Computational Environmental Science

Cellular Automaton Model of Forest Fire Simulation

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Abstract: Forest fire simulation is used to gain insights and conduct predictions on possible occurrence of forest fire to have the most effective protocols in place in case of wildfire breakouts. A Cellular Automaton has been generated which uses Moore's neighbourhood and stochastic ignition probability to mimic the various factors which lead to potential increase in speed and area of fire spread. The model includes the wind speed, wind direction, fire intensity, presence of water source and density of forest. Wind speed and direction can be modified to experiment with the relative time for the fire to reach the town. Water and forest will be placed in between fire source and town to slowdown the spread of fire. This can also reduce the destruction caused by the fire; Short-term and long-term interventions have been taken to extend the time for the fire to reach the town. This has also effectively reduced the intensity of the fire, thus reducing the damage on the landscape. The CA model effectively shows the effect of wind speed and direction on the spread of fire on different types of landscape features. Effectiveness of interventions were also accurately modeled through a realistic CA model.

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1. Introduction and Background (Literature Review) – [guideline 1 page]

Cellular Automata was invented by Stanislaw Ulam and was used by John Von Neumann to solve the problem of self-reproduction in a logical system (Schwartz, von Neumann & Burks, 1967). Wolfram (2002) stated that the cellular automata model can be widely used in the fields of science to investigate the relationship between a program and a set of rules. Wolfram (2002) argued that the traditional mathematical models have never come close to capture the high complexity in biology, but a simple Cellular Automaton model can produce a high level of variations of new models for the biological system. The forest fire simulation is a cellular automaton model. The state changes according to the transition function after each time step. It will have several parameters describing it, which includes ignition probability of terrain, wind, and water. These parameters affect the results and they are described and used by Rothermel (1972), Trunfio (2004), Encinas, White, Rey & Sánchez (2007), and Ghisu, Arca, Pellizzaro & Duce (2015).

Rothermel (1972) used a mathematical model to predict the rate of fire spread and intensity applicable to a wide range of wildland fuels. The model is a dynamic equation with parameters including heat capacity, propagating flux, reaction intensity, wind and slope coefficient. Rothermel (1983) stated that the fire prediction process includes estimating the inputs such as weather, fuel types, fuel maps in the area. Trunfio (2004) used the equation introduced by Rothermel (1972) to compute the wind direction and the combustion condition of cell. The model used hexagonal cell and a different neighbourhood pattern, which produced different results compared to models using square cell and Moore neighbourhood. It is predicted that the fire will propagate according to the wind direction, positive slope, and the humidity of areas (Trunfio, 2004). It is unlikely that the fire will spread faster in a high humidity area than a low humidity area. Moreover, Encinas et al. (2007) implemented a hexagonal cellular automaton and it integrates weather and land conditions. This model used complex transition functions to calculate the influence of wind.

Encinas et al. (2007) proved that if the area is flat and there is no wind present, the fire will spread outwards to have a circular form. Otherwise, the direction and speed of the fire will be affected. Ghisu et al. (2015) created an interacting automaton to model the forest fire. This model produced good estimation results but it is hard to implement. Researches have shown that the factors which affect the fire spread are wind and topography, and these factors are also the main causes of wildfires (Ghisu et al., 2015; Encinas et al., 2007).

Our experiment is to simulate the forest fire and investigate the factors that affect the fire spread. We are required to consider a lake in the area, different ignition probability of vegetations, and the relative time for the fire to reach the town. This requires the transition function to calculate the ignition probability of every cell after each time step. According to all previous models and their conclusions above, it can be confirmed that the fire spread will be affected by wind direction, wind speed and terrain conditions. In the simulation results of Bodrožić, Stipaniev & Šeric (2006), it has been shown that the fire spreads faster in land with dense, higher flammability vegetation. Hence, in our experiment, we have assumed that the fire will spread the fastest in the scrubland, and the slowest in the dense forest. We also assumed that the fire speed will be slowed down by the lake and the dense forest.

2. Materials and Methods - [guideline 1-2 pages]

Design concepts

Our CA model uses Moore's Neighbourhood (**Figure A1**) to determine the next state of each cell after each time step. As shown in **Figure A1**, the cardinal directions represent the four adjacent cells, and the intermediate directions represent the four corner cells. The next state of a cell is affected by its neighbour. A stochastic-based method is implemented into the neighbour rules. The ignition probability of a cell is directly affected by the fire intensity of its neighbour states, and also the wind direction. A cell may change to burning state if and only if it has at least one neighbour that is on fire. Cells with more burning neighbours are more likely to change to burning state, but the outcome is unpredictable. Additional complexity such as wind direction and fire intensity are implemented to make the simulation more realistic.

The terrain map consists of a large area of chaparral, a lake, a canyon with scrubland, and a dense forest. Characteristics of the landscape is represented in the form of cells and the terrain type will remain fixed. Different type of terrain has different ignition probability, and the lake cannot be burned. Chaparral has moderate flammability and medium burning duration, which makes it the best element for spreading the fire. Scrubland has high flammability but very short burning duration, hence, it is only useful for speeding up the spreading process, but not increasing the spreading distance. Dense forest has low flammability and long burning duration. Thus, the forest can be used as a natural barricade to slow down the fire speed. However, if the forest starts catching on fire, it will reinforce the fire strength and cause neighbouring cells to burn.

Modelling of wind direction has been implemented in the CA model. The default wind direction is south. Hence, in this case, the spread of fire is more vigorous towards the south direction, which implies the ignition probability of the centre cell will be affected more by its neighbour cells in the top row, and less in the bottom row. According to Rothermel (1972), this is also due to the presence of solid mass transport, flame contact, radiation and convection (**Figure A2**). The fire shape is more elliptic if there is a wind condition, otherwise it spreads in circular direction (**Figure A3**).

In our model, we have high, medium and low fire intensity for different burning duration remaining. Cells with high fire intensity has the greatest chance to cause their neighbouring cells to burn, and vice versa. Burnt out cells will remain burnt out. In terms of regrowth, according to data acquired from Yellowstones after the wildfire in 1988 (Boyle, 2013), it takes 25 years for the regrowth of forest while it takes up to 4000 years for a landscape to grow back to its native state (Brahic, 2008). Therefore, it is impossible to model the regrowth process since it will require large number of time steps. Due to the large difference between the burning duration of chaparral and scruband as compared to the dense forest, the full combustion of the forest is not modelled unless the time step is large.

The flowcharts below describe the spread of forest fire. Effects of wind (left), Effects of vegetation (right).

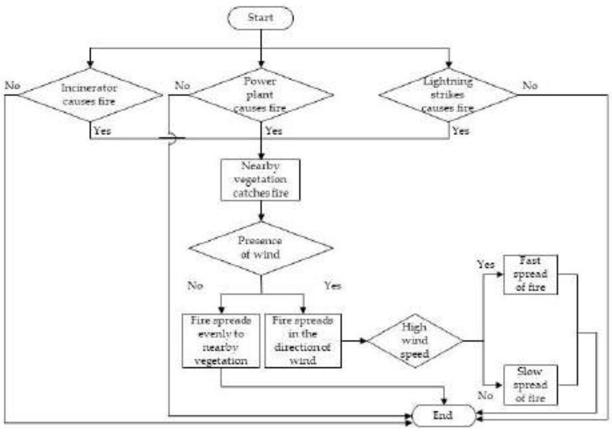


Figure 1. Flowchart depicting the effect of wind and speed of wind on spread of fire.

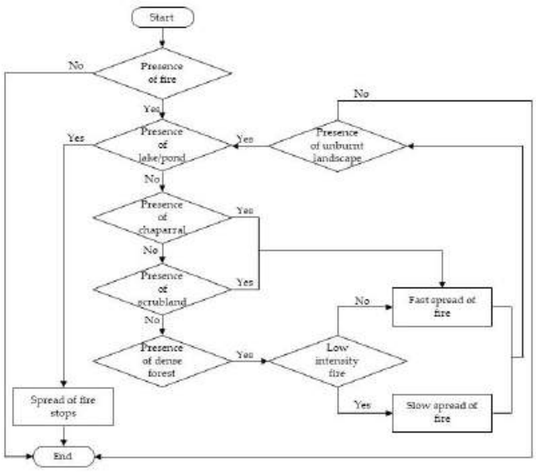


Figure 2. Flowchart depicting the effect of different types of vegetation on the spread of fire.

Assumptions

It is assumed that the current season is summer, which is the season where more forest fires occur due to the increase in heat. In summer of 2017 (Wildfire Season Summary, 2017), British Columbia had over 1.2 million hectares of land burned, while the Detwiler Fire in California burned over 30000 hectares of land (Detwiler Fire General Information, 2018). It is also assumed that the chaparral area is completely flat and the canyon do not contain rain shadow areas, hence the slopes are covered by chaparrals and scrubland. Due to time constraint and complexity, it is assumed that the fire speed is not affected by the slope. The wind strength is assumed to be 10 mph. It is assumed the timescale is 15 days (1500 time steps), and that the burning duration of chaparral is 3.5 days, grassland is 5 hours and dense forest is 1 month.

It is assumed that every ignited cell will start with high fire intensity. The fire intensity changes to medium once the burning duration remaining for a cell drops below 50% of its original duration and change to low if duration remaining is less than 30%. A cell with high fire intensity will increase the ignition probability of its neighbour by a value, β. The reduction in fire intensity of a cell will lower the chance of it affecting its neighbouring cells to burn, this is done by multiplying a penalty to the value β. It is assumed that the penalty for medium intensity is 0.5, and low intensity is 0.29.

To assume the base ignition probability for chaparral, scrubland and dense forest, we have used the data compiled by Ross & Hubley (2017). Since the timescale assumed is 15 days, hence, only wildfires that are shorter than 20 days have been considered. According to the previous data of wildfires histories, it has been roughly estimated that the average rate of spread is 9.7 km^2/h. Therefore, sensible estimations have been made in assuming the ignition probability for each burnable terrain.

3. Results [guideline 2-3 pages]

The model uses the constant parameter below:

- Timescale : 15 days represented as 1500 time steps in the model
- Dimension and Grid : 2D dimension, 200 × 200
- Area of land : 2500 km^2, each cell is 0.0625 km^2
- Wind direction : South
- Wind speed : 10 mph (≈ 16 km/h)
- Base ignition probability of chaparral : 40%
- Base ignition probability of grassland : 80%
- Base ignition probability of forest : 3.87%

The wind strength was experimented to estimate the duration for the fire to reach the town. It was required to change the time steps to a larger number in some cases to make the fire reaches the town.

Wind speed (mph)	Duration of fire spread from power plant to town (day)
5	9.8
15	3.1
20	2.6
25	1.9

Table 1. Effects of wind speed on duration of fire spread from power plant to town

Wind speed (mph)	Duration of fire spread from incinerator to town (day)
5	19.2
15	7
20	5
25	4.4

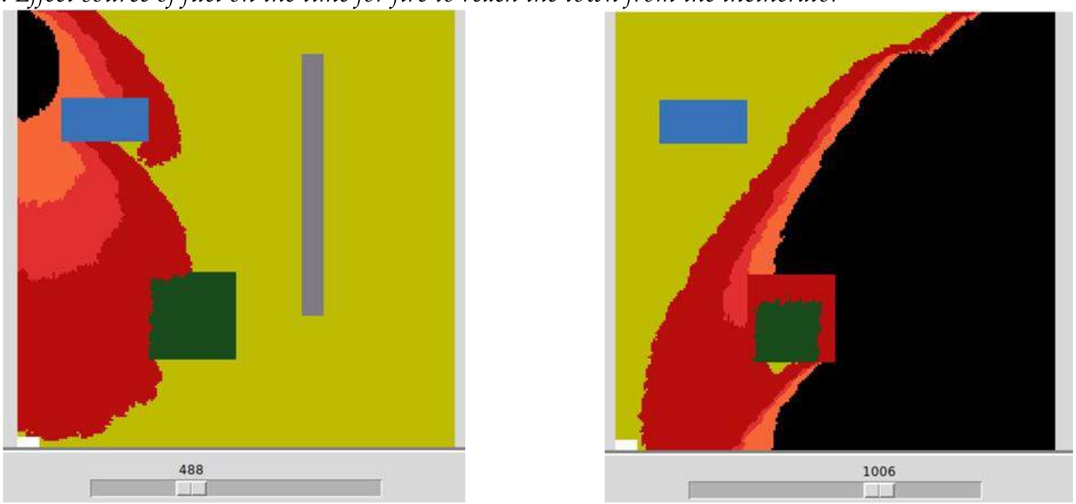
Table 2. Effects of wind speed on duration of fire spread from incinerator to town

The direction of wind clearly influences the direction and speed of spread of fire. According to the results in **Table 1** and **Table 2**, it has been proved that the rate of fire spread is directly proportional to the wind strength. Hence, it can be deduced that the total area burned will be directly proportional to the wind strength too.

3.1. Relative time of fire reaching the town

The time taken for fire to spread to the town depends on various variables implemented in the model, including the speed and direction of wind, source of fuel and structure of landscape. The fire spreads out faster when in contact with scrublands or chaparral than forest. The forest and lake acts as a barrier, but in a high intensity fire, the forest will catch fire and cause higher damage.

3.1.1. Effect source of fuel on the time for fire to reach the town from the incinerator



(**a**) (**b**)

Figure 1. The spread of fire according to different source of fuel: The source of fire is (**a**) the existing power plant; and (**b**) the proposed incinerator, resulting in approximately 5 days and 10 days respectively to reach the town.

3.1.2. Effect of wind direction on the time for fire to reach the town from the incinerator

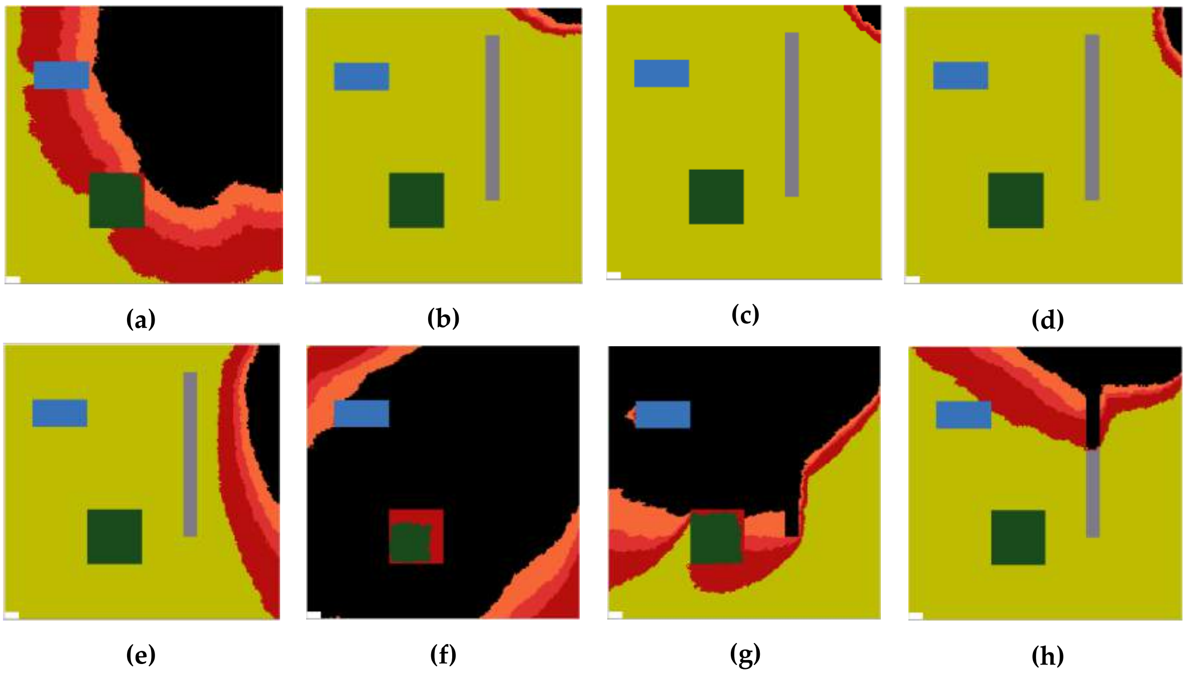


Figure 2. The spread of fire according to wind direction with the proposed incinerator as the fuel: The time steps is kept at a constant of 1000 while the wind direction is from (**a**) none present; (**b**) North; (c) North East; (d) East; (e) South East; (f) South West; (g) West; and (h) North West, respectively.

3.2. Intervention

Interventions were being experimented with to find the best implementation method so as to contain the spread of forest fire. This can effectively reduce the damage done to the landscape and increase the duration before the fire spreads to the town.

3.2.1. Short-term intervention

Short-term intervention allows the attempt to contain the fire immediately but with a lower effectiveness. This can only slowdown the spread but is unlikely to fully contain the fire.

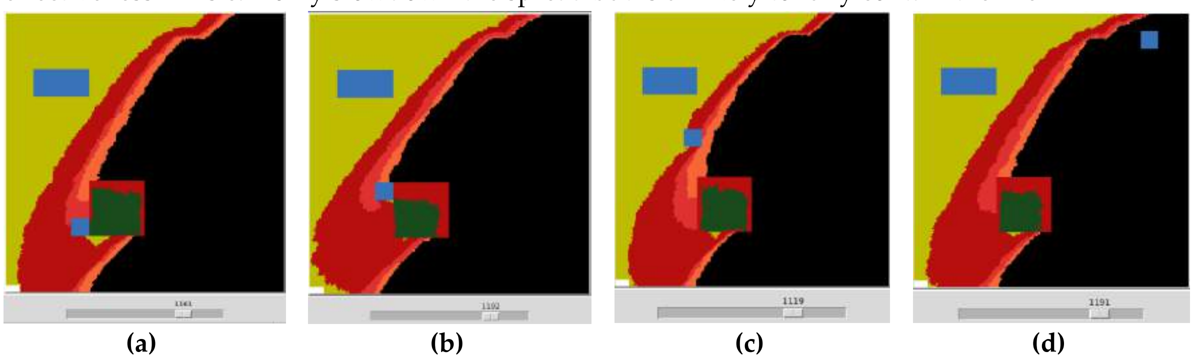
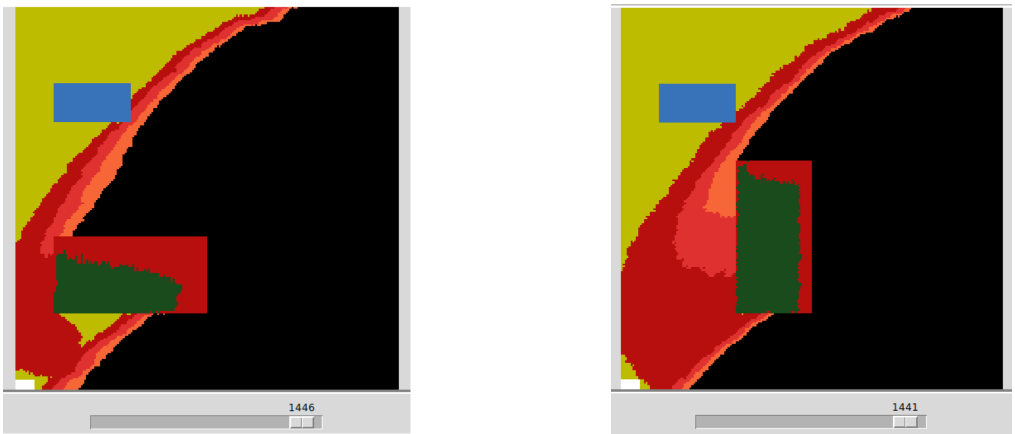


Figure 3. The spread of fire according to location of water drop with the proposed incinerator as the fuel: The water drops are on the **(a)** south east of the forest; **(b)** north east of the forest; **(c)** in between then south west of the lake and the north east of the forest, respectively; and **(d)** approximately 6km away from south west of the incinerator.

3.2.2. Long-term intervention

Long-term intervention allows a longer delay before the fire spreads to the town, providing more time for protocols to be implemented to contain the fire. The results below show an increased delay of 4.5 days for the fire to reach the town.



(a) (b)

Figure 4. The spread of fire according to location of forest expansion with the proposed incinerator as the fuel: the area of forest is expanded double of the original area towards the (**a**) West, and (**b**) North, respectively, both resulting in approximately two and a half weeks to reach the town.

4. Discussion [Guideline 1-2 pages]

With the current power plant and the proposed location of the incinerator, if a forest fire were to be fueled by either source, it takes approximately 5 days and 10 days respectively for the fire to reach the town, assuming that no action has been taken to put out the fire. However, this is an unrealistic assumption as an effort would have been made to put out the fire at some point. In terms of wind direction, if the fire starts at the incinerator, the wind blowing towards south-west direction causes the highest damage to the landscape and reaches the town in the shortest duration as compared to other wind directions as fire is spread according to the direction of the wind.

As a short-term intervention, since the amount of water available to be dropped is limited to 10 km^2 (160 cells), the longest delay of fire spread was found when the water was dropped at an approximated distance of 6km to the south west of the incinerator. In terms of long term interventions, the area of dense forest is expanded, with the horizontal expansion to the west being slightly more effective than a vertical expansion to the north.

The results found are reliable as all numerical data are from creditable past researches. However, with each run, the results may vary slightly since a randomizer is used to ensure the realistically of the model. When assumptions like direction and wind speed is changed, the spread of fire will change in direction and speed accordingly, leading to different results. The model could be more realistic if the duration since the last forest fire, regrowth, gradient of wind and terrain are added. These were not implemented as regrowth requires longer time step, resulting in higher computational expense. The duration from the last forest fire determines the change in vegetation due to regrowth process is important due to the changes in vegetation. With a recent forest fire, it is likely that scrublands and chaparrals have started to regrow, and forest may have an abundant growth of young forest stands which according to Heon, Arseneault & Parisien (2014), creates a fuel-mediated negative feedback on fire activity. In terms of change in vegetation structure, (Managing fire in natural grasslands, 2017) states that grasslands may develop into woodlands in the duration of 10 to 20 years. Lake can also act as a water source for regrowth and nearby chaparral may be denser due to the same reason. The gradient of wind which highly depends on the terrain are not implemented in this CA model as well as the height and gradient of slopes are not provided.

According to (Koo et al., 2005), the gradients of terrains and wind determines the direction of the spread of fire, affecting the result of the CA model significantly.

This CA model has similar results as compared to the results found from the CA model by Bodrožić, Stipaniev & Šeric (2006). Both models show similar effects in terms of flammability of vegetation and effects of wind on the landscape. It was also seen that experimenting with a similar model to that of Trunfio (2004) and Encinas et al. (2007), which uses hexagonal cell and different neighbourhood pattern would be beneficial in terms of gaining more insights and deeper understanding. This is because a centre hexagonal cell will have equal distance to all of its neighbours, thus the results produced will be different when compared to a square cell model. However, Trunfio (2004) indicated that hexagonal cell might have negative impact on flat areas because it does not have the symmetrical properties of a square lattice.

In this model, the wind direction and wind speed are assumed to be constant, which is not realistic in a real-life situation. The model could be improved by implementing a dynamic wind function, which changes the wind direction and speed from time to time. This could greatly affect the results produced as it has been proved in **Table 1** and **Table 2** that the rate of fire spread is directly proportional to the wind speed.

For additional complexity, the terrain could be made uneven. Currently, it is assumed that the landscape is completely flat, and slopes are not present in the canyon. Rothermel (1972) claimed that fire spreads faster on positive slope, and spreads relatively slow on negative slope. The effects of wind on negative slope have also been considered. If this is combined with the dynamic wind function, the model could be more realistic, and the results could be more accurate.

The variation temperature and humidity which is caused by changing of seasons may affect the ignition probability and rate of spread of fire. It is predicted that the rate of spread of fire is directly proportional to the temperature, and inversely proportional to the humidity.

In a real-life wildfires situation, fire spotting could happen if the wind speed is too strong. In the current model, the fire could only spread to its neighbour. Strong wind could blow the ember to a far distance away from the source, causing the fire to spread in another location. It is worth considering this if the wind speed assumed is large, since it is highly possible for fire spotting to happen causing the fire to reach the town much faster.

5. Conclusions [Max 0.5 pages]

Cellular Automata model provides a realistic image of fire spread and can be used to make accurate estimations for the speed of fire spread. Cellular Automata model can also provide an effective outcome of proposed interventions, providing us the ability to choose the intervention with the best outcome at a low expense of risk and cost. Though so, the model would be more accurate if computational expense is not as limited and more information about the local history of forest fire and geographical structure of the landscape was given.

It has been concluded that the spread of forest fire may be contained if efforts were made in an early stage and natural landscapes can be used as a barrier. This can be done with the use of the lake and dense forest. Information collected from the history of forest fire in the landscape can provide deeper insights to the physical characteristics of the landscape. From this Cellular Automata model, it can be concluded that with frequent and close observation on the landscape and protocols ready to be implemented for different degrees of spread of forest fire by authorized parties, the proposed location may be used to build the incinerator.

Several improvements including dynamic wind function, gradient of terrain, and fire spotting behaviour could be implemented to make the model more realistic and effective in terms of estimating the results. It is also worth considering different seasons as structure of vegetations and humidity may vary.

<u>**THE LENGTH OF YOUR REPORT TO THIS POINT SHOULD NOT EXCEED 7 PAGES (around 3500 words)**</u>

Appendix A [Nothing below here will count towards your word/page limit]

	NW	N	NE	
	W	C	E	
	SW	S	SE	

Figure A1. Moore's Neighbourhood
("Moore neighborhood", 2015)

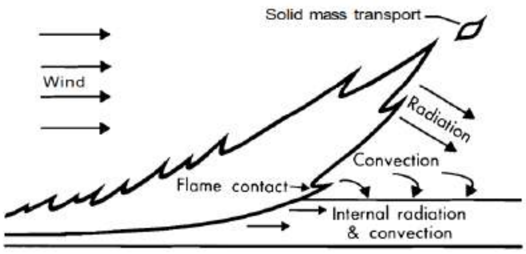


Figure A2. Schematic of wind-driven fire
(Rothermel, 1972)

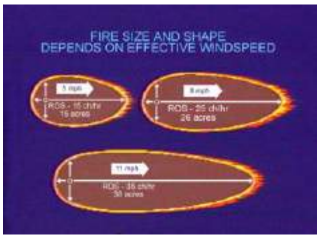


Figure A3. Effects of windspeed on fire shape
("Unit 11: Fire Behavior Prediction System", 2008)

```
# Probability of fire starting
chaparral_chance = 0.4 * fire_bonus * np.random.rand(GRID[0], GRID[1])
grassland_chance = 0.8 * fire_bonus * np.random.rand(GRID[0], GRID[1])
forest_chance = 0.0387 * fire_bonus * np.random.rand(GRID[0], GRID[1])
```

Figure A4. Estimation of ignition probability of chaparral, grassland and dense forest.

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