International Journal of Computational Intelligence and Applications

CRITICAL DENSITY IN A FIRE SPREAD MODEL UNDER ENVIRONMENTAL INFLUENCE

XIAODONG LI and WILLIAM MAGILL*
School of Computer Science and Information Technology
RMIT University, GPO Box 2476v, Melbourne, VIC 3001, Australia

Small changes in spatial pattern on a landscape can sometimes produce dramatic ecological responses. Such transition ranges are associated with critical environmental conditions such as tree density. As the landscape becomes dissected into smaller patches of trees, landscape connectivity may suddenly become disrupted, which may have important consequences for the behaviours of forest fire, i.e., how it spreads. Landscape connectivity depends not only on the tree density but also many other environmental conditions such as land height, flammability, and wind conditions. To determine how the critical densities are affected by the changes in these conditions, we developed a fire spread simulation model using a multi-agent (i.e., bottom-up) approach. This model simulates an artificial environment where bush are randomly generated and fire can be ignited and then spread across the environment according to some 'interaction rules'. The emergent fire spread behavours at the landscape level are determined by such micro-level 'interaction rules'. This model takes into account some major environmental factors that influence fire growth. By varying these variables under controlled conditions, this research aims to show how varied environmental conditions affect the critical density, and hence influence the spread and growth of fire.

Keywords: Percolation, Complex systems, Emergent behaviour, Fire modelling.

1. Introduction

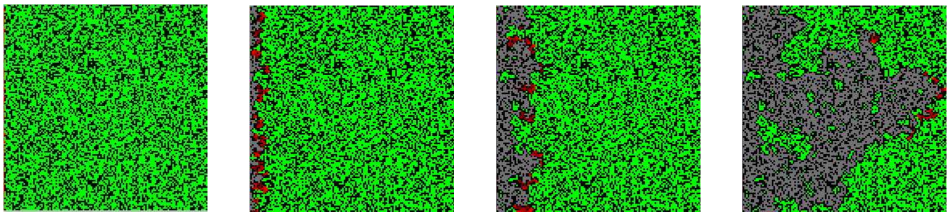
Every year bushfires across Australia and the rest of the world devastate enormous areas of land and take a heavy toll on human life. These fires spread rapidly, and without adequate models to predict their growth, firefighters are unable to contain them as efficiently as they would otherwise be able to. One of critical environmental factors that affect the spread of bushfire is bush density. If the landscape is very densely populated with trees, the fire is likely to spread; if the landscape is only sparsely populated, then the fire is likely to die out. Now the question is: "what is the critical density of trees (between 0.0 and 1.0) that is needed on the landscape for the fire to spread continuously in a sufficiently large environment?"

Questions like these are subjects of study in percolation theory. [1,2] To illustrate, consider a two-dimensional lattice as the landscape where grid cells are randomly filled. Percolation theory predicts that a uniformly random distribution of filled

---

*Email: xiaodong@cs.rmit.edu.au

cells that comprises at least 0.5928 of the landscape has a very high probability of spanning the lattice. As the critical density p_c is reached, isolated patches of filled cells become connected to form one continuous (percolating) cluster. Each filled cell of the percolating cluster is joined with a neighbouring occupied cell along at least one horizontal or vertical edge (see Fig. 1). If fire starts from one side of the lattice, it should be able to traverse or "percolate" across this landscape through this formed cluster. If the landscape were filled with trees below this critical density ($p_c < 0.5928$), tree clusters would occur as smaller, isolated patches. The landscape becomes disconnected as the percolating cluster is broken into many smaller patches. This would prevent a fire from spreading across the landscape. Small changes in tree density on a landscape therefore could have discernible impact on the fire spread behaviours.



t = 0 t = 40 t = 130 t = 600

Fig. 1. A simplified forest fire model with 61% tree density. No other environmental factors such as land height or flammability are considered here. Fire starts at the left edge, and it reaches the right edge at t = 600.

There have been some attempts in studying the effect of tree density have on the fire-spread behaviours.[3,4] However they are mostly simplified fire models considering only one or two environmental conditions such as the tree density while ignoring many others. In the context of fire spread, we suggest that the critical phenomenon such as the forming of a continuous percolating cluster on a landscape is not an inherent property of a landscape, but emerges from the interplay of fire's interaction with the environment. For examples, firespread can be also influenced by variation in land height, flammability of different materials, wind strength and directions. Our objective in this research is to investigate the effect of these environmental factors have on the critical densities of trees on a landscape. The *critical density* p_c is defined as the density of bush at which fires have equal chance of thriving or starving (approximately 50% chance thriving or starving). A fire starves if it fails to spread to any of the environment's borders and thrives if it does manage to do so. If the environments were suitably large, bush densities just below this value would cause all fires to starve and all densities greater would enable all fires to thrive. Since the environments are not suitably large in order to constrain the run time, there will be a region around this critical density where some fires thrive and some starve. This region is defined as the *critical region.*

The paper is organised as follows: Section 2 describes the simulation model and the environmental variables used. Section 3 briefly describes how we set up the experiments. The experimental results and analysis are given in Section 4. Finally a summary and directions for future research are presented in Section 5.

2. Description of the Model

The model consists of a number of basic components. First it has an artificial world (i.e. a 2-dimensional grid) where bushes are placed randomly across the landscape. A fire can be generated at a particular spot on such a landscape or many fires can be created along one side of the artificial world. Once started, fires can then spread into their neighbourhood by looking around locally and following certain local interaction rules (involving variables that work on a local area such as flammability or variables that are globally applicable such as wind). The environment itself is represented by a 2d area made up of squares representing land of a certain height with or without bushes. There is no global control on how fires should spread since the fire only spreads as individual units, not as a whole. Macro or system level dynamics will emerge as a consequence of many such local interactions.

The model takes into account some of the most influential factors contributing to the development and spread of bushfires.[5,6,7] These environmental factors include *bush density, bush flammability, heat conditions, land height, wind direction* and *wind magnitude.* With different initial conditions, the fire will either rapidly spread out of control, die prematurely, or survive for moderate periods of time before being overcome by unfavourable conditions. By varying these variables under controlled conditions, this research aims to show how they influence the spread and growth of bushfire. We will briefly describe each of the above major contributing factors on fire spread below.

- *Bush density* - Bushes are initially generated and allocated at random on the 2d lattice. The chosen probability value represents the proportion of bush-covered land to non-bush covered. The fire is allowed to spread into each of its four neighbouring cells (north, south, east and west) whenever there is fuel present there. Percolation theory tells that the critical density p_c is about 0.5928 when considering only tree density in the model. This critical value of 0.5928, which can be approached with a suitably large environment, will alter once other factors are taken into account.
- *Bush flammability* - the actual flammability of a piece of fuel. Bushes are given a random value within a minimum and maximum flammability values, linearly selected.
- *Heat condition* - The temperature, together with the humidity and recent weather conditions (lack of rain, etc) can be grouped together under the classification

of heat conditions. A value of 1.0 represents standard conditions (and hence no modification of the chance of a bush igniting) and 0 removes all chance of ignition. Values can approach infinity, where the chance of ignition will approach 100%.

- *Land height* - The minimum and maximum heights are specified, over which the ground will slope using a constant gradient along the X or Y-axis.
- *Wind* - Two aspects of the wind are modelled. The first is its direction, the second its strength. Together, these aspects are able to shape the growth of the fire by adjusting the ignition level of surrounding fuel. Fuel that is located downwind of the current location would have an increased likelihood of igniting. On the other hand, fuel that is located upwind of the current location would have a reduced chance of igniting. The adjustment to the ignition levels would come from the strength of the wind. The wind in this simulation is able to remain static for the duration of a run, or able to fluctuate in both direction and strength.

The proposed model uses a probability distribution over the landscape to determine the spread of a fire. The probability of a cell (on the 2d landscape) catching fire is calculated based on the values of given environmental variables at that particular cell. The basic algorithm is described in the following paragraphs.

Assuming we have an initial probability P_I , denoting the probability of a cell catching a fire without considering variables other than the amount of fuel there. When land height is taken into account, the probability is modified as follows:

$$P_{IL} = \begin{cases} P_I + height_{diff} \cdot \alpha & \text{if } height_{diff} \leq T; \\ 0.0 & \text{otherwise.} \end{cases} \tag{1}$$

where P_{IL} is the new probability taking into account land height difference, $height_{diff}$, between the current cell and a neighbouring cell being measured. α is a scaling factor (discussion on how to choose an appropriate value for α is beyond the scope of the paper). If the $height_{diff}$ is greater than a threshold T, then P_{IL} is set to 0.0, which means no fire can spread over to such a cell.

For wind conditions, assuming the magnitude M_W and angle of the wind A_W are known, contribution to the probability by wind can be calculated as follows:

$$P_{ILW} = P_{IL} + (M_W sin(A_W) x_{dist} - M_W cos(A_W) y_{dist})\beta \tag{2}$$

P_{ILW} is the new probability after considering P_{IL} and wind conditions. The above $M_W sin(A_W)$ and $M_W cos(A_W)$ give the measurement of magnitude of wind along X and Y-axis respectively. The wind direction determines either a positive or negative value for the distance variables x_{dist} and y_{dist}, according to the location of a cell and the current cell. β is a scaling factor. Finally the equation below gives the modified probability P_{ILWH} when heat condition h (ignition level) is considered[6]:

$$P_{ILWH} = \begin{cases} P_{ILW}(1 - (1 - h)^2), & \text{if } h \leq 1; \\ P_{ILW} + (1 - P_{ILW})(1 - \frac{1}{h})^2, & \text{otherwise.} \end{cases} \tag{3}$$

The above P_{ILWH} is the probability value used to determine the likelihood of a cell catching fire. As the simulation run proceeds in discrete time steps, if a cell is adjacent to a fire and its probability value is above a pre-specified threshold, then the fire will be able to spread to this cell (the same applies to all other cells surrounding the fire). At each time step, the probability value at this cell will be reduced by a factor of Δ_P, until it is below a minimum specified. The result of this is that the fire will die out.

3. Experimental Design

Our objective is to determine under what conditions a young fire may starve or thrive. The fires investigated are placed around such a borderline state, between thriving and starvation. Results from each model developed for a set of parameter values were derived from **20** runs, with the results summarised. This enables a clearer picture of what percentage of fires thrives at specific bush densities.

This study, by allowing for a greater number of variables, makes the study of the critical density a more difficult task. It would be unfeasible to study the impact on critical density for all combinations of variables that allow for a critical region (certain combinations with one free variable will result in fires that always thrive or starve no matter what the value of the free variable). Therefore each sample will build upon a reasonable value of the previous sample. Generally, samples taken around the critical density, at the lower bound of the critical region and at the upper bound of the critical region will suffice to reveal the size of the critical region.

4. Results and Analysis

The first simulation runs were completed with average values for variables that needed to be present and the exclusion of ones that could be optional. Once these runs had been accomplished, more variables were altered systematically until the final trial runs utilized all of the major variables outlined in Section 2. A summary of all trial runs is provided in Table 2.

4.1. *Effects of High and Low Variation Fuel Flammability Levels*

To begin with, the model incorporated a ground that remained flat, a forest of average density, an average range of flammability and no wind. A fire starts from the centre of the landscape and spreads outwards. This kept the initial model very simple, in line with the goal of building up to more complex models. We used a lattice of size 256x256. Flammability of bush represented as fuel randomly allocated across the lattice within the range of 5 to 30 (see Table 1). Note that fuel (i.e., flammability) can vary from 0 to 100.

Results of trial runs are given in Table 2 a). With 62% of the land covered in bush, more than 95% of the fires were starved before reaching the border. When the bush density was increased to 66%, all 20 fires managed to reach at least one of the borders, making the critical region about 4% (from a bush density of 62% to

Table 1. Main variables affecting fire in a simple forest environment.

Model parameters	Initial value	Description
world size	256x256	Horizontal and vertical size of the world
density	0.62-0.66	The proportion of bush in the environment
min-fuel	5(or 15)	The minimum flammability of any bush
max-fuel	30(or 20)	The maximum flammability of any bush
ignition-level	1.0	The head conditions at the time

Table 2. Critical region and critical density for each simulated experiment.

Simulated experiment	Fuel range	Ignition level	Critical region	Critical density
a) Effect of high variation fuel flammability levels	[5, 30]	1.0	[0.62, 0.66]	0.63
b) Effect of low variation fuel flammability levels	[15, 20]	1.0	[0.58, 0.62]	0.605
c) Effect of land height	[5, 30]	1.0	[0.60, 0.66]	0.615
d) Effect of heat condition with a low ignition level	[5, 30]	0.8	[0.62, 0.66]	0.64
e) Effect of heat condition with a high ignition level	[5, 30]	1.25	[0.56, 0.60]	0.58
f) Effect of a static weak wind	[5, 30]	0.8	[0.60, 0.68]	0.64
g) Effect of a static moderate wind	[5, 30]	0.8	[0.59, 0.66]	0.63
h) Effect of a static strong wind	[5, 30]	0.8	[0.58, 0.66]	0.61
i) Effect of a dynamic weak wind	[5, 30]	0.8	[0.57, 0.68]	0.63
j) Effect of a dynamic moderate wind	[5, 30]	0.8	[0.59, 0.66]	0.62
k) Effect of a dynamic strong wind	[5, 30]	0.8	[0.60, 0.68]	0.63

a bush density of 66%) in size. The critical density would be approximately 63%, where it can be seen that approximately half of the fires would have thrived and half would have starved. For low variation in fuel levels such as the range of [15, 20], the average flammability of bush should therefore be the same (about 17.5) as for the range for high variation [5, 30]. Only the variation is not as great as before. As shown in Table 2 b), the result of such a low variation is a shift in the placement of the critical density to the range [0.58, 0.62], though the critical region is approximately the same size.

4.2. *Effect of Land Height*

In this experiment, changes in the land's topology are simulated. The parameters from Table 1 are used, this time with the ground sloping upwards from north to south. The fire again begins in the centre and spreads outwards. This time, rather than spreading fairly uniformly (over repeated trials) over all four compass directions, the fire tends towards the south. The bias is introduced by the slope of the ground that aids in the spread of the fire in that direction. Note that in one trial, the fire could reach more than one border. It is found that the critical density is slightly lower than the critical density found for high variation fuel flammability levels (Table 2 c)), due in part from every fire that thrives does so by reaching at least the southern border. The critical region is about the same size as previously, from 60% to 66%.

4.3. *Effect of Heat Conditions*

The growth and spread of fires under normal heat conditions (an ignition level of 1.0) has already been demonstrated in Section 4.1 (with a flat land). This section will present results from trials using an ignition value of 0.8 (representing milder conditions, perhaps recent rain) and its reciprocal value of 1.25 (representing no recent rain and perhaps high temperatures with low humidity). Once again values from Table 1 were used, except for the ignition level. The results from the simulation runs with an ignition level of 0.8 are given in Table 2 d). The critical density has risen, as would be expected. The rise is only slight, however, rising from about 63% to about 64%. From the previous models we have seen no change in the size of the critical region and this one is no different. The critical region remains the same size, covering the area just above 62% to just above 66%.

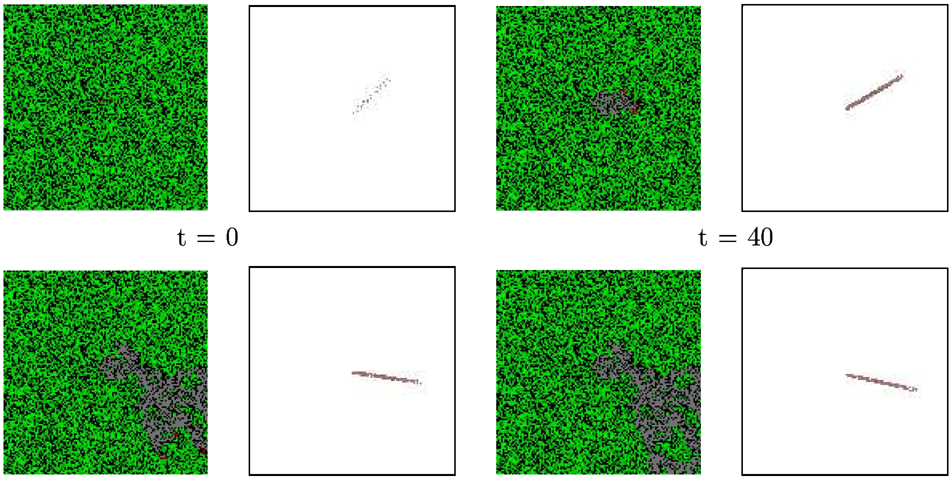
Under higher heat conditions, with an ignition level of 1.25, the critical density drops. The results, as given in Table 2 e), show that the critical density has dropped from about 63% to 58%.

4.4. *Effect of Wind*

Wind can be set as either static or dynamic. If the wind is set as static, then it will remain of the same strength and magnitude throughout the simulation run as it did when the run began. If the wind is dynamic then the user can set the rate at which the wind will alter during the simulation, known to the model as the fickleness of the wind (see Fig. 2). The next two sections will describe a model that incorporates a static wind as well as a dynamic wind in addition to previous parameter values.

Table 3. Main variables affecting fire in a static wind environment.

Model parameters	Initial value	Description
world size	256x256	Horizontal and vertical size of the world
density	See Table 2	The proportion of bush in the environment
fuel range	[5, 30]	The minimum and maximum flammability of any bush
land height range	[0, 255]	The minimum and maximum height (at northern border)
wind angle	45	The angle of the wind direction in degrees
wind magnitude	**0.2, 0.4, 0.6**	The magnitude of the wind
ignition level	0.8	The heat conditions at the time



t = 0

t = 40

t = 150

t = 200

Fig. 2. A simulation run of a dynamic wind with an initial angle of 45 and magnitude of 0.4. The wind magnitude and direction can be dynamically altered during the run according to fickleness (i.e. the level of variation of wind magnitude and direction; see Section 4.4.2). Note that the land slopes upwards from north to south.

4.4.1. *Effect of a Static Wind*

Static wind can alter in terms of its strength or its direction. Since this model incorporates a sloping ground as described in Section 4.2, only different magnitudes will be examined. The direction of the wind will not be altered, pointing in a direction partially opposing the contribution of the slope to the fire spread. This also aids in cutting down on the combinations of possible parameter values. The wind was therefore set at three different strengths: weak (0.2), moderate (0.4), and strong (0.6). The direction of the wind remained constant at 45 degrees, or northeast. The full set of parameters is listed in Table 3. The densities of the forests in the models can be found in Table 2, as each model will have different densities according to where the critical region lies. For example, the results using the wind magnitude of 0.2 (representing a static weak wind) can be found in Table 2 f). It can be seen that although the critical density has not changed too much, shifting perhaps a little higher than in the previous models, the critical region has changed in size. It appears to cover an area of perhaps 8%, up from a size of 4% or 5% in previous models. This is the first significant size increase or decrease seen so far. This means there is a greater distribution of densities over which fires have the potential to either thrive or starve, rather than be highly influenced one way or the other. The second static wind model used a moderate strength wind. The parameter values from Table 3 were used again, with the wind magnitudefor static moderate wind being 0.4 this time (see Table 2 g)). It is found that the moderate strength wind makes more of an influence on the fire's spread than the weak wind. Interestingly enough, this does not seem to alter the critical density by much. The critical density has only dropped marginally, to perhaps a little below 63%. The size of the critical region has also dropped slightly to about 7%.

The third static wind model involved using a wind of strong magnitude. The parameter values from Table 3 were used again, with the wind magnitude being 0.6. The critical density has clearly dropped (see Table 2 h)). Whilst the density from the weak wind model to the moderate wind model showed perhaps half a percent drop, going to the strong wind model has resulted in a drop of at least a whole percentage point, down to a bush density under 61%. The size of the critical region remained almost the same as in the previous model for a static moderate wind.

4.4.2. *Effect of a Dynamic Wind on Fire Spread*

Dynamic wind can alter not only in terms of its initial strength and direction, but also in how much these values change over time. This model will therefore vary how quickly the wind changes in both strength and direction, a value that has been termed fickleness. The initial direction of the wind has been kept at 45 degrees and its strength is set to moderate (0.4). The different levels of fickleness used are, low (0.8), moderate (1.6), and high (2.4). The magnitude of wind is 0.4; the remaining parameters have the same settings as those in Table 3.

The first model using a dynamic wind investigated the effects of low variation in the wind's angle and magnitude. The fickleness of the wind was set at 0.8. The results as given in Table 2 i), are fairly similar to those of a static moderate wind. The critical density is around 63% or perhaps just under, but the size of the critical region has grown to about 11%.

The second model using a dynamic wind investigated the effects of more moderate variation in the wind's angle and magnitude. The fickleness of the wind was set at 1.6. The results are very similar to those of the previous model investigating small wind variations. The critical density dropped around half a percentage point to just over 62% and the size of the critical region remains about 7% (Table 2 j)).

The third model using a dynamic wind investigated the effects of a high variation in both the wind's angle and magnitude. The fickleness of the wind was set at 2.4. The results are very similar in certain aspects to both of the other two dynamic wind models. Also in common with the lowly fickle wind model is the critical density, back at about 63% (Table 2 k)). The critical region, however, has grown in size, covering an area of about 8%. Although fires tended to thrive more readily under moderately fickle winds, this situation has not continued with highly fickle winds. One explanation is that the wind changes too rapidly and at certain points forces the wind back onto already burnt land. The fire, quickly starved of fuel, becomes extinguished before long.

5. Conclusion

Critical densities are not just a property of landscapes, but one that emerges from the fires' interactions with the environment.[8] In this research we have developed a simulation model that incorporated the major environmental factors contributing to the spread and growth of fire.[5,6,7] Although the simulation model developed here is a rather simple one, it may be used as a tool for preliminary study of fire spread behaviours. For example, fire fighters can use the model to obtain an estimated safe tree density value so as to avoid catastrophic fire spreads across a landscape.

The results of our experiments indicate that the critical region did not seem to alter in size for any variables, with the exception of wind. The strength and fickleness of the wind had a small effect on the size, with a moderate wind experiencing small changes in magnitude and angle generating the largest critical region. The critical density lay around bush densities of 60%-65% and shifted for almost all combinations, but not by much. The major exception was in hot, dry heat conditions where the critical density dropped to 58%.

Investigation in the future will need to look at how relevant the representation used in the model is to the real-world phenomena. For example, a strong wind in the model appeared to influence the fire as a strong wind might in the real world, and similarly for topology. It would be desirable to incorporate real-world data into the simulation model. Scans of maps should be used and converted into appropriate model data. Proper scaling is necessary in order to allow certain parameters (such as topology and wind) to function in a more realistic manner. Bushfires that have actually occurred should be simulated in order to verify the model and point out shortcomings. All these things require new and manageable methods for inputting data into the simulation.

References

1. D. Stauffer and A. Aharony, *Introduction to Percolation Theory*, 2nd edition (Talor and Francis, Long, 1991).
2. C. Adami, *Introduction to Artificial Life* (Springer-Verlag, New York, 1998).
3. M. Resnick, *Turtles, Termites and Traffic Jams* (The MIT Press, Cambridge, Massachusetts, 1994).
4. D.G. Green, Simulation Studies of Connectivity in Ecological Systems,*Pacific Conservation Biology*, **1**(3) (1994) 194 - 200.
5. P.L. Andrews, Use of the Rothermel Fire Spread Model for Fire Danger Rating and Fire Behavior Prediction in the United States, *Proceeding of the Conference on Bushfire Modeling and Fire Danger Rating Systems*, eds. N.P. Cheney and A.M. Gill, CSIRO Division of Forestry, Australia, 1991, 1-8.
6. T. Foster, *Bushfire: History, Prevention and Control* (Terry Hills, Hong Kong, 1976).
7. R.E. Luke and A.G. McArthur, *Bushfires in Australia* (AGPS, Canberra, 1978).
8. B.T. Milne, A.R. Johnson, T.H. Keitt, C.A. Hatfield, J. David and P.T. Hraber, Detection of critical densities associated with pinon-juniper woodland ecotones. *Ecology* **77** (1996) 805-821.