Modeling Fire Dynamics, Human Behavior, and Power Supply in Complex Systems Using Agent-Based Models (ABMs)

Abstract

Extreme weather events, such as wildfires, are increasingly characterized by their frequency, intensity, and duration due to the impacts of climate change. These events can be understood as complex adaptive systems (CAS), where environmental factors, infrastructure, and human behavior interact in unpredictable and dynamic ways. This project leverages Agent-Based Models (ABMs) on NetLogo to simulate and analyze the interplay between fire spread, power supply disruption, and resident behavior in such scenarios.

The model incorporates critical factors such as wind dynamics, cascading power outages, and risk-based evacuation strategies to capture the emergent behavior of the system. Key findings reveal the intricate relationships between fire propagation, power infrastructure vulnerability, and evacuation effectiveness, offering insights into the resilience of communities under varying conditions. By framing wildfires and their cascading effects as a complex adaptive system, this project highlights the importance of interdisciplinary approaches in understanding and mitigating the impacts of climate-driven disasters.

I. Introduction

Wildfires represent a critical challenge to urban and semi-urban settings, where dense populations, interconnected infrastructure, and environmental vulnerabilities converge. Understanding the dynamics of fire spread in such settings is essential for improving disaster preparedness, mitigating risks, and enhancing community resilience. Fires do not act in isolation but interact with infrastructure, such as power grids, and influence human behavior, creating cascading effects that amplify the complexity of these events.

Modeling these interactions presents significant challenges. Environmental factors such as wind speed and direction, the flammability of materials, and geographic variations influence fire behavior. Infrastructure vulnerabilities, particularly power grids, can exacerbate the situation by triggering cascading failures when critical components are compromised. Meanwhile, human responses, such as evacuation decisions and movement patterns, further complicate the system (Siam et al., 2022), as they are influenced by both individual perceptions of risk and broader systemic impacts like power outages.

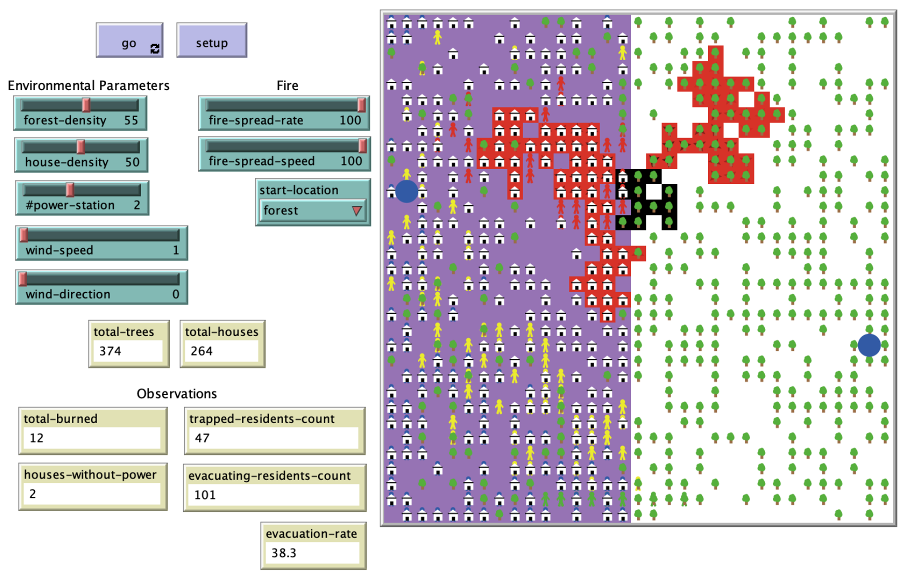
The objective of this study is to develop an Agent-Based Model (ABM) that simulates and analyzes the interactions between fire dynamics, power supply disruptions, and human evacuation behavior. The model aims to provide a better understanding of these interconnected systems and identify key factors that influence their behavior during extreme events.

II. Methodology

The ABM model is built on NetLogo, based on basic tutorials of *Introduction to agent-based modeling* by Wilensky & Rand 2015, and also inspired by the built-in Fire Models from NetLogo library. The environment is a dynamic grid environment representing urban and forested areas, integrating environmental, infrastructural, and human components.

Model Design

Agents include houses, trees, residents, power lines, and power stations, modeled as turtles to facilitate interaction logic. The simulation environment includes all the agents mentioned. On the left purple region (residential area), there are houses distributed randomly and connected to nearby power stations (blue circles) through power lines, which have a blue dot on the roof as shown in the picture below. The urban environment also contains residents and trees as urban vegetation. In contrast, the right side represents a forest and could potentially have power stations. In the model, fires represent the spread of flames across the environment, where red patches indicate active burning and black patches show post-fire burned areas. Residents are the human agents whose behaviors, such as evacuating (yellow), trapped (red), and safe (green), are influenced by proximity to fire, risk perception, and power availability.



The adjustable inputs include forest density (0-100), house density (0-100), the number of power stations (#1-5), wind speed (0-100), wind direction (0-360°), fire spread rate (0-100), fire spread speed (0-100), and fire start location (forest, house, power station). Monitoring outputs are total patches burned, houses without power, trapped/evacuating residents counts, evacuation rate, and plots such as forest/house percentage burn vs. time (ticks) and power supply (# of houses with power) and resident status vs. time (ticks).

Model assumptions include: 1) Wind dynamics (speed and direction) remain constant during each simulation run; 2) residents move towards safety (bottom of the map) and adjust their behavior based on real-time fire risks and power availability; 3) power outages cascade through the grid, affecting connected houses immediately when power stations are damaged.

Key Features
The **fire spread mechanism** is governed by proximity, wind dynamics, and environmental conditions. Wind speed and direction enhance the likelihood of fire propagation in downwind patches. Flammable entities, such as trees, houses, and power stations, ignite probabilistically based on their distance from the fire and their flammability. Power stations are critical for **power outage simulation**. When a fire reaches a power station, it triggers cascading effects by cutting off electricity to connected houses through the power grid. Real-time monitoring tracks the number of houses without power, influencing resident behavior and evacuation likelihood. In terms of **evacuation dynamics**, residents evaluate risk based on proximity to fires and whether their homes are affected by power outages. When risk exceeds a threshold, evacuation is triggered. Evacuating residents move toward safer areas (the bottom of the map), avoiding burned areas if possible. Residents may become trapped if surrounded by fire.

III. Results

I simulated under varying conditions to capture meaningful dynamics of fire spread, power outages, and evacuation. Fires spreading in the forest, urban areas, and in a combined environment of both settings were modeled for interpretation of fire dynamics changes.

A. Fire Spread Simulations

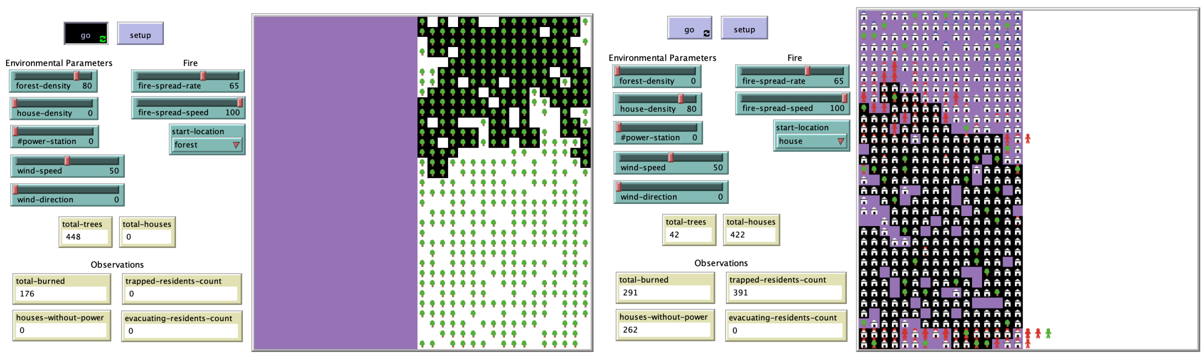
Forest Fires
I started with no urban setting, only fire spread ignited and spread in the forest. The only considered input is forest density. I tested different values of density, ran each value three times, and recorded the average percentage of forest burned in the table below. The tipping point occurs when the tree density parameter crosses a critical threshold, resulting in a nonlinear behavior. At a density of 64%, even a small increase in tree density dramatically alters fire spread dynamics. Below this threshold, the fire's progression is limited and cannot spread across the forest.

Forest Density	50	60	63	64	65	70
Average % Burned	17.4	27.6	38.7	40.8	74.2	97.1

When additional parameters, such as wind speed and direction, were introduced, fire dynamics became more complex. For example, when wind direction aligned with areas of higher tree density, the fire spread more rapidly. Higher wind speeds exacerbated this effect, particularly in forests with densities close to the tipping point. By adding further control over the fire spread rate, scenarios with low wind speeds demonstrated the potential for intervention, limiting fire damage to 20-30% of the forested area even at higher densities. However, high wind speeds consistently led to near-total devastation in areas above 65% density in this case.

Urban Fires

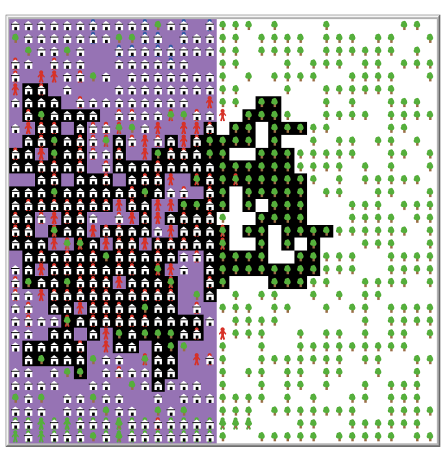
For urban fires, I focused on house density, power supply, and evacuation behavior. While in forested areas, fire spread is heavily influenced by tree density, in urban settings, the spread of fire is influenced not only by house density but the connection to power grids while also influencing residents' behaviors in the presence of power infrastructure. Similarly, urban areas with a high density of houses become highly vulnerable when a fire starts. The fire can easily spread from house to house, exacerbated by the cascading effects of power outages. Power outages occur when houses burn and trigger earlier evacuations. In contrast, fire spread is slower in sparsely populated areas, causing less impact on residents, which simulates fire in suburban areas in the real world case. More residents could reach the bottom of the area and be considered "safe" with less housing-populated simulations that show a higher evacuation rate compared to populated cases.

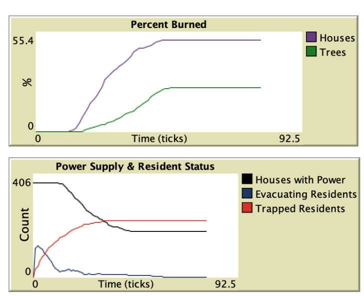


Sample simulations of Forest Fires and Urban Fires.

Urban and Forest Fires Combined

When both urban areas and forests are present in the simulation, the fire ignition location plays a critical role in determining how the fire spreads and how different environmental and infrastructural factors interact. I tested different fire initiation locations - forest, house, and power station - while keeping other parameters consistent to understand the unique dynamics and outcomes of each scenario.



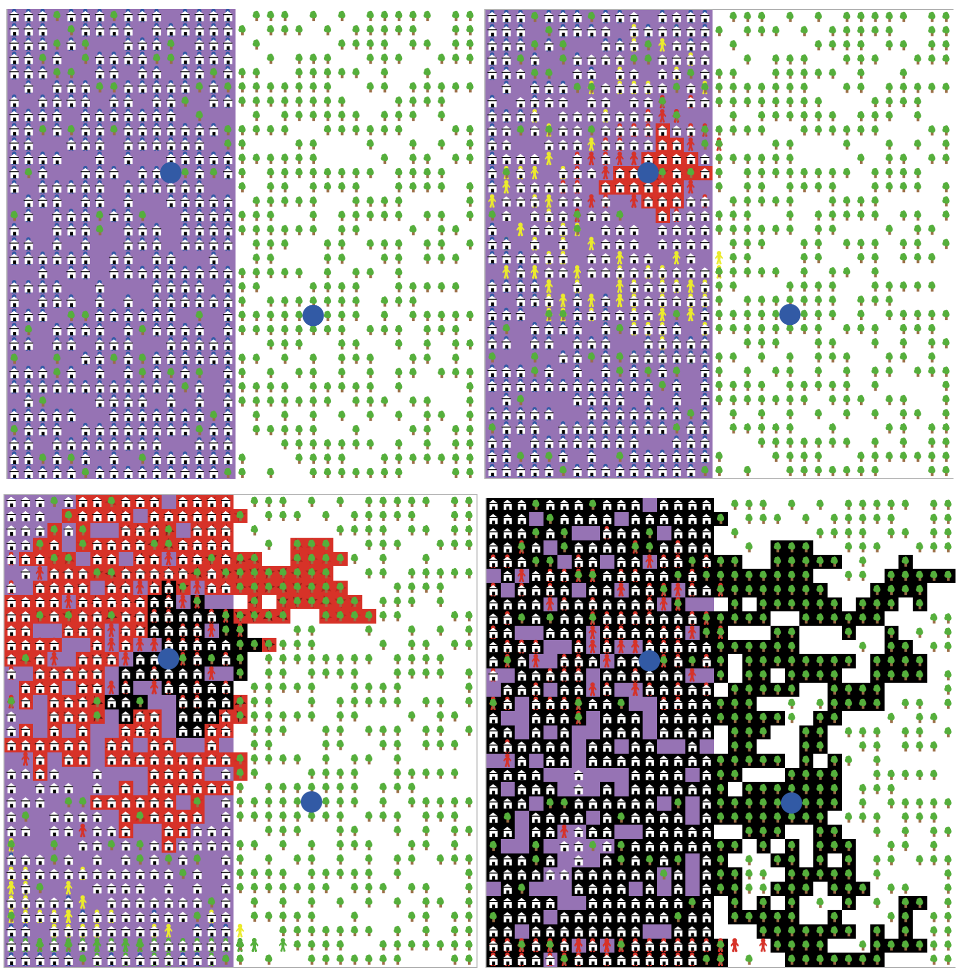


The ignition location primarily determines whether the fire will prevail. If the fire starts closer to the other landscape - such as in the forest but near the housing areas - it is highly likely to spread into the urban environment, as shown in the simulations. This result underscores the importance of understanding the interactions between urban and forested areas, which can help in developing more effective mitigation and evacuation strategies in a realistic complex environment.

B. Power Outage & Evacuation Simulations

In my design, the connectivity of the power grid is influenced by housing density. In areas with high housing density, houses are closely packed and interconnected by many power lines, while in sparsely connected grids, houses are spread out with fewer connections between them and fewer power stations.

A key factor in power outages in my model is that power goes out when a house is burned or the power station in a nearby patch gets destroyed. This means fires must first reach close before power failures occur. As fires spread across the environment, they progressively burn more houses, and as each power station is affected by the fire, the associated power grid connections are lost, causing cascading outages. This has a significant impact on residents' behavior, as power loss is set to influence their sense of safety and urgency in evacuation decisions.

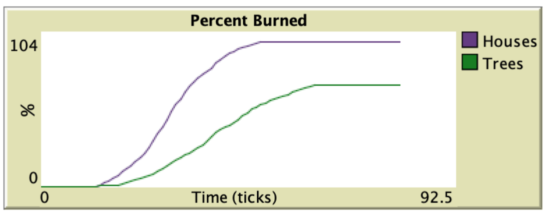


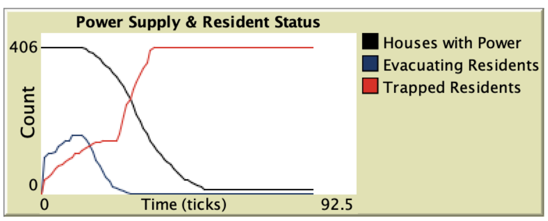
Progress of a fire starting at a power station and propagating through houses and forest

The impact of power outages on evacuation behavior is evident in the simulations. When a fire reaches key residential areas and burns houses, the loss of power accelerates evacuation. Residents who lose power may feel a heightened sense of danger, leading them to evacuate sooner, as they perceive the absence of power as an indicator that their homes are no longer safe. Conversely, areas where power outages occur less frequently or later in the fire's progression experience slower evacuations, as residents may feel safer or more capable of staying longer without power disruptions.

To further develop the analysis, I came up with a **case study** where a fire starts at a power station and then spreads through houses and the forest. The situation might be similar to Maui Fire in August 2023, when the fire was sparked by broken power lines (NBC, 2023). Nearby vegetation under high winds and dry weather fueled the fire for further development.

In this simulation, many residents become trapped as the fire spreads quickly, especially in areas with higher housing density. In these regions, the densely packed houses and interconnected power grid result in rapid power outages as the fire spreads from house to house. This cascading effect not only affects the houses but also the power lines and stations supplying them, causing widespread power loss. The rapid loss of power makes evacuation more urgent, forcing residents to leave their homes earlier due to the perceived loss of safety. I can assume that in areas with sparse housing density, where houses are more spread out and power grid connections are fewer, the fire's progress is slower. As a result, power outages occur more gradually, and residents in these areas may not feel the same urgency to evacuate until the fire gets closer. These residents may also have more time to make evacuation decisions since they are less likely to experience immediate power loss and may feel safer for a longer period.





IV. Discussion and Conclusion

The current simulation model has several limitations that should be addressed in future iterations. First, the model operates on simplified assumptions, such as uniform wind conditions and idealized power connection/evacuation logics. In reality, wind patterns can be highly variable, influenced by factors like terrain, seasonality, and local weather conditions. Other environmental parameters, soil moisture, plant flammability as fuels and many others are not considered as well. Additionally, evacuation behaviors are shaped by complex psychological, social, and logistical factors, many of which are not fully captured in the model. The current representation of the power grid's connectivity relies on housing density, which oversimplifies the real-world complexity of power networks. Real power grids have more intricate structures with redundancies that affect how outages propagate during emergencies. And decentralized power systems exist. This simplification means that the model might not fully account for the nuanced dynamics of real-world evacuations.

From the feedback of one classmate during the Q&A session in the project presentation, another limitation is the assumption of uniform flammability for both houses and trees. In practice, the materials used in housing construction and the type of vegetation present in an area greatly affect fire behavior. For example, certain materials are more fire-resistant, and specific tree species may burn at different rates. Accounting for this variation could improve the model's realism.

Lastly, the evacuation logic assumes that power loss directly triggers evacuation, but in reality, evacuation decisions are based on multiple factors, including perceived risk, available evacuation routes, modes of transportation, and individual circumstances, which the current model does not fully consider. It can also be implemented that people evacuate using various forms of transportation, and their evacuation destinations such as shelters etc.

To improve the model, incorporating real-world data would be highly beneficial. Historical fire spread patterns, wind data, and actual power grid layouts could provide more accurate simulations, enabling the model to better reflect real-world scenarios. By testing the model against real fire incidents or case studies where data is available, I could assess the model's predictive capabilities and identify areas where it may fall short. This would also help validate the model's assumptions and refine its parameters for better accuracy.

In conclusion, the simulations effectively demonstrate the complex interactions between fire dynamics, power outages, and human evacuation behaviors during emergencies. While the model has limitations in its assumptions and design, it provides a valuable foundation for understanding how urban areas can prepare for and respond to disasters. The insights gained from the model underscore the importance of considering the interconnectedness of fire spread, power and housing infrastructure failure, and human responses when designing cities and emergency systems. Moving forward, incorporating real-world data and refining evacuation logic will enhance the model's accuracy and applicability, ultimately contributing to adaptive disaster management and urban planning strategies for human communities.

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