Fire Spread Simulation using Cellular Automata

Carlos Mauricio Reyes Escudero, Franco Hernandez Piloto, Hivan Canizares Diaz

June 10, 2024

Abstract

Forest fires pose significant environmental risks, impacting ecosystems, property, and human lives. Predicting fire spread is essential for effective prevention and control strategies. In our project, we employ cellular automata (CA) to model fire propagation in a forest. Our CA-based model represents the forest as a grid of cells, each in one of five states: water, ground, grass, forest, or fire. The state of each cell evolves over time according to a set of rules that take into account the states of neighboring cells and environmental factors such as wind and fuel type. By simulating fire spread, we aim to predict where could be vegetation zones and water zones or not inflammable zones based on the ignition point, its relation with the wind speed and direction and the fire spread rate.

1 Introduction

Understanding and predicting the spread of forest fires is crucial for effective prevention and control strategies.In this project, we aim to simulate the spread of fire in a forest using cellular automata, a powerful computational tool for modeling complex systems,with parameters like wind speed and direction,humidity, fire's intensity and fuel type.

2 Background

Cellular automata (CA) are discrete mathematical models that consist of a grid of cells, where each cell can exist in one of a finite number of states. The state of each cell evolves over time according to a set of rules that depend on the current state of the cell and the states of its neighboring cells. These rules are applied simultaneously to all cells in the grid, resulting in a dynamic system that can exhibit complex behavior despite its simple underlying rules.Our CA-based model represents the forest as a grid of cells, each in one of five states: water, ground, grass, forest, or fire. The state of each cell evolves over time according to a set of rules that take into account the states of neighboring cells and environmental factors such as wind and fuel type. Several environmental factors play a crucial role in determining the spread and behavior of forest fires. Among these factors, wind direction and speed, temperature, and fuel type are particularly influential.In the following sections every factor is explained.

2.1 Wind direction and speed

Wind direction and speed significantly impact the rate and direction of fire propagation. Strong winds can accelerate the spread of fire by supplying oxygen and carrying embers to unburned areas, while changes in wind direction can alter the fire's path. To accurately model the effects of wind on fire spread, our CA model incorporates an equation that considers both wind direction and speed.(direction=angle) The equation used in our model is:

$$e^{0.1783 \times v \times \cos(\theta)}$$

from Rothermal's model (Rothermal, 1972), 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), which proposed a mathematical formulation to account for the influence of wind on fire propagation. The equation takes into account the wind speed and direction, as well as the orientation of the cell relative to the wind direction, to calculate fire spread rate from a burning cell to its neighbors.

2.2 Fire's intensity or local temperature

Fire's intensity plays a crucial role in determining the ignition and burning rates of vegetation. Higher fire's intensity can increase the likelihood of ignition and accelerate the rate of fire spread, while lower fire's intensity may slow down or even halt the fire's progression. Our CA model incorporates fire's intensity as a parameter in the transition rules governing cell state evolution.

2.3 Fuel type

The type of fuel present in the forest, such as different vegetation types or dead organic matter, can significantly influence the fire's behavior. Certain fuel types may be more flammable or burn at higher rates than others, affecting the overall fire spread. Our model accounts for fuel type by assigning grass state and forest state to the automata,where grass's burning rate is higher than the forest's burning rate.

3 Methodology

3.1 Initialization

It is called only once in the first step of the simulation:

1. Grid Setup:
   - The forest is represented as a grid of cells, each of which can be in one of several states: ground, water, forest, grass, fire, or ashes.
   - The initial state of each cell is determined based on predefined conditions.
2. State Assignment:
   - If the present state of a cell is `1`, it is set to *ground*.
   - If the present state of a cell is `2`, it is set to *water*.
   - If the present state of a cell is `3`, it is set to *forest*, and the duration for which it can burn is initialized.
   - If the present state of a cell is `4` or `5`, it is set to *grass*, and the duration for which it can burn is initialized.
3. Boundary Conditions: Cells at the boundaries of the grid (within a 5-cell margin) are set to `bed rock(void)`.

3.2 Functions and Parameters

1. Duration Constants:
   - `grass_dur`: The duration for which grass can burn.
   - `forest_dur`: The duration for which forest can burn.
2. Wind Vector: The wind vector is calculated based on the wind angle, using the cosine and sine functions.
3. Fire Temperature Function: `fire_tmp(val)`: A function that returns the temperature of a burning cell based on its burn time.
4. Temperature(fire's intensity) Calculation:
   - `temperature(x, y, k)`: A function that calculates the local temperature at cell `(x, y)` by considering the influence of neighboring cells within a radius of `k`.
   - The function iterates over neighboring cells and adjusts the temperature based on whether the neighboring cell is in the *fire*| or *water* state.
   - The influence of wind is incorporated by calculating the cosine of the angle between the wind direction and the vector from the current cell to the neighboring cell.

3.3 Execution

It is called at each step, and each cell runs it independently and in parallel thanks to run the code using shaders for speed:

1. Fire Spread Dynamics:
   - If a cell is in the *fire* state, its future state is determined based on the remaining burn time. If the burn time is exhausted, the cell transitions to *ashes* state.
   - If a cell is in the *grass* or *forest* state, it transitions to *fire* if the burn time is exhausted. Otherwise, the burn time is reduced based on the local temperature(fire's intensity).
2. Ignition Point: A specific cell at coordinates `(sfx, sfy)` is set to *fire* with an initial burn time of `0`.
3. Wind Influence
   (a) Wind Direction and Speed:
   - The wind direction and speed are critical factors that modify the fire spread. The wind vector is calculated using the wind angle.
   - The cosine of the angle between the wind direction and the vector from the current cell to a neighboring cell is used to adjust the temperature and, consequently, the fire spread rate.

   (b) Temperature Adjustment: The local temperature is adjusted based on the relative position of burning cells and the wind vector. This adjustment is exponential, reflecting the increased likelihood of fire spread in the direction of the wind.

3.4 Code Explanation

The following section explains the key components of the code used in the fire spread simulation, focusing on the initialization of parameters, the calculation of fire temperature, and the influence of environmental factors such as wind and water.

3.4.1 Initialization of Parameters

```
float grass_dur = 31.0;
float forest_dur = 45.0;
int fire_amount = 0;
vec2 wind = vec2(cos(wind_angle), -sin(wind_angle));
```

- `grass_dur`: This variable represents the duration for which grass can burn, set to 31.0 units of time.
- `forest_dur`: This variable represents the duration for which forest can burn, set to 45.0 units of time.
- `fire_amount`: This integer variable is used to keep track of the amount of fire present in the simulation.
- *wind*: This vector represents the wind direction, calculated using the cosine and sine of the wind angle. The wind vector influences the direction and speed of fire spread.

3.4.2 Fire Temperature Function

```
float fire_tmp(float val){
return exp(-(val-0.7)*(val-0.7));}
```

`fire_tmp(val)`: This function calculates the temperature of a burning cell based on its burn time. The function uses a Gaussian distribution centered at 0.7 to model the temperature, which decreases as the burn time deviates from this center.

3.4.3 Temperature Calculation Function

```
float temperature(uint x, uint y, int k){
float temp = 0.0;
uint p = x + y * WSX;
for(int i = int(x)-k; i <= int(x)+k; i++) {
     uint ii = uint((i+int(WSX))) % WSX;
     for(int j = int(y)-k; j <= int(y)+k; j++) {
          uint jj = uint((j+int(WSY))) % WSY;
          uint kk = ii + jj * WSX;
          if(data_present[kk] == fire){
          vec2 posit = vec2(float(x)-float(i),float(y)-float(j));
          float cosine = dot(wind, posit)/sqrt(dot(posit, posit));
          float rel_temp = fire_tmp(data_values[kk]);
          temp += rel_temp * exp(0.1783 * wind_speed * cosine);
          }
          if(data_present[kk] == water){
          vec2 posit = vec2(float(x)-float(i),float(y)-float(j));
          temp *= sqrt(dot(posit, posit)) / (13 * sqrt(2));
          }
     }
}
return temp; }
```

`temperature(x, y, k)`: This function calculates the local temperature at cell `(x, y)` by considering the influence of neighboring cells within a radius of `k`.

- *temp*: This variable accumulates the temperature contributions from neighboring cells.
- The nested loops iterate over the neighboring cells within the specified radius `k`.
- `ii` and `jj`: These variables handle the wrapping around the grid edges using the modulo operation.
- `kk`: This variable represents the index of the neighboring cell in the linearized grid array.
- If a neighboring cell is in the *fire* state, the function calculates the relative position vector *temp* and the cosine of the angle between the wind direction and this vector.
- The relative temperature `rel_temp` is calculated using the `fire_tmp` function which calculates the temperature of a burning cell based on its burn time, and the local temperature *temp* is adjusted based on the wind influence.
- If a neighboring cell is in the *water* state, the local temperature *temp* is reduced based on the distance to the water cell.

3.5 Halting Conditions

The simulation checks the state of the board in equidistant timestamps, to verify whether there exists a block in fire, so it stops when the amount of fire reaches zero. When there is no fire in the terrain, there is no posible transition to any other state. It will always stops because the fire will necessarily extinguish or burn a combustible block, and since the former are finite, the simulation is fated to reach its end somehow, somewhere.

4 Results

The analysis of the fire spread rate data in conjunction with the wind vector direction revealed interesting insights into the potential presence of water bodies or dense vegetation in certain areas surrounding the ignition point.

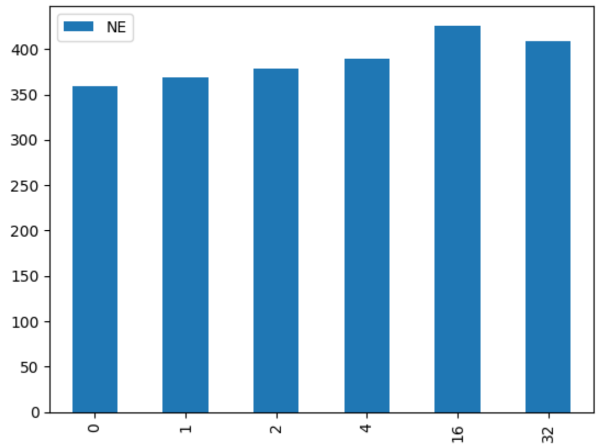

Figure 1: Fire spread rate against wind speed in NE direction

The fire spread rate is highest in the northeast (NE) direction, and the wind direction vector is aligned with that same NE direction, it suggests that the fire is propagating more rapidly in the direction of the prevailing wind.

This could indicate that there is denser vegetation or more continuous fuel loading in that particular direction from the ignition point. Denser vegetation and higher fuel continuity would provide more combustible material for the fire to consume, thereby facilitating faster propagation in that direction, especially when aided by the wind.

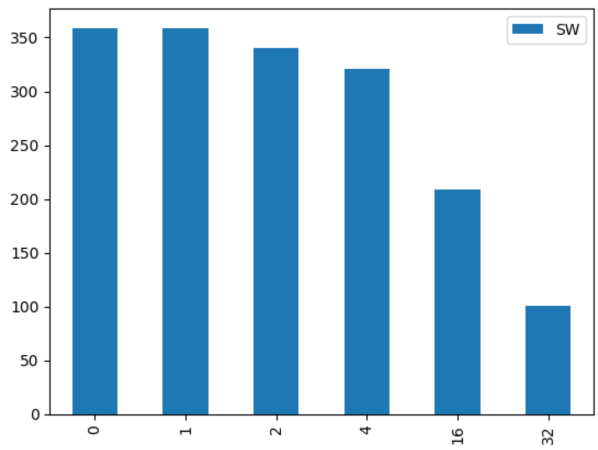

Figure 2: Fire spread rate against wind speed in SW direction

Notably, the graphic depicted a significantly lower fire spread rate in the westward (W) direction, which coincided with the wind vector pointing in the same westward orientation.This observation suggests a strong possibility of the presence of water zones or areas with low fuel density near the ignition point in the westward direction. The presence of water bodies or non-burnable areas would act as natural barriers, impeding the propagation of fire in that direction, even with the wind blowing towards that area. Consequently, the fire spread rate in the westward direction would be significantly lower compared to other directions.

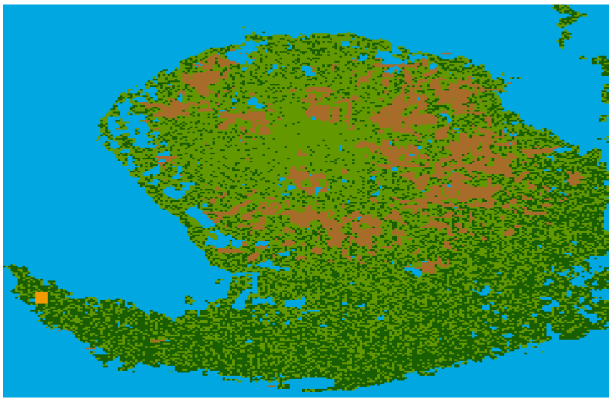

Figure 3: Ignition Point

The direction NE exhibiting the highest rate of fire spread coincides with the presence of denser vegetation in that area relative to the ignition point. This observation is consistent with the well-established principle that continuous and dense fuel sources facilitate more rapid fire propagation. The increased fuel availability and continuity in this direction likely contributed to the accelerated fire spread, especially when coupled with the influence of wind direction and speed. Conversely, the direction SW with the lowest observed fire spread rate corresponds to the presence of water zones or areas with low fuel density near the ignition point. Even with the wind blowing towards that area, the lack of continuous fuel sources and the presence of water effectively slowed down or halted the fire's progression. These findings reinforce the importance of accurately modeling and incorporating environmental factors, such as vegetation density, fuel continuity, and the presence of water sources, into fire spread simulations. By accounting for these critical elements, our cellular automata model can provide valuable insights into the complex dynamics of fire propagation and the conditions that influence its behavior.

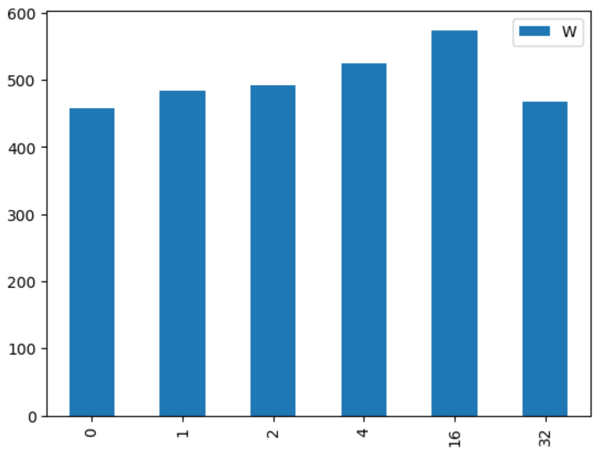

Figure 4: Fire spread rate against wind speed in W direction

.

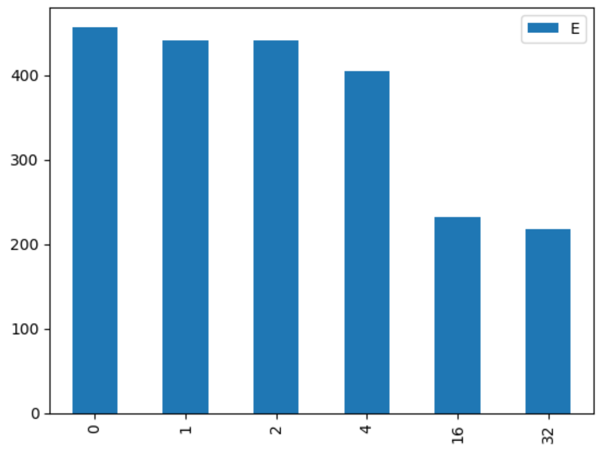

Figure 5: Fire spread rate against wind speed in E direction

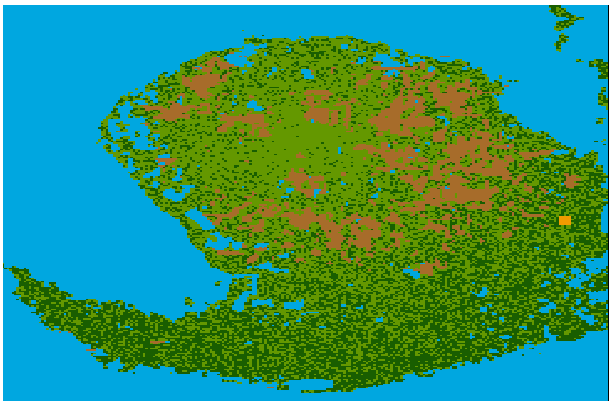

Figure 6: Ignition point

In this case like the previous one we can see that the figure 4 shows the highest fire spread rate in the W direction which could a dense vegetation, and the figure 5 shows the lowest fire spread rate in the E direction most notable when the wind speed increases,this could be explain by the lake of fuel in that direction or the proximity to the coast. And finally in the Figure 6 it is possible to watch that our hypothesis is accomplished looking at the ignition point.

It is important to note that these interpretations are reliable only when the observed fire spread rates in the respective directions are significantly high or low. If the fire spread rates fall within a moderate range, additional information about fuel characteristics, topography, and other environmental factors would be necessary to make more accurate inferences about the underlying reasons for the observed fire behavior.

The confirmation of these hypotheses underscores the importance of considering the interplay between environmental factors and their effects on fire behavior. By accurately modeling and understanding these interactions, our research contributes to the development of more effective fire prevention and management strategies, ultimately minimizing the risk of catastrophic fire events and their associated economic and environmental impacts.

5 Conclusion

The findings of this study highlight the significant impact of wind direction and speed, as well as vegetation density and the presence of water bodies, on the rate and direction of fire spread. Through extensive simulations and statistical analysis, we have demonstrated that in the direction of the wind vector align with high values of fire spread rate , our model suggests a high probability of the presence of denser vegetation in that direction, particularly when coupled with higher wind speeds. Conversely, our results indicate that the rate of fire spread is substantially lower in directions where vegetation density is sparse or where water bodies are present. In cases where the fire spread rate is significantly low in a particular direction, our model suggests a high probability of the presence of water sources in that vicinity, acting as natural barriers to the fire's progression.

These observations underscore the importance of accurately modeling and incorporating environmental factors, such as wind patterns, vegetation distribution, and water sources, into fire spread simulations. By accounting for these critical elements, our cellular automata model can provide valuable insights into the complex dynamics of fire propagation, enabling more effective prevention and mitigation strategies.

Furthermore, the findings of this study have practical implications for fire management and resource allocation. By identifying the areas most susceptible to rapid fire spread based on wind direction, vegetation density, and proximity to water sources, fire management authorities can prioritize their efforts and allocate resources more efficiently. This targeted approach can potentially minimize the risk of catastrophic fire events and reduce the associated economic and environmental impacts.

While our cellular automata model has demonstrated promising results, further research is warranted to refine the model's accuracy and incorporate additional environmental factors, such as topography and fuel moisture content. Additionally, integrating real-time data from remote sensing and meteorological sources could enhance the model's predictive capabilities and enable more dynamic and responsive fire management strategies. In conclusion, this study underscores the importance of considering wind direction and speed, vegetation density, and the presence of water bodies in fire spread simulations. By accurately modeling these critical factors, our cellular automata approach provides valuable insights into fire propagation dynamics, contributing to the development of more effective fire prevention and management strategies

6 References

The Cellular Automata Studio using shaders can be found at https://github.com/pascal-ballet/CellularAutomataStudi