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Article

A cellular automaton-agent hybrid model for forest fire spread and intelligent suppression

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Abstract

Forest fires are complex spatiotemporal phenomena influenced by local interactions, environmental conditions, and human intervention. In this study, we propose a hybrid modeling framework that integrates a probabilistic cellular automaton (CA) for fire propagation with mobile intelligent agents for active suppression. The fire dynamics are governed by neighbor-dependent stochastic rules modulated by vegetation density and wind intensity, while suppression agents dynamically move toward burning sites and probabilistically extinguish fires. We conduct systematic multi-scenario experiments to examine (1) the impact of wind speed, (2) vegetation density, and (3) the number of suppression agents on fire evolution. Results reveal nonlinear relationships between these parameters and suppression efficiency, including threshold effects and diminishing returns in agent scaling. The model demonstrates how spatial structure, stochasticity, and adaptive control jointly shape fire outcomes. Our framework provides a flexible platform for studying coupled human-environment dynamics and offers insights into optimal resource allocation for wildfire management.

Keywords cellular automata; forest fire modeling; multi-agent systems; wildfire suppression; complex systems; spatial dynamics.

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1 Introduction

Wildfires represent one of the most destructive natural-human coupled disturbances, shaping ecosystems, threatening infrastructure, and causing substantial economic and environmental losses worldwide. Over the past decades, considerable effort has been devoted to understanding wildfire dynamics through mathematical and computational models. Classical approaches, such as differential equation models and continuum-based reaction-diffusion frameworks, have provided valuable insights into average fire behavior and large-scale trends. However, these approaches often struggle to capture the inherently discrete, heterogeneous, and stochastic nature of real landscapes, where local interactions, spatial variability, and human interventions play decisive roles in fire evolution.

Cellular automata (CA) have emerged as a powerful alternative for modeling wildfire dynamics due to their ability to represent complex spatiotemporal processes through simple local rules (Zhang et al., 2015). In CA-based fire models, each cell represents a patch of vegetation that can transition between different states (e.g., healthy, burning, or burned) depending on the states of neighboring cells and environmental conditions such as wind and fuel availability. This bottom-up modeling paradigm naturally captures emergent fire patterns, including spreading fronts, clustering, and fragmentation, which are difficult to reproduce using purely continuous models. As a result, CA models have been widely applied to explore fire spread, risk assessment, and landscape-level resilience.

Despite these advances, most existing CA wildfire models remain largely passive representations of environmental dynamics: fire spreads according to predefined rules, but human intervention is either absent or modeled in a highly simplified and static manner. In many studies, suppression is treated as a global parameter (e.g., a fixed probability of extinguishment) rather than an explicit, spatially situated process carried out by mobile actors. Consequently, these models overlook a crucial aspect of real-world wildfire management—the adaptive, goal-directed, and spatially constrained behavior of firefighting teams.

In parallel, multi-agent systems (MAS) have been increasingly used to simulate human decision-making and coordinated action in complex environments. However, the integration of mobile intelligent agents into cellular automaton wildfire models remains underdeveloped. Most agent-based fire studies either decouple agents from the fire dynamics or rely on coarse-grained grid representations that dilute the fine-scale spatial interactions central to CA modeling. There is thus a clear need for a unified framework that tightly couples probabilistic fire propagation with adaptive, spatially aware suppression agents within a single, high-resolution CA environment.

To address this gap, this paper proposes a hybrid Cellular Automaton-Agent (CA-Agent) model for wildfire spread and suppression. The model combines a stochastic, neighbor-dependent fire propagation mechanism with a team of mobile intelligent agents that actively seek and extinguish burning cells. Unlike previous approaches that treat suppression as a uniform or random process, our agents exhibit targeted pursuit behavior, continuously updating their positions based on the evolving spatial distribution of fire. This design enables a more realistic representation of firefighting dynamics and reveals nontrivial interactions between fire spread, environmental conditions, and human intervention.

Specifically, the model introduces three core innovations: Coupled stochastic fire-agent dynamics. We develop a tightly integrated framework in which fire propagation and agent behavior co-evolve on the same cellular grid. Fire spread is probabilistic and neighbor-driven, while agents dynamically adapt their movements in response to real-time fire patterns. This bidirectional coupling allows us to study feedback loops between environmental processes and human actions, which are largely absent in conventional CA fire models. Spatially adaptive suppression agents. Instead of applying suppression uniformly across the landscape, we introduce mobile agents that identify the nearest burning cells and move stepwise toward them. Extinguishment occurs locally and probabilistically upon contact. This represents a shift from abstract “global control” to embodied, location-based intervention, capturing the constraints and strategies of real firefighting operations. Multi-parameter experimental framework linking environment and agency. We design a systematic experimental protocol that jointly varies wind intensity, vegetation density, and the number of suppression agents. This allows us to disentangle the relative contributions of environmental forcing and human capacity, revealing nonlinear effects such as threshold transitions in fire containment and diminishing returns in agent deployment. By embedding intelligent agents within a high-resolution cellular automaton, the proposed model bridges the gap between environmental dynamics and human decision-making. Beyond wildfire research, the framework offers a general platform for studying other coupled human-natural systems where local interactions, spatial structure, and adaptive control are critical.

2 Related Work

The modeling of forest fire dynamics using cellular automata (CA) has become a central research direction in wildfire simulation due to the capability of CA models to represent spatial heterogeneity and localized interactions at fine spatial scales. Classical CA-based approaches describe wildfire propagation by incorporating environmental variables such as vegetation structure, wind conditions, and terrain characteristics (Freire and DaCamara, 2019). Early research by Karafyllidis and Thanailakis (1997) introduced a CA framework for predicting wildfire spreading probabilities, establishing one of the earliest discrete formulations for fire propagation in heterogeneous landscapes. Subsequently, Alexandridis et al. (2008) developed a CA wildfire model validated using historical large-scale fire events.

Later studies integrated geographical information systems (GIS) with CA models to improve spatial realism and environmental representation in fire behavior simulations (Yassemi et al., 2008). Stochastic CA formulations were further introduced to capture probabilistic fragmentation and uncertainty in fire spread processes across complex terrains (Trucchia, 2020). Several works have extended CA wildfire modeling through optimization strategies and physics-informed modifications to better approximate continuous simulators such as FARSITE (Finney, 1998).

Recent developments have incorporated intelligent computation into CA frameworks. Zhou et al. (2018) combined multi-agent algorithms with CA to enhance spatial diffusion modeling of forest fires, while machine learning-assisted CA models have been proposed to dynamically learn state transition rules from environmental data (Xu et al., 2022). Extensions of CA modeling have also been applied to grassland wildfire simulations, demonstrating the adaptability of CA approaches across different vegetation ecosystems (Li et al., 2023).

Parallel to CA-based research, agent-based modeling (ABM) has been employed to represent autonomous entities interacting with wildfire environments. Hybrid simulation approaches integrating agent behaviors with environmental dynamics have shown improved realism in wildfire management scenarios (Katan et al., 2021). Agent-based wildfire studies further emphasize the importance of embedding suppression strategies directly into spatial simulations (Niazi et al., 2007). In addition, deep learning surrogate models have recently been proposed to accelerate wildfire burned-area prediction relative to computationally intensive CA simulations (Sahila et al., 2025). Comprehensive review studies highlight the evolution of wildfire modeling from empirical and physical formulations toward discrete, data-driven, and hybrid computational frameworks (Sullivan, 2007).

More recent research has focused on integrating fire-atmosphere coupling mechanisms into CA-like simulation structures (Achtemeier, 2013), optimizing wildfire propagation algorithms (Tinoco, 2022), and validating operational CA wildfire simulators for risk assessment applications (Finney, 1998). Probabilistic extensions such as Bayesian and latent dynamic CA models have also been introduced to quantify uncertainty in spatiotemporal wildfire forecasting (Grieshop and Wikle, 2023). Despite these advances, most existing approaches model wildfire spread as a passive environmental process without explicitly coupled intelligent response mechanisms. In contrast, the present study embeds adaptive suppression agents directly within a CA wildfire framework, enabling dynamic interactions between agents and fire propagation processes and addressing a key limitation in current forest fire simulation methodologies (Xu et al., 2024).

3 Methodology

We develop a hybrid modeling framework that couples a stochastic cellular automaton (CA) for wildfire propagation with a population of mobile intelligent suppression agents operating on a shared spatial lattice. The model is implemented on a two-dimensional square grid of size $L \times L = 50 \times 50$, where each cell represents a homogeneous patch of vegetation that can exist in one of four discrete states: healthy fuel EMPTY, state 0, actively burning BURNING,state1, irreversibly burned BURNED, state 2, or successfully extinguished EXTINGUISHED, state 3. The system is initialized with a single ignition point placed at the center of the domain to ensure spatial symmetry at the onset of the simulation and to avoid boundary-driven artifacts in early fire evolution. Time advances in discrete steps, and all cells are updated synchronously at each iteration.

Fire propagation is governed by a probabilistic, neighbor-dependent rule that integrates both local interaction and environmental forcing. For each healthy cell, the probability of ignition depends on the number of burning neighbors within its Moore neighborhood eight adjacent cells and on two global control parameters: a baseline vegetation parameter α_0 and a dimensionless wind intensity parameter (w). Specifically, the effective spread propensity is defined as α_{eff}=clip[(1-α_0)+0.45w,,0.1,,0.9], ensuring that fire spread remains within physically plausible bounds. The ignition probability is then given by $p_{spread}=1-(1-\alpha_{eff})^{n_f}$, where n_f is the number of burning neighbors. This formulation captures nonlinear contagion effects: isolated burning cells have limited influence, whereas clustered fires dramatically increase local risk. Once ignited, a burning cell transitions to the burned state with a fixed probability of 0.12 per time step, representing fuel consumption and thermal decay.

To represent active human intervention, we introduce N_a mobile suppression agents that operate on the same grid as the fire dynamics. Each agent is initialized at a random location and possesses only local spatial awareness of current burning cells. At every time step, an agent identifies the nearest burning cell using a Euclidean distance metric, moves one grid cell in the direction of that target, and attempts suppression upon contact. If the agent occupies a burning cell, extinguishment occurs with probability 0.8, converting the cell to the EXTINGUISHED state. Agents are bounded within the domain and do not collide or coordinate explicitly; their collective effect emerges from parallel, decentralized pursuit of active fires. This design captures essential features of real firefighting: spatial constraints, limited speed, and probabilistic success.

To systematically evaluate the coupled fire-agent dynamics, we conduct three controlled experimental suites, each repeated across multiple stochastic trials to reduce random variability. In Experiment 1, we vary wind intensity w = 0.1, 0.4, 0.7 while holding vegetation density $\alpha_0=0.5$ and agent count $N_a=20$ constant, isolating the role of atmospheric forcing. In Experiment 2, we vary vegetation density through $\alpha_0=0.8,0.5,0.2$ (representing sparse, normal, and dense fuel conditions) while fixing wind w = 0.2 and agents $N_a=20$. In Experiment 3, we scale the number of agents $N_a=10,20,40$ under fixed environmental conditions $\alpha_0=0.5,w=0.2$ to assess diminishing returns in suppression capacity.

For each configuration, we record time series of two primary system-level metrics: (i) the total number of burning cells at each step, characterizing fire intensity, and (ii) the cumulative number of extinguished cells, quantifying suppression effectiveness. Simulations terminate when no burning cells remain or when 250 time steps are reached, whichever occurs first. Ensemble averages across trials are computed to produce smoothed trajectories for comparative analysis.

This methodological framework enables a direct, transparent coupling between stochastic environmental processes and adaptive agent behavior, providing a reproducible platform for studying how spatial structure, randomness, and human intervention jointly shape wildfire outcomes.

4 Experiment

To systematically investigate the coupled dynamics between stochastic wildfire propagation and intelligent suppression agents, we designed a set of controlled numerical experiments that disentangle the roles of environmental forcing and human intervention. All experiments were conducted on a 50×50 cellular grid initialized with a single ignition point at the center. Each configuration was repeated across two independent stochastic trials with different random seeds to reduce noise and ensure statistical robustness. Simulations were terminated when no burning cells remained or when a maximum of 250 time steps was reached. Two primary system-level metrics were recorded at each step: (i) the number of actively burning cells, representing fire intensity, and (ii) the cumulative number of extinguished cells, representing suppression performance. Ensemble-averaged trajectories were then computed and visualized as time-series curves.

4.1 Impact of Wind Intensity

In the first experimental suite, we examined how wind intensity modulates fire spread and suppression outcomes while keeping vegetation density $\alpha_0=0.5$ and the number of suppression agents $N_a=20$ constant. Three wind scenarios were tested: low $w=0.1$, moderate $w=0.4$, and high $w=0.7$.

The results reveal a strongly nonlinear relationship between wind intensity and fire evolution. Under low wind conditions, fire expansion remained spatially localized, allowing suppression agents to reach and extinguish burning cells efficiently. The number of burning cells peaked early and declined rapidly, while the cumulative extinguished cells increased steadily toward a high final value, indicating successful containment.

As wind intensity increased to $w=0.4$, the fire exhibited faster lateral propagation and larger transient clusters of burning cells. Although agents were still able to suppress the fire eventually, the peak fire intensity increased and the time required for full containment was significantly prolonged. The extinguished-cell curve showed a delayed rise, reflecting increased difficulty in tracking and reaching dynamically evolving fire fronts. Under high wind $w=0.7$, the system crossed an effective “containment threshold.” Fire spread became more fragmented and spatially dispersed, overwhelming local suppression capacity. Agents frequently encountered newly ignited cells faster than they could extinguish existing ones, leading to persistent burning pockets. Consequently, the final number of extinguished cells was markedly lower than in the other scenarios, while the burned area increased. These findings suggest that wind introduces a critical regime shift in which conventional localized suppression strategies lose effectiveness.

4.2 Effect of Vegetation Density

The second experiment focused on the role of vegetation density, represented through the parameter α_0, while fixing wind at $w=0.2$ and agent count at $N_a=20$. Three landscape conditions were compared: sparse fuel $\alpha_0=0.8$, moderate fuel $\alpha_0=0.5$, and dense fuel $\alpha_0=0.2$.

In sparse vegetation scenarios, ignition probability remained relatively low even in the presence of burning neighbors. Fire clusters were small and short-lived, enabling agents to rapidly eliminate active flames. The extinguished-cell curve increased smoothly and saturated quickly, indicating efficient suppression with minimal burned area.

In the moderate vegetation case, fire dynamics displayed richer spatiotemporal patterns, including branching fronts and transient clusters. Suppression performance remained effective overall, but with noticeable temporal fluctuations in the number of burning cells. This regime represents a balanced interplay between environmental risk and agent capability.

Under dense vegetation, fire propagation was substantially amplified due to higher baseline flammability. Burning clusters grew more rapidly and persisted longer, often forming large contiguous regions that were difficult for agents to penetrate. Although agents still contributed to suppression, their impact was less pronounced, and the final burned area was significantly larger. These results demonstrate that vegetation density critically controls system vulnerability and defines the operational limits of localized firefighting strategies.

4.3 Experiment 3: Scaling of Suppression Agents

The third experiment investigated how the number of suppression agents affects fire outcomes under fixed environmental conditions $\alpha_0=0.5, w=0.2$. Three agent densities were tested: $N_a=10$, 20, and 40.

Increasing the number of agents from 10 to 20 produced a substantial improvement in suppression performance. Fires were contained more rapidly, peak burning intensity was reduced, and the total number of extinguished cells increased markedly. This suggests that a moderate increase in resources can significantly enhance system resilience.

However, scaling from 20 to 40 agents yielded diminishing returns. While containment occurred slightly faster, the marginal benefit in terms of reduced burned area and increased extinguishment was comparatively small. This saturation effect arises because agents begin to compete for the same burning targets rather than exploring new regions, leading to redundant coverage. The results indicate the existence of an optimal agent density beyond which additional resources offer limited efficiency gains.

4.4 Integrated Interpretation

Taken together, the three experimental suites reveal a coherent picture of coupled fire-agent dynamics. Wind and vegetation density act as primary drivers of environmental risk, while agent density determines adaptive response capacity. The system exhibits clear nonlinearities, including threshold transitions under high wind and saturation effects under excessive agent deployment.

Importantly, the results demonstrate that suppression effectiveness is not solely a function of agent quantity but depends critically on spatial accessibility and temporal coordination with evolving fire patterns. The hybrid CA-Agent framework thus captures key trade-offs between environmental forcing and human intervention, offering a flexible platform for exploring wildfire management strategies.

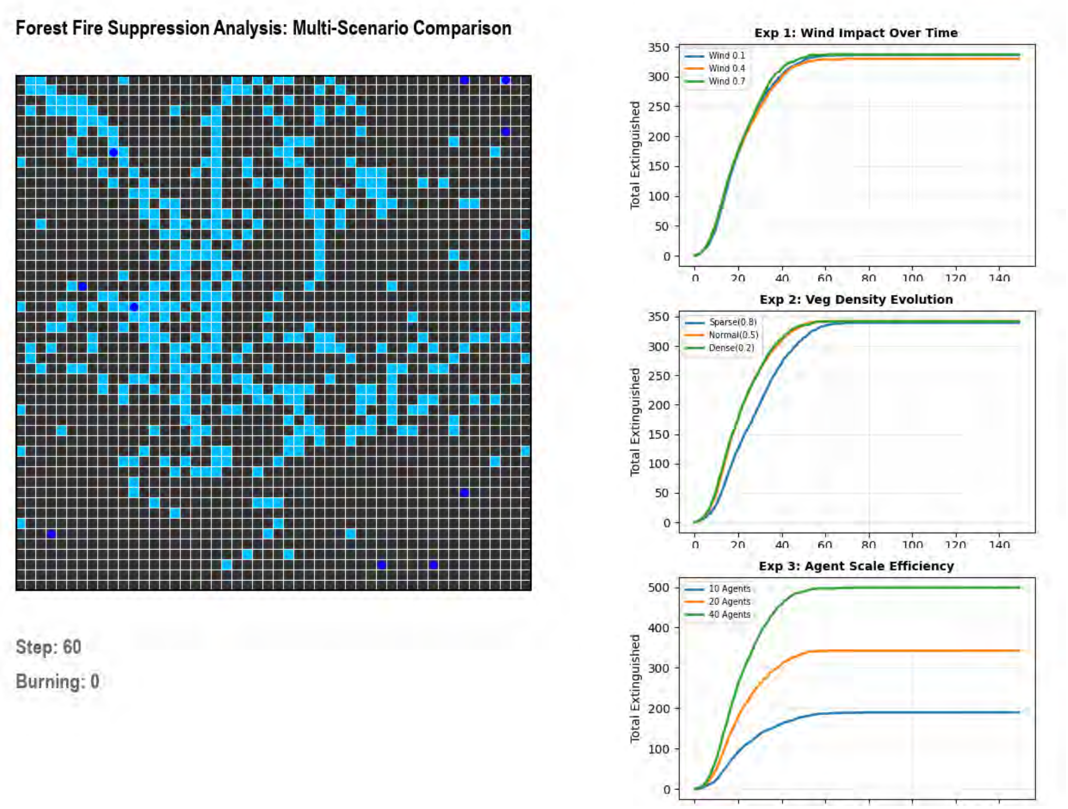

Fig. 1 Spatiotemporal illustrations of forest fires.

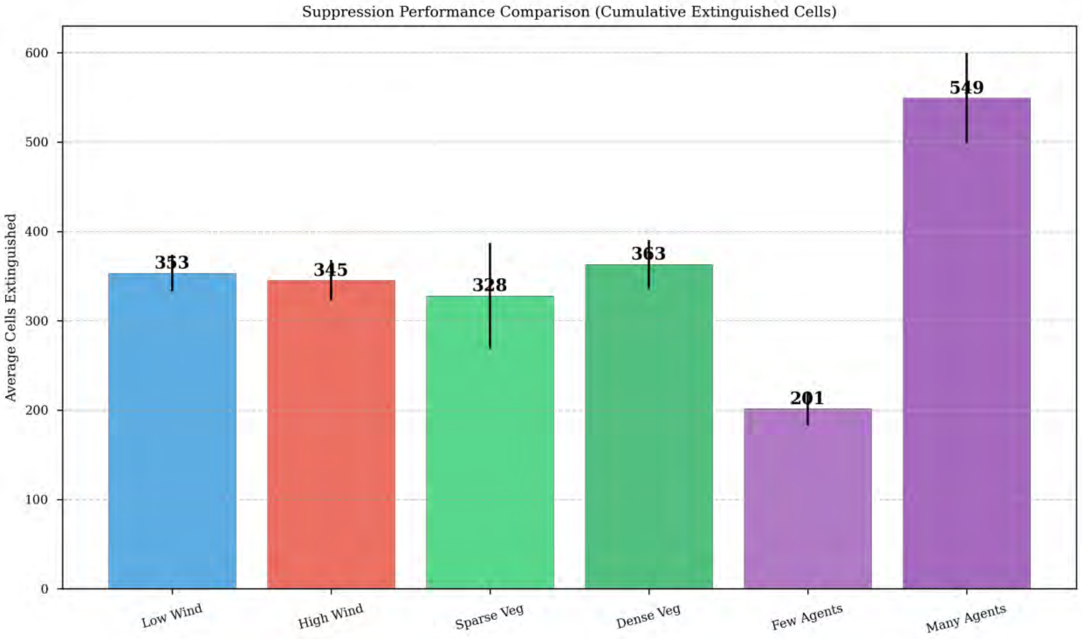

Fig. 2 Suppression Performance Comparison diagram.

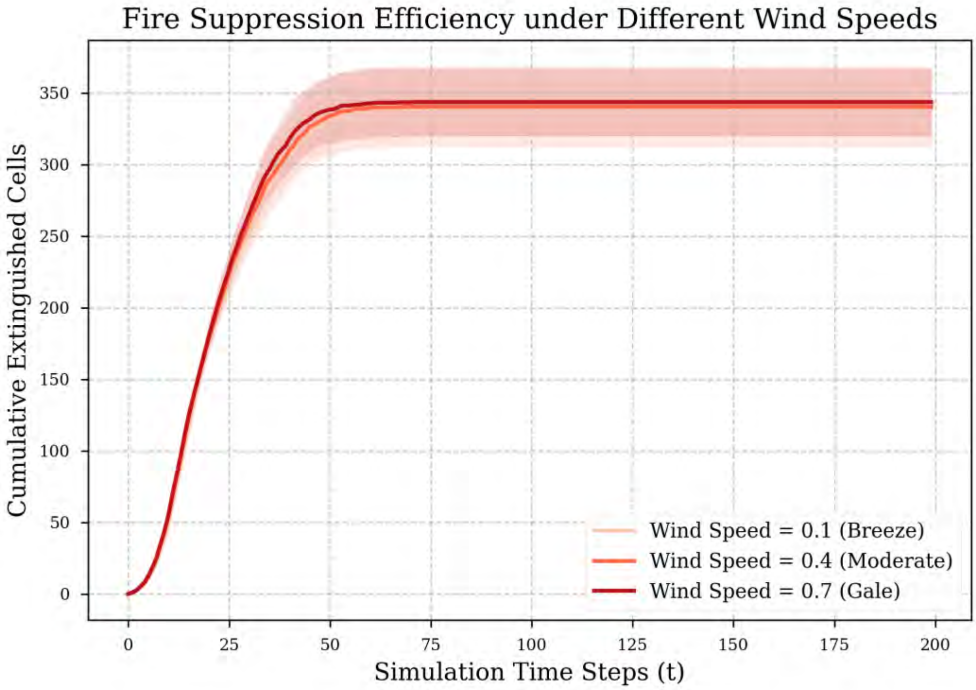

Fig. 3 Fire Suppression Efficiency under Different Wind Speeds diagram.

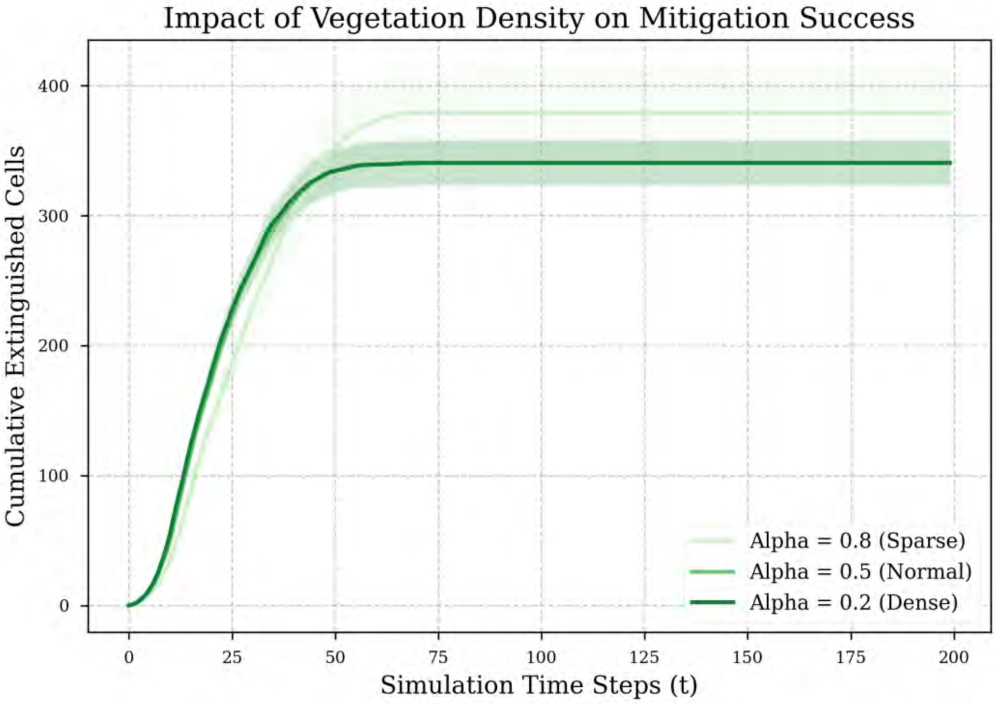

Fig. 4 Impact of Vegetation Density on Mitigation Success diagram.

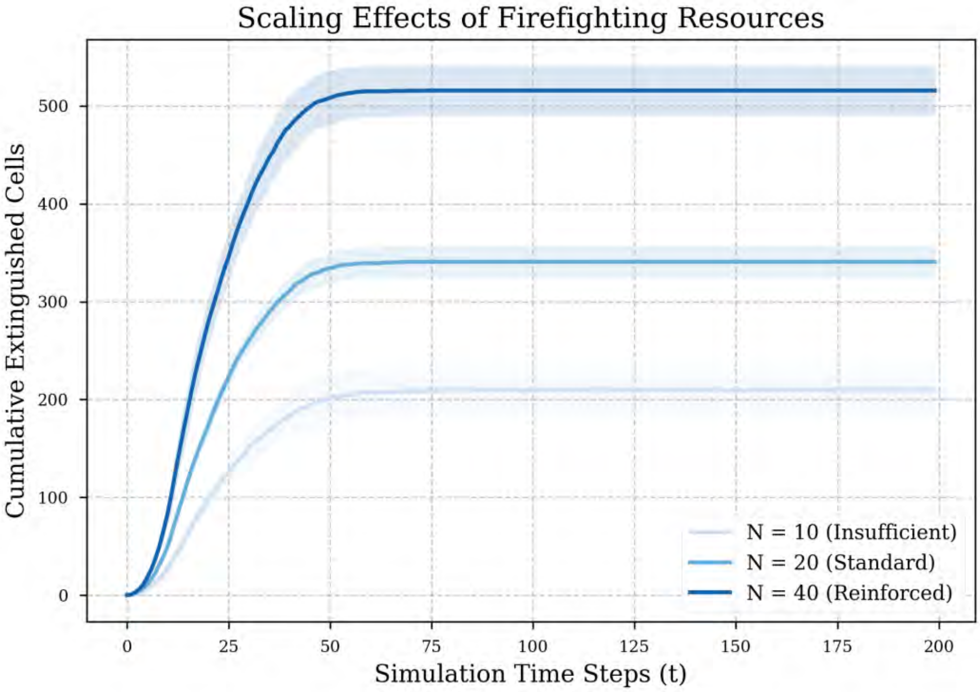

Fig. 5 Scaling Effects of Firefighting Resources diagram.

5 Conclusions

This study presented a hybrid cellular automaton-agent framework for exploring the coupled dynamics of wildfire spread and intelligent suppression. By embedding mobile, goal-directed agents directly within a stochastic fire-propagation lattice, the model moves beyond traditional passive wildfire simulations and captures the mutual feedback between environmental processes and human intervention. Systematic numerical experiments revealed that fire outcomes are shaped by nonlinear interactions among wind intensity, vegetation density, and suppression capacity. In particular, we observed threshold-like behavior under strong wind conditions and clear diminishing returns when agent density exceeded a moderate level, indicating that effective wildfire control depends more on spatial strategy than on sheer resource quantity.

Beyond reproducing plausible fire patterns, the framework offers a flexible platform for investigating broader human-environment interactions in spatially complex systems. Future work may incorporate terrain heterogeneity, dynamic weather fields, and learning-based agents to further enhance realism and decision-making capability. Overall, the proposed approach demonstrates how relatively simple local rules can generate rich collective behavior while providing actionable insights for the design of adaptive, spatially aware wildfire management strategies.

References

Alexandridis A, Vakalis D, Siettos CI, Bafas GV. 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, 204: 191-201. https://doi.org/10.1016/j.amc.2008.06.046

Achtemeier GL. 2013. Field validation of a free-agent cellular automata model of fire spread with fire-atmosphere coupling. International Journal of Wildland Fire, 22: 148-158

Finney MA. 1998. FARSITE: Fire Area Simulator—Model Development and Evaluation. USDA Forest Service, RMRS-RP-4

Freire JG, DaCamara CC. 2019. Using cellular automata to simulate wildfire propagation and to assist in fire management. Natural Hazards and Earth System Sciences, 19: 169-179. https://doi.org/10.5194/nhess-19-169-2019

Grieshop N, Wikle CK. 2023. Data-driven modeling of wildfire spread with stochastic cellular automata. arXiv preprint

Karafyllidis I, Thanailakis A. 1997. A model for predicting forest fire spreading using cellular automata. Ecological Modelling, 99: 87-97. https://doi.org/10.1016/S0304-3800(96)00194-4

Katan J, et al. 2021. Toward an agent-based approach to simulating wildfire behavior. Preprint

Li Y, et al. 2023. A novel method of modeling grassland wildfire dynamics based on cellular automata. ISPRS International Journal of Geo-Information, 12(12): 474. https://doi.org/10.3390/ijgi12120474

Niazi QS, et al. 2007. Verification and validation of an agent-based forest fire simulation model. Academia

Sahila A, et al. 2025. Statistical dynamics of wildfire burned area from cellular automata models. Scientific Reports, 16(1): 998. doi: 10.1038/s41598-025-30851-3

Sullivan AL. 2007. A review of wildland fire spread modelling, 1990-present: Mathematical analogues and simulation models. arXiv preprint

Tinoco CR. 2022. Wildfire simulation model based on cellular automata. Proceedings, 246 - 256. https://doi.org/10.1007/978-3-031-14926-9_22

Trucchia A. 2020. An operational cellular-automata-based wildfire simulator. Fire, 3(3): 26

Xu Y, et al. 2022. Modeling forest fire spread using machine learning-based cellular automata in a GIS environment. Forests, 13(12): 1974. https://doi.org/10.3390/f13121974

Xu C, et al. 2024. A forest fire prediction model based on cellular automata and machine learning. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3389035

Yassemi S, Dragicevic S, Schmidt M. 2008. Design and implementation of an integrated GIS-based cellular automata model to characterize forest fire behaviour. Ecological Modelling, 210: 71-84

Zhang WJ, Qi YH, Zhang ZG. 2015. A cellular automaton for population diffusion in the homogeneous rectangular area. Selforganizology, 2(1): 13-17

Zhou G, Wu Q, Chen A. 2018. Forestry fire spatial diffusion model based on multi-agent algorithm with cellular automata. Journal of System Simulation, 30(3): 824-831. https://doi.org/10.16182/j.issn1004731x.joss.201803007