracy is given in Table 6. As expected, changes in wind speed and direction have a much greater influence on simulation accuracy than temperature and humidity. Table 7 shows the level of influence of the four meteorological variables on simulation accuracy.

The results for Phases 1 and 2 suggest that the baseline weather series obtained from the Southern Cross AWS was probably not a major source of error for these phases, which is consistent with Fig. 4. For Phase 3A, the simulation with the greatest accuracy occurs under WD – 15°. This result is consistent with de Mar's (2008) analysis that transient westerly winds occurred during this phase at the fire site and affected the shape of the perimeters. As the winds observed at the Southern Cross AWS were northerly, subtracting 15° would compensate by increasing the westerly component.

In Phase 3B, although the wind direction was clearly incorrect at the beginning of the period (see Fig. 5, up to 2100), no simple uniform alteration of wind direction improved accuracy. This is because this phase involved a change in wind direction, so any uniform alteration in wind direction to correct the spread at the beginning of the phase would also introduce additional error at the end of the phase and vice versa. In terms of wind speed, the results are *consistent* with the wind speed being under-estimated by 20 km h^{-1} during Phases 3A and 3B. We emphasise, however, that Fig. 5 makes apparent that the *rate of spread* was under-estimated during Phases 3A and 3B, and that variance in wind speed is just one of several possible explanations.

Table 6. The effect of uncertainty in meteorological input series on the accuracy (*K*) values for simulations

The bold typeface indicates the highest accuracy for each phase

Meteorological series	Phase 1	Phase 2	Phase 3A	Phase 3B
Wind speed				
U10 – 20	0.00	0.04	0.19	0.25
U10 – 15	0.14	0.32	0.24	0.29
U10 – 10	0.34	0.38	0.28	0.33
U10 – 5	**0.63**	0.46	0.31	0.37
U10	0.62*	**0.49**	0.33	0.42
U10 + 5	0.52	0.44	0.36	0.49
U10 + 10	0.43	0.39	0.38	0.53
U10 + 15	0.39	0.36	0.40	0.55
U10 + 20	0.35	0.34	**0.44**	**0.58**
Wind direction				
WD – 15	0.23	0.31	**0.47**	0.41*
WD – 10	0.33	0.36	0.43	0.41*
WD – 5	0.51	0.43	0.38	0.42*
WD	**0.62**	**0.49**	0.33	**0.42**
WD + 5	0.59	0.40	0.29	0.41*
WD + 10	0.37	0.31	0.25	0.40
WD + 15	0.23	0.33	0.22	0.38
Temperature				
T – 15	0.67*	0.33	0.31	0.36
T – 10	**0.68**	0.48*	0.32	0.38
T – 5	0.66*	0.48*	0.33*	0.39
T	0.62	**0.49**	0.33*	0.42
T + 5	0.59	0.47	**0.33**	0.44*
T + 10	0.60	0.46	0.33*	0.45*
T + 15	0.59	0.46	0.33*	**0.46**
Relative humidity				
RH - 15	0.44	0.41	0.33*	**0.52**
RH - 10	0.51	0.45	0.33*	0.50*
RH - 5	0.57	0.47	**0.33**	0.48
RH	0.62	**0.49**	0.33*	0.42
RH + 5	0.67*	0.49*	0.30	0.38
RH + 10	**0.68**	0.48*	0.30	0.36
RH + 15	0.63	0.48*	0.29	0.34

*not significantly different from the highest accuracy at the 95% confidence level.

Influence of vegetation cover on simulation accuracy

In addition to meteorological variables, the rate of forward spread predicted by the baseline fire behaviour model for the majority sand-plain heath vegetation depends on an elevated fuel cover score (PCS) (Gould *et al.* 2007). This variable measures the level of canopy cover of the elevated fuel layer within a 5-m radius of a sample point and is a value between 0–4, where 0 indicates that elevated fuel is absent within the 5-m radius and 4 indicates a continuous cover of shrubs.

Table 8 shows that no single PCS value produced the most accurate simulation under all four phases. Maximum simulation accuracy was obtained under a low PCS (1.5) for Phases 1 and 2 and high PCS (≥3) for Phases 3A and 3B. This bi-modal result could be due to genuine differences in the PCS of the vegetation associated with each phase. The fire site had a higher cover of tamma scrub than heath-scrub: although spatial data on the distribution of the types was not available in the vegetation input layer, Tamma scrub was present in some areas burnt during Phase 3B according to (de Mar 2008). Alternatively, the higher best-fitting PCS values in Phase 3 might be compensating for inaccuracy in other input variables.

Influence of length-to-breadth ratio on simulation accuracy

The aim of this experiment was to determine an appropriate length-to-breadth ratio for simulating two-dimensional fire

Table 8. Accuracy (*K*) of four simulated phases of the Boorabbin Fire, using alternative percentage cover scores (PCS)

The greatest *K* value for each phase is shown in bold font

PCS	Phase 1	Phase 2	Phase 3A	Phase 3B
1	0.41	0.40	0.27	0.31
1.5	**0.62**	**0.49**	0.33	0.42
2	0.44	0.40	0.38	0.55
2.5	0.35	0.34	0.46	0.57*
3	0.29	0.30	0.50	**0.58**
3.5	0.25	0.28	0.53	0.55
4	0.21	0.25	**0.54**	0.51

*not significantly different from the highest accuracy at the 95% confidence level.

Table 7. Summary of the effect of uncertainty in meteorological input variables on the range accuracy (*K*) values of simulations

The accuracy range for each meteorological variable is given as the difference between the maximum and minimum accuracy obtained (single figure) and the corresponding range (in parenthesis)

Meteorological series	Phase 1	Phase 2	Phase 3A	Phase 3B
Wind speed	0.63 (0.00–0.63)	0.45 (0.04–0.49)	0.25 (0.19–0.44)	0.33 (0.25–0.58)
Wind direction	0.39 (0.23–0.62)	0.18 (0.31–0.49)	0.26 (0.22–0.47)	0.05 (0.38–0.42)
Temperature	0.09 (0.59–0.68)	0.16 (0.33–0.49)	0.02 (0.31–0.33)	0.10 (0.36–0.46)
Relative humidity	0.24 (0.44–0.68)	0.08 (0.41–0.49)	0.04 (0.29–0.33)	0.18 (0.34–0.52)

spread in the sand-plain heath of the fire site, as there are no published fire shape behaviour models suitable for the discontinuous vegetation similar to that found there. In discontinuous heathland, two-dimensional fire spread from a point source would be expected to have a narrow, 'cigar-like' shape (M. Cruz, pers. comm.), as the discontinuity of the vegetation would constrain fire spread on the flanks. Thus, relatively high length-to-breadth ratios of 6 : 1, 9 : 1, 12 : 1 and 15 : 1 were evaluated. As length-to-breadth relationships are in general known to depend on wind speed, a wind speed-dependent ratio (Luke and McArthur 1978; Cheney and Sullivan 2008) with simple modifications was also evaluated. The modifications increased the ratio by 4 and 8 to account for the narrow shapes expected under discontinuous fuel.

Table 9 reveals that the effect of length-to-breadth ratio on simulation accuracy was bi-modal, with accuracy improving as the ratio increased for Phases 1 and 2, whereas the inverse was observed for Phases 3A and 3B. For Phases 1 and 2 the calculated accuracy (*K*) and inspection of Fig. 4 indicates that a length-to-breadth ratio of at least 12 : 1 is an appropriate fire shape ratio for this vegetation type under these weather conditions. Phases 3A and 3B are difficult to interpret due to uncertainty in other factors. It may be the case that the lower length-to-breadth ratios were preferred because they compensated for discrepancies in wind direction that seem to have been present in Phase 3, by generating additional lateral spread in a westerly direction; however, this is highly speculative.

Influence of fire behaviour model on simulation accuracy

The aim of this experiment was to verify that the semiarid heath fire behaviour model HE (Cruz *et al.* 2010) is an appropriate model for predicting rate of spread in the sand-plain heath of the fire site; results are shown in Table 10.

The study found that over the initial two phases for which the weather data seem most reliable, the most accurate fire spread predictions were made by the HE and HG FBMs. This result affirms the common sense practise of selecting a model based on the characteristics of the fire site vegetation and suggests that HE is a satisfactory model for the sand-plain heath vegetation of the fire site for non-extreme fire danger conditions.

Table 9. Accuracy (*K*) of four simulated phases of the Boorabbin Fire, when simulated under several fire shape behaviour models
The greatest *K* value for each phase is shown in bold font

	Phase 1	Phase 2	Phase 3A	Phase 3B
Fixed L : B				
6 : 1	0.52	0.43	0.36	**0.44**
9 : 1	0.58	0.47	0.34	0.43*
12 : 1	0.62	0.49*	0.33	0.42*
15 : 1	**0.64**	**0.49**	0.33	0.41
Grassland L : B				
+0 : 0	0.48	0.39	**0.36**	0.44*
+4 : 0	0.58	0.46	0.34	0.43*
+8 : 0	0.63*	0.49*	0.33	0.42

*not significantly different from the highest accuracy at the 95% confidence level.

For Phases 3A and 3B, the mallee–heath model MH1 scored the highest accuracy. Although it is possible that the mallee–heath models better predict rate of spread compared with the HE model under the strong wind conditions of Phase 3, the potential discrepancies in the weather and vegetation (PCS) data discussed previously mean that this conclusion is highly uncertain.

Discussion

Evaluation of the Australis fire simulation system

This fire spread simulator validation case study has allowed us to draw several conclusions about the Australis simulator as applied to the 2007 Boorabbin Fire in WA.

The 50-m cell spacing at which the simulations in this study were performed was of sufficiently small size that the Australis random grid generation did not play any part in the analysis, with any effects being smaller than any other sources of inaccuracy considered. Although this cell spacing resulted in simulations using ~110 000 cells, each simulation was completed in ~3 min on a PC computer, which made tractable the extensive sensitivity analyses performed in this study.

As expected, variance in wind data (speed and direction) contributed most to variance in simulation output. Variation of temperature, relative humidity, fuel characteristics, fire behaviour model and fire shape model (length-to-breadth ratio) also caused variation in simulation output, although to a lesser degree. The study indicates that differences between the actual fire ground weather and the weather recorded from the nearest weather station (75 km distant from the fire) may be a major source of simulation error. The availability of gridded weather forecasts, which have recently been made available from the Bureau of Meteorology in Australia at a 12-km resolution, may improve this situation; however, no archived data were available for this study.

The simulated fire progression in Phases 1 and 2 was consistent with the input data and fire behaviour model being broadly accurate. In these phases, the largest mismatches between simulated and reconstructed fire progression could be clearly attributed to inaccuracies in the vegetation map or choice of initial fire location at the start of the simulation. In Phases 3A and 3B, which occurred in extreme fire danger conditions and with identifiable inaccuracies in wind direction, simulation

Table 10. Accuracy (*K*) of four simulated phases of the Boorabbin Fire, when simulated with alternative fire behaviour models
The greatest *K* value for each phase is shown in bold font

RoS model	Phase 1	Phase 2	Phase 3A	Phase 3B
HE	**0.62**	0.49*	0.33	0.42
MH1	0.31	0.49*	**0.49**	**0.56**
MH2	0.50	0.45	0.36	0.54
MH3	0.45	0.43	0.38	0.56*
SH	0.47	0.42	0.21	0.37
HG	0.60*	**0.49**	0.33	0.53

*not significantly different from the highest accuracy at the 95% confidence level.

accuracy was lower and exhibited under-prediction of the head fire rate of spread. This suggests a problem with inaccuracies in *at least one of* wind speed, vegetation data (PCS) or fire behaviour model; however, the source of the inaccuracy could not be resolved with the available data. The under-prediction of rates of spread in extreme conditions by FBMs that are derived from experimental fires in more benign conditions is a known and ongoing problem. In principle, simulation studies such as this one might be able to supply additional data points for extreme fires; however, this would only be possible where weather and fuel variables have been very accurately characterised.

Of the existing Australian FBMs, the semiarid heath model of (Cruz *et al.* 2010) with a 12 : 1 length-to-breadth fire shape ratio was found to be the most suitable for the sand-plain heath present in the fire area, under non-extreme conditions.

We believe the level of accuracy demonstrated by the simulations in Figs 4 and 5 is sufficient to make some contribution to fire management. Although there are large inaccuracies in some phases, the most relevant consideration is how simulation outputs compare to *whatever fire spread prediction methodology is currently in use*, both in terms of accuracy and timeliness. Where fire spread simulation is not used, fire spread prediction is a manual process involving looking up rate-of-spread tables for particular fuel types. In the case of Australis, the FBMs and vegetation maps are the same as those currently used in WA; Australis is essentially automating a process that was (at the time of the Boorabbin Fire) performed by hand using paper maps, fire behaviour model tables and calculators.

Validation technique

The fire simulator validation technique used in this study has several distinctive features, each of which has advantages and limitations compared with alternative approaches to simulator validation. The comparison of simulated spread with reconstructions of historical fires may be compared to validation based on experimental fires. Experimental fires have the advantage that high-quality data may be extracted in real time: weather data can be gathered directly at the time and place of the fire, the fuel burnt can be sampled and measured beforehand and the entire progress of the fire front can be recorded readily. The disadvantage of experimental fires is that costs limit the number and size of fires that can be made; and the need for safety means that experimental fires cannot be started in extreme conditions – those for which field data are the most valuable. In contrast, wildfire studies are not limited to small fires in benign conditions; however, the ability to draw conclusions may be limited by the availability of reliable data.

In this study, the quantitative accuracy measure K has been used to compare simulations of different phases of a fire, and also to compare simulations using alternative parameter settings. This measure could also be used for comparing simulator accuracy on other fires, or for comparing simulators (on the same fire). However, a protocol for calculating K would need to be standardised to ensure that results could be meaningfully compared. For example, as noted by Finney (Finney 2000) and Filippi *et al.* (Filippi *et al.* 2014), the K measure for a particular simulation and a particular set of reconstructed fire perimeters will vary depending on the size of the unburnt area surrounding the fire that is included in the analysis, as this will count as area correctly predicted as 'never burnt'. If such a standardised protocol were developed, the attainment of at least some minimum score on a wide range of fires might be used as a necessary (but not sufficient) requirement for adoption of a simulator in an operational setting.

One very important point that should be stressed is that no single validation study is sufficient to establish the validity of a fire simulation system. Even if the Australis simulator had perfectly reproduced each of the phases of the Boorabbin Fire, this would constitute only *evidence for validity* that should increase the confidence in the system for similar fires – not *proof of validity*. We believe that only the cumulative results of similar analyses (which are ongoing with Australis) will build up a picture of the predictive capabilities and limitations of a system. This time-consuming task is predicated on the availability of high-quality data from historical fires and motivates presentation of this validation technique.

Conclusion

The very features that make it difficult to validate the performance and accuracy of computer simulation of wildfire spread are exactly those that affect the use of such simulation technology 'in the field'. As well as conducting simulation model validation using historical fire data, there is a pressing need to collect accurate fire data *during* active wildfires, rather than conducting analysis after the event. Such data gathering efforts include regular fire front mapping coupled with the recording of fire ground weather conditions. Together with consolidated Geographic Information System (GIS) data, fuel types, fuel load and the development of FBMs that are experimentally calibrated for extreme fires, these data will facilitate (1) simulator and fire behaviour model validation studies attaining a level of rigour that could not be achieved in the study presented here, and (2) more accurate prediction of 'live' wildfires, which currently may be compromised by source data quality. Fire and land management agencies are to be encouraged to address these data issues.

Acknowledgements

The authors gratefully acknowledge the Department of Parks and Wildlife (DPaW), WA, and Paul de Mar of GHD Pty Ltd for providing the reconstructed fire spread perimeters and post-fire satellite imagery of the Boorabbin Fire; the Bureau of Meteorology for making available the Southern Cross Airport weather observations; the WA Land Information Authority (Landgate) for pre- and post-fire satellite imagery of the Boorabbin Fire; the Department of Fire and Emergency Services of Western Australia (DFES) for the pre-European vegetation database; and Stuart Matthews of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for supplying fuel moisture tables for semiarid shrublands. The paper benefited from comments by Neil Burrows and Lachie McCaw of DPaW. The work was funded by the Australian Research Council, DFES and Landgate.

References

Achtemeier GL (2013) Field validation of a free-agent cellular automata model of fire spread with fire–atmosphere coupling. *International Journal of Wildland Fire* **22**, 148–156. doi:10.1071/WF11055

Arca B, Duce P, Laconi M, Pellizzaro G, Salis M, Spano D (2007) Evaluation of FARSITE simulator in Mediterranean maquis. *International Journal of Wildland Fire* **16**, 563–572. doi:10.1071/WF06070

Bureau of Meteorology (2008) Meteorological aspects of the Boorabbin Fire (28 December 2007–8 January 2008). Western Australian Regional Office, Bureau of Meteorology, Perth, WA. Available at http://www.bom.gov.au/wa/sevwx/fire/20071228/boorabbin_fire_rpt.pdf [Verified 18 May 2012].

Burrows ND, Ward B, Robinson A (2009) Fuel dynamics and fire spread in spinifex grasslands of the Western Desert. *Proceedings of the Royal Society of Queensland* **115**, 69–76. Available at http://search.informit.com.au/documentSummary;dn=590969984229226;res=IELHSS [Verified 8 July 2014].

Catchpole W, Bradstock R, Choate J, Fogarty L, Gellie N, McCarthy G, McCaw L, Marsden-Smedley J, Pearce G (1998) Cooperative development of prediction equations for heathland fire behaviour. In 'Proceedings of the 3rd International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology', 16–20 November 1998, Coimbra, Portugal. (Ed. DX Viegas) Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI), pp. 631–645. (Coimbra, Portugal)

Cheney NP (2010) Fire behaviour during the Pickering Brook wildfire, January 2005 (Perth Hills Fires 71–80). *Conservation Science Western Australia* **7**, 451–468.

Cheney P, Sullivan A (2008) 'Grassfires: Fuel, Weather and Fire Behaviour.' (CSIRO Publishing: Collingwood)

Coleman JR, Sullivan AL (1996) A real-time computer application for the prediction of fire spread across the Australian landscape. *Simulation* **67**, 230–240. doi:10.1177/003754979606700402

Congalton RG, Green K (1999) 'Assessing the Accuracy of Remotely Sensed Data: Principles and Practices.' (CRC Press: Boca Raton, FL)

Cruz MG, Matthews S, Gould J, Ellis P, Henderson M, Knight I, Watters J (2010) Fire dynamcis in mallee–heath: fuel, weather and fire behaviour prediction in South Australian semi-arid shrublands. Bushfire CRC. Available at http://www.bushfirecrc.com/resources/research-report/report-fire-dynamics-mallee-heath [Verified 8 July 2014].

de Berg M, Cheong O, van Kreveld M, Overmars M (2008) 'Computational Geometry.' (Springer: Berlin)

de Mar P (2008) Goldfields Fire 13 (Boorabbin Fire) – Fire Development Chronology. GHD Pty Ltd, Sydney. Available at http://www.dec.wa.gov.au/pdf/boorabbin/goldfields_fire_13_chronology.pdf [Accessed 8 July 2014].

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D, Alsdorf D (2007) The Shuttle Radar Topography Mission. *Reviews of Geophysics* **45**, RG2004. doi:10.1029/2005RG000183

Filippi J-B, Mallet V, Nader B (2014) Representation and evaluation of wildfire propagation simulations. *International Journal of Wildland Fire* **23**, 46–57. doi:10.1071/WF12202

Finney MA (1994) Modeling the spread and behavior of prescribed natural fires. In 'Proceedings of the 12th International Conference on Fire and Forest Meteorology', 26–28 October 1993, Jekyll Island, GA. Society of American Foresters, pp. 138–143 (Bethesda, MD)

Finney MA (2000) Efforts at comparing simulated and observed fire growth patterns. Systems for Environmental Management, Missoula, MT. Available at http://www.firemodels.org/downloads/farsite/publications/Finney_2000_FarsiteValidation_FinalReport.pdf [Verified 8 July 2014].

Finney MA (2002) Fire growth using minimum travel time methods. *Canadian Journal of Forest Research* **32**, 1420–1424. doi:10.1139/X02-068

Finney MA (2004) FARSITE: fire area simulator – model development and evaluation. USDA Forest Service, Rocky Mountain Research Station, RMRS-RP-4, revised (Missoula, MT).

Finney MA, Ryan KC (1995) Use of the FARSITE fire growth model for fire prediction in U.S. national parks. In 'The International Emergency Management and Engineering Conference', 9–12 May 1995, Nice, France. (Eds JD Sullivan, JL Wybo, L Buisson) The International Emergency Management and Engineering Society, pp. 183–189 (Dallas, TX)

Gould JS, McCaw WL, Cheney NP, Ellis PF, Knight IK, Sullivan AL (2007) 'Project Vesta – Fire in Dry Eucalypt Forest: Fuel Structure, Fuel Dynamics and Fire Behaviour.' (Ensis–CSIRO: Canberra).

Hernández Encinas L, Hoya White S, Martin del Rey A, Rodríguez Sánchez G (2007) Modelling forest fire spread using hexagonal cellular automata. *Applied Mathematical Modelling* **31**, 1213–1227. doi:10.1016/J.APM.2006.04.001

Johnston P, Kelso J, Milne GJ (2008) Efficient simulation of wildfire spread on an irregular grid. *International Journal of Wildland Fire* **17**, 614–627. doi:10.1071/WF06147

Kourtz PH, O'Regan WG (1971) A model for a small forest fire. to simulate burned and burning areas for use in a detection model. *Forest Science* **17**, 163–169.

Lagae A, Dutré P (2008) A comparison of methods for generating Poisson disk distributions. *Computer Graphics Forum* **27**, 114–129. doi:10.1111/J.1467-8659.2007.01100.X

Linn R, Reisner J, Colman JJ, Winterkamp J (2002) Studying wildfire behavior using FIRETEC. *International Journal of Wildland Fire* **11**, 233–246. doi:10.1071/WF02007

Lopes AMG, Cruz MG, Viegas DX (2002) FireStation – an integrated software system for the numerical simulation of fire spread on complex topography. *Environmental Modelling & Software* **17**, 269–285. doi:10.1016/S1364-8152(01)00072-X

Luke RH, McArthur AG (1978) 'Bushfires in Australia.' (Australian Government Publishing Service: Canberra)

Matthews S, Gould J, McCaw L (2010) Simple models for predicting dead fuel moisture in eucalyptus forests. *International Journal of Wildland Fire* **19**, 459–467. doi:10.1071/WF09005

McArthur AG (1966) 'Weather and Grassland Fire Behaviour.' (Forest Research Institute, Forestry and Timber Bureau of Australia: Canberra)

McArthur AG (1967) 'Fire Behaviour in Eucalypt Forests.' (Forest Research Institute, Forestry and Timber Bureau of Australia: Canberra)

McCaw L (1997) Predicting fire spread in Western Australia mallee–heath shrubland. PhD thesis, University of New South Wales.

Mell W, Jenkins MA, Gould J, Cheney P (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* **16**, 1–22. doi:10.1071/WF06002

Miller JD, Yool SR (2002) Modeling fire in semi-desert grassland/oak woodland: the spatial implications. *Ecological Modelling* **153**, 229–245. doi:10.1016/S0304-3800(02)00015-7

Noble IR, Gill AM, Bary GAV (1980) McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology* **5**, 201–203. doi:10.1111/J.1442-9993.1980.TB01243.X

Perry GLW, Sparrow AD, Owens IF (1999) A GIS-supported model for the simulation of the spatial structure of wildland fire, Cass Basin, New Zealand. *Journal of Applied Ecology* **36**, 502–518. doi:10.1046/J.1365-2664.1999.00416.X

Santoni P-A, Filippi J-B, Balbi J-H, Bosseur F (2011) Wildland fire behaviour case studies and fuel models for landscape-scale fire modeling. *Journal of Combustion* **2011**, 613424. doi:10.1155/2011/613424

Schönfisch B (1997) Anisotropy in cellular automata. *Bio Systems* **41**, 29–41. doi:10.1016/S0303-2647(96)01664-4

Sirakoff C (1985) A correction to the equations describing the McArthur forest fire danger meter. *Australian Journal of Ecology* **10**, 481. doi:10.1111/J.1442-9993.1985.TB00909.X

Sullivan AL (2009*a*) Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire* **18**, 349–368. doi:10.1071/WF06143

Sullivan AL (2009*b*) Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369–386. doi:10.1071/WF06142

Sullivan AL (2009*c*) Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models. *International Journal of Wildland Fire* **18**, 387–403. doi:10.1071/WF06144

Sullivan A, Knight I (2004) A hybrid cellular automata/semi-physical model of fire growth, In 'Complex 2004, Proceedings of 7th Asia-Pacific Complex Systems Conference', 6–10 December 2004, Cairns. Central Queensland University, pp. 64–73 (Rockhampton, Qld)

Tymstra C, Bryce RW, Wotton BM, Taylor SW, Armitage OB (2010) Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Canadian Forest Service, Northern Forestry Centre, NOR-X-417 (Edmonton, AB). Available at http://cfs.nrcan.gc.ca/bookstore_pdfs/31775.pdf [Verified 8 July 2014].

Viney NR (1991) A review of fine fuel moisture modelling. *International Journal of Wildland Fire* **1**, 215–234. doi:10.1071/WF9910215

Zeigler BP, Praehofer H, Ki TG (2000) 'Theory of Modelling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems.' (Academic Press: San Diego, CA)