A heat transfer simulation model for wildfire spread

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Abstract: A new approach to fire spread simulation based on heat transfer events is described. The new simulation model is patch based with irregular patch shapes and sizes, which overcomes the influence of grid geometry on fire shape. It captures fire behaviour phenomena such as point fire acceleration and the dependence of fire rate of spread on line fire width. The new event based simulation model is efficient since the computational effort is focussed on the fire front where the majority of heat transfer takes place. It captures a wider range of fire behaviour phenomena than fire front propagation systems as it allows interaction between neighbouring parts of the fire, unlike the Huygens' principle approach which disregards such interaction.

In the simulation model, each patch represents a parcel of land with state parameters for fuel type, load and moisture, temperature and burning state. When the temperature of an unburnt patch reaches ignition temperature, it changes from a *flammable* state where heat received is converted into temperature change, to a *burning* state where fuel is converted into generated heat. When all fuel in a patch is consumed, the patch changes state to *burnt*. The frequency of heat transfer events between neighbouring patches, that is, the rate of heat transfer, depends on the temperature gradient and properties of the communication links connecting them. The effective conductivity of the inter-patch links are dynamic and are influenced by slope, wind speed and direction.

An important step in creating the simulation model is to calibrate the internal simulation arameters, which capture the rates of heat generation, heat transfer and heat consumption, against a fire behaviour model for each fuel type present in the landscape. This creates a mapping between environmental parameters such as wind speed, direction, slope and fuel moisture and the internal simulation parameters, so that for a given fuel type and environmental parameters, the correct fire spread rate is predicted by the simulation model. Initial results given by this new heat transfer simulation model are demonstrated via simple wildfire scenarios and by using data from an extreme grass fire with actual fuel, ignition and weather data.

Keywords: wildfire, simulation, discrete events

1. Background

A new approach to fire spread simulation based on discrete heat transfer events is presented. The aims of this research are to create a discrete abstraction of the fundamental heat transfer process which underpins wildfire spread, one that is physically realistic, yet tractable and suitable for high speed, discrete event simulation. We aim to develop a simulator that can be extended to model fire and atmosphere interaction, which can run rapidly on a PC and will be developed as a tool for both training and in-the-field fire prediction operations. Our intent is to model fire spread which depends not only on the landscape topography, fuel and weather parameters, but also on the fire geometry and intensity, that is, to model phenomena not captured by the Huygens principle of wave propagation approach.

1.1 Related Research

Most wildfire simulators adopt one of the three different approaches listed here:

- Fire front propagation systems where the rate of fire spread at the fire front is calculated from local environmental conditions known as Huygens' principle of wave propagation and projected forward in time e.g. SIROFIRE (Coleman & Sullivan, 1995), Farsite (Finney, 1998), Prometheus (Tymstra, 2004). Simulations run on a personal computer, generally use accurate GIS layers of landscape properties but require complex algorithms in order to handle the geometry of convergent fire fronts, for example, Knight & Coleman (1993). These types of simulators only track the fire front and additional post-processing is required to estimate fire front depth or the burning period at any location.

- Physics based, fire-atmosphere interaction simulators that model convective fluid flow of the atmosphere, radiation, combustion, etc. by solving the relevant differential equations over a fine mesh in space and time (Clark *et al.,* 1996, Linn *et al.,* 2003, Serón *et al.,* 2005). These simulators require significant computational resources (i.e. supercomputers) because of the detailed computation of the entire system. These simulators are not suitable for operational use with today's computing capabilities. Also, the high fidelity to the physics is disproportionate to the often coarse fuel, meteorological and experimental fire behaviour data that are available as inputs.

- Cellular automata simulators (e.g. Berjak & Hearne, 2002, Dunn & Milne, 2004) mostly prescribe rate of spread via a delay in propagating fire from a cell to its neighbours. Because these simulators simply track whether a cell is burning, rather than tracing the fire front, the algorithms are much simpler, but the grid geometry can influence the shape of the fire. For example, a fire in a northerly wind will have a different shape from one with a NW wind (after rotation).

The simulation model presented here is based on discrete *patches*, where the landscape is divided into an irregular network of patches and simulates the physics of fire spread at an appropriate level of abstraction for a wildland fire simulator. The abstraction is not so coarse that fire spread is independent of fire geometry and intensity, but abstract enough that simulations can be performed within minutes on a modern personal computer. To our knowledge, only the computationally intensive physics-based simulators take into consideration heat transfer via numerical solution of the heat equation involving all cells in the model.

In contrast with this, our method of heat transfer is via the explicit communication of heat from hot patches to cooler neighbouring patches via discrete heat transfer *events*, in accordance with the Second Law of Thermodynamics. The frequency of heat transfer events depends on the temperature gradient between neighbours as well as environmental factors such as wind and slope. This event-based method of simulating heat transfer is more efficient than an algorithm that updates all cells synchronously since the majority of heat transfer occurs near the fire front where the temperatures and temperature gradients are highest.

The heat transfer simulation model is constructive rather than presciptive, that is, the spread of fire is a consequence of how the model is constructed. The rate of fire spread is derived by the underlying simulation algorithm in a manner which reflects the physical process. That is, ignition of a patch occurs when it receives sufficient heat to ignite, rather than a prescribed time after its neighbour ignites, as with the fire front propagation approaches. A calibration is performed for each fuel type in the landscape to derive the appropriate internal simulation parameters so that the simulated rate of spread of fire matches the rates in empirically derived fire behaviour models.

Our use of discrete irregular patches as opposed to a regular grid is to avoid the well-known problem found in regular cell-based approaches where the geometry of the grid imposes distortions on the front propagation when wind is not orthogonal to the grid (Kourtz & O'Regan, 1971).

In the following sections, we describe the concepts behind the model in greater detail (Section 2) and the components of the simulator (Section 3). We then present some preliminary results to demonstrate the capabilities of the simulator (Section 4) followed by concluding remarks.

2. Modelling Method

2.1 Concepts

We construct a discrete, spatial model of the spread of wildfire over the landscape as follows: the landscape is discretised into patches (see Figure 1), each modelled by a mathematical object called a *finite state automaton*. The automaton captures, via its state vector, static landscape information about the patch of land such as location, area, fuel type, elevation and a list of neighbouring cells. The state vector also stores dynamic data including the fire state (see Figure 2), remaining quantity of fuel and current temperature. All changes to the system occur through *events*: ignition (patch starts burning), burning (conversion of fuel to heat), burnout (patch runs out of fuel), heat transfer (movement of heat from a patch to its neighbour) and weather changes are all events which may cause the automaton for a given patch to change state. The location and rate of spread of fire is determined from the spatio-temporal distribution of ignition events and the fire position can be mapped using the current state of the patches laid out in a map as in Figure 3. The following sections describe these processes in greater detail.

2.2 Heat generation

Heat is *generated* by the burning of fuel. Each patch has a quantity of fuel determined by the product of fuel load, patch area and heat content. Heat is generated by a patch from the time it ignites until all fuel is consumed. A simplifying assumption in the simulation model is that the rate of heat generation within a patch throughout the burning period is constant. That is, each patch of a given fuel type and load burn with the same intensity.

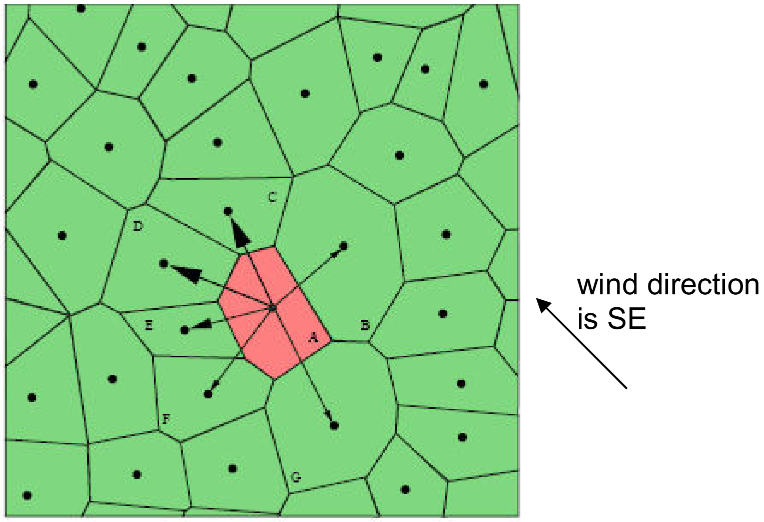

Figure 1 Layout of patches showing communication of heat to neighbours depending on distance and direction. The red cell is burning and the quantity of heat communicated to each of its neighbours is indicated by the size of the arrow and influenced by the wind direction.

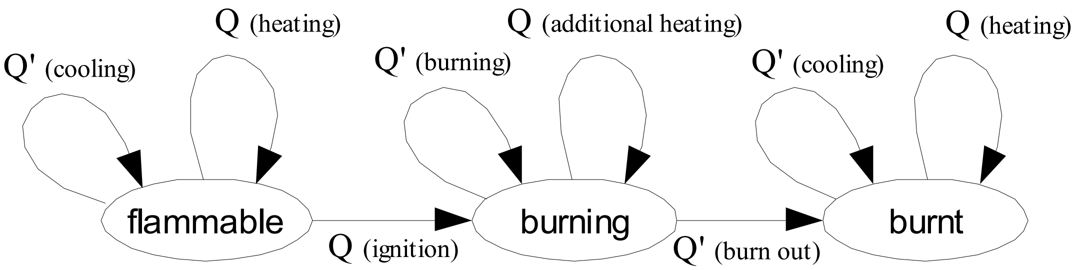

Figure 2 Dynamic state of a patch as it heats to ignition, consumes fuel while burning and burns out.

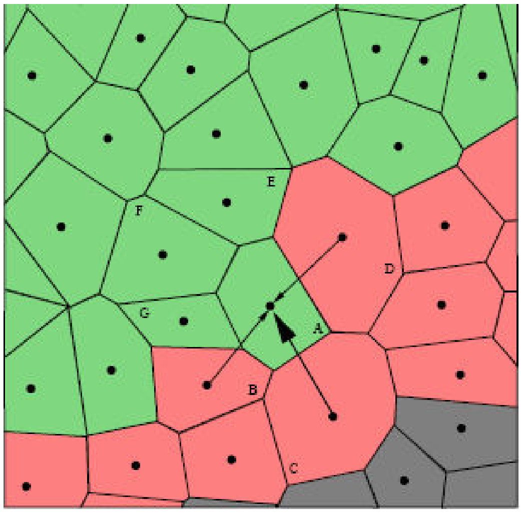

Figure 3 A series of ignited patches showing the fire front and several patches (B,C,D) contributing heat before ignition of patch A.

2.3 Heat consumption

When a patch receives heat, it causes its temperature to increase proportionally to the quantity of heat and inversely proportionally to the *heat capacity* which is a product of patch area, fuel load and specific heat. The total heat required to ignite a patch is the heat capacity times the difference between ignition temperature and ambient temperature. The heat capacity, therefore, is a proxy for the total energy that is consumed consisting of: the heat to raise fuel to ignition temperature, the heat to vaporise fuel moisture and the heat of combustion (to change the fuel state from not burning to burning). The heat capacity of a patch therefore varies with the fuel moisture which is affected by the ambient temperature and humidity. Fuel moisture is relatively simple to calculate in fine fuels (i.e. grass) because it depends on the current temperature and relative humidity (e.g. McArthur (1960)). For forest fuels the fuel moisture depends on the temperature and relative humidity history.

2.4 Heat transfer

Generation of heat by a burning patch leads to differences in temperature between neighbouring patches. Physically, there are three mechanisms for heat to be redistributed: conduction, convection and radiation. While these three mechanisms have different functional relationships to the temperature field, they all act to move heat from regions of high temperature to low temperature. In this simulation model, we use the mathematically simplest mechanism (conduction) as a proxy for all transfer of heat, but recognise that all the mechanisms actually contribute. Heat transfer is achieved by passing discrete packets of heat from a patch to one of its neighbours, decreasing the temperature of the source patch and increasing the temperature at the destination. The packet size is constant for the entire simulation and variations in rate of heat transfer are achieved by varying the frequency of heat transfer events. Spatial variation in heat transfer rate is achieved by varying the *effective conductivity* of the links between neighbouring patches. Figure 1 demonstrates how the amount of heat transfer from a patch to its neighbours depends on the wind direction with high conductivity downwind and low conductivity into the wind. Effective conductivity also depends on the distance between the patch centres, length of the common boundary and the direction of the link with respect to the slope direction.

All patches also have the atmosphere as a neighbour and a proportion of heat in each patch is lost to the atmosphere (Figure 4). The atmosphere is assumed to remain constant in temperature so that hotter patches lose more heat than cooler ones; that is, the rate of heat transfer is proportional to the difference between the patch temperature and the initial temperature. Because of our explicit modelling of links between patches, the inclusion of an atmosphere cell in the simulation model is simple, and in future work can be extended to include more atmosphere cells and interaction between the fire and atmosphere.

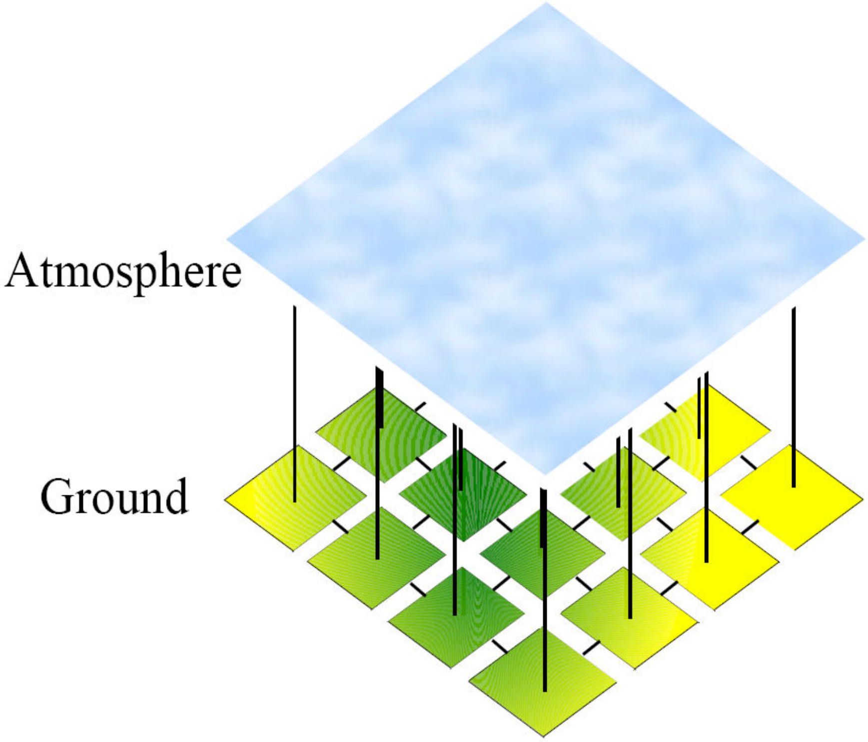

Figure 4 Schematic showing the connection of the ground patches with the atmosphere cell. In reality the ground patches are irregular, not square.

2.5 Fire state

Each patch of ground can be in one of three states: unburnt, burning or burnt (see Figure 2). Additional state data is used to capture the temperature of each patch; this allows the simulation algorithm to determine the heat transfer between neighbouring patches. When the temperature of an unburnt patch reaches ignition temperature, and there is available fuel in the patch, its state changes to burning (the ignition event). A burning patch generates a packet of heat periodically (a burn event) at discrete time intervals determined by the burn quantum (quantity of heat released for each burn event) divided by the burning rate (equal to the burning intensity times the square root of patch area). This heat is released into the burning patch, raising its temperature. The occurrence of each burn event also reduces the remaining fuel by the burn quantum until there is no fuel left in the patch; the patch changes state to burnt and cannot re-ignite.

2.6 Patch structure

The patches are created from approximately evenly spaced points placed *irregularly* over the landscape, called Halton points (Halton, 1960). It has been found previously, for example (Kourtz & O’Regan, 1971, Sullivan & Knight, 2004), that a regular grid causes artificial distortions to the fire shapes generated by some simulators. Using irregularly spaced points avoids this problem as is demonstrated in Section 4.1. Around each Halton point, a polygon is constructed which contains all the land that is closer to that point than to any other, called the Voronoi cell. The *neighbours* of each patch are the patches with a common boundary as pictured in Figure 3. The patch structure is static (i.e. does not change throughout the simulation) and is pre-calculated, however as previously discussed, part of the state vector for each patch will change through time capturing the dynamic effect of fire on that area of landscape modelled by the patch. The fuel type for each patch is determined from the predominant fuel found within the patch. The position of the fire at any point in time can be determined by the states (unburnt, burning, burnt) of all of the patches laid out in geographical co-ordinates as in Figure 3.

3. Simulator description

The simulation consists of an *initialisation phase*, where static patch data such as location and fuel type are designated, followed by a *simulation phase*. In the initialisation phase, a set of *static data* is loaded into the simulator. This static data consists of the location, fuel type, fuel load and elevation of each patch, as well as a list of neighbours with which each patch interacts; and a *fuel table*. The fuel table lists the heat transport and combustion parameters of each fuel type: specific heat, ignition temperature, (fire-line) burning intensity, heat capacity with moisture dependence and effective conductivity with wind/slope dependence. In other words, the fuel table contains the experimentally derived fire behaviour model for each fuel type translated into parameters that can be used directly in this simulation model. The procedure to convert a fire behaviour model into the parameters in the fuel table is described in Section 3.1 below.

During the simulation, *dynamic data* represents the *state* of the whole *fire system* being modelled. This includes the *patch fire state* of all patches, the global *weather state*, and an *event queue*, which drives the temporal evolution of the simulation. The *patch fire state* consists of the patch's temperature, the amount of remaining unburned fuel mass, fuel moisture, and a flag indicating whether the cell is currently burning and can be visualised as in Figure 2. The *global weather state* records the current ambient (i.e. distant from any fire front) air temperature, relative humidity, wind direction and wind speed. The *event queue* is a time-ordered list of scheduled simulation events which capture the spatio-temporal behaviour of the complete fire-on-landscape system. Each event object on the list denotes the type of event, the time of its scheduled occurrence, and the location (patch or patches) at which it will occur (c.f. discrete event simulation (Zeigler, 1984)). There are five types of events: an *ignition* event allows user-input ignition of patches in order to initiate the simulation as well as ignition of unburnt patches that reach ignition temperature, a *burning* event signals the combustion of one burn quantum of fuel, a *burnout* event signals that the fuel in a patch is exhausted and no further burning events occur for that patch, a *heat transfer* event signals that a heat quantum has been transferred between neighbouring cells, and a *weather change* event which allows the user to input changes to wind speed, direction, temperature and relative humidity.

Before starting the simulation, user-input events representing fire ignitions and weather state changes are inserted into the global event queue. The simulation proceeds by sequentially removing the earliest event from the queue (wherever it may occur), calculating the local patch state changes caused by the event, and then inserting zero or more new events into the queue to trigger future patch state changes which will be caused by the currently active event via inter-patch heat transfer or patch burnout. At any point in time, a map can be generated showing the states of each patch laid out geographically as in Figure 3.

3.1 Calibration

The spread of fire in the simulator is represented using the ignition times of patches and their location relative to each other. Different sets of *simulation parameters*, namely, effective conductivity, heat capacity, ignition temperature and burn intensity produce different simulated rates of spread. Effective conductivity determines how quickly heat is transferred between patches given a particular temperature gradient, burn intensity governs how quickly heat is generated, and heat capacity determines how much heat is required for a patch to reach ignition temperature.

In nature, the environmental parameters, namely, windspeed, temperature, relative humidity, fuel type and slope, control the rate of spread of fire. A fire behaviour model, for example, the CSIRO grassland meter, (Cheney *et al.*, 1998) describes the relationship between these environmental parameters and the rate of spread of fire derived from observations of experimental and wild fires.

To ensure that the simulation model predicts the same rate of spread as a fire behaviour model for a given fuel type and environmental conditions, a calibration mechanism is utilised. The calibration mechanism determines the mapping from environmental parameters to internal simulation parameters that results in the same rate of spread as the fire behaviour model. Because the fire behaviour model is a continuous function of environmental parameters, a perfect fit would require an infinite number of parameters, so instead we minimise the misfit of the simulated rate of spread over the range of conditions for which the fire behaviour model is valid. When calibrating our model, we estimate burn intensity and derive two relationships between simulation and environmental parameters that reproduce the rate of spread in the fire behaviour model. The two relationships are between

a) wind speed and effective conductivity
b) fuel moisture and heat capacity

This step was performed using non-linear regression against the empirically derived CSIRO cut grass meter (Cheney *et al.,* 1998). For line fires in winds up to 80 km/h and fuel moistures in the range 2 to 15%, the average variance between the rate of fire spread for a line fire in the calibrated grass fuel and the CSIRO cut grass meter is 6.5%. A smaller variance could be obtained by adding more parameters to map the environmental parameters (wind speed, fuel moisture) to the simulator parameters (heat capacity, effective conductivity, burn intensity), but is not warranted given that the observed standard deviation of rates of spread is of the order of 20%.

4. Initial Results

In this section, we demonstrate the application of the simulation model using simple examples. In each example, a 2 km × 2 km area of cut grass fuel with 2% fuel moisture is employed. This corresponds to a temperature of 40°C and a relative humidity of 5% (i.e. extreme fire danger). The irregular patches are on average 1 hectare = 10^4 m^2 in area. The first two examples show that the adoption of an irregular grid does produce realistic looking fire shapes, i.e. that the fire spread rates are independent of the grid structure. In the absence of wind, the fire shape is circular as in Figure 5. When there is a wind, the fire shape is approximately elliptic. The rate of spread accelerates from a point ignition up to a steady rate of spread as shown in a wind driven fire in Figure 6. The same shape (except for the orientation) is predicted regardless of wind direction, as seen in Figure 7. The third example shows the dependence of the rate of fire spread on the width of the fire line ignited, Figure 8.

4.1.1 Point fire, no wind

Previous cell-based fire simulation models are based on a contagion process on a regular grid. Fire spread in such simulation models is influenced by the underlying grid (Kourtz & O'Regan, 1971) and produces polygonal instead of circular fires in the absence of wind. This approach was extended to include a neighbourhood of cells beyond the four closest cells, up to the nearest 64 cells (O'Regan *et al.*, 1976), which reduces the influence of the grid at the cost of an increased neighbourhood. In preliminary work, we also found that the regular grid has a profound influence on the shape of wind-driven fires. The two examples presented here demonstrate that on our irregular grid, the fire spread is not influenced by the grid structure. The reason for this is that any patch or cell based approach inevitably produces errors in fire shape because the fire can only reach *discrete* points. When the grid is regular, the same errors are magnified in certain directions, whereas for an irregular grid the errors are different for each patch and therefore cancel each other out over time.

In the first example (Figure 5), the patch closest to the centre of the area is ignited in the absence of wind. The figure shows the fire position at 2 hour intervals. A rate of spread of about 55 m/h is predicted in all directions with an approximately circular fire shape.

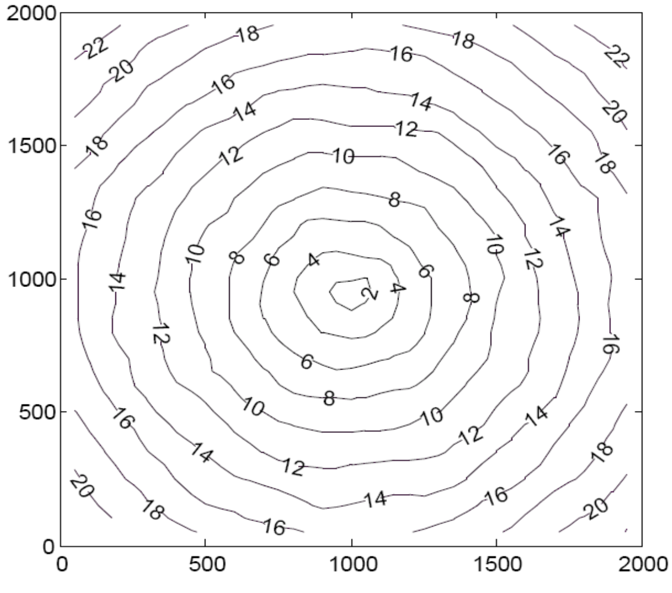

Figure 5 Fire spread contours at 2 hour intervals for a point ignition in no wind. The *x* and *y* axis labels are distances in metres. The fire spreads at about 55m/h equally in all directions.

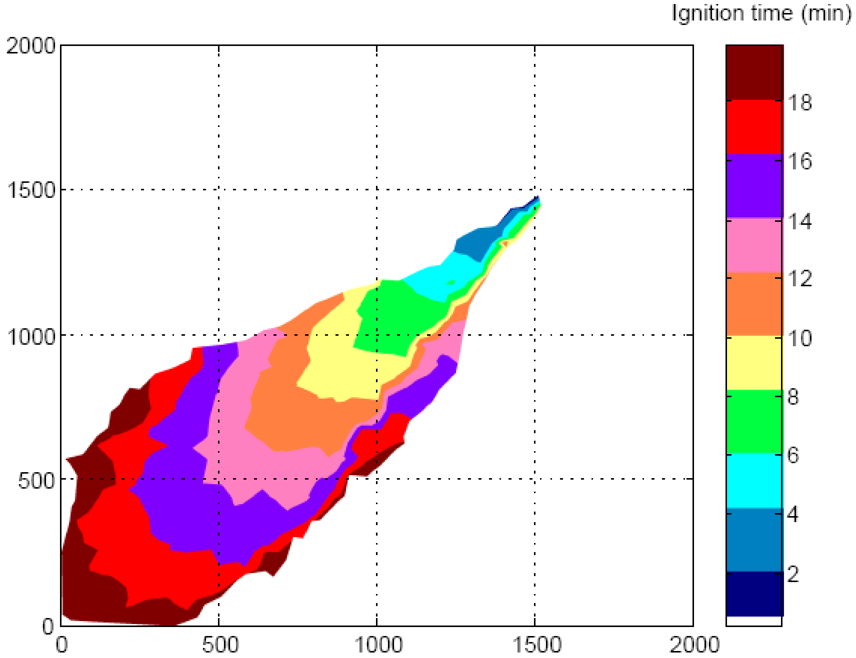

Figure 6 Fire spread for a point ignition in a 30 km/h NE wind. The *x* and *y* axis labels are distances in metres and the shading is the ignition time in minutes relative to the initial ignition. The forward fire spread in the first 6 minutes is less than for the third 6 minutes.

4.1.2 Point ignition with wind

In the second example (Figure 6), a single patch (at approximately (1500,1500) in the co-ordinate system shown) is ignited in the presence of a northeasterly wind. The fire spreads in a southwesterly direction as expected. In the first 6 minutes, the fire travels less than the diagonal of the grid, but in later 6 minute intervals, a slightly larger distance is travelled by the fire. This possibly indicates acceleration of the fire.

4.1.3 Point ignition, wind from different directions

In the third example (Figure 7), a cell near the northeast corner of the area is ignited in the presence of a 30 km/h wind. The burnt area 15 minutes after ignition is drawn for four different simulations for wind directions of 0° (northerly), 30°, 60° and 90° (easterly). In each case, the head fire covers approximately the same distance and the width of the fire is also similar. Some differences occur due to the irregularity of the underlying grid. The fire travels over a kilometre in 15 minutes at approximately 6 km/h. The maximum spread direction is clearly in the direction the wind blows.

4.1.4 Point versus line ignition

It is well-known that a point fire accelerates from a slow rate of spread up to the line-fire rate of spread. It has been noted in fire experiments in tropical grasses that fires less than 75 m wide spread significantly slower than those greater than 75 m in width (Cheney *et al.,* 1993). Further experiments (Cheney & Gould, 1995) indicate that the width at which the line-fire rate of spread is achieved is dependent on the wind speed.

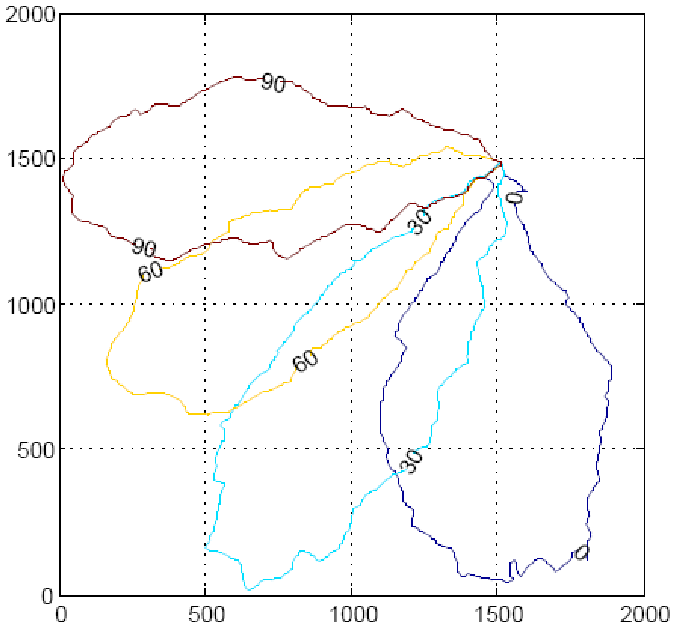

Figure 7 Fire position after 15 minutes for a point ignition for a 30 km/h wind for wind directions of 0° (northerly), 30°, 60° and 90° (easterly). The fire shapes are similar in length and width.

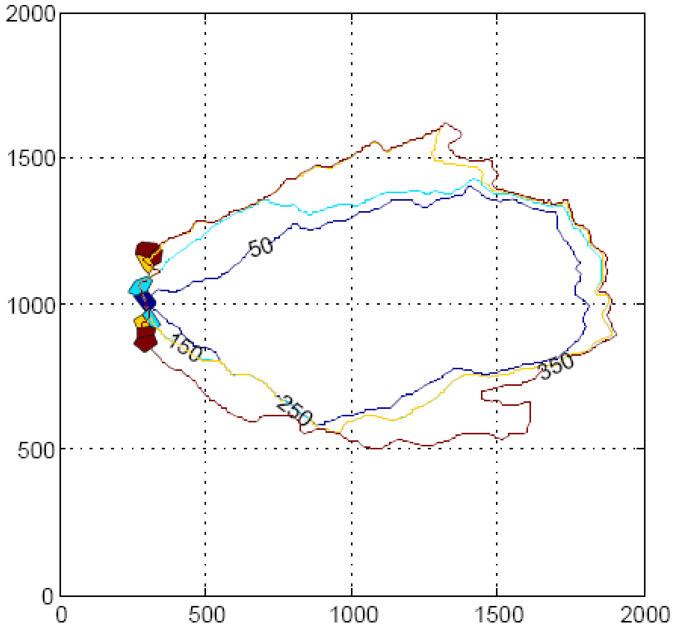

Figure 8 Fire position after 15 minutes for line ignitions of different widths for a 30 km/h westerly wind. The contour labels are the width of the initial north-south line ignition in metres. The ignition patches are shaded. The 50, 150, 250,and 350 m width contours correspond to the ignition of the central 1, 3, 5 and 9 patches respectively. The 50 m width fire travels more slowly (i.e. the head of the fire doesn't travel as far in 15 minutes) in the initial stages. For wider fires, the rate of spread of the head fire is independent of ignition width.

In Figure 8, several simulations are presented for a westerly wind speed of 30 km/h, but with different ignition patterns. A north-south line of cells (at x = 300 m) is ignited and the burnt area after 15 minutes is drawn for each simulation. The contour label indicates the width of the initial ignition. The 50, 150, 250 and 350 m width contours correspond to the ignition of the central 1, 3, 5 and 9 cells respectively. The distance covered by the fire ignited at the single patch is significantly less than for 3 or more patches in a line. For fire widths 150 m or greater, the head fire covers approximately the same distance in 15 minutes.

As for point fire acceleration, the dependence of the fire spread rate on the width of the fire front is a consequence of, and is derived by, our heat transfer based simulation model. Point fires spread the heat to all neighbours, thus reducing the amount of heat transferred to the downwind neighbour. Line fires, on the other hand, do not transfer heat to their lateral burning neighbours which are at approximately the same temperature and transfer most of their heat downwind leading to faster fire spread than for a point fire. This type of behaviour can only be artificially imposed on a Huygens' principle simulation model (for example, Farsite (Finney, 1998)) which otherwise assumes that all parts of the fire act independently of the rest of the fire.

4.1 Wangary fire reconstruction

On 10th and 11th January 2005, the Wangary fire burnt over 77 000 ha of grassland, stubble, shrubby woodland and forest fuels in the Lower Eyre Peninsula, South Australia. The predominant fuel was wheat stubble. The final perimeter is shown as a black line in Figure 9. Approximately 2000 ha was burnt on 10th January and is shaded black. On the morning of 11th January, the fire escaped control on the southern edge in the presence of a strong northwesterly wind. Average wind speeds recorded at the Port Lincoln Airport peaked over 50 km/h with gusts up to 83 km/h. Relative humidity dropped below 10% from 0840 until 1300 hours. The topography is relatively flat, and in view of the strong winds present during the fire, the role of topography in fire spread is not considered in the simulation below.

We have obtained GIS data of the vegetation cover of the Eyre Peninsula and the weather observations from the Port Lincoln Airport (co-ordinates (43,13)) on the east coast of the Lower Eyre Peninsula. The GIS data is at 50 m resolution and consists of three vegetation categories, grass, native forest and pine forest, plus water bodies. An irregular patch network was generated for the 60 km × 50 km region with patches approximately 0.25 km^2 in area. Each patch was assigned the most common vegetation within its boundaries. The area burnt on 10th January was set to have no fuel and a single ignition point at 1000 hours on the 11th January at the midpoint of the southern edge was assumed. The timing was estimated by running a series of simulations with ignition at the same point but different starting times and comparing the area burnt. We used the fuel parameters derived from the CSIRO cut grass meter for patches with grass fuel. For forest fuels, we assumed that the rate of spread was one-third that of grass. The average wind speeds from the Port Lincoln weather station were used as input to the simulation.

Using the data described, we performed a simple reconstruction of the Wangary fire, the purpose of which is to demonstrate the capabilities of the simulator, rather than to gain a detailed understanding of the growth of the Wangary fire. Some of the approximations in the following reconstruction are: single ignition point at a place and time that may not coincide with the actual point or time of re-ignition, inclusion of only 2 fuel types with no variability in fuel load, no suppression activities, and use of the Port Lincoln Airport weather data without consideration for the difference between weather there and at the fire ground. Without adequate data of the actual timing of the fire spread and more detailed fuel and weather data, it is not possible to draw any firm conclusions on the progress of the fire throughout the day or on the correctness of the assumptions that went in to generating this simulation.

Having noted the uncertainties in the input data, we present the results of the simulation in Figure 9. The fire travels in a south-easterly direction initially. Between 1300 and 1400 hours the fire heads to the east and at around 1400 hours the fire spreads in a northeasterly direction along a wide front. This general pattern is similar to what occurred except that the actual fire spread much more rapidly before 1300 than in the simulation. For example, a newspaper report notes that the fire arrived in the coastal town of North Shields at 12.45 pm (Sproull, 2005). The simulation took 2.5 minutes on a Pentium IV PC with 3.2 GHz processor speed and 2 Gb of memory.

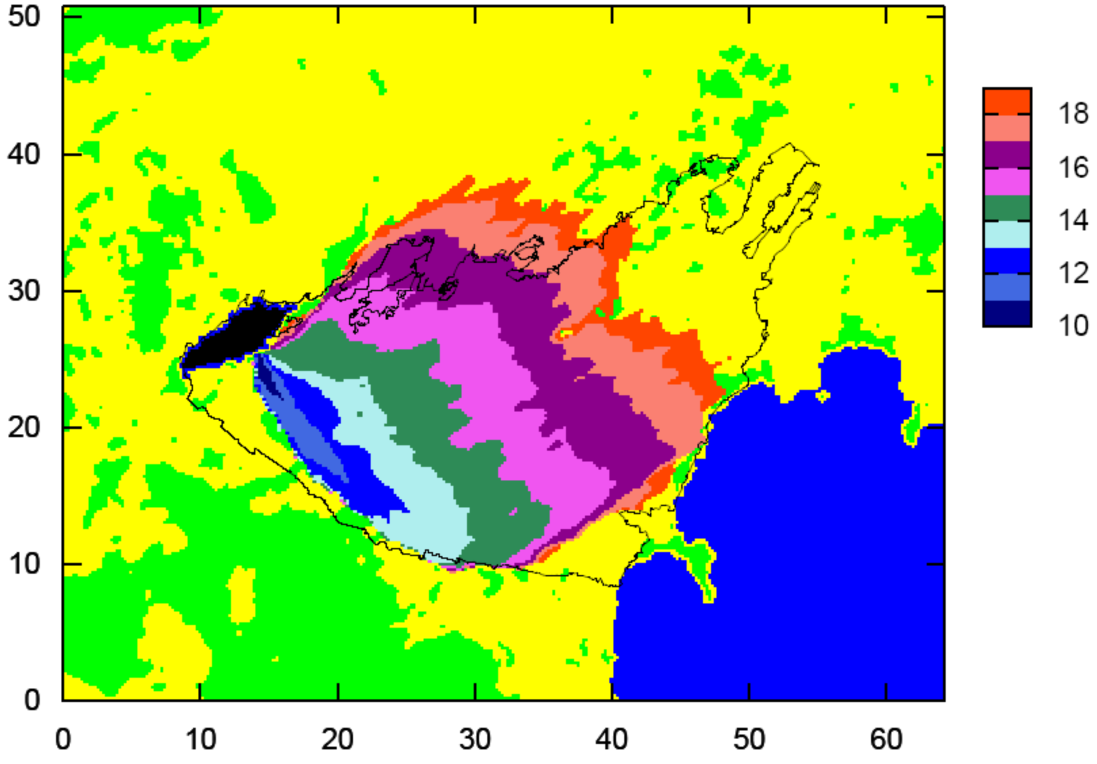

Figure 9 Results of simulation of the Wangary Fire. In the simulation the burnt out region (black) was reignited at 1000 hours. The simulated fire position is shown at hourly intervals up to 1900 hrs and the actual fire area burnt outlined in black. The two fuel types grassland (yellow) and forest (green) are shown for the unburnt area. The fire initially travelled southeast from the single ignition point before the westerly, then southwesterly wind changes. Tick marks on the axes are at 10 km intervals.

5. Concluding Remarks

We have described and implemented a new method for fire spread simulation. It is based on the transfer of discrete quantitites of heat between neighbouring patches and can be calibrated to produce the rate of spread observed in fires. As it is based on the underlying physics of heat transfer, it exhibits properties inherent in natural fires, such as point fire acceleration and the dependence of fire spread rate on fire width.

By using an irregular grid, the simulation model is not subject to fire shape problems observed in many cellular automata type models. This was demonstrated with example fires in no wind and in a variety of wind directions.

Heat transfer in the simulation model is carried out via discrete events which mostly occur near the fire front. This method of simulation avoids global updates of slowly varying parameters far from the fire front and results in a very efficient simulator which can be implemented on desktop personal computers. This was demonstrated with the simulation of the Wangary fire on a desktop PC in 2.5 minutes of processor time.

The design of the underlying model is flexible and has been created with the intention that it will allow the simulation model to be extended to include, for example, an atmosphere layer. This will allow us to investigate the important role of fire-atmosphere interaction in future.[1]

6. References

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