Cellular Automata for Wildfire Spread and Recovery

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Github

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Abstract

This study presents two distinct approaches to forest fire spread modeling using cellular automata: multi-agent-based (Model 1) and multi-parameter (Model 2) simulations. Model 1 explores various cell states and firefighting interventions, while Model 2 accounts for factors such as ground elevation, wind speed and direction, vegetation type, and density. The goal of this work is to simulate realistic forest fires and evaluate intervention strategies. Experiments on both models reveal the complex dynamics of forest fires and the effectiveness of different intervention techniques. Results highlight the potential for developing more comprehensive models by combining both approaches. Future work includes incorporating additional strategies, such as fire lines and aerial support, as well as prevention methods.

1. Project Description

The system being studied in this project is the complex and dynamic phenomenon of forest fire spread. Forest fires are influenced by a multitude of factors, including fuel availability, weather conditions, and topography, which interact in intricate ways to determine the fire's behavior and rate of spread. Accurate prediction and simulation of forest fire spread are essential for effective resource allocation, decision-making, and firefighting operations, as well as for forest management and the protection of ecosystems, human life, and property.

Overall, this work focuses on developing two paradigms of modelling: multi-agent-based and multi-parameter modelling. We denote them as Model 1 and Model 2 in the subsequent sections. We perform several experiments on both the models to observe the behaviour of forest fires in a spectrum of environmental settings. Model 1 also takes into account a possible intervention strategy. Model verification is performed including edge cases to assert the correctness of the modelling. We believe that one could extend our attempt to devise informed decisions while countering wildfires. The overall structure of the report is organized as follows: section 2 goes over the existing work in forest fire modelling; section 3 details the conceptual model of the two models that we focus on; section 4 presents how the simulation is implemented; section 5 describes the experimental and validation techniques we designed to examine the behaviour of our forest fire simulation; section 6 concludes our work and opens discussion for future work.

2. Literature Review

Cellular Automaton is a computational model that simulates the behavior of a system using a grid of cells, each with a set of rules for how they interact with their neighboring cells. In the context of forest fires, CA can be used to simulate the spread of the fire by dividing the forest into a grid of cells and modeling the spread of fire from one cell to its neighboring cells based on factors such as wind direction, vegetation density, and terrain type [1].

Type of vegetation, vegetation density, wind direction, humidity, and terrain type must all be taken into account in building an effective fire spread model. There have already been a number of models that determine the spread of fire using some or all of these factors, using a variety of techniques.The authors in [2] introduce a two-dimensional grid model of a forest where each cell's condition is determined by factors such as plants, temperature, humidity, and fire. The model has rules that control its evolution based on interactions between nearby cells and variables such as wind direction, slope, vegetation, and fire severity. The model also includes control parameters for studying the effects of interventions like firebreaks and fuel reduction.

In a similar study, [3] models the spread of fire by taking into account various factors that affect fire spread, such as wind direction and speed, fuel load, and topography. The model accurately reproduced the observed spread of the Spetses fire in 1990 and has the potential to be used to the prediction of future fires in surroundings that are comparable. [4] demonstrates a cellular automata-based model for modeling fire patterns on varied environments. The modeling of landscape heterogeneity, the initial outbreak of fires, and the spread of fire fronts throughout the terrain are some of the factors which are considered.The model is validated by testing on a series of simulated scenarios, including variations in landscape heterogeneity, fire frequency, and fire suppression efforts.

3. Conceptual Model

Model 1 is a multi-agent model that focuses on the characteristics of the trees, their interactions with each other, and an intervention. Model 2 is a single-agent multi-parameter model that focuses on the structural properties of the forest.

3.1. Model 1

Model 1 simulates the spread of fire and the recovery process in a forest with two different types of trees and also accounts for an intervention strategy, watering. The model incorporates stochastic elements, such as fire spread probability, burnout probability, self-recovery probability, neighbor recovery probability, and complete recovery probability. Additionally, we account for factors like water resources and water fraction, which represent the amount of available water for firefighting and the proportion of burning trees that can be watered, respectively.

The cells exist in one of 5 states:

- `INERT`: The cell is healthy and not on fire. This state represents undamaged, non-burning vegetation.
- `BURNING`: The cell is on fire, and can spread fire to neighboring cells.
- `BURNT`: The cell has been damaged by fire and is no longer burning. Fire cannot be spread by this cell.
- `RECOVERING`: The cell is in the process of recovering from being burnt. This state represents regrowth of vegetation. After some time, recovering cells will become inert cells.
- `WATERING`: A previously burning cell is being watered. It will begin regrowing soon.

At the end of each iteration, a certain proportion (`WATER_FRACTION`) of burning cells is chosen randomly to water with the upper limit of number of watered cells set to `WATER_RESOURCE`.

Each cell in the forest grid represents a tree of one of the two types. The tree types have different `BURN_TIME`s and `GROWING_TIME`s, and each tree object has attributes for its state.

- `BURN_TIME`: The minimum number of iterations a cell burns before reaching the `BURNT` state.
- `GROW_TIME`: The minimum number of iterations a cell takes to go from the `RECOVERING` state to the `INERT` state.

The following are the transition rules:

- If a cell is burning, its neighboring cell will catch fire with a probability of `FIRE_SPREAD_CHANCE`.
- Each burning cell burns for `BURN_TIME`, and then stops burning with a probability of `BURNOUT_PROB`.
- A burnt cell recovers with a probability of `SELF_RECOVERY_PROB`.
- A burnt neighbour of a recovering cell begins recovering with a probability of `NEIGHBOR_RECOVERY_PROB`.
- After `GROW_TIME`, recovering cells becomes inert with the probability of `COMPLETE_RECOVERY_PROB`.
- A watered cell starts recovering in the next iteration.

We initialise the forest with a given proportion of tree types and start the fire at a specified location, depending on the initial conditions.

3.2. Model 2

Model 2 is based on the CA model developed in [3]. This model accounts for the geographical factors affecting the probability of spread of fire. The proposed approach intends to simulate the spread of forest fires by considering multiple factors that can affect the form and pace of spread. These variables include ground elevation, wind speed and direction, type of vegetation and density. The methodology makes use of matrices like the state matrix to account for these terrain-specific factors.

These factors affect the P_{burn} probability which determines the cell will transition into a burning state cell.

$$P_{burn} = P_h * (1 + P_{veg}) * (1 + P_{den}) * P_w * P_s \quad (1)$$

where P_h is a constant probability that, in the absence of wind and on a flat surface, a cell close to one that is currently burning will also catch fire at the subsequent time step. The probability of fire spreading are governed by P_{den}, P_{veg}, P_w and P_s, which are the density and type of vegetation present, the wind speed, and the slope respectively. To get a corrected probability that accounts for all of the previously listed variables, these probabilities are multiplied by the fixed probability P_h.

The impact of vegetation type and density is accounted for by two distinct probabilities, namely P_{veg} and P_{den}, respectively.

There are three types of vegetation covers:

- 1 represents agricultural areas
- 2 represents shrubs
- 3 represents pine trees

There are 3 scales of vegetation densities considered:

- 1 represents sparse vegetation
- 2 represents moderately dense vegetation
- 3 represents dense vegetation

In this study, the wind-effect relationship considers the impact of both wind velocity and direction. The following equations are used to estimate the constants c_1 and c_2, where θ is the angle between the direction of the fire's spread and the direction of the wind. Probability P_w is a function of the angle θ

$$P_w = exp(c1 * V) f_t \tag{2}$$

$$f_t = exp(V * c2(cos(\theta) - 1)) \tag{3}$$

The slope angle between the neighboring cells is calculated by using the following formulas:

- For adjacent cells: $\theta_s = tan^{-1}(\frac{E_1 - E_2}{l})$
- For diagonal cells: $\theta_s = tan^{-1}(\frac{E_1 - E_2}{l\sqrt{2}})$

where E_1, E_2 represent the altitudes of the two cells and l is the length of the side of the square.

The cells exist in one of the 4 states:

- `NO VEGETATION/CITY`: These cell contains no forest fuel and cannot be burned.
- `INERT`: The cell is healthy and has not been damaged yet.
- `BURNING`: The cell is on fire, and can spread fire to neighboring cells.
- `BURNT`: The cell has been damaged by fire and is no longer burning. Fire cannot be spread by this cell.

The transition rules are as follows:

- If a cell is in `BURNING` state at the current time step it will be in `BURNT` state at the next time step.
- The state of a cell that has been burned down in the previous step stays the same
- If a cell is burning, its neighboring cell will catch fire with a probability of P_{burn}.
- A cell in `No Vegetation/CITY` state remains the same and thus it cannot catch fire.

4. Simulation

4.1. Model 1

We implemented a simulation model using Python to represent the forest and the fire dynamics. In order to incorporate mixed vegetation, we performed agent based modelling where each agent is modelled using a `Tree` class with attributes such as its `tree_type`, `STATE`, `BURN TIME` and `GROW TIME`. The `simulateStochasticFire` class is the main simulation class that contains the forest grid, parameters for fire and recovery probabilities, and methods to initialize the fire, update the state of each tree in the grid, and animate the simulation.

To validate our implementation, we first initialized the simulation with different initial conditions and observed the resulting fire spread and recovery patterns. We then performed a series of experiments by varying parameters such as fire spread probability, burnout probability, self-recovery probability, and water resource availability. By analyzing the output, we can assess the effectiveness of different firefighting strategies, the impact of water resources on fire containment, and the rate at which the forest recovers from the fire.

The simulation model generates an animation of the forest grid, where each cell is colored according to its state. It also computes the proportion of burning and burnt cells in the forest at each time step, allowing us to analyze the fire dynamics and the effectiveness of the implemented intervention strategy.

Legend:

- Lighter shades: Tree Type 1 (`Tree 1`)
- Darker shades: Tree Type 2 (`Tree 2`)
- Green: `INERT`
- Blue: `WATERED`
- Yellow: `RECOVERING`
- Black/Grey: `BURNT`
- Red: `BURNING`

4.1.1 Verification

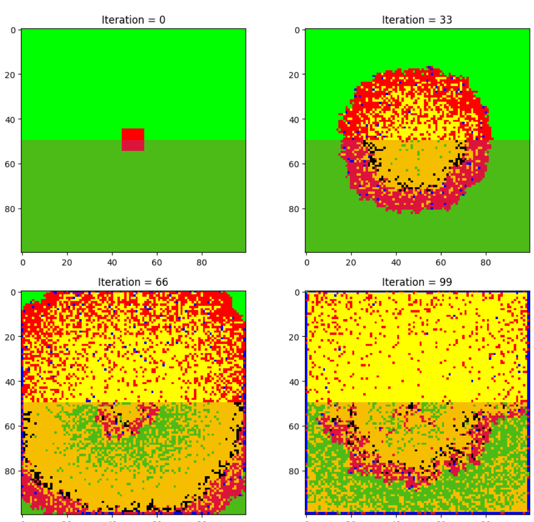
Inorder to test the correctness of the model, we perform some simulations that helps us to qualitatively verify the simulation. We consider a mixed vegetation as follows: The forest has two trees: `Tree 1` and `Tree 2` in equal proportions. The forest is designed in such a way that `Tree 1` and `Tree 2` comprises of the top and bottom halves of the forest respectively. Throughout the verification process, we keep the `BURN_TIME` and `GROW_TIME` of `Tree 2` fixed whereas we would change these parameters in `Tree 1`. All simulations are run for 100 steps on a 100×100 forest with the following parameter setting:

- `FIRE_SPREAD_PROB` = 0.3
- `BURNOUT_PROB` = 0.6
- `SELF_RECOVERY_PROB` = 0.03
- `NEIGHBOR_RECOVERY_PROB` = 0.1
- `COMPLETE_RECOVERY_PROB` = 0.05
- `WATER_FRACTION` = 0.04
- `WATER_RESOURCE` = 0.02
- `Tree2_BURN_TIME` = 10
- `Tree2_GROW_TIME` = 15

The fire starts at the center of the grid in all simulations. We set `Tree 1` with different combinations of the following high and low `BURN_TIME` and `GROW_TIME`:

- `HIGH_BURN_TIME` = 100
- `LOW_BURN_TIME` = 2
- `HIGH_GROW_TIME` = 100
- `LOW_GROW_TIME` = 5

Figure 1. Verification 1 - Tree 1 with `HIGH_BURN_TIME`, `HIGH_GROW_TIME`



The results are presented in Tables 1 to 4. The inference for each of the results are as follows:

Figure 2. Verification 2 - Tree 1 with `LOW_BURN_TIME`, `LOW_GROW_TIME`

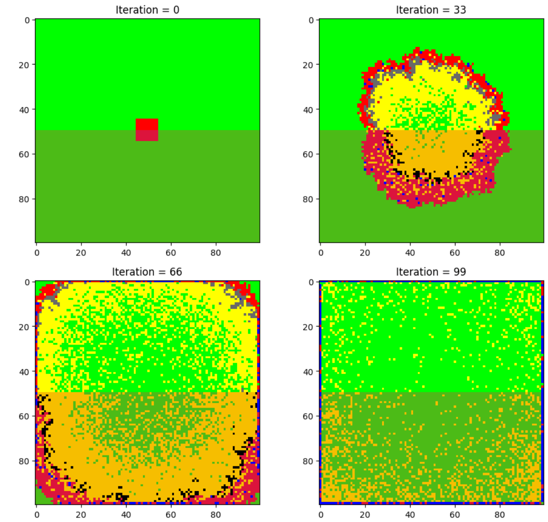
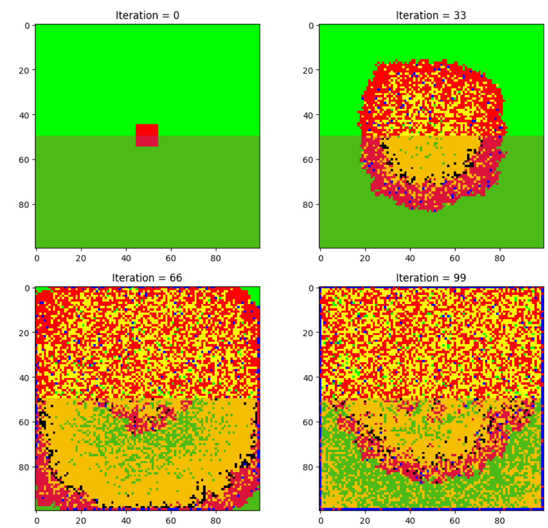
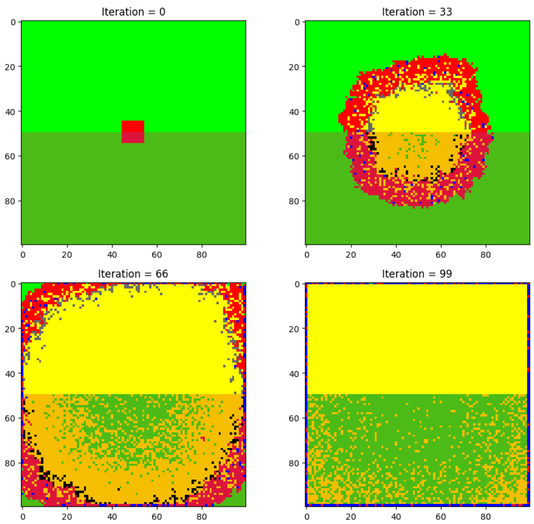


Figure 3. Verification 3 - Tree 1 with `HIGH_BURN_TIME`, `LOW_GROW_TIME`



- Figure 1: In this setting, we expect `Tree 1` to burn for a longer time and recover very slowly. Thus, if our implementation is correct, we should expect that `Tree 1` portion of the forest has more trees in the `BURNING/RECOVERING` state. The figure clearly portrays this behaviour.
- Figure 2: In this setting, we expect `Tree 1` to burn and recover very quickly. Thus, if our implementation is correct, we should expect that `Tree 1` portion of the forest has more trees in the `INERT` state. The figure clearly portrays this behaviour.

Figure 4. Verification 4 - Tree 1 with LOW_BURN_TIME, HIGH_GROW_TIME



- Figure 3: In this setting, we expect Tree 1 to burn for a longer time but recover very quickly. Thus, if our implementation is correct, we should expect that Tree 1 portion of the forest has more trees in the BURNING state. The figure clearly portrays this behaviour.

- Figure 4: In this setting, we expect Tree 1 to burn for a very short time and but recover very slowly. Thus, if our implementation is correct, we should expect that Tree 1 portion of the forest has more trees in the RECOVERING state. The figure clearly portrays this behaviour.

From these inferences, we can assert that the model is implemented correctly.

4.2. Model 2

We write an object-oriented code in Python to build the simulation model. The ForestFire class defines the environment variables need for the simulation like vegetation matrix, density matrix, altitude matrix, and the initialization of the forest grid. The initialization is done with helper functions. The get_slope method computes the slope matrix based on the altitude matrix by considering the difference in altitude of a cell and 8 of its neighbors. The important get_wind function initializes the wind matrix which is hard coded and computes the power of the wind along each direction. We run the simulation on a 100×100 grid for 100 generations and use colormap to visualize it. We conduct various experiments to capture the effect of the simulation parameters on the growth dynamics.

5. Experiments and Validation

5.1. Model 1

We conducted a series of experiments using our simulator to study the behavior of forest fires under various initial conditions and probability values, which can be found in the code repository. Each experiment was run on a 100 x 100 grid, for 100 iterations. The experiments were designed to showcase the impact of different parameters on fire spread and recovery.

Experiments 1, 2, and 3 demonstrate fire spread under three distinct initial conditions. Experiments 4 and 5 both show the spread when FIRE_SPREAD_CHANCE is high, with the watering effect disabled in Experiment 5, resulting in aggressive fire growth (red) and slower regrowth (yellow to green).

Experiments 6 and 7 illustrate the effect of BURNOUT_PROB. At low values, trees take much longer to stop burning, as shown in Experiment 6. The impact of COMPLETE_RECOVERY_PROB on fire spread is interesting; when the value is high, trees recover fully more easily, making it harder for the fire to die down. This can be observed by comparing the later iterations of Experiments 8 and 9.

Figure 14 displays burning and total affected cell proportions for nine experiments.

All experiments show a sigmoidal curve for affected area due to fire dynamics and limited forest size.

In Experiment 1, fire starts centrally and spreads to edges, decreasing burning trees proportion around iteration 50. Experiment 2 starts in a corner with burning trees proportion increasing continuously. In Experiment 3, fire starts in both corners, rapidly affecting the forest with burn proportion peaking and falling around iteration 60. Experiments 4 and 5 show watering impacts burning trees proportion, while affected trees proportion stays nearly constant. Increasing WATER_FRACTION and WATER_RESOURCE lowers peak fire proportion from 0.6 in 5 to 0.2 in 4. Burn proportion curves for Experiments 6 and 7 are similar, with 6 slightly higher due to low BURNOUT_PROB. Experiments 8 and 9 emphasize previous observations, with an upward dip in 9 burn proportion due to high COMPLETE_RECOVERY_PROB causing reburning.

5.2. Model 2

Multiple scenarios were tested using Model 2 simulator. The goal of these experiments was to model the effect of geographical factors and burn probabilities on the spread of fire. The experiments were run on a 100 x 100 grid for 100 iterations.

Experiment 10 demonstrates the spread of fire with under no special conditions. This provides as a baseline for comparison. Experiment 11 represents the spread of fire

Figure 5. Experiment 1 - Fire starts in the center

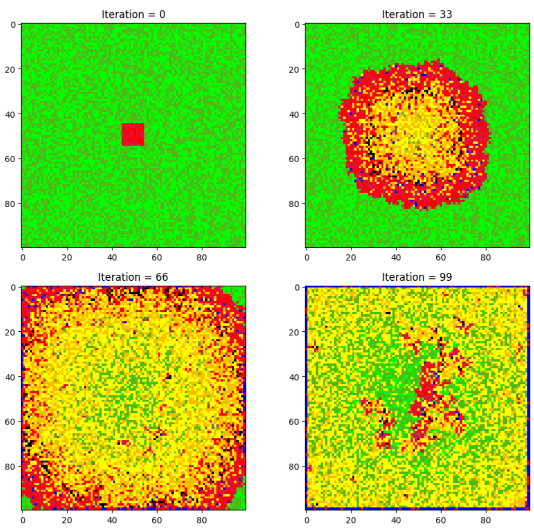
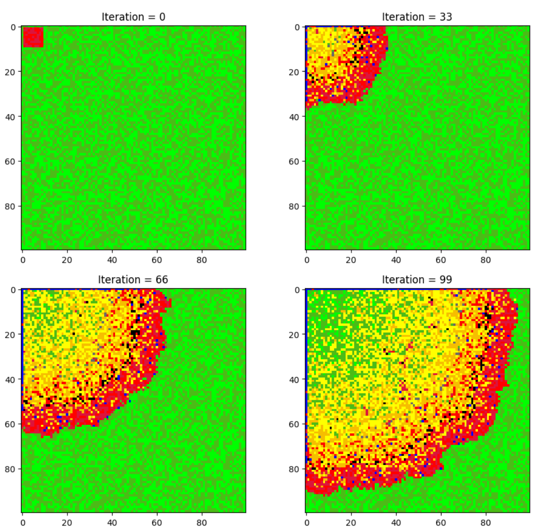


Figure 6. Experiment 2 - Fire starts in a corner



under different initial conditions. At generation 0 the cells on the diagonal are in `BURNING` state. Experiment 12 illustrates the spread of fire when the transition rule that a cell in `BURNING` state will become a `BURNT` state cell in the next step is modelled with a probability $P_{continuous}$. At higher values it is observed that the fire spread is faster. Experiment 13 showcases that the fire does not spread when all the neighboring cells are in `NO VEGETATION/CITY` state.

Figure 15 displays the ratio of forest that was set on fire based on the density and type of vegetation. The data shows that areas with densely packed vegetation and Pine trees are more likely to be burned compared to other types of vegetation and densities. Additionally, the third plot supports the fact that fire does not spread in the absence of vegetation in the surrounding cells.

Figure 7. Experiment 3 - Fire starts in two corners

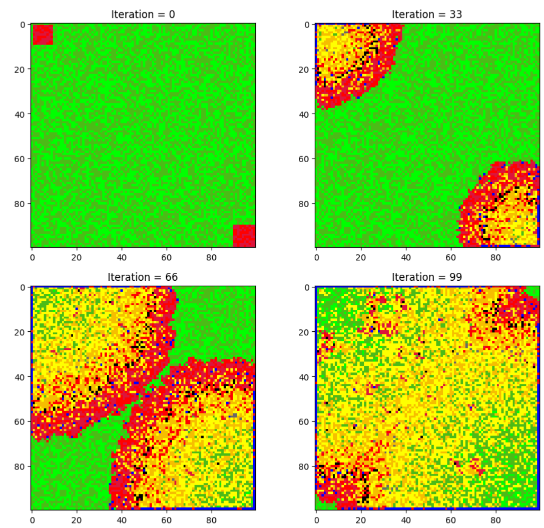


Figure 8. Experiment 4 - High Fire Spread Probability with watering

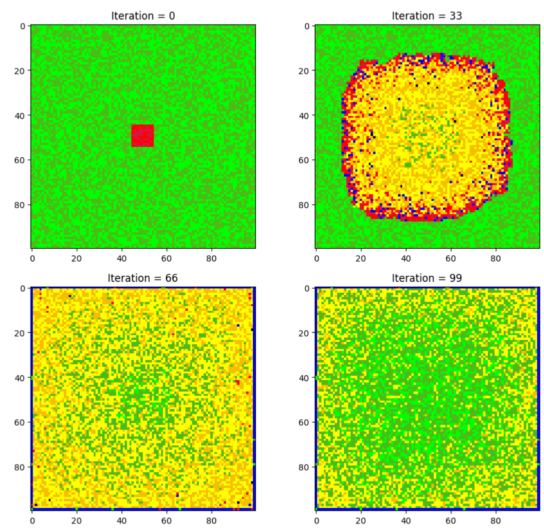


Table 1. Experiment 13 - No Vegetation/ City

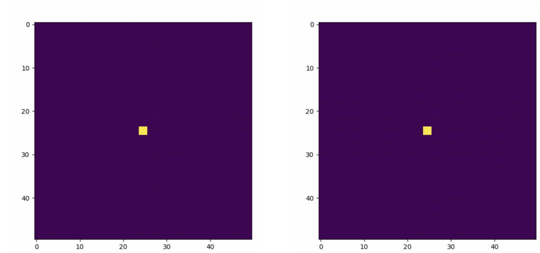


Figure 9. Experiment 5 - High Fire Spread Probability without watering

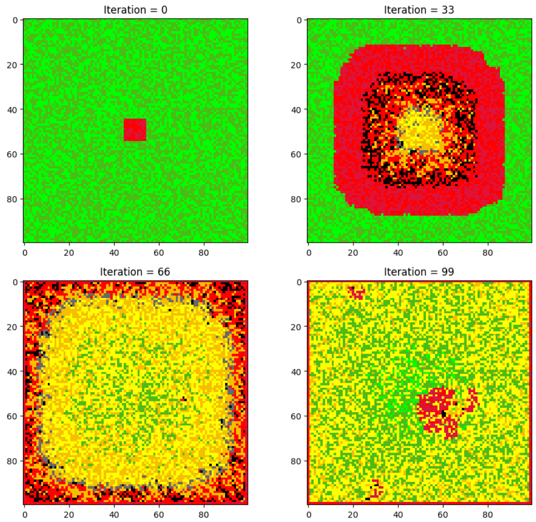


Figure 10. Experiment 6 - Low Burn Out Probability

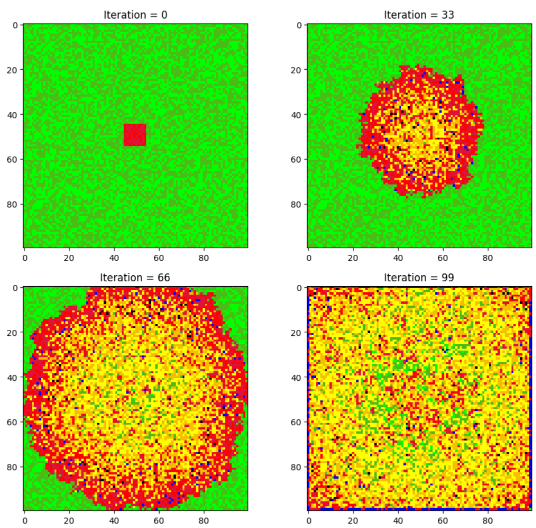


Figure 11. Experiment 7 - High Burn Out Probability

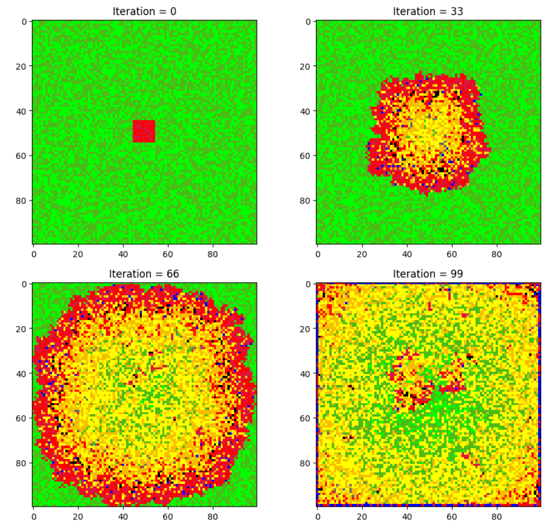
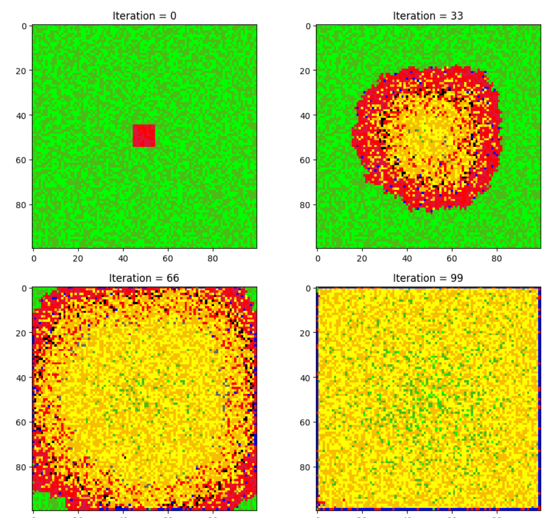


Figure 12. Experiment 8 Low Complete Recovery Probability



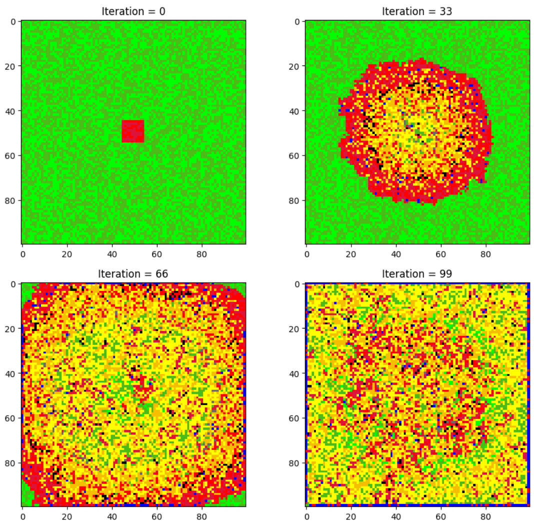
5.2.1 Initial condition

In the first experiment, we initiate the fire at various locations and in various shapes. When the fire is initiated around the diagonal of the square grid, the width of the fire band along the diagonal increases until the whole square grid is filled. This is the expected behavior of spread given how the model has been set up. The visualization can be seen in ?

5.2.2 Burn Probability

The burn probability parameter introduces characteristic features in the simulation. When set to a high value such as 0.9, the fire evolution is coarse and the fine features are not visible. When set to a low value of 0.1, we can see dendrite-like features forming in the fire. For a low value, there is additional growth of fire perpendicular to the principal direction albeit the growth itself is slow (Experiment 12). For a high value, the frontier moves at a faster pace without the spreading in the perpendicular direction. The aforementioned experiments are to understand the effect of fundamental simulation parameters. In the next 2 experiments, we introduce the effect and wind to study the effect of environmental conditions on how the fire spreads. This gives the ability to adapt the model to realistic conditions and quantify the effect of environmental conditions.

Figure 13. Experiment 9 High Complete Recovery Probability



5.2.3 Effect of wind

This is one of our interesting experiments. We add in environmental conditions by simulating the blowing of wind along the east direction. When the wind is not on, the evolution of fire is circular around the initiation point (Experiment 13). When wind is turned on, the fire spreads only in NE and SE directions. We found wind to be one of the most important parameters in governing how the simulation proceeds.

6. Conclusion and Future Work

In conclusion, this study presents two distinct models, Model 1 and Model 2, for simulating forest fire spread and investigating the effects of different environmental conditions and interventions. While both models demonstrate promising results in their respective domains, there is potential for combining them to develop an even more realistic and comprehensive model of fire spread. Additionally, future work could explore incorporating other intervention strategies, such as fire lines created by bulldozers, prescribed burns, and aerial support from helicopters or air tankers, to further enhance the model's applicability in real-world scenarios. Moreover, prevention strategies can also be integrated into the model to study their effectiveness in mitigating the risk of forest fires. These may include vegetation management practices, infrastructure improvements, and public awareness campaigns. To improve computational efficiency and enable real-time decision-making, machine learning techniques and parallel computing can be employed to speed up the simulation process. In this way, the refined model could potentially be used to inform on-ground decisions during firefighting operations, ultimately contributing to more effective forest management and protection strategies.

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7. Appendix

7.1. Division of Labour

- Keerthan - Simulation, Verification of Model 1
- Manvitha - Conceptual Model Building, Experiments & Validation for Model 1
- Vishal - Conceptual Model Building, Experiments & Validation for Model 2
- Aishwarya - Simulation, Experiments and Validation for Model 2

Figure 14. Plots for all Experiments

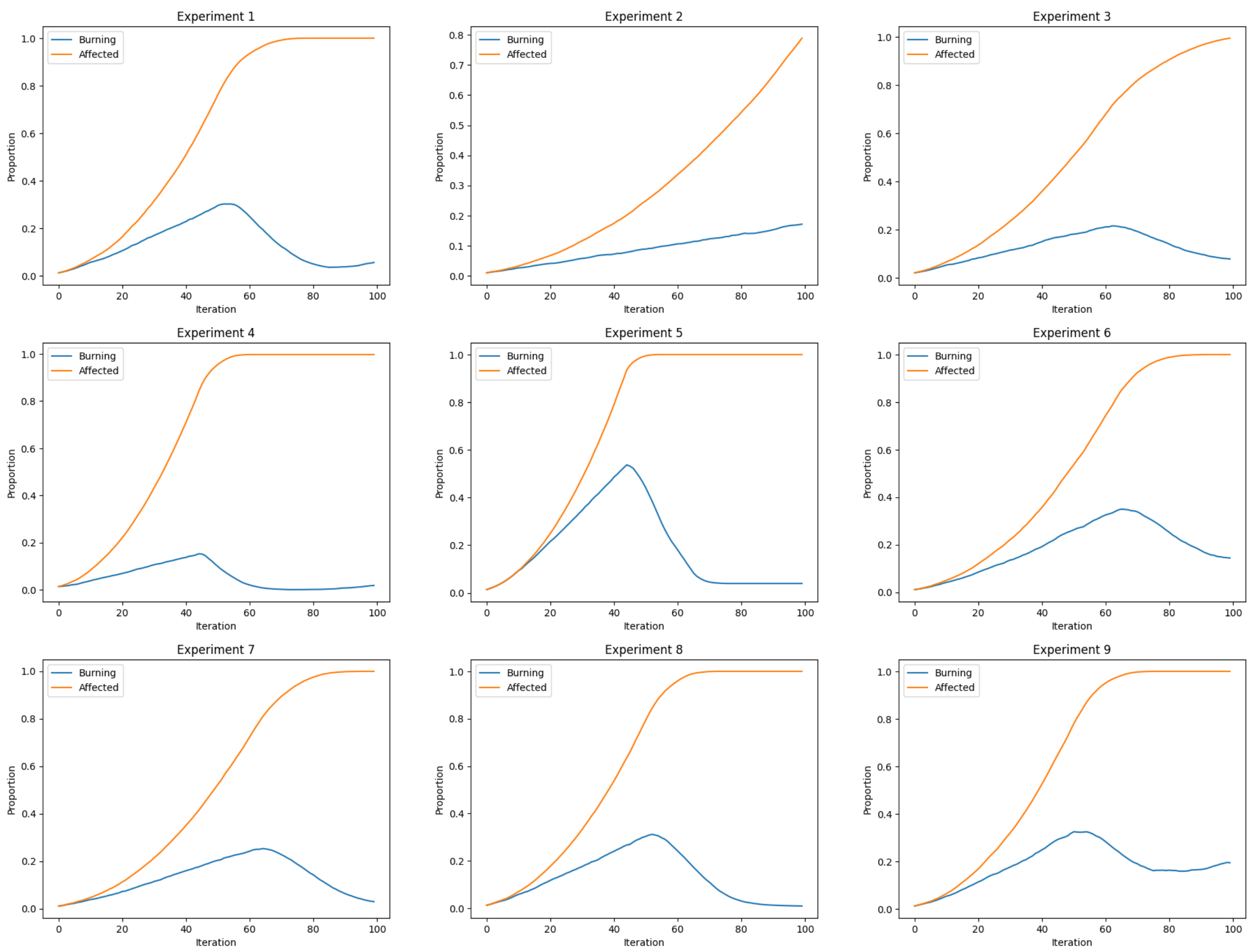

Figure 15. Proportion of Forest Burnt in Model 2

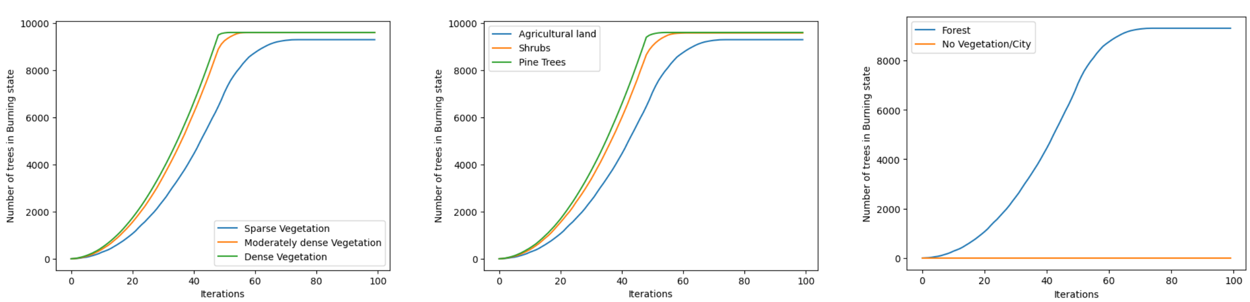

Figure 16. Experiment 10 - No Special Environment Conditions

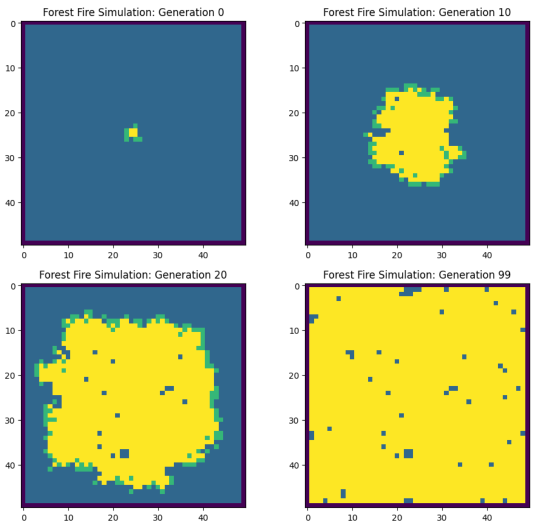

Figure 17. Experiment 11 - Simulation with different Initial Conditions

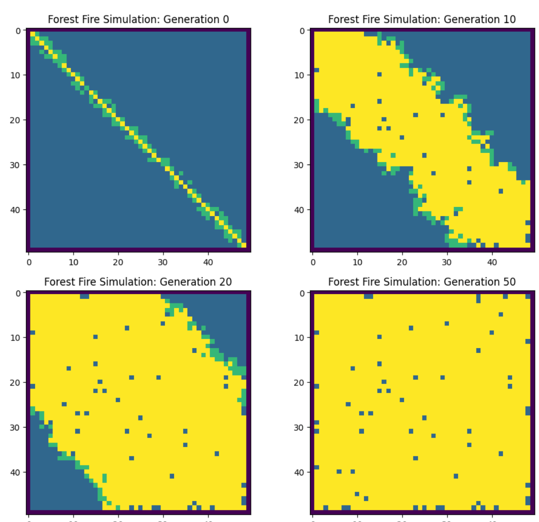

Figure 18. Experiment 12 - Effect of Changing burn probability from 0.1 to 0.9

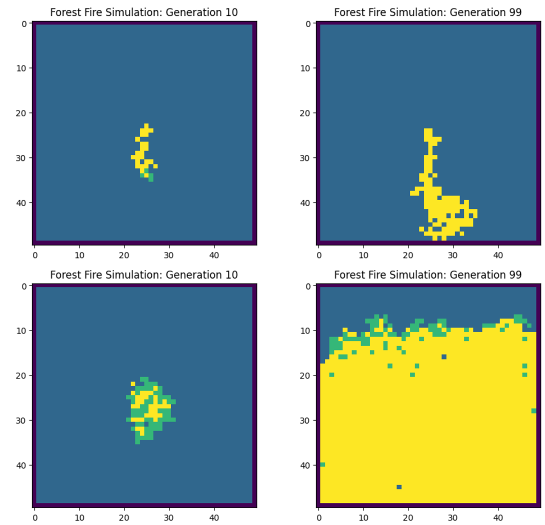

Figure 19. Experiment 13 - Simulation with wind on and off