Final project

Minerva University

CS166 - Modeling and Analysis of Complex Systems

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Final project

-1,1	0,1	1,1
-1,0	0,0	1,0
-1,-1	0,-1	1,-1

NW	N	NE
W	.	E
SW	S	SE

Table 1. Shows the code for each direction and neighbor's location.

Description of the scenario.

In this project, we are simulating a forest fire. First, we have downloaded tree density information from a real-world map of coordinates of 50N, 90W (Canada). The factors that are included in this simulation are the wind direction, the strength, and the density of trees in each small cube area.

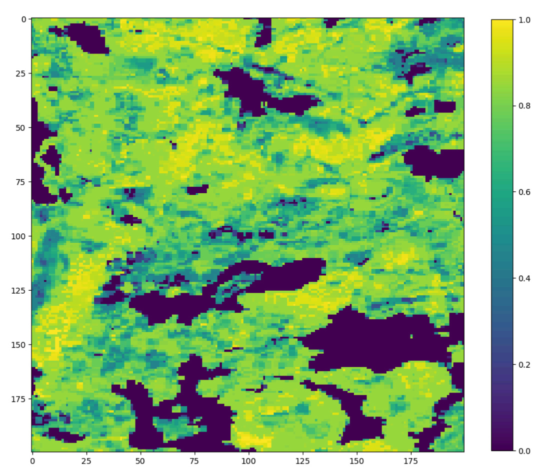


Image 1. Map of 50N, 90W (Canada) in grid cells.

a. Simulation goals and measure of interest.

In this simulation, we will simulate how wind strength direction and tree densities affect the fire spread. By doing this simulation, we are able to find how different factors affect the state of the fire after a certain time step. We can also use the simulation to find ways to reduce the spread of the fire. In this implementation specifically, we want to measure how much different types of firebreaks make an impact in real-life forest fires.

b. Rules of the simulation and how they capture the scenario.

Rules of the simulation:

- One random cell is chosen to set fire
- We make a copy of the grid state before each update.
- Based on the Moore Neighborhoods, we calculate the probability of burning for each neighbor:
    - We find the dot product between 1. the neighbor's location relative to the burning tree (table 1. Top image) and 2. The direction of the wind (table 1. Bottom image, but has the same numerical values as the top image). This comes from the logic that vectors that are in the same direction would have a positive dot product.

      Possible values dot products take are:

      -2 (exact opposite direction),
      -1 (135 degree angle difference),
      0 (90 degre angle differnece),
      1 (45 degree angle difference),
      2 (exact same direction).

      Therefore, we can use this information to determine how likely it is for each neighbor to catch on fire based on the wind.

    - Then, we use the sigmoid function to transform these values to values between 0 and 1 by integrating the factor of wind strength: sigmoid_transformation = 1 / (1 + np.exp(-dot_product * self.wind_strength)).
    - We set a base_probability that balances how much both density and wind factors influence the burning probability of neighbors: spread_prob = self.data[ni, nj] * base_probability + sigmoid_transformation * (1 - base_probability)
- Then, for each neighbor cell, we randomly sample values between 0 and 1. If it is smaller than the probability of burning for that neighbor, we set it on fire.
- The cell that initially spread the fire is set as charred so it would not burn again.
- The updates are made synchronously.
- All steps in the simulation are visualized in an animation.

c. The underlying assumptions/limitations of the simulation are:

- It assumes that the wind has constant one direction and strength.
- It assumes that a fire spreads only by being neighbors and does not take into account factors like tree heights and how far the leaves extend, ember transport, radiant heat, or varying fire intensities.
- Regarding grid firebreaks, there is an assumption that fires cannot spread by jumping and similar.
- We do not take into account different factors like humidity, elevation, slope, rocky hills, or seasonal changes.
- There is an assumption that the equation we use for the probabilities represents the

real-world probabilities.

d. Parameters

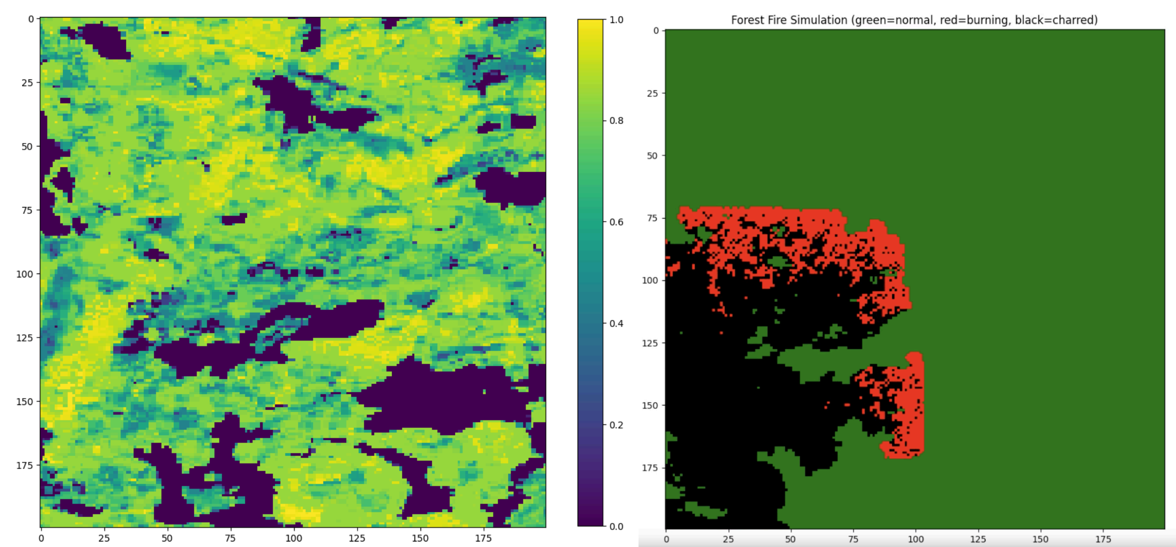
- Wind strength: sigmoid_transformation takes account of the wind strengths, which contributes to finding the probability of a neighbor burning. High values would increase the effect of the wind direction. When the wind strength is zero, the wind direction should not matter.
- Wind direction: The dot product is calculated and inputted into the sigmoid_transformation. This is simply to assign higher probabilities to those neighbors that are on the side of the wind when the strength is sufficient.
- Base_probability: This determines how much both wind factors or density factors influence the probabilities. It is complicated to find the balance between the two. Ideally, the density of the neighbors should affect the fire spread (0 density means that it will not burn at all). Similarly, wind factors should impact the spread of fire. In this implementation, I chose 70% impact of wind factors and 30% density factor (handled the cells with a density of 0 manually, since probability calculation was still giving them some chance to burn when it is impossible)
- Grid_size and Firebreak_coverage: Grid firebreaks can be changed by putting small and big individual square sections. In real life, it would be costly and unproductive to put too small squares of Grid firebreaks. Plus, it is almost impossible to make perfect lines of firebreaks. And because of the way we set up the simulation, we might oversimplify the impact of firebreaks since putting perfect small squares would contain fire immediately in the given grid. Therefore, I chose grid_size = 50, firebreak_coverage = 0.6.

- <u>Percentage</u>: When creating a random fire_break, it is important to set up a value that is realistic yet impactful. Though putting a high percentage can effectively prevent the fire outbreak, it could be costly and unproductive. Therefore, there is a tradeoff between the effectiveness of fire outbreak prevention and the utility of trees (air purification, production material, space for animals, etc). We chose 20% in the simulation.

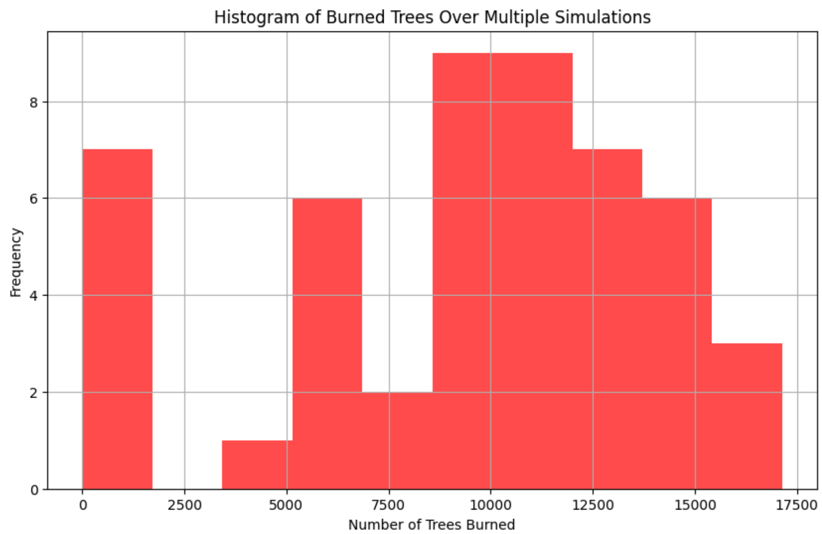
e. The quantities of interest are how much of the trees end up burning after a certain amount of steps. This will help us see what type of prevention strategies are more effective and how much impact firebreaks bring compared to no prevention strategy.

Simulation results.

No prevention strategy



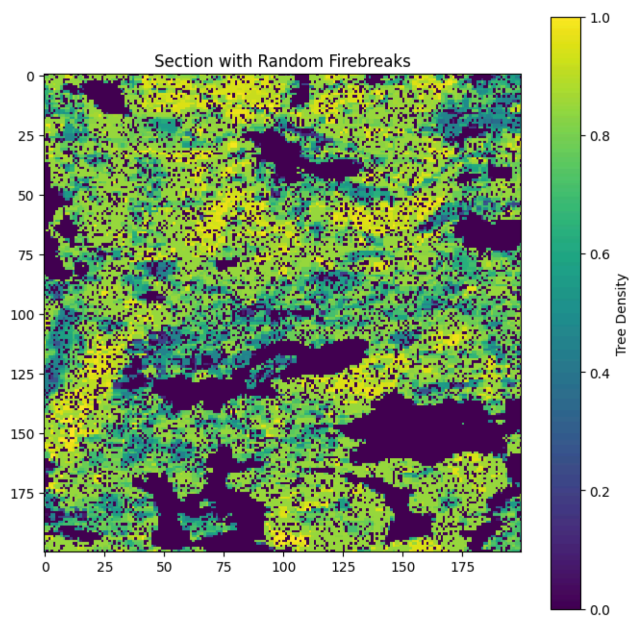
Graph 2. (left) Natural state of the forest. (right) One simulation, random timestep of the burn. Green shows normal unburned trees, red represents fire, and black shows already burned trees.

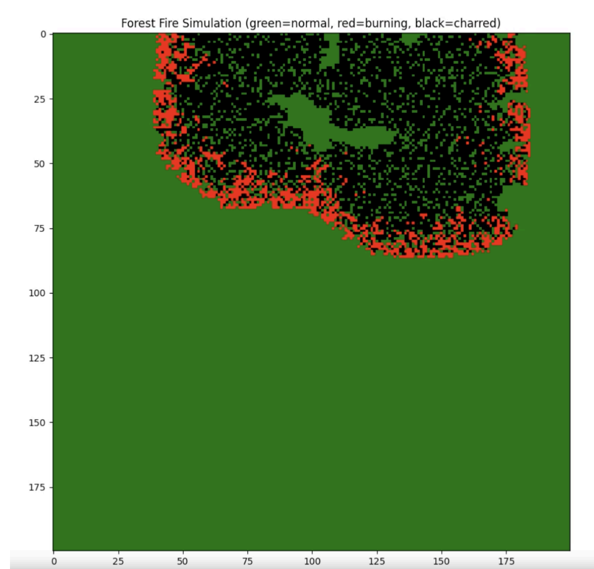


Graph 1. Distribution of the number of trees burned after 100 time steps. Wind direction is North-West, and strength is 0.5. No prevention strategy was implemented. Mean: 9335.28; 95% Confidence Interval: (8012.87, 10626.61)

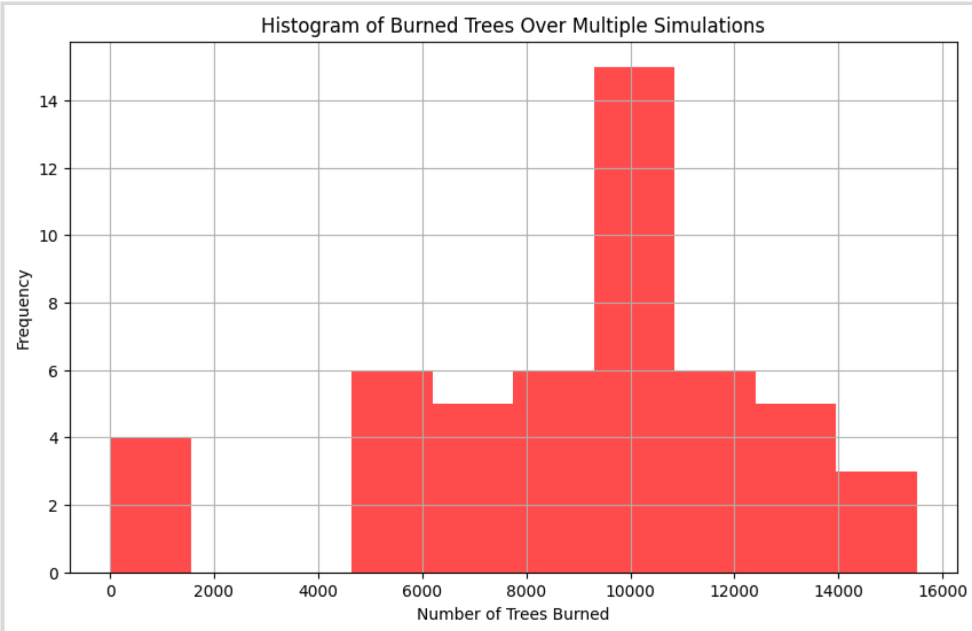
In Graph 1, we can see there are a few simulations that resulted in 0 to 2000 tree cells burnt, and the right-hand side shows that many simulation results ranged between 3,000 and 17,000 tree cell burns. The median is around 10,000. The mean is 9335, and the confidence interval is (8012.87, 10626.61)

Random firebreaks strategy





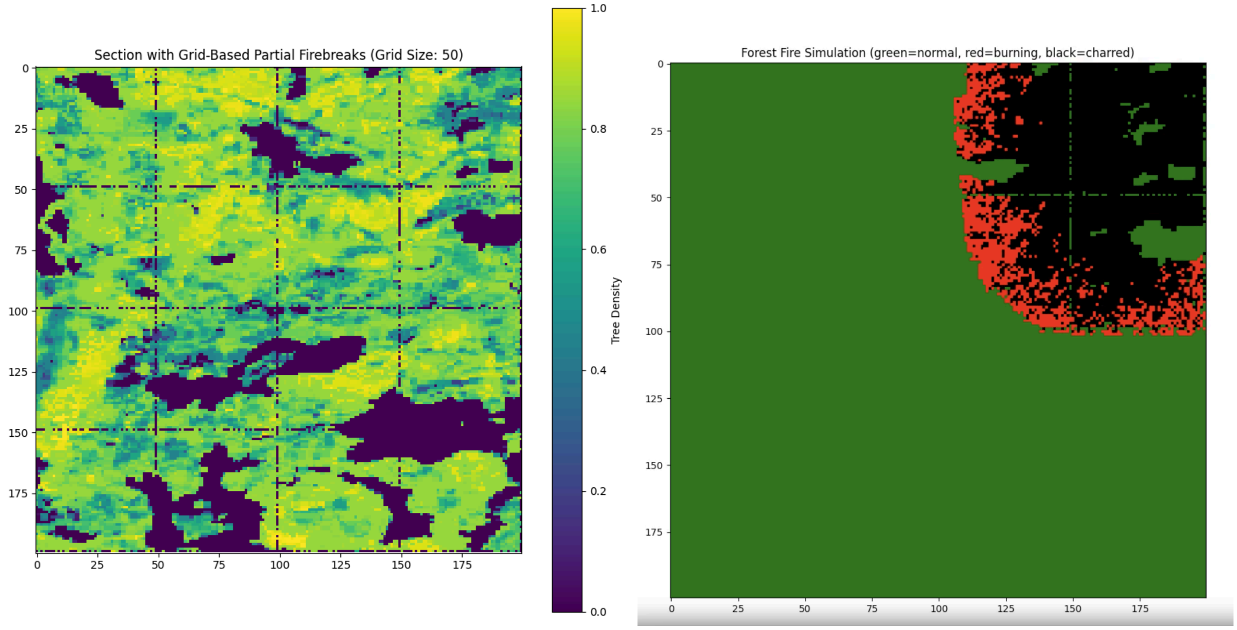
Graph 2. (left) Random firebreaks placed with 20% coverage. (right) One simulation, random timestep of the burn. Green shows normal unburned trees, red represents fire, and black shows already burned trees .



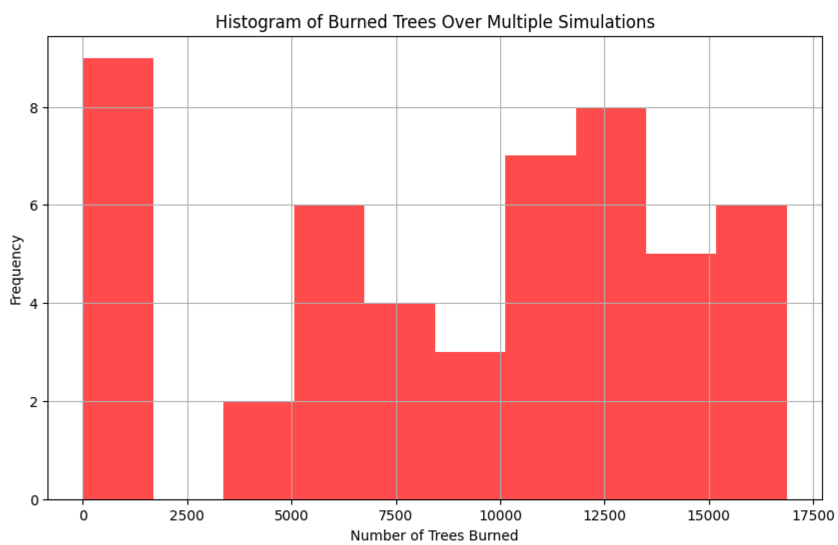
Graph 3. Distribution of the number of trees burned after 100 time steps. Wind direction is North-West, and strength is 0.5. Random firebreaks with 20% coverage were implemented. Mean: 9074.08
95% Confidence Interval: (8043.72, 10036.44)

Graph 2 shows how the random firebreaks at 20% were allocated. Graph 3 shows that there are a few simulations that resulted in 0 to 2000 tree cells burnt, and the right-hand side shows that it ranged between 3,000 to 17,000 tree cell burns. The median is around 10,000. The mean is 9074, and the confidence interval is (8043.72, 10036.44). Generally, it has descriptive statistics similar to those of no strategy. It sightly has a smaller mean and smaller upper bound. However, there is no clear evidence that one is over the other, especially since the trial run was 50.

Grid firebreaks strategy



Graph 4. (left) Grid fire breaks were implemented where grid_size = 50, and firebreak_coverage = 0.6. (right) One simulation, random timestep of the burn. Green shows normal unburned trees, red represents fire, and black shows already burned trees.



Graph 5. Distribution of the number of trees burned after 100 time steps. Wind direction is North-West, and strength is 0.5. Grid firebreaks were implemented. Mean: 8859.92; 95% Confidence Interval: (7388.48, 10311.75)

Graph 4 shows the way we have set up the firebreaks. In Graph 5, we can see that the median values are below 2000, and there is another area of distribution between 3,000 and 17,000. The mean shows to be 8860, and the 95% CI is (7388.48, 10311.75), which is broader than the above strategies. We can see that the CI does not inform about the median around 0-2000. Compared to the random firebreak strategy, it seems to have a smaller mean, smaller value for the lower bound, and slightly higher upper bound. While there is no clear difference, based on the histogram, and a slightly smaller mean and lower bound, we could propose that grid firebreaks could be more effective. If we were to choose a higher value for the firebreak_coverage parameter, it could help significantly minimize the fire spread.

Uncertainty in the results.

The width of the 95% confidence intervals is approximately 2000-3000, which is broad. This could be because the results in the simulation were only run on 50 trials. To get more accurate results and narrower widths of 95% confidence interval, we would need to run more trials (e.g., 200, 500, and 1000 trials, but the wait time can be significantly long).

In conclusion, grid firebreaks seem to have a slightly better impact on the fire spread, and it could even improve by playing with the parameters. However, it is important to set those parameters to something plausible in real life. Random firebreaks did not show much impact with 20% coverage; however, increasing it will definitely make a difference, but there is a tradeoff that we need to balance. For example, if we were to implement 50% random firebreaks, it would reduce the risk a lot, but we would lose so many resources. Therefore, based on how many of the forest trees we are willing to give up and how much money we have for forest fire prevention projects, we can choose the type of firebreak and with what parameters.

Link to notebook: forest-cover-data-download.ipynb

AI statement: I used AI to debug my codes. Used Grammarly for the written part.