A Cellular Automaton Approach to Fire Propagation Simulation

Lucas Trindade[1,*]

[1]University Federal Rural de Pernambuco, Department of Computer Science, Brazil
[*]lucas.tlima@ufrpe.br

ABSTRACT

Wildfires represent a significant environmental and economic challenge, posing risks not only to ecosystems but also to human populations and infrastructure. They destroy vast forested regions, release large quantities of carbon into the atmosphere, and accelerate biodiversity loss, while also degrading air quality and impacting local economies. The increasing frequency and severity of wildfires, often attributed to climate change, underscore the urgent need for reliable predictive models. Such models can guide prevention efforts, support decision-making during emergencies, and optimize the allocation of firefighting resources. In this context, we present a simulation of wildfire propagation using a cellular automaton (CA) framework. This approach, implemented in Python, incorporates a visual enhancement where unburned areas are displayed in green, improving interpretability of results and aiding in the differentiation of affected regions. The model reproduces fire spread dynamics by simulating local interactions between neighboring cells, governed by probabilistic rules that capture the stochastic nature of real fires. This methodology offers a computationally efficient alternative to traditional differential equation-based models, which can be complex and resource-intensive.

Introduction

Wildfires are among the most destructive natural disasters, causing significant ecological and economic damage worldwide. The increasing frequency of wildfires due to climate change has made fire prediction and prevention critical areas of study. Traditional models for predicting fire spread rely on complex differential equations and computationally expensive simulations. However, cellular automata (CA) offer an alternative approach that is both computationally efficient and conceptually simple.

Cellular automata are discrete, grid-based computational systems where each cell evolves according to predefined rules based on the states of its neighbors. Originally conceived for theoretical studies in computation, CA have since been applied in diverse areas, including epidemiology, traffic flow, and ecological modeling. In wildfire simulation, CA are particularly useful for studying how local interactions — such as heat transfer between adjacent areas — can lead to large-scale spread patterns. Their simplicity allows for rapid prototyping, and their flexibility enables the inclusion of diverse factors such as wind speed, terrain slope, and vegetation density.

Our model builds upon these advantages, employing a grid where each cell exists in one of three possible states: unburned (green), burning (red), or burned (black). The initial ignition occurs at the center of the grid, from which the fire propagates outward. The visual enhancement of coloring unburned cells in green significantly improves the interpretability of dense simulations, enabling users to quickly assess the progression and extent of the fire.

Results

The simulation results confirm that the CA-based approach captures the essential qualitative characteristics of wildfire spread. When the spread probability parameter is increased, the fire propagates rapidly and covers a larger area within fewer time steps. Conversely, lower probabilities result in slower, more localized fires. This adjustable parameter allows the model to represent different environmental conditions, such as variations in fuel availability or humidity levels.

One of the main contributions of this implementation is the improved visualization of fire spread dynamics. By representing unburned cells in green, burning cells in red, and burned cells in black, the simulation output becomes more intuitive and accessible. This enhancement is particularly valuable in time-series analyses, where distinguishing between unburned and burned areas can be challenging in large grids.

Figure X. Snapshot of the wildfire simulation. Green represents unburned terrain, red indicates burning cells, and black denotes areas already burned. This color scheme improves visual clarity and facilitates temporal analysis of fire spread patterns.

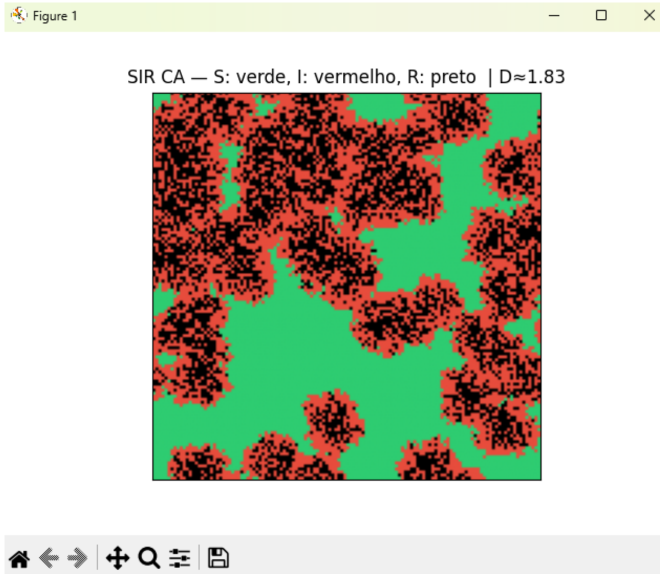

Figure 1. Visualization of the running cellular automaton model, illustrating different stages of fire propagation on a two-dimensional grid.

Discussion

The CA model demonstrates the potential of rule-based simulations for capturing the dynamics of wildfire spread. While it does not yet incorporate complex environmental influences such as wind, terrain elevation, or heterogeneous fuel distribution, its modular design makes such enhancements feasible. These additions would improve realism and predictive accuracy, enabling the model to support more detailed risk assessments.

Moreover, the probabilistic transition rules used in the current version could be further refined by incorporating data-driven methods. For example, machine learning algorithms could be trained on historical wildfire datasets to adaptively adjust spread probabilities under varying environmental conditions. Such integration could bridge the gap between simplified educational models and operational forecasting tools.

The adoption of CA for wildfire modeling offers advantages beyond computational efficiency. It provides a transparent framework in which each step of the fire's progression can be visually and analytically traced, supporting both academic studies and public awareness initiatives. By refining and expanding this approach, researchers can contribute to more effective wildfire preparedness and mitigation strategies.

Methods

Our fire simulation is built on a two-dimensional grid where each cell represents a segment of land and exists in one of three possible states: unburned (green), burning (red), or burned (black). The simulation begins with a single ignited cell at the center of the grid, simulating the start of a wildfire.

The transition rules governing fire propagation are based on a probabilistic approach. A burning cell will transition to a burned state in the next time step, while neighboring unburned cells may catch fire depending on a predefined spread probability. This probability can be adjusted to reflect different environmental conditions such as dryness, wind influence, and vegetation density. The simulation progresses in discrete time steps, updating all cell states synchronously.

Python was chosen for implementation due to its flexibility and the availability of powerful libraries. NumPy is utilized for efficient array operations, while Matplotlib provides a visual representation of fire spread over time. The new green coloration for unburned cells is implemented through a custom colormap, enhancing result clarity without impacting computational performance.

Conclusion

Our cellular automaton-based fire simulation, now with green-highlighted unburned areas, provides a valuable and adaptable tool for studying wildfire propagation. Its modular structure allows for easy customization and expansion, making it a strong foundation for future developments in fire modeling. While simplified, this approach demonstrates the potential of rule-based simulations to provide insights into natural disasters. Future research should focus on integrating additional real-world factors, such as wind patterns and humidity levels, to enhance the accuracy and applicability of the model. By advancing such models, we can contribute to better fire management strategies, minimizing damage and improving response efforts.

References

- Alexandridis, A., Vakalis, D., Siettos, C. I., and Bafas, G. V. (2008). A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through spetses island in 1990. Applied Mathematics and Computation.
- Arai, K. (2013). Cell based gis as cellular automata for disaster spreading predictions and required data systems. Data Science Journal.