Computational Environmental Science

Modeling a forest fire using Cellular Automata

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Abstract

Forest fires are a prevalent issue in many parts of the world. Because they pose such a problem in certain regions, being able to precisely simulate their behaviour is crucial for the effective application of preventive measures and risk minimisation strategies. One such way of simulating forest fires makes use of Cellular Automata (CA).

The primary objective of this project is to provide the town officials of a certain town with a precise and realistic simulation of potential forest fires that could arise in the proximity of the town as well as preventive measures that would decrease the negative impact of such fires.

This model uses modified transition rules to account for terrain types, wind conditions and burning neighbours. The model was able to successfully identify the most threatening prevailing winds and the best locations to deploy possible mitigation measures with the purpose of delaying the fire from reaching the town. The results of the model are fairly similar to other academic sources whose experiments were conducted using real historical data and yielded an accuracy of up to 82% when predicting burnt areas.

1. Introduction

Forest fires are increasing in numbers continually, having a significant effect on both the ecosystem and the economy [1]. The environmental consequences include the reduction of annual precipitation and overall humidity of the plants resulting in a lower flash-point for the vegetation. Erosion of the soil speeds up after a forest fire due to destroyed vegetation, causing the upper fertile soil layer to disappear. Huge quantities of carbon dioxide are released, accelerating global warming. Finally ash, scale and small plant pieces can cause direct surface pollution in bodies of water. The economic consequences include damage to properties and infrastructures [2].

Cellular automata (CA) have been employed to model fire spread because of their grid-based nature, which allows them to reference digital data collected from geographical information systems. Individual cells can also be used to represent different types of terrain. This allows them to easily recreate real scenarios with the data, thus enabling realistic simulations/recreations of fire propagation to take place [3]. A CA simulation modelled after the island Brač has been noted to produce a fire front similar to historical forest fires. [4]

In J. L. Coen, W. Schroeder, S.Conway, and L.Tarnay's paper [5], it was mentioned that newer models used 3D computational fluid dynamics (CFD) coupled with a combustion physics module to simulate wildfires. These models can parameterise fires in detail by accounting for phase changes, large-scale weather patterns and representing details of various wildland fuels combusting. The model also uses the fundamental laws of physics of fluids, such as the 2nd law of thermodynamics and the ideal gas law. This enables fires to dynamically interact with fluid mediums, enabling it to create firenadoes and simulating the growth of fire plumes into massive pyrocumulonimbus storms, and other kinds of dynamic environmental feedback.

In "Forest fire spread simulating model using cellular automaton with extreme learning machine" [6], a CA based model can simulate wildfires with adjustable wind speed and direction, as well as cell igniting probabilities. Wind direction is accounted for in the four cardinal and intercardinal directions, and a matrix controls the probability weights of a cell igniting in neighbouring cells.

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The primary purpose of this project is to study the spread of a forest fire near the specified town under different circumstances such as the wind direction, and suggest short and long term interventions . Following the Introduction, the materials and methods used to create the model will be specified. The Results part of the report will go over the findings of the project while the Discussion section will summarise the results and compare them with other, existing models. Finally, all sources used in this report will be written down in the References section, and any other relevant information will be featured in the Appendices at the end of the report.

2. Materials and Methods

A CA based model has been used to simulate a forest fire by representing various terrain using different cells, each one having unique rules controlling its behaviour. The area around the town is represented as a 100x100 cell grid. Conway's "Game of life" [7] was used as a basis for the model. The model has been extended to accept more states compared to the original and, because of this, all the cell states required by the model for correct functioning can be represented. The transition function of the cells has also been altered to accept more parameters apart from the status of the neighbouring cells such as wind speed, direction and vegetation when considering whether to change the state of the current cell.

2.1. Algorithm overview

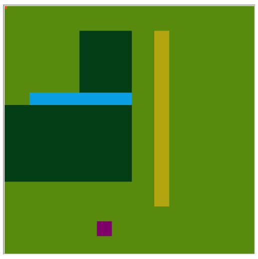

Figure 1. t = 0 configuration

The model is based on probabilistic transitions between generations to simulate the non-deterministic behaviour that natural forest fires exhibit. The three states that can catch on fire are *Scrubland* (**S**), *Chaparral* (**C**) and *Forest* (**F**). Each one varies in how easily it catches fire and how long it can burn for. Once a cell with a burning state has burned for a sufficiently long period of time, it burns out after which it cannot catch fire again.

The three main factors that combined together determine the probability of a flammable state cell igniting are the individual ignition probabilities of **S**, **C,** or **F** states, the number of burning neighbours according to the Moore neighbourhood as well as the wind direction and intensity. The ignition probability is evaluated once during each generation.

One of the fundamental requirements of the model is to output the relative time that it takes for the fire to reach the town. The model successfully monitors the generations elapsed since the start of its run time and outputs the time in days that it takes for the burning state to reach the town.
The model supports adding potential fire breaks and water drops during a specific generation. The cells with these states are assumed to be resistant to ignition.

2.2. Model assumptions and parameterization

The eight possible wind directions encoded into the model are equal to the eight principal wind directions. It is possible to vary the wind vector's magnitude or remove the wind effect entirely. The model can have its temporal resolution modified, i.e. the number of generations in time, and multiple generations can happen per day. The more generations per day the more accurate the approximation of reality (note: if the generations per day are increased, the ignition probabilities of the model have to be decreased accordingly, since they are evaluated more often).

Both the power plant and proposed ignition source ignition locations have been encoded into the model. Their locations have been exposed as parameters and can therefore be changed or disabled entirely.

The *Scrubland*, *Chaparral* and *Forest* states in the model have specific ignition probabilities and can also burn for different numbers of generations after which they burn out and cannot ignite again. The default ignition probabilities of *Scrubland*, *Chaparral* and *Forest* states are in decreasing order and the default burn durations in increasing order, meaning that the *Scrubland* state catches fire the easiest and burns for the least amount of time while the *Forest* state catches fire the hardest and burns for the most amount of time. All of these probabilities as well as the burning durations can be set to custom values in the model.

2.2.1. Transition rules

The transition rules between cells have been set to accommodate for various variables such as wind direction, wind magnitude, neighbours of cells currently burning and the terrain types of individual cells. The probability of a cell catching fire is determined by the following equation:

$$p_{i,j} = a_{i,j} * \sqrt[Z]{\frac{\sum_{x\in\{0,1,2\},y\in\{0,1,2\}}(burning\_neighbours_{i,j} \odot Wind\_Direction_{W,D,E})_{x,y}}{\sum_{x\in\{0,1,2\},y\in\{0,1,2\}} Wind\_Direction_{W,D,E,x,y}}}$$

Where i, j are the coordinates of the cell, $a_{i,j}$ is a state-specific ignition probability for the cell, $burning\_neighbours_{i,j}$ is a 3x3 boolean matrix of the surrounding burning neighbours (with 1 meaning that a cell is burning and 0 meaning is is not) and $Wind\_Direction_{W,D,E}$ is a 3x3 matrix with the wind direction and wind speed dependent cell-specific coefficients. W represents the wind direction, E is the base used in the exponential wind scaling and D is the exponent. The D exponent value is multiplied by $sin(\pi/4)$ for the upwind corner values to better simulate the effects of wind. The $burning\_neighbours_{i,j}$ and $Wind\_Direction_{W,D,E}$ 3x3 matrices are multiplied element-wise after which the resulting 3x3 matrix is summed up. Then, it is normalised to a range between 0 and 1 by dividing the result by the maximum possible value the element-wise multiplication could ever reach in order to obtain a probability value. Because this value tends to overpower the state-specific ignition probability component of the equation ($a_{i,j}$) and has a higher than optimal effect on the final ignition probability ($p_{i,j}$), it is reduced by applying a Z-th root. Because the value before the root application is between 0 and 1, the root reduces the normalised wind and burning neighbour component towards 0.

The $Wind\_Direction_{W,D,E}$ 3x3 matrix is defined for wind direction values W in the following way:

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} E^{D\sin(\pi/4)} & E^D & E^{D\sin(\pi/4)} \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$
W = North wind (N)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} 1 & E^{D\sin(\pi/4)} & E^D \\ 1 & 0 & E^{D\sin(\pi/4)} \\ 1 & 1 & 1 \end{bmatrix}$$
W = North-East wind (NE)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} 1 & 1 & E^{D\sin(\pi/4)} \\ 1 & 0 & E^D \\ 1 & 1 & E^{D\sin(\pi/4)} \end{bmatrix}$$
W = East wind (E)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & E^{D\sin(\pi/4)} \\ 1 & E^{D\sin(\pi/4)} & E^D \end{bmatrix}$$
W = South-East wind (SE)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ E^{D\sin(\pi/4)} & E^D & E^{D\sin(\pi/4)} \end{bmatrix}$$
W = South wind (S)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} 1 & 1 & 1 \\ E^{D\sin(\pi/4)} & 0 & 1 \\ E^D & E^{D\sin(\pi/4)} & 1 \end{bmatrix}$$
W = South-West wind (SW)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} E^{D\sin(\pi/4)} & 1 & 1 \\ E^D & 0 & 1 \\ E^{D\sin(\pi/4)} & 1 & 1 \end{bmatrix}$$
W = West wind (W)

$$Wind\_Direction_{W,D,E} = \begin{bmatrix} E^D & E^{D\sin(\pi/4)} & 1 \\ E^{D\sin(\pi/4)} & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$
W = North-West wind (NW)

The parameter values can be changed, however the default ones used for the model are as follows: D = 2, E = 5, Z = 2.

The following are examples of the $burning\_neighbours_{i,j}$ 3x3 matrix:

$$burning\_neighbours_{i,j} = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Neighbours burning to the north, north-east and south.

$$burning\_neighbours_{i,j} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

Neighbours burning to the north-west, east and west.

Each iteration of the simulation represents a quarter of a day. Since different varieties of vegetation burn for different amounts of time, the time required for a cell to be completely burnt out is based on the type of vegetation it represents.

2.2.2. Terrain

The state-specific ignition probabilities ($a_{i,j}$) have been calculated based on research papers done on the average headfire spread on different vegetation types. The parameters were tweaked until the model yielded results which were similar to that of the sourced literature:

Terrain type	Average headfire spread (CA)	Average headfire spread (real)	Wind (CA)	Wind (real)	Ignition probability $a_{i,j}$ (%)	Time required to burn out
Forest [8]	20.83 m/hr	18 m/hr	2, north	4 km/hr	0.4	720 hrs
Chaparral [9]	41.6 m/hr	42 m/hr	4, north	7.5 km/hr	0.8	240 hrs
Scrubland [10]	83.3 m/hr	80.4671 m/hr	2, north	3.2 km/hr	0.1	18 hrs

Table 1. Comparison of Team 13's model vs historical fire spread models

The average headfire spread of the cellular automata model was calculated by taking the "length" of the fire on the y-axis averaged over 20 iterations. These tests were done with a northern wind. Based on the findings of the simulations, one unit of wind in the model roughly corresponds to a real wind of 2 km/hr. It is assumed that the vegetation types have equal density, fuel, and moisture levels across all their cells. This is implicitly represented in the ignition probability, as the parameters were tweaked empirically so that the headfire spread in the model matched closely with the headfire spread seen in the literature.

2.2.3 Wind

The literature has proposed a number of empirical connections to model the impact of wind on the rate of fire spread [11-13]. We calculate the wind coefficient based on the direction and magnitude of the wind,with regards to the status of the neighbours of a cell. Based on the wind conditions, a cell can have a varying impact on its neighbours. This is illustrated by the $Wind\_Direction_{W,D,E}$ 3x3 matrix in the above section.

2.3. Numerical Investigations

Simulations were carried out to predict the time needed for the fire to reach the town, with altering starting fires from the incinerator and power plant under winds of different magnitude and direction. Various short and long term intervention measures such as fire breaks, increased dense forest area, and aerial water drops were added to the model. The tests were carried out with the added intervention measures to measure which were the most effective in delaying the spread of the fire.

3. Results

3.1. Spatial-temporial evolution of the fire

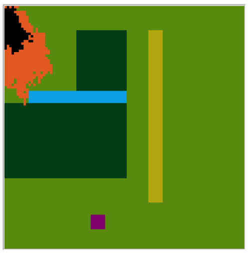

Figure 2. t = 82

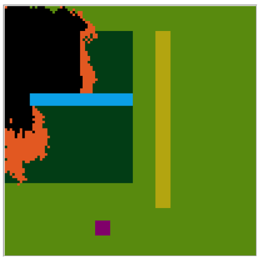

Figure 3. t = 295

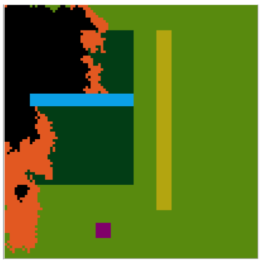

Figure 4. t = 333

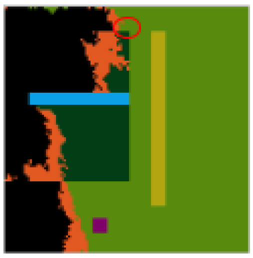

Figure 5. t = 442

Fig. 2 - Fig. 5 were configured with a northerly wind and a fire starting from the power plant. In Fig. 2, the fire spreads to the forest, and goes through the forest in Fig. 3. Chaparral takes 82 generations to burn through vs the forest's 213. In Fig. 5, the fire breaks out from the forest and spreads westwards towards the town. The red circle on coordinate (10, 51) is also a common point where the fire would break out from the forest and spread to the town by spreading down the chaparral and scrubland. In Fig.4, the fire head of the eastbound fire is closer to the source than that of the southbound fire, even though the eastbound fire has to go through more forest cells. This was because the northern wind matrix assigns the highest weight to northern neighbours, so that they are more probable to ignite.

3.2. Varying wind direction with times

Testing different wind directions is important as it reveals which wind direction propagates the fire towards the town fastest. Studying the spread of fire with a "dangerous" wind direction will give a better idea of how to direct the forest extension project and where to place fire-breaks. From the observations noted on **Table 2**, the wind direction with the least time taken for a power plant fire to reach the town is as follows: N, NW, W, NE, and SW, while S and SE extinguished naturally. Eastern and southern winds are less destructive as they are more likely to spread off-screen. Northern winds are the most dangerous because the fire can take a more direct path towards the town.

From **Table 3**, which is the same experiment but with the fire starting at the incinerator, the rankings are as follows: NE, N, E, W, NW, SE, S, SW. These are also expected values, with W and E being inverted due to them being placed at the opposite top corners.

3.3 Short term interventions

3.3.1 Aerial water drop

A limited quantity of water is available to be dropped aerially to help suppress forest fires. According to the Wildfire Operational Guidance document [17], it is paramount that the water is dropped during the early stages of the fire to prevent it from reaching its full potential. The water must be dropped close to the ignition points at the early stages of the fire for maximum effect. The guidance document also mentions that aerial drops have little effect when dropped on areas with large vegetation, such as the dense forest, so the best option is for the water to be dropped close to the incinerator. It is rare for a water drop to be able to completely extinguish a forest fire. Instead, it is best used to prevent the fire from spreading in a certain direction.

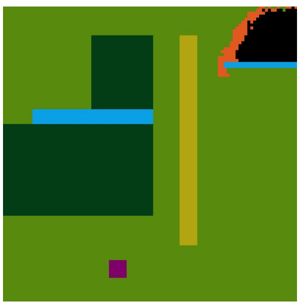

Figure 6. The water drop location yielding the best results (76, 20) - (100, 21)

From the results in **Table 4** found in **Appendix A**, it is clear that fire suppression using water drops is an effective way of slowing down the spread of fire especially if the fire is ignited from the incinerator. The difference is largely based on the wind direction but aerial water drops are extremely versatile in their placement.

3.4. Long term interventions

3.4.1 Expand dense forest area

One of the long term interventions implemented in the model was the expansion of the dense forest area, north of the town. Due to the low probability of catching fire, dense forest effectively slows down the spread of the fire by an incredible amount.

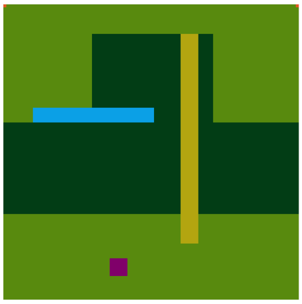

Figure 7. Expanded dense forest to the East

From the tests conducted in the above sections, it is obvious that the fire reaches the town the fastest when the wind originates from the north. The existing forest is able to slow down the fire originating from the power plant, but that is not the case if it originates from the incinerator. After experimenting with different locations, Figure 7 shows the new layout of the area, after the dense forest has been mirrored on the y-axis. After the extension of the forest, experiments showed that, although the general behaviour of the fire had not changed, the time needed for the fire to reach the town during prevailing winds had nearly doubled. The exact values can be found in **Appendix A**.

3.4.2 Implement fire breaks

Another long term intervention implemented in the model is the creation of fire breaks at specific locations near the town. Fire breaks are able to slow down or completely stop the fire from progressing past certain points. Having identified the incinerator as the most dangerous fire source, the ideal scenario is for the fire breaks to be located to the East of the town, where the fire isn't slowed down by the dense forest. The below figures show the best positions for a fire break to be created.

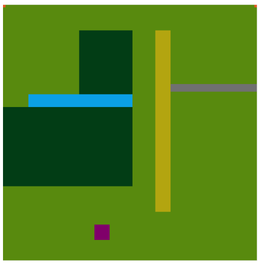

Figure 8. Fire break east of the canyon (66, 35) - (100, 36)

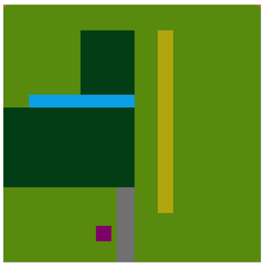

Figure 9. Fire break east of the town (47, 71) - (50, 100)

When the fire break is closer to the town, the rate at which the fire spreads is slower than if it is near the canyon because the only way for the fire to reach the town is through the forest. The exact values can be found in **Appendix A**.

4. Discussion

A fire under a northern wind spreads to the town the fastest, while a southern wind takes significantly more time. For an incinerator fire, an eastern wind spreads fire to the town somewhat fast, and western winds spread fire to the town faster than southern winds, albeit also slowly. **Table 3** shows that the wind directions in terms of time taken by the fire to reach the town is as follows: NE, N, E, W, NW, SE, S, SW. **Figures 6-9** display the most effective way to implement the proposed intervention methods, with **Tables 4-10** hosting the exact values gathered. As expected, the long-term interventions are more effective in slowing down the spread of the fire when compared to the short-term intervention methods, but are significantly harder and more time consuming to implement.

While the model does seem to represent fires in conditions where there is little to no wind fairly well, it cannot accurately represent forest fires with high winds, as the modelled fire spreads way too slowly in those conditions. This is because the model can only make a cell combust when there is a fire among its immediate neighbours, meaning that the top speed for the fire spread is limited to $500m^2$ per 6 hours in the current parameter configuration.

In real life, high winds can amplify the spread of fire tremendously. High winds can pick up embers and scatter them miles away, causing "ember showers" that create multiple firefronts. [14] In the 2009 Black Saturday bushfires, embers were able to travel up to 20-40 km away from their sources and start spot fires. [15] Not being able to model wind carrying ember makes the model very inaccurate at simulating fires in high winds. As such, the short term interventions and the long term plans for fire prevention suggested in this report should not be considered if the town is located in a windy area.

The model assumes that the density/fuel count and the moisture level are constant across the cells of the same type. These attributes would vary a lot realistically (e.g. a herd of goats live near the western border of the map, and grazes the chaparral there, resulting in less fuel). Not accounting for these values probably made the fire spread more uniform than it should be.

The model also assumes that the terrain is of equal elevation. Fires spreading upwards tend to travel faster. When the heat from the fire rises upwards, it "preheats" the vegetation uphill, drying them up and thus more susceptible to ignition, and the opposite is true as well. [16] This means that the scrubland in the canyon would be much harder to ignite if the canyon was steep enough. The last significant simplification is the lack of dynamic winds, although it wouldn't be too important for meeting the client's requirements as prevailing winds are only considered.

As the wind calculations were inspired by the model by Zheng et al. [6], it is fitting that this model would be compared to theirs. The biggest difference is that their cell ignition probability was derived from training an extreme learning machine on real historical data from the areas that they were running simulations on. This historical data includes moisture levels of fuel, wind speed and direction, slope of terrain, humidity, and so on. The fire spreading pattern seems to correspond to Zheng et al.'s **Figure 5** fire spread pattern. It was also stated by the authors that "higher wind velocity leads to the smaller spreading angle in the windward direction," which is also true for this model. Zheng et al.'s model was able to predict 58.45% to 82% of burnt areas when matched against historical data it was trained on, so these figures would be an upper bound to the accuracy of this model.

To make the model more realistic, it is imperative that detailed data about the town's surroundings are collected to tune the parameters against. It would also be nice to add all of the features stated in the critiques section, although it might be hard to implement ember showers due to the nature of CAPyLE only supporting < 9 cell neighbourhoods.

5. Conclusions

When compared with literature, the model seems to be able to produce a relatively similar fire spread pattern, which has been noted to be quite accurate to historical data. It is also able to simulate fires well in no to low wind situations. The model is also quite accurate in modelling the spread of fires after an intervention measure is introduced and can be used to decide which one is the most effective when it comes to hindering the progress of the fire, and where it should be placed for the best results.

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Appendix A

Wind direction	Mean number of days to reach town	General observations
N	108	Headfire travelling upwind reaches town first, burning through forest. Flank fires took significantly longer to reach town.
E	458	Forest significantly delays initial south flank fire from the power plant. Fire travelling downwind burns through the chaparral slowly until (10,51) where the forest ends. A flank fire broke out and headed south, and burned through chaparral relatively quickly. Both southern flank fires reached the town around the same time.
S	N/A	Fire spreads from the power plant in a radius of approximately $1km^2$, then completely stops propagating. Fire completely dies down in 45 days.
W	236	Fire spreads the same way as an eastern wind initially, but burns slower. When the eastern fire travels until (10,51), the fire travels down the scrubland the fastest. At the southern end of the canyon, the fire spreads to the west and hits the town.
NE	300	Fire spreads north of the forest first. Flank fire spreads slowly to the east, as it seems to propagate towards the river. When the fire breaks out from north of the forest, it spreads east towards the town. Flank fire from (10,51) was still spreading when the other fire front hit the town.
NW	112	The fire propagates in an extremely diagonal way. Due to this pattern, the fire that propagates from the lower half of the forest hits the town first before the flank fires from the upper half diagonal fire (the fires are separated by the river).
SE	N/A	Similar to southern wind. Completely dies off at generation 307.
SW	462	Northern forest fire stopped after somewhat burning through the upper half of the forest. Fire burns slowly through the east before reaching (10,51), then slowly burns towards the south by following the chaparral, and spreads to the town eventually.

Table 2. Comparison of varying wind directions vs fire from power plant reaching town

Wind direction	Mean number of days to reach town	General observations
N	68	Fire head spreads to the south, while flank fires spread to the west slower. Predominantly burns through chaparral and scrubland.
E	121	Headfire reaches eastern border on the 200th generation. Flankfires going towards the south-east were somewhat impeded by the forest.
S	591	Spreads instead of stagnating in an area around the source. Spreads to the west significantly faster than to the north.
W	236	The fire travels to the southern border relatively fast. Fire spread uniformly when travelling westwards, though slowly.
NE	53	Like a northern wind, but the spread was more diagonal.

NW	244	No significant difference from a western wind.
SE	346	Headfires spread to the west, while the flankfires snake down the south slowly. As that happens, the flankfires are also spreading into the forest due to the eastern wind, which impedes the fire's spread significantly.
SW	597	Fire spreads southwards on the patch of chaparral to the right of the canyon. When the fire spreads to the southern end of the canyon, it spreads to the west towards the town.

Table 3. Comparison of varying wind directions vs fire from incinerator reaching town

Wind direction	Mean number of days to reach town
N	77
NW	287
NE	56

Table 4. Results obtained after aerial water drops are used to suppress the fire ignited from the incinerator, as seen in **Figure 6**

Coordinates used for testing : (76, 20) - (100, 21)

Wind direction	Mean number of days to reach town
N	108
NW	114
NE	302

Table 5. Results obtained after the dense forest has been expanded, as seen in **Figure 7,** during prevailing winds if the fire originates from the power plant

Coordinates used for testing : [10:41, 50:71] and [40:71, 51:101]

Wind direction	Mean number of days to reach town
N	90
NW	347
NE	74

Table 6. Results obtained after the dense forest has been expanded, as seen in **Figure 7,** during prevailing winds if the fire originates from the incinerator

Coordinates used for testing : [10:41, 50:71] and [40:71, 51:101]

Wind direction	Mean number of days to reach town
N	106
NW	108
NE	287

Table 7. Results obtained after a fire break is created east of the canyon, as seen in **Figure 8,** during prevailing winds if the fire originates from the power plant

Coordinates used for testing : (66, 35) - (100, 36)

Wind direction	Mean number of days to reach town
N	75
NW	303
NE	57

Table 8. Results obtained after a fire break is created east of the canyon, as seen in **Figure 8,** during prevailing winds if the fire originates from the incinerator

Coordinates used for testing : (66, 35) - (100, 36)

Wind direction	Mean number of days to reach town
N	102
NW	107
NE	302

Table 9. Results obtained after a fire break is created east of the town, as seen in **Figure 9,** during prevailing winds if the fire originates from the power plant

Coordinates used for testing : (47, 71) - (50, 100)

Wind direction	Mean number of days to reach town
N	90

NW	370
NE	56

Table 10. Results obtained after a fire break is created east of the town, as seen in **Figure 9,** during prevailing winds if the fire originates from the incinerator

Coordinates used for testing : (47, 71) - (50, 100)