Humidity and Wind Effects on Wildfire Propagation: A Probabilistic Cellular Automaton Approach

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Abstract

Wildfire propagation is a complex phenomenon influenced by environmental factors such as humidity and wind. In this work, we implement a probabilistic cellular automaton model to investigate the impact of fixed wind direction and varying humidity levels on fire spread dynamics. Ensemble simulations were conducted for three humidity levels (H=0.2, 0.5, 0.8), each averaged over 30 independent runs. Results indicate a monotonic decrease in burned area as humidity increases, demonstrating the suppressive effect of moisture on fire propagation. The model highlights the usefulness of cellular automata as simplified yet powerful tools for studying complex spatial phenomena.

1 Introduction

Wildfires represent a major environmental and socio-economic challenge. Their dynamics depend on vegetation density, moisture content, wind conditions, and terrain features. Due to the nonlinear and spatially distributed nature of fire propagation, analytical solutions based on differential equations are often insufficient to capture emergent patterns.

Cellular automata (CA) provide a discrete modeling framework capable of simulating complex global behavior arising from simple local interactions. Because fire spread depends primarily on local neighbor interactions, CA models are particularly suitable for studying wildfire dynamics.

In this work, we develop a probabilistic two-dimensional cellular automaton model incorporating humidity and wind direction as environmental parameters. The objective is to evaluate how moisture levels influence fire propagation under fixed wind conditions.

2 Theoretical Background

2.1 Cellular Automaton Framework

A cellular automaton is defined by four fundamental components:

1. **Lattice:** A two-dimensional discrete grid representing the forest.
2. **States:** Each cell assumes one of four states:
   - 0 – Empty
   - 1 – Tree (unburned)
   - 2 – Burning
   - 3 – Burned
3. **Neighborhood:** Moore neighborhood (eight adjacent cells).
4. **Transition Rule:** A probabilistic rule determining state evolution.

The state evolution follows:

$$\sigma_i(t+1) = \phi(\sigma_{N(i)}(t))$$

where σ_i is the state of cell i and $N(i)$ denotes its neighborhood.

2.2 Probabilistic Modeling of Humidity and Wind

To capture environmental variability, the ignition process is modeled probabilistically.

The ignition probability for a cell i at time $t+1$ is defined as:

$$P_{i,t+1} = P_{base} \cdot f(U) \cdot f(V)$$

where:

- P_{base} is the intrinsic propagation probability.
- $f(U) = (1 - U)$ represents humidity damping, with $U \in [0, 1]$.
- $f(V) = 1 + \alpha(\vec{V} \cdot \vec{d}_{ij})$ represents wind influence.

Here, $\vec{V}$ is a fixed wind vector and $\vec{d}_{ij}$ is the unit vector from a burning neighbor j to cell i. Alignment between wind and propagation direction increases ignition probability, while opposite alignment decreases it.

3 Methods

Simulations were performed on a 100×100 lattice with initial tree density of 0.7. A fixed wind vector $\vec{V} = (1, 0)$ was applied, representing constant horizontal wind.

For each humidity level ($H = 0.2$, 0.5, 0.8), 30 independent simulations were executed. A fixed random seed was used to ensure reproducibility. Simulations terminated when no burning cells remained.

The primary metric evaluated was the total burned area at the end of each simulation.

4 Results

The average burned areas obtained were:

Humidity	Mean Burned Area	Standard Deviation
0.2	15.47	19.50
0.5	4.50	4.16
0.8	1.43	0.92

Results indicate a clear monotonic decrease in fire spread with increasing humidity. Low humidity exhibits both higher mean burned area and significantly larger variance, reflecting stronger stochastic amplification.

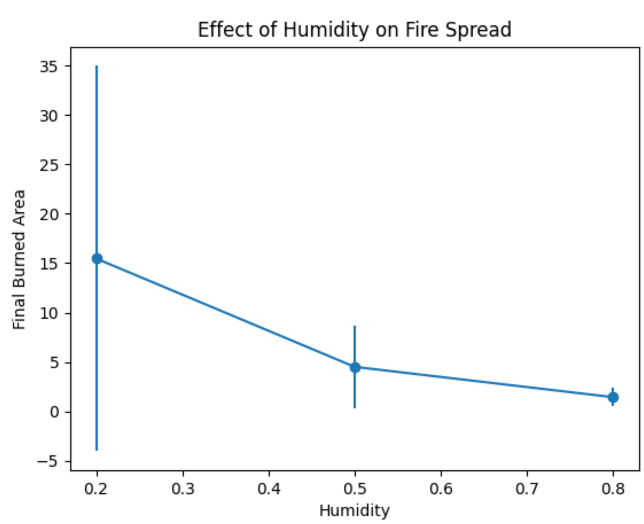

Figure 1: Average burned area as a function of humidity. Error bars represent standard deviation over 30 independent simulations.

5 Discussion

The model demonstrates how simple probabilistic rules can reproduce essential features of wildfire propagation. Increased humidity suppresses fire spread, while low humidity enhances both propagation and variability.

The large variance observed at low humidity suggests proximity to a critical transition regime, where small stochastic fluctuations may lead either to rapid extinction or larger outbreaks.

However, several limitations exist:

- Spatial and temporal discretization may introduce anisotropic artifacts.
- Fuel homogeneity was assumed.
- Topography and variable wind fields were not included.

Despite these simplifications, the model captures key qualitative behaviors.

6 Emergent Phenomena

The simulations illustrate emergent behavior, where global propagation patterns arise from local probabilistic interactions. The transition between extinction and sustained spread resembles phase transition phenomena often observed in complex systems.

Due to algorithmic irreducibility, final outcomes cannot be predicted analytically without executing the simulation step-by-step, emphasizing the importance of computational modeling.

7 Conclusion

This study demonstrates that probabilistic cellular automata provide an effective framework for modeling wildfire propagation. Humidity plays a critical suppressive role, reducing both average burned area and variability. Even simplified models are capable of capturing essential features of complex environmental systems.

Code Availability

The full source code and datasets are available at:

https://github.com/IgorBLQ/forest-fire-cellular-automaton

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