Using Cellular Automata to Investigate the Relationship Between the Spread Rate of a Forest Fire and Wind Speed

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Abstract

There have been many studies conducted to investigate the effects of forest fires on developing civilizations and in their behaviour has been modelled with intrinsic detail. The aim of this paper is to model (using cellular automata) how quickly a forest fire will spread near a town in the USA. Many different factors have been taken into consideration such as the type of vegetation around the town, the landscape and the wind direction and speed. All of these have an effect on how the fire will spread and in which direction it will spread most quickly. The main benefit of running this simulation is to suggest what preventative measures can be taken to stop the fire from reaching the town as well as where and when they should be implemented.

1. Introduction and Background (Literature Review)

Conway's Game of Life (or more generally, cellular automata) involves taking an array of cells and defining states (which the cells can take) and transitions (how neighbouring cells are affected by one another). It has many applications such as random sequence generation (Wolfram, 1986), cryptography as well as many real-world systems. As such, forest fires have been extensively modelled using Cellular Automata (CA) since the 1990's (Karafyllidis, 1996) due to the intrinsic locality of fire behaviour i.e. a fire spreading to a point depends almost exclusively on whether the points around it are on fire. Due to this, various software has been developed to model forest fire in practical applications, such as FARSITE (Kanga and Singh 2017) which is widely used by U.S. federal and state land management agencies to simulate forest fire spread and identify the best use for resource benefit across a given landscape.

Each of these deterministic applications model each cell as being one of a variety of states, one configuration expressed by Xiaoping being: S = 0 (unburned), S = 1 (early burning), S = 2 (full burning, has the ability to ignite surrounding cells), S = 3 (extinguishing), or S = 4 (extinguished) (Xiaoping, 2017). These states, coupled with transition functions can comprehensively describe how parts of an environment can behave during a fire and can lead to emergent, dynamic behaviours. These transition functions take into account the properties of the current cell, as well as its neighbours to decide what state the cell should be in after the next time step, as seen in numerous other studies (Xiaoping, 2017 & Bodroži, 2006). Bodroži argues that vegetation characteristics and wind speed as parameters are enough to gain results satisfactory enough for practical use. However, he does not consider the scale of the simulation since this assumption would be fine for localised forest fires but a cellular automata model with more computational methods would be required to give more accurate results for larger simulations.

The properties modelled in the cell differ from study to study but using work by Xiaoping and Wang we have identified 3 key properties to define the simulation of a forest fire: terrain, wind and combustibility (Xiaoping, 2017 & Wang, 1992). Xiaoping also modelled a correction coefficient, but since we are not modelling after a real fire we have omitted that. Typical forest fire simulations use many input parameters but Xiaoping used remote sensing images as inputs to increase the operating efficiency of his simulation. However, as a result of this his simulation has omitted optimization of forest fire correction and cell automaton time step which would otherwise improve the accuracy of the simulation. Wang also identified a lookup table for the combustibility of different terrains. However, these figures are modelled from China's environment and so may differ to the specification terrain we are modelling, although we can use these figures to generate ignition thresholds for different vegetation that are in proportion to one another. The result of Xiaoping's work also provided an optimal time step for this type of system as ⅛ (assuming each cell has 8 neighbours) * time it takes for a cell to fully burn. This figure ensures the spread of fire maintains the most accurate spread rate (concentric circles). (Xiaoping, 2017). Using these identifications Xiaoping predicted that forest fires could be more accurately and efficiently modelled.

2. Modelling Methodology

Modelling of forest fires (wildfires) naturally lends itself to a cellular automata approach. Any given area regardless of the number of various terrain types can be represented using cells. The state of each cell corresponds to a specific type of vegetation (Fig 1.). Additional states can then be used to represent the process of a fire burning, such as just caught fire, burning completely and burnt out. Then in order to model the spread of a fire, transition rules of varying complexity are applied to each cell to see whether it will change state.

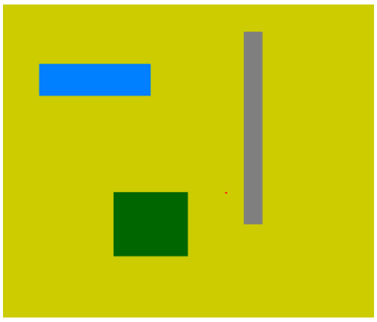

Figure 1 CA model of terrain, yellow representing chaparral, green forest, blue lake and grey canyon

2.1 Description of Model

The model we will be testing is a 50km^2 area region in the USA that is prone to forest fires whereby a town is situated 50km away from a power plant to the north and a waste incinerator 70km to the north east that are both potential sources of a fire. In this model we will be considering various terrain types (see Fig 1) to see how they affect the spread of fire. In addition, each terrain type will be assigned a fuel resource parameter to simulate when the fire will extinguish for a given type of vegetation. We will also be exploring how the time it takes for the fire to reach the town varies with the wind speed and wind direction. As a result of this modelling we will explore the possibility or short-term intervention involving a drop of 10km^2 water and where the best place for this us along with longer term intervention such as extending the area of the forest.

2.2 Timestep

The model uses the dimensions of 200 by 200 cells with each cell representing 0.25km^2. Having more cells allows us to more easily analyse the fire spread through different materials, however there is a trade-off here between the number of cells and computational performance of the simulation. The timestep between generations that our model incorporates is 30 minutes, since we are investigating intricate behaviour of fire spread it makes sense to make the timestep appropriately small, longer time steps will not capture the detail regarding the fuel resource parameter as effectively. Within each time step, each cell will go through a sensing phase to determine whether it should set alight dependant on how many cells around it are on fire along with the wind speed and direction. A flow diagram representing the processes each cell goes through for each generation can be seen below (Fig 3).

2.3 Resource Ignition thresholds

The burning thresholds we have applied to model the ignitability of each type of vegetation in our model are based from the paper Wang whereby he gives details about the fuel combustion coefficient. We used these combustion values to apply thresholds to our materials that are proportional to the fuel load values of those in their paper. Since we have different burning states we have applied separate initial thresholds for a cell that is surrounded by cells that have started to burn, and cells that are in full flames (Appendix Fig 1). These initial threshold values for a given cell are then modified dependant on the states of its surrounding neighbours and the wind speed modifier. Then in order to induce randomness we generate a random number for each cell, if the random number is less than the modified threshold then that cell sets alight.

2.4 Fuel resource parameters

Vegetation	Fuel resource burning time per Km.
Canyon grass	4 hours
Chaparral	84 hours (3.5 days)
Forest	300 hours (12.5 days)

Figure 2 Fuel resource parameters

The vegetation burning times we have applied have been inspired by the fuel load times that Burgan and Scott discuss in their paper. We have applied these to our different types of vegetation to represent how long they will burn for (Fig 2) and have identified an average time that each vegetation will burn for. In addition to this each cell goes through different burning states as it burns, these are “Start burning”, “burning” and “end burning”. The time it stays in each of these states while on fire is relative to its fuel resource parameter. In our model each cell represents $0.25km^2$, as such the above fuel resource parameters are modified to reflect this (Appendix Fig 2). The numbers used represent the number of 30-minute generations that the material will burn for. In our model we have not considered the effect of regrowth because it is negligible factor for our model since the fire will burn out before there is any chance for vegetation regrowth.

2.5 Wind modelling

To model the wind, we used an equation based on a part of Rothermal’s model (Rothermal, 1972), $K_{\varphi} = e^{0.1783 \cdot v \cdot \cos\varphi}$, which is derived from real world data and used prevalently in the field. Specifically, Rui’s study on forest fires effectively utilised Rothermal’s model and has been cited by at least 56 other studies (Rui, 2017). The wind factor takes into account the direction of the wind, it’s speed and the angle between the wind direction and the fire direction, which was simplified to 45-degree intervals to represent the cardinal directions due to time constraints and the smaller scope of the project. At the beginning of the simulation this formula is run, returning a list of 8 weights corresponding to the 8 cardinal directions, which is then applied to each cell’s neighbours throughout the rest of the simulation to emulate the effects of wind (Appendix Fig 3).

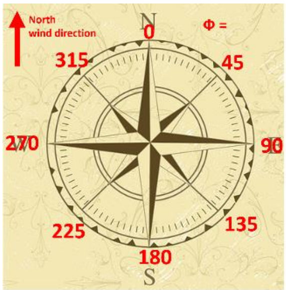

Figure 3 cardinal direction represented as angles based on wind direction

2.6 Model mitigation and intervention measures

In our model we also explore the appliance of mitigation and intervention measures that can help to reduce the impact/effectiveness of forest fire spread. In particular we will be looking at how dropping a $10km^2$ area of water will affect the time taken for the fire to reach the town. Upon dropping the water, we have made the assumption that it will not be dropped until after 240 generations (5 days), then following that we make the assumption that the vegetation where the water was dropped will become flammable again after 96 generations (2 days). As a longer-term mitigation measure we will be exploring how doubling the size of the forest in different directions affects the fire spread rate.

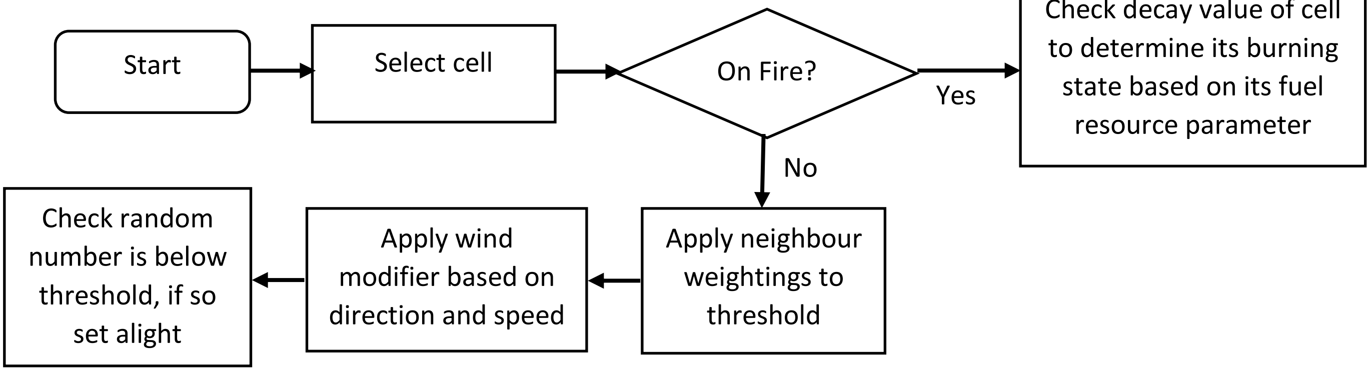

Figure 4 Flow chart describing the process a cell goes through during each transition

3. Results

3.1 Testing the effects of wind speed

The first test we considered was the relative time taken for the fire to reach the town based on whether it starts at the power plant or incinerator respectively and the wind speed that we apply. We assumed a prevailing wind direction (southerly wind). The dependent variable in this test is be the speed of the wind (Appendix table 1-2).

As can be seen opposite there is a strong correlation between the time it takes for the fire to reach the town and the wind speed that the model is supplied with. This supports the work done by Thanailaki's and Karafyllidis' observations regarding the effects of weather conditions. In addition, we can conclude from this data that a fire starting at the Power plant is going to reach the town much more quickly, this is most likely because of the shorter distance required to reach the town along with the forest slowing the progress of the fire beginning at the incinerator.

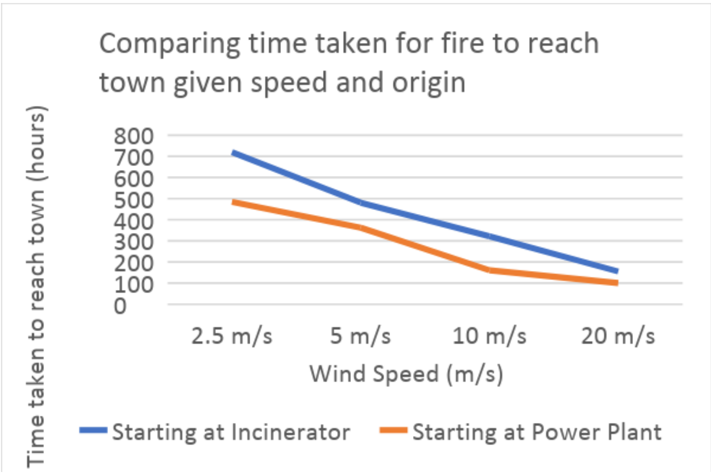

Figure 5 Graph of Results for fire time to reach town based on location and speed

3.1 Testing the effects of short-term intervention

The following test simulates a short-term intervention measure and how it will affect the time it takes for the fire to reach the town when starting at the incinerator. The intervention measure we simulate is dropping a 10km^2 area of water. The dependent variable here is the location of the drop. The wind direction is going south-west and the speed is 10m/s (average wind speed in California). Refer to the methods section above for more information (Appendix table 3).

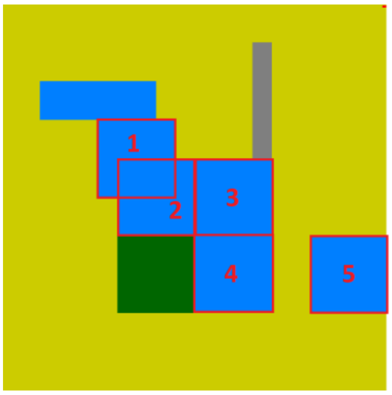

Figure 6 Locations of Water Drops

The test cases we considered correspond to the drop locations as outlined by Figure 6, these were chosen as they would directly impact the fire's ability to spread since they were being dropped on top of the fire front. As can be seen from the results both test cases 1 and 2 had little to no impact on the mean time taken for the fire to reach the town. This is expected since we observed during our testing that the fire will reach the town most quickly as it goes around the forest, since its combustibility index makes the fire slow down as it travels through it. Therefore, when dropping the water in the locations of 2,3 and 4 the fire is slowed by a few hours since the fire is having to travel further as it needs to traverse these drop locations before it can reach the town. The reason why test case 2 was particularly effective is because at the time of the drop the fire front here was particularly large and a large area of fire was extinguished, meaning that the next fastest route to reach the town was for the fire to spread along the eastern side of the forest.

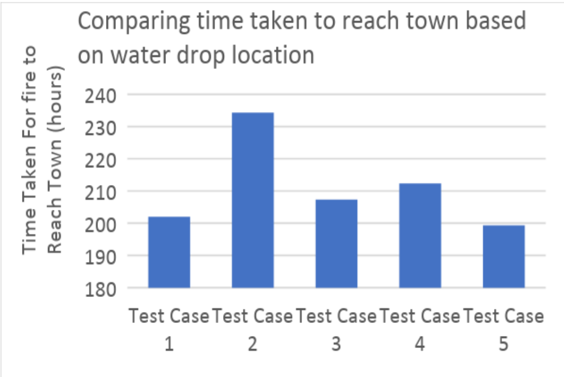

Figure 7 Graph showing results of Water drop intervention strategy

3.3 Testing the effects of wind-direction

The third test we carried out was an exploration of the effect wind direction has on the time the fire takes to reach the town based on it starting at the incinerator. The only dependant variable is the actual direction, the speed being a constant 3.5m/s (Appendix table 4). This was chosen as it is the average wind speed in California, USA where the most forest fires occur (reference 7).

The results opposite provide evidence as to the optimal wind direction for the fire to spread quickest. Since the Incinerator lies exactly North east of the town it makes sense for the best wind direction to be that of South East which is clearly evident in the results above. If we compare this to what we expect the worst wind direction to be (North East) we see that it takes almost twice as long for the fire to reach the town. Therefore, we can conclude that the wind direction is an important factor when analysing the time taken for the fire to spread from one location to another.

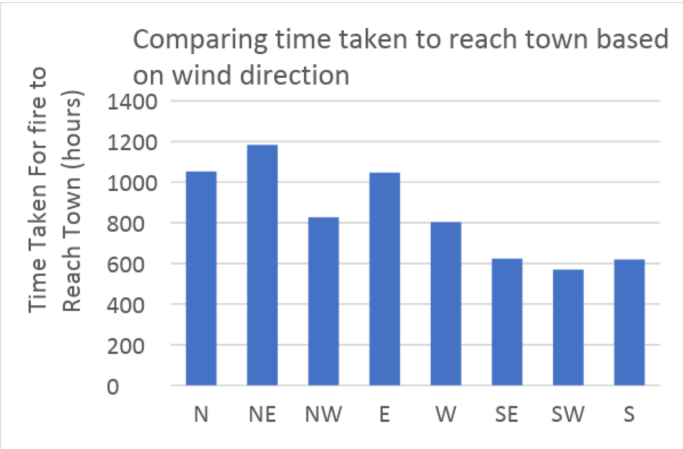

Figure 8 Graph showing results of varying the prevailing wind direction

3.3 Testing the effects of long-term mitigation

The final investigation we undertook was an approach to a more long-term solution to the forest fire problem, namely the effects of expanding the forest two-fold in a given direction. The effectiveness of each direction was determined by how much longer the fire took to reach the town compared to before the expansion. The wind speed used here is kept at a constant 10 m/s in a south-west direction with the fire starting at the incinerator (Appendix table 5).

Expanding the size of the forest by a factor of two does have some impact on the time taken for the fire to reach the town. The reason for this is that the forest has a lower ignition chance than other vegetation. The results opposite conclude that the most effective direction to extend the forest are to the north and west, this makes intuitive sense since this obstructs the otherwise quickest route for the fire to reach the town.

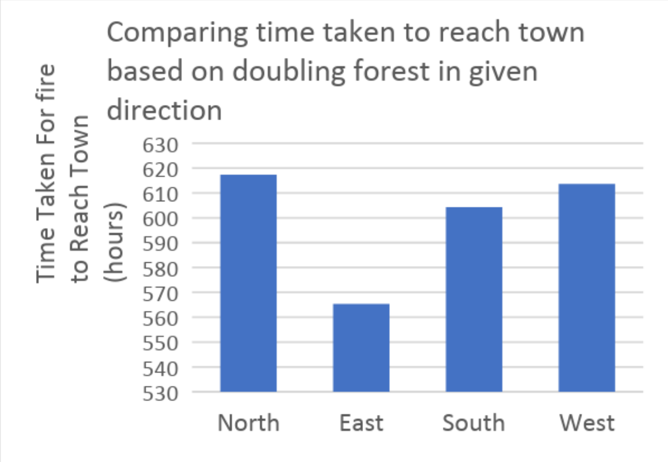

Figure 9 Graph showing results of varying the forest size in given direction

4. Discussion

The forest fire model we produced offered results to each of the town official's questions. Our results suggest that the speed of the wind increases linearly with time, as seen in Figure 5, with the fire reaching the town roughly 30% quicker from the powerplant compared to the incinerator at lower wind speeds, the difference in time becoming almost negligible at extremely high speeds. At California's average wind speed of 3.5m/s, the fire would reach the town in 16 days from the power plant and 25 days from the incinerator. These figures provide potentially useful information in terms of evacuation times in the event of an uncontrollable fire.

If a water drop were to be utilised the best location would be just north of the forest, providing an additional 235 hours to evacuate time, as seen in Figure 7. North of the forest is the best location as it intercepts the fire's least path of resistance; due to the forest slowing it down, and the prevailing southerly wind pushing the fire south. Following this, the forest's best location for expansion is also North for the very same reasons, as seen in Figure 9. An interesting further topic of investigation is the installation of a fire breaker stretching from above the forest to the west of the area, forcing the fire to take the longer route around the forest.

As is intuitive the fire reached the town the quickest when the wind was blowing in a south-westerly direction from the incinerator, while taking the longest if wind is in a north-easterly direction, as seen in Figure 8. Since the prevailing wind direction in this location is South this means the town is in quite a compromising position.

It is proposed that the town officials expand the forest in a northerly direction, as well as ready a water-drop in that location to prolong the time it takes for the fire to reach the town. It is felt that the proposed location of the incinerator is an appropriate place, as although the prevailing wind is southerly, it is in the furthest location away from the town, in a safer place than the power plant.

Toe extend the model, and gain more significant results, greater accuracy would be required regarding the assumptions that have been made. This includes the relative time materials would burn before running out of fuel for that specific location as we based ours on a Chinese model that used different vegetation. If given more funding a study into the specific materials in that location could give more accurate decay and ignition values, leading to a more representative model. Furthermore, the current model assumes a flat environment, whereas a further study could incorporate elevation into the model leading to higher accuracy like Xiaoping's model (Xiaoping, 2017). However, the system remains quite robust even if the fire is modelled to start at different locations or other variations, due to the locality of the transition functions. Furthermore, comparing our model to the contour maps in Karafyllidis's study, a striking similarity is seen, such as there being concentric circles with uniform vegetation and no wind, with bulges as these two factors change, suggesting our model is valid and correlates with other studies (Karafyllidis, 1997). Further explorations could involve extending the timescale that the model uses to potentially model the regrowth of future vegetation. This could give rise to interesting scenarios such an additional forest fire occurring where some vegetation may have regrown.

5. Conclusion

By utilising a cellular automata approach to modelling forest fires, we have produced a model that reflects the intricacies of fire behaviour given several considering factors. Clearly the factor of wind is hugely influential to this behaviour and as our model demonstrates the speed of the wind along with the direction is greatly influential to its spread rate. However, one must not overlook the importance of the vegetation that a fire interacts with. It is the case that materials with higher ignition thresholds cause a fire spread to slow, yet these materials generally have a higher fuel resource parameter and so once set alight, will burn for longer. Therefore, there is a trade-off between the length a fire burns for and the time it takes to spread. In most cases though people are more concerned with how fast a fire spreads so that the relevant safety precautions can be made such as evacuation. That is where our modelling becomes particularly useful, since the work done regarding fire intervention and mitigation demonstrates the optimal actions the relevant authorities can take to slow a potential forest fire and safeguard human life.

Appendix

```python
cell = int(cell)
ignition_factor = 0
if cell in [LAKE, BURNING, BURNT, END_BURN]: return ignition_factor
neighbours = neighbours.astype(int)
fully_burning_threshhold = [0.04, 0.01, 0, 0.1, 0, 0, 0.04]
fully_burning_factor = 20
start_burning_threshhold = [0.02, 0.005, 0, 0.05, 0, 0, 0.04]
start_burning_factor = 10

# add to cell ignition factor by multiplying
# windspeed modifier and the cells burning threshhold
# if a random number is less than the resulting number add
# the burning factor multiplied by the wind speed modifier

for index, neighbour in enumerate(neighbours):
    if neighbour == BURNING:
        if fully_burning_threshhold[cell] * wind[index] >= random.uniform(
                0, 1):
            ignition_factor += int(
                math.floor(wind[index] * fully_burning_factor))
    if neighbour in [START_BURN,END_BURN] and \
    start_burning_threshhold[cell] * wind[index] >= random.uniform(0,1):
        ignition_factor += int(
            math.floor(wind[index] * start_burning_factor))

# if the cell is has already started to burn then a burning factor is
# automatically applied

if cell == START_BURN: ignition_factor += start_burning_factor
return int(ignition_factor)
```

Figure 1 Code that determines whether a given cell will ignite

```python
generation = 0.5
cell_size = 0.25
chaparral_decay_km = 168
forest_decay_km = 600
canyon_decay_km = 8

chaparral_decay = chaparral_decay_km*cell_size*(1/generation)
forest_decay = forest_decay_km*cell_size*(1/generation)
canyon_decay = canyon_decay_km*cell_size*(1/generation)
```

Figure 2 Code determining the fuel resource parameter of each vegetation type

```python
def wind_speed_rvalue(direction, speed):
    if direction in DIRECTIONS:
        list_directions = np.array(
            ["N", "NE", "E", "SE", "S", "SW", "W", "NW"])
        item_index = np.where(list_directions == direction)[0]
        listWeights = np.zeros(8)
        angle_interval = 45
        angle = 0  #initialises weight
        wrapped = False
        for x in range(
                8
        ):  #goes through array, including wrapping round and weights the directions
            listWeights[(x + item_index) % len(list_directions)] = k_wind(
                speed, angle)
            angle = angle + angle_interval
        rearranged_index = [
            7, 0, 1, 6, 2, 5, 4, 3
        ]  #rearranges list so is in same order as the CA programme
        return listWeights[rearranged_index]


def k_wind(speed, angle):
    return np.exp(0.1783 * speed * np.cos(np.deg2rad(angle)))
```

Figure 3a Code determining the list of wind weight

```python
def r_value(
        combust_index, wind_speed, psi
):  # wind speed as m/s, psi is angle between wind dir & fire dir,
    # temp in celcius

    temp = 35  #highest temp in texas in july
    humidity = 70  #average texas humidty (most forest fires there). refine later
    w = math.floor(wind_speed / 0.836)**(2 / 3)  #wind level

    kp = math.exp(0.1783 * wind_speed * math.cos(psi))
    r0 = 0.03 * temp + 0.05 * w + 0.01 * (100 - humidity) - 0.3

    r = r0 * kp * combust_index

    return r
```

Figure 3b Code determining the calculation of wind R-value

Wind Velocity (m/s)	Time for fire to reach town (hours)			
	Result 1	Result 2	Result 3	Average (mean)
2.5	482(Appendix Fig 8)	493	479	484.6
5	359	366	362	362.3
10	160(Abstract Fig 9)	158	164	160.6
20	100	101	100	100.3

Table 1 Results for wind speed test (fire starting at Incinerator)

Wind Velocity (m/s)	Time for fire to reach town (hours)			
	Result 1	Result 2	Result 3	Average (mean)
2.5	719(Appendix Fig 8)	729	712	720
5	584	571	586	480.3
10	322(Abstract Fig 9)	319	323	321.3
20	156	155	154	155

Table 2 Results for wind speed test (fire starting at Power Plant)

Location (see figure6)	Time for fire to reach town (hours)			
	Result 1	Result 2	Result 3	Average (mean)
Test 1	202 (Appendix Fig 10)	206	199	202
Test 2	234 hours	238 hours	231 hours	234.3
Test 3	210	208	204	207.3
Test 4	211	212	214	212.3
Test 5	201	200	196	199.3

Table 3 Results for water intervention tests

Wind velocity (cardinal directions, with constant speed of 3.5m/*	Time for fire to reach town (hours)			
	Result 1	Result 2	Result 3	Average (mean)
N	1049(Appendix Fig 11)	1072	1037	1052.6
NE	1177(Appendix Fig 11)	1189	1185	1183.6
NW	825	832	826	827.6
E	1046	1033	1062	1047
W	802	806	804	804
SE	620	624	629	624.3
SW	571	568	572	570.3
S	625	621	614	620

Table 4 Results for wind direction tests

Direction of forest expansion (cardinal directions)	Additional time for fire to reach town compared to before expansion (hours)			
	Result 1	Result 2	Result 3	Average (mean
N	616 (Appendix fig 8)	604	632	617.3
E	557	576	563	565.3
S	603	602	608	604.3
W	612	624	605	613.6

Table 5 Results for doubling forest size

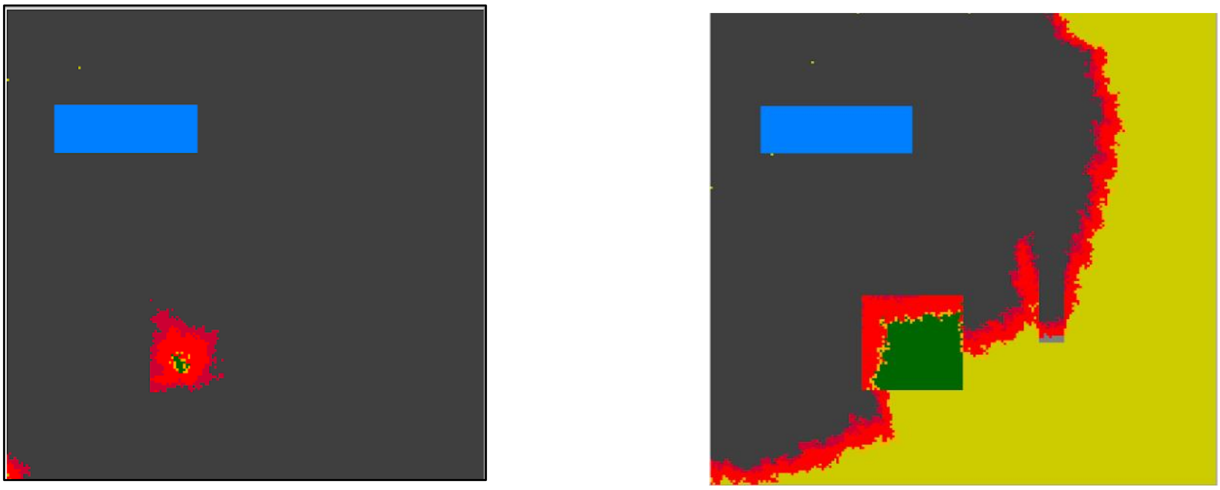

Figure 4 Screen captures depicting the fire spreading from the incinerator (left) and power plant (right) at 5 m/s with a south prevailing wind

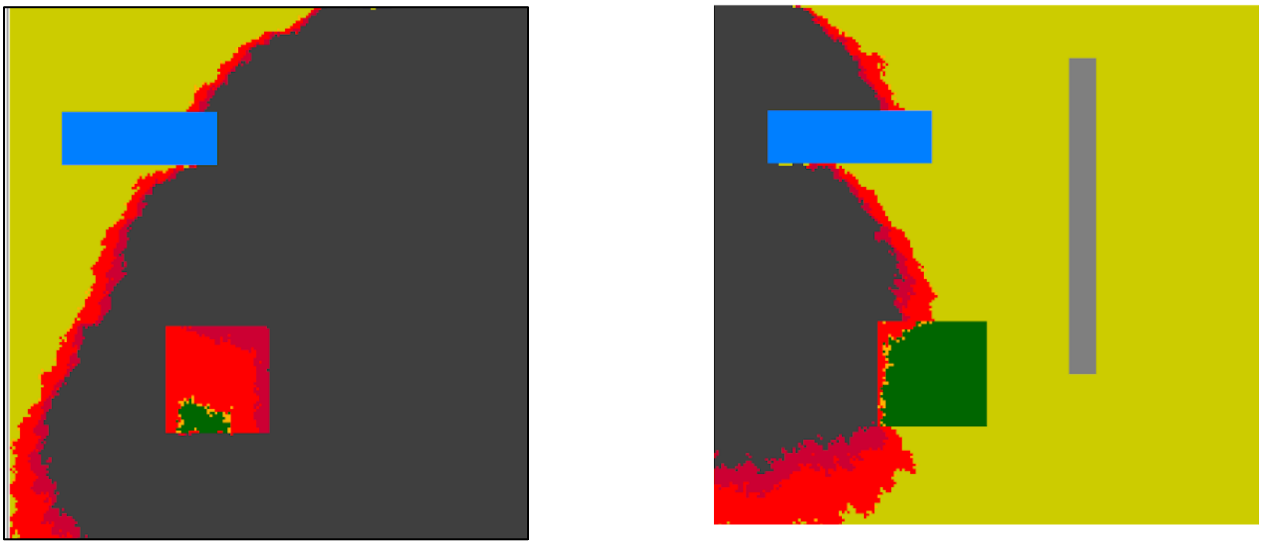

Figure 5 Screen captures depicting the fire spreading from the incinerator (left) and power plant (right) at 10 m/s with a south prevailing wind.

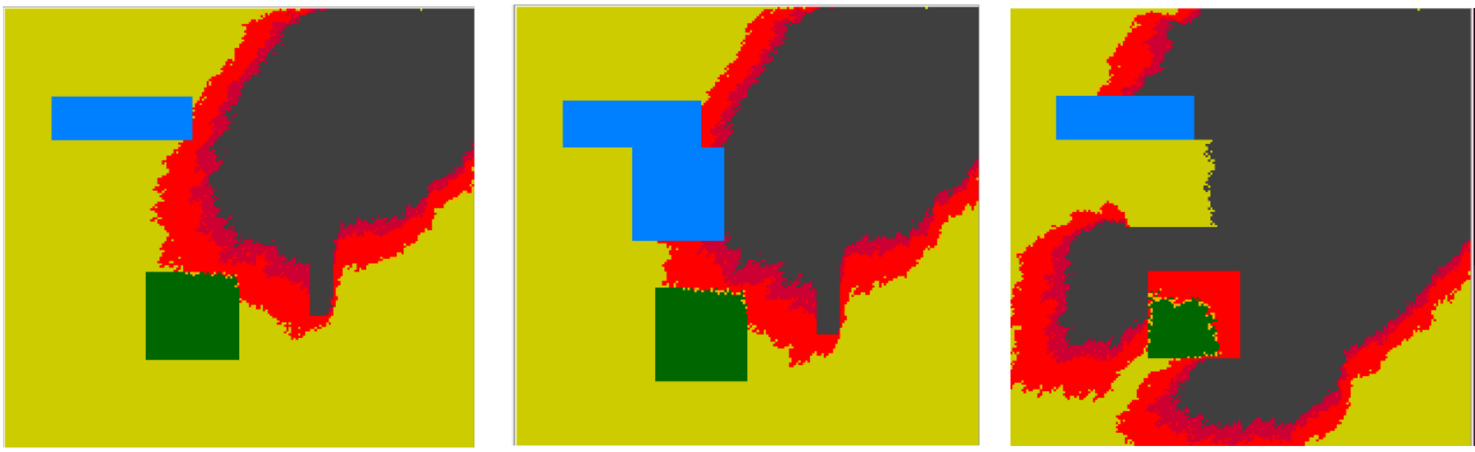

Figure 6 Screen captures representing the fire as it spreads from the incinerator and the simulation of a water drop just south of the lake. Image 3 shows the vegetation becoming flammable again when the water is dried up.

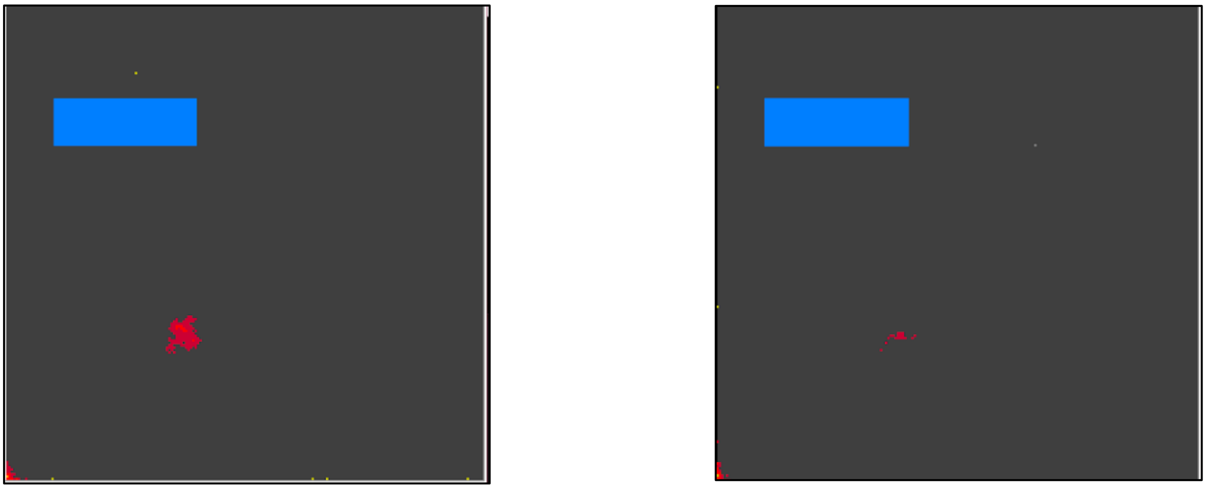

Figure 7 Screen captures representing the fire as it spread from the incinerator with a north wind direction (top left image) and a north east wind direction (right image) with a speed of 3.5 m/s

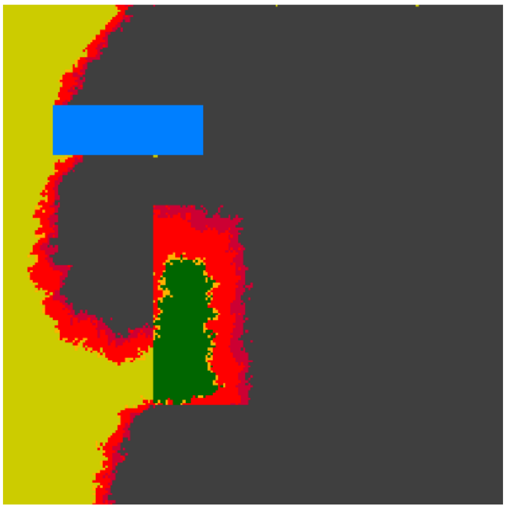

Figure 8 Screen capture depicting the fire as it spread from the incinerator with a south wind direction with the forest expanded to the north.

Bibliography

1. Karafyllidis, I., Thanailakis, T., A model for predicting forest fire spreading using cellular automata, Ecological Modelling, 1997, 99(1), pp. 87-97
2. Xiaoping, R., Hui, S., Yu, X,., Zhang, G., Wu, B., Forest fire spread simulation based on cellular automata, Natural Hazards, 2017, 91(1) pp. 309-319
3. Bodrožic, L., Stipanicev, D., Seric, M., Forest fires spread modelling using cellular automata approach, 2008, pp. 1-10
4. Wang, Z.F, Current forest fire danger rating system, International association for fire safety science symposium, 2011, pp. 121-125
5. Wolfram, Stephen, Random Sequence Generation by Cellular Automata, Advances in Applied Mathematics 7, 1986, pp. 123-169
6. Scott, Joe, Burgan, Robert, Standard Fire Behaviour Fuel Models : A comprehensive set for use with Rothermel's surface fire spread model, 2005, pp. 1-80
7. Verisk Insurance Solutions, 2017, Facts and Statistics: Wildfires, https://www.iii.org/fact-statistic/facts-statistics-wildfires#Top%2010%20Most%20Wildfire%20Prone%20States,%202017
8. Rothermel, A Mathematical Model For Predicting Fire Spread In Wildland Fuels, 1972
9. Rui et al, Forest fire spread simulation algorithm based on cellular automata, 2017, pp. 4