Network Science - Project 2
Group 36

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1. INTRODUCTION

In Portugal, forest wildfires are a recurrent theme every year during its driest seasons [1]. Large masses of forest get destroyed as a result of these fires and it is a real problem for the environment and the local habitat, affecting the species populations and distribution as well as destroying homes, buildings, animal and human lives.

Forest planning and preventive measures should be taken to minimize the damages made to the forest. Reducing the flammable materials around populated areas and inside forests themselves is a common approach to decrease the destruction made by fire to local structures [2, 3]. Another approach used is controlled burns made to the forest [4]. As an example, in 2013, during a massive wildfire in California (USA), firefighters limited the spread of the fire by burning some areas in a controlled fashion [5]. This approach suggests that the density and connectivity of the forest have some influence on the spread of the fire front.

In this project, we try to understand the impact of clustering in forest fires. To this end, we built a model of fire propagation based on cellular automata that takes into account wind and height, as well as a simulator that can run this model.

2. MODEL

The world is a complex and chaotic system. Modeling it can be quite a challenge and modeling wildfires is no different. The sheer amount of variables that come at play make it virtually impossible to reason about a possible model and to analyze its results. Simplifying is the answer to tackle this complexity and that's what is at the core of our model.

A considerable amount of wildfire models have been proposed. E. Pastor, et al [6] lists all the fire models from 1940 till 2003. In this article, the authors distinguish fire models according to 3 features: The nature of the equations, the variables studied, and the physical system modeled. Following these characteristics, we can classify our model as being theoretical, focused on the spread of the fire and the physical model is based on rules that state the propagation of the fire.

2.1 Model description

Our model can be seen as an adaptation of two previously proposed models [8, 9]. Both models and ours are based on cellular automata. We consider an NxM grid composed of cells that represent the forest. Each cell can be either a tree or an empty cell. The tree in the cell at row i and column j will be referenced as $tree_{ij}$. A tree is placed in a cell with probability $PGrowth$. Trees can have 3 discrete states: Normal, burning and dead. Albeit only having this limited amount of states, we also consider a more continuous state representation that describe how burned a tree is. The mapping from continuous states to discrete states can be seen in figure 1.

$$state_{discrete} = \begin{cases} Normal, & state_{continuous} = 0 \\ Burning, & 0 < state_{continuous} < 1 \\ Dead, & state_{continuous} = 1 \end{cases}$$

Figure 1: Mapping of a tree's continuous state to its discrete state

In our model, any number of fires may originate at a given time and can start randomly at any place around the grid. Trees have a tolerance threshold to the fire and may only start burning if any of its neighbor cells (the 8 cells around the tree) are also burning. We call this threshold ρ_{ij}. A tree's neighborhood has an influence of δ_{ij}. How δ_{ij} is computed will be discussed in 2.2. If at least one neighbor tree is burning, the chance that $tree_{ij}$ also starts burning is given by: $P_{ij}^{ignites} = max(\alpha - \delta_{ij} + \rho_{ij}, 0)$, where α is the system's general resilience coefficient. α can be seen as the humidity present in the forest that makes it more difficult or easier for a tree to ignite. Furthermore, for $tree_{ij}$, its state $state_{ij}$ at time step t evolves according to the following equation: $state_{ij}^{(t+1)} = state_{ij}^{(t)} + \delta_{ij}^{(t)} + tree_{ij}^{burn\_rate}$.

2.2 Wind and height model

Thus far, our model displays some similar characteristics to the Drossel-Schwabl fire model [9]. However, this model doesn't take into account the influence of wind and topology in the propagation of the fire. To mitigate this issue, we introduce the notion of wind and height into our model based on some of the ideas proposed by Hernandez Encinas et al [8].

To encode wind and height's influence we use what we named the "neighbors influence" to a tree. As aforementioned, we represent it with the letter δ and it is given by a combination of the continuous states of the neighbors of

$tree_{ij}$ with the current value of wind and height around said tree.

2.2.1 Wind

The wind is modeled using two variables, namely the wind intensity and its direction. The wind direction at cell ij is given by a 3x3 matrix called the wind matrix:

$$W_{ij} = \begin{bmatrix} w_{i-1,j-1} & w_{i-1,j} & w_{i-1,j+1} \\ w_{i,j-1} & 1 & w_{i,j+1} \\ w_{i+1,j-1} & w_{i+1,j} & w_{i+1,j+1} \end{bmatrix}$$

Figure 2: The wind model for the neighborhood of $tree_{ij}$

Each entry of this matrix represents the wind intensity around the cell. As an example, lets suppose the wind was blowing from North to South. In this case, the entries in the first row should be bigger than every other entry in the matrix. The weights for matrix W_{ij} can be obtain by using a physical model such as the one described in [10]. In our adaptation, we assumed the wind to be constant throughout the entire grid, i.e, the W_{ij} matrix is the same for every cell and each weight is given by a linear function that takes in the current wind intensity and direction and outputs the corresponding wind model $W = WindModelGenerator(WindDirection, WindIntensity)$.

2.2.2 Height

In our model, we also take into account the height difference between different points in the grid. The fire-front is known to display a higher rate of spread when it is going up a hill compared when it's descending. The height influence for a given cell is obtained through a linear function that receives the height difference between two cells and outputs a value between 0 and 1. The value comes closer to 1 if the fire is going upwards in a slope. The possible values that this function outputs for a given tree can be encoded in a similar matrix to the one used in the wind model, named M_{ij}.

2.2.3 Putting it all together

We now have all the necessary information to define the neighborhood influence of a $tree_{ij}$. More specifically:
$\delta_{ij} = \sum_{(\alpha,\beta)\in V_m} [W_{i+\alpha,j+\beta} * M_{i+\alpha,j+\beta} * state_{i+\alpha,j+\beta}]$
where $Vm = \{(-1,-1),(-1,0),(-1,1),(0,-1),(0,0),(0,1),(1,-1),(1,0),(1,1)\}$, that specifies how to obtain the surrounding cells of a given tree.

3. SIMULATOR

The simulator was developed in Javascript, a language well-known to facilitate user interaction.

The simulator itself is a grid of ROW x COLUMNS cells which can be either empty or occupied by a tree. A tree has one of the states mentioned in section 2.1. Each state is represented by a color: starting from a shade of green (depending on the type of tree or, in particular, its fire threshold) it will turn red when it catches on fire and eventually turn black when it is dead. If the cell is empty it will show the terrain underneath. As previously mention, the terrain

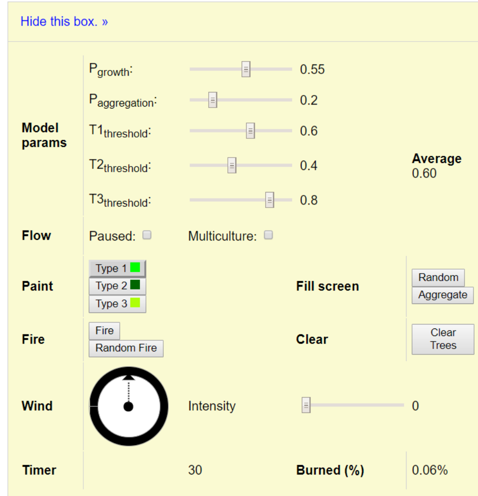

Figure 3: User Interface of ths simulator

can vary in height, which is also represented with different colors. The heights were generated using Perlin noise [7]. Figure 4 shows the simulator with no trees, displaying only the terrain, where the higher the ground, the lighter the color. Figure 5 shows a simulation running. In green, the trees that still haven't burnt, where we can also faintly see the terrain below. In black, the trees that are already dead, and at the border between the two, some red cells indicating a burning tree.

A simple user interface was developed, so as to make interaction possible. It's possible to change the fire threshold of all three types of trees, together with the $PGrowth$ parameter. For forest-aggregation distribution (explained in section 4.4.1), the $PAggreg$ parameter can be changed as well. It's also possible to light a specific cell on fire, or set fire to a random cell. The simulation can be paused at any moment in time. The user can fill the screen with any of the three types of trees available, according to $PGrowth$ or $PAggreg$, depending on the chosen distribution. If the user wants to study multiculture, this is made available by a simple check box. Ticking it will make the simulator take into account all of the tree types and their respective fire thresholds when filling the screen. In multiculture, the distribution of each type of trees is done considering the average of all the fire thresholds. This is useful when trying to compare multiculture with monoculture, as will be studied in the following sections. If we want to take into account the effect of the wind, we can control it's intensity and direction. We can also control how many timesteps have occurred and the percentage of the trees that have already burned in that time. Finally, it is also possible for the user to draw with a brush where he wants the trees to be located in the canvas, thus allowing for better interactivity. Of course, this tool serves more as a fun way to explore the simulations, rather than an object of study. Overall, a wide arrange of variables can be controlled in order to provide many different environments and situations.

4. ANALYSIS

In this section, we present an analysis of the model previously described in 2 with the help of our custom-built sim-

Figure 4: Terrain

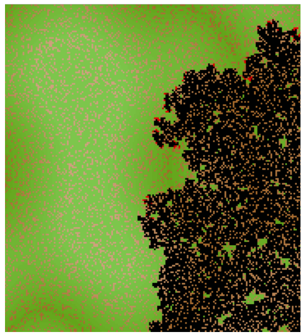

Figure 5: Simulation

ulator. With this study, we try to answer some questions related to the impact of forest density in the propagation of fire. Particularly, we focus on answering the following research questions (RQ):

RQ1 Does the fire spread at the same rate in a forest composed of a single tree type [1] opposed to a forest composed of multiple tree types?

RQ2 Does a denser forest have a higher probability of being more damaged in the presence of a fire?

RQ3 Do wind and height increase the rate and spread of the fire?

To evaluate these questions we considered multiple different environments and examined the results. The considered scenarios were the following:

- **Scenario 1**: Monoculture vs Multiculture in a dense forest with no influence of the wind and height.
- **Scenario 2**: Monoculture vs Multiculture in a randomly distributed forest with no influence of the wind and height.
- **Scenario 3**: Monoculture vs Multiculture in a more realistic distributed forest with no influence of the wind and height.
- **Scenario 4**: Monoculture with the influence of wind and height

4.1 Setup

To obtain the values necessary for our analysis we ran the simulation numerous times for each one of the environments contemplating different analysis points.

In terms of the simulator settings used during our testing sessions, we fixed the grid size to 200x200, meaning that our forest was at most composed of 40000 trees. In the case of scenarios 1, 2 and 3, we set the wind intensity to 0 and considered the height to be constant around the entire grid. Regarding environment 4, we fixed the direction of the wind to always point from south to north. Overall, we ran our tests with α set to a value of 0.8.

4.2 Scenario 1

4.2.1 *Rate of fire spread*

In this scenario, the rate of fire was tested in a fully dense forest, or $PGrowth = 1$. After several runs, the overall results were intuitive. As shown on Figure 6, monocultures tend to burnout faster depending on how low the fire threshold (ρ) is. Forests with higher thresholds took longer to achieve the same burnt percentage as the ones with a lower value. If the threshold is too high, the forest may not even significantly burn, as is the case of $\rho = 0.8$.

Another interesting fact is that forests tend to burnout exponentially faster with lesser values of ρ while a greater value will guarantee a more slow paced and linear burn rate.

For every tested threshold, once the forest is on fire, the burn rate is really fast, only slowing down towards the end where less trees are available to burn. This behaviour tends to show up earlier on a forest that has a lower value of ρ when compared to other, thus, forests with lesser values of ρ will burnout faster and their burn rate will decrease earlier.

A scenario where a forest is composed of more than one tree type is more realistic so the experience was repeated but, this time, with multiple types of trees, also randomly distributed. However, the average of their fire thresholds was taken into account, in order to compare them with monocultural environments.

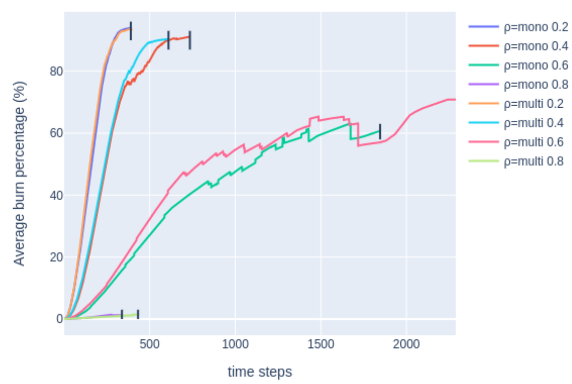

Figure 6: Burned percentage of the forest as a function of time steps

The results are also depicted in figure 6 and they show that having different types of trees in a forest with a certain fire threshold average will produce similar results to having a monocultured forest that is composed of trees with that specific fire threshold. For example, a monocultured forest with $\rho = 0.2$ will burn out as fast as a forest composed of half trees with $\rho = 0.1$ and half with $\rho = 0.3$ on any distribution.

Even though the burning rate was similar between the two cases, multicultured forest tend to take more time to stop burning, which could be explained by the diversity of types of trees.

4.3 Scenario 2

In this scenario, we start with a forest that is composed by only one type of tree at a given time and the wind and height have no influence on the behaviour of the system. After gathering relevant information about a monoculture forest,

[1] The type of a tree is based on its threshold of resistance to fire that corresponds to the parameter ρ in the theoretical model

we move on to a more diverse forest. In the multicultural approach, we composed the forest with different types of trees and, just like previously, wind and height were not considered in the simulations. Additionally, we considered a random distribution of the trees as described in section 2.1.

4.3.1 *Monoculture*

In this test, we observed how the fire affected the forest in terms of the burnt area. We ran diverse simulations considering different values of ρ and the results can be consulted in figure 7. With this plot, we can already see some interesting phenomena that reveal a lot about the influence of the density of the forest. The first thing that we can easily notice is the fact that, overall, the plot seems to start with really low values, close to 0, and suddenly "explodes" in an exponential fashion, stagnating when it reaches values closer to 1. This exploding behavior shows us that the fire propagation in our model can be seen as an epidemic and the point upon which it explodes can be seen as the epidemic threshold. From now on, we will refer to this value as λ. As an example, for a fire threshold of $\rho = 0.1$, we can see that the epidemic threshold lies around the value λ=0.5.

Considering the epidemic thresholds, we can observe another interesting behavior: **As ρ grows, λ starts to drift towards 1.**
The opposite also happens, meaning that as ρ reaches 0 it tends towards values around $\lambda = 0.5$. This is related to the fact that we considered a random distribution of trees around the grid which is the same type of distribution as the one considered in percolation theory, for lattices in the dimension $d = 2$. It is known that large clusters tend to appear when we reach a probability of 0.5 (in our case PGrowth) making it more probable for an outbreak to happen since each tree can indirectly reach more trees.

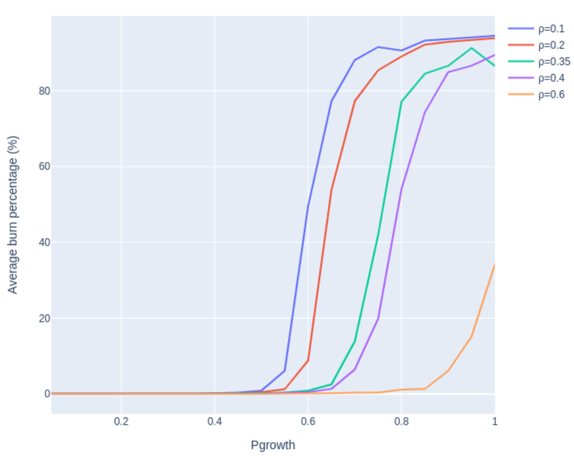

Figure 7: Average percentage of burnt trees as a function of $PGrowth$ in a monoculture scenario.

4.3.2 *Multiculture*

In figure 8 we can see the simulation results where we plotted, again, the average percentage of burnt trees as a function of the parameter $PGrowth$ for different types of trees, and the similarities between the monoculture scenario

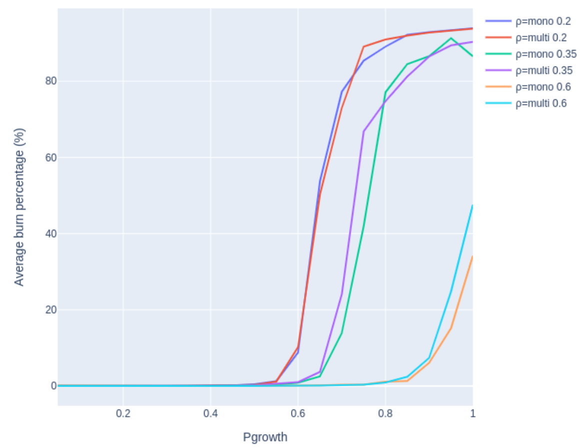

Figure 8: Average percentage of burnt trees as a function of $PGrowth$ in a multiculture scenario opposed to monoculture.

and the one considered in this test are uncanny. We can immediately see that the distributions are almost identical and show the same behavior overall.

This result is great! Let's say that we know a certain forest composed of multiple types of trees and on average has $\rho = C$. Now, consider an identical forest (or at least with the same $PGrowth$) that is made of only one type of tree with $\rho = C$. If the two forests were to catch on fire, in theory, and on average, they would burn approximately the same amount of trees. Apart from its fun aspect, this result has some practical applicability. Suppose a farmer wants to plant trees in his large plot of land. The farmer may want to plant only one type of tree in his property. Let's say this tree is eucalyptus and has a fire threshold of $\rho = 0.2$. The farmer now plants the trees randomly throughout his land. Sadly, a fire happens and the farmer loses close to 90% of his trees and has to replant. Knowing that if he plants another type of tree alongside the eucalyptus (keeping in mind the ratio of eucalyptus and birch should stay balanced), he can reduce the damage done to the forest in case of a fire. The farmer buys some birch trees ($\rho = 0.6$) which are harder to ignite. By introducing this new type of tree, the forest now has a combined fire threshold of 0.4 which reduces the chances of the forest burning up to 90% considerably.

As one might think, randomly planting trees is not a realistic scenario and forests seem to show some sort of correlation in the way they are spread around the land. In our next scenario, we ran the simulation in a grid where the trees were distributed in such a way that they would form a more natural forest topology.

4.4 Scenario 3

In this section, we take a look at a more realistic tree distribution and the corresponding effects of fire in forests where the displacement of the trees follow said distribution. Furthermore, we tune the scope of our tests in order to compare the results sprout by this new distribution with the previously obtained ones.

4.4.1 *Forest-aggregation distribution*

In order to obtain a more realistic randomly generated forest we need to use a different distribution. Due to the lack of a better name, we call the subsequent distribution ”forest-aggregation” due to its tendency to aggregate trees.

This distribution can be manipulated through the $PAggreg$ parameter. Given a maximum number of trees that should be planted, the distribution will plant a tree in a random place around the grid with probability $PAggreg$. and a tree in the neighborhood of an already planted tree of the same type with probability $1 - PAggreg$.

In figures 9 and 10 we can see how increasing and decreasing the $PAggreg$ parameter changes the topology of the forest. For values of $PAggreg$ close to 0, the forest will show very tightly coupled and distinguishable clusters of trees, and as the parameter increases the more apart trees start to get.

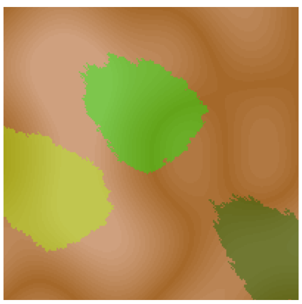

Figure 9: Example of a possible forest distribution for $PAggreg = 0$

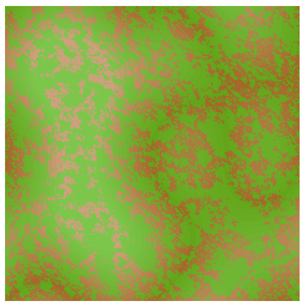

Figure 10: Example of a possible forest distribution for $PAggreg = 0.2$

4.4.2 *Random forest vs forest-aggregation distribution*

In order to compare the random with the forest-aggregation distribution, we chose a fixed value of $PAggr$ that we considered generating realistic-looking forests and ran the simulation for different types of trees considering, again, monoculture and multiculture scenarios.

In figure 11 we can see that the distribution of the average percentage of burnt trees behaves in the same way as in randomly distributed forests. Not only does it show the same behavior has it also is consistent in both monoculture and multiculture scenarios and the result discussed in 4.3 still applies in this scenario. We argue if this behavior emerges from the random factor introduced by $PAggr$.

As future work, one might test if these results still hold in a scenario where an accurate distribution of trees is used. Another interesting case to consider is the fact that the grid size is limited. Does the same still hold for infinitely large grids?

4.5 Scenario 4

The environment used to test wind influence on fire spreading was a monocultured forest with $\rho = 0.4$.

In order to answer **RQ3** it was decided to analyze what is the impact of changing wind intensity, as shown in Figure 14. The results show that a forest is more likely to burnout with lesser values of wind intensity. For values greater than 0.5 the amount of burnt trees decreases drastically, thus, one can conclude that wind impacts fire spread severally, causing it to decrease, based on how intense it is.

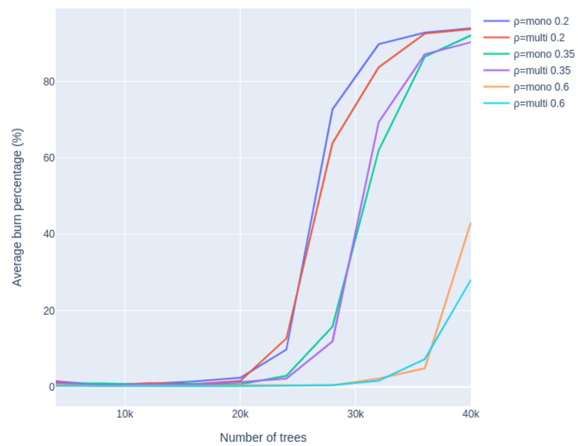

Figure 11: Monoculture vs multicuture in a forest-aggregation scenario with an aggregation parameter of 0.2. The number of trees considered corresponds to the average number of trees in a randomly distributed grid of size 200x200 and for each $PGrowth$ in the range 0 to 1.

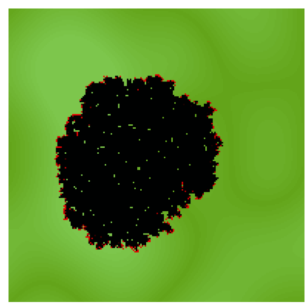

Figure 12: Fire spreading along a monocultured forest with no wind.

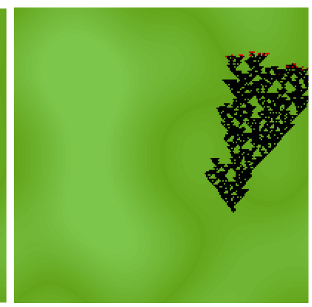

Figure 13: Fire spreading along a monocultured forest with maximum wind intensity.

The aforementioned phenomenon can be directly explained by analyzing how wind intensity impacts fire spreading topology, as seen in both Figure 12 and Figure 13. Without any wind influence, fire tends to spread circularly since a tree on fire has a direct impact on all neighbor trees. Adjusting the wind intensity to its maximum value, the fire starts to spread in a triangular manner, since a tree on fire has almost no impact on neighbors that are in the opposite direction of the wind.

Regarding the rate of fire spread with wind and the influence of height, our model displays some limitations that make their influence almost neglectable and unnoticeable. The influence of height is so minimal and instant that no actual influence seems to happen getting overshadowed by the wind influence and the neighbors influence (δ). Regarding the spread of fire, wind cannot have an influence over it due to the fact that it is limited to move the fire front at most one cell further at a time step.

4.6 Discussion

In this section we discuss the results obtained earlier and try to answer the research questions that were raised. **Regarding research question 1:** From our experiments in

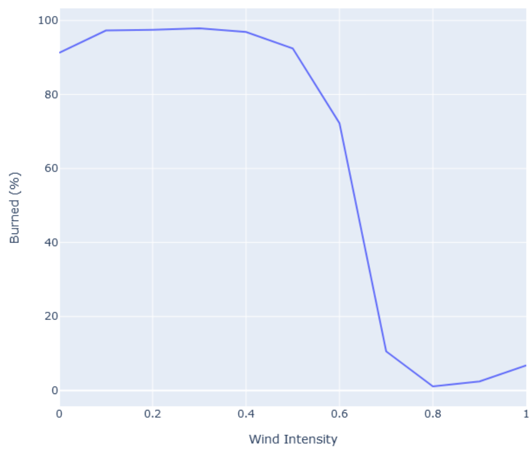

Figure 14: Burned percentage of the forest as a function of Wind Intensity.

section 4.2, we found that the fire usually spreads at the same rate, whether it's in a monocultered or multicultured forest. In a more practical stance, this means that having a set of various types of trees for any reason (whether monetary, aesthetic or land related) instead of only one single type could be desirable, as long as we guarantee the same resistance to fire of the tree set as a whole.

Regarding research question 2: We can say that indeed denser forests are susceptible to more damage caused by fires. In section 4.3 we exposed some evidence which shows that when large clusters form, the average burn percentage of the forest in the case of a fire increases drastically. In the real world, this could be interpreted as evidence of the importance of regularly cleaning and clearing the forests, leaving some distance between the trees, so as to prevent the formation of clusters that could become a fire hazard. Additionally, in section 4.4 we showed that for a more realistic distribution of trees the same results apply. **Regarding research question 3:** in section 4.5 we analysed the effects of wind and height to the spread of fire. We can conclude that, in our model, the wind affects the amount of forest burned due to its influence on the direction of the propagation of the fire and the limited size of the grid. Due to the limitation imposed by our model, we cannot conclude the exact effect of wind speed on the spread of fire.

5. CONCLUSION

In this project we took a simulated approach to try and analyse the impact of clustering and different tree types in forest fires, as well as the influence of external factors, such as wind and height. First we envisioned a model inspired by two already existing ones and then we built a simulator that could run this model. To answer our proposed questions, we ran thousands of simulations and considered different scenarios in order to understand how these factors were connected.

We found that although different tree types may not affect as much the amount of trees burned as we initially expected they would, the clustering of trees is an aspect that can greatly increase it. This results raises awareness to the importance of preventive measures as forest cleaning.

Finally, we showed that the wind can have an impact in the way the fire is spread, which emphasizes the danger of the work that firefighters have to do, and how they need to plan ahead, always taking into consideration new meteorological and topological conditions.

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