Investigating the Use of Agent-Based Modeling for Wildfire Prevention: A Simulation Study

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**THESIS SUBMITTED IN PARTIAL FULFILLMENT
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Abstract

Wildfires pose a growing threat resulting from climate change, the loss of biodiversity and human activity (Jones et al., 2024). This research explores economic and sustainable firefighting approaches using autonomous drone swarms, traditional aircraft, and hybrid models. A simulation framework created in Python using the agent-based modeling library Mesa (ter Hoeven et al., 2025) simulates these methods focusing on cost, environmental impact, and computational efficiency. Drones, planes, fires, and resource stations were modeled as agents in the environment with parameters supported by current research. Results from 1000 steps over 1000 simulation iterations prove that drone swarms significantly and consistently outperform manned aircraft in both sustainability and cost. Hybrid systems offer the fastest response but with higher emissions and costs. This research contributes an open-source framework for evaluating aerial firefighting strategies, designed to support evidence-based guidelines and encourage sustainable and frugal fire management.

1. Data Source, Ethics, Code, and Technology (DSECT) Statement

1.1 Data Source

This thesis does not use any datasets or human/animal data. All data used in the project is synthetically generated through simulations developed by the author. No external data owners are involved, and no consent was necessary. All data was produced locally using custom agent-based models created in Python using the mesa library. The parameters of the simulation are taken from cited research.

1.2 Figures

All Figures, plots, tables and visualizations included in the thesis were created by the author using the original simulation output. No external or copyrighted images were used. Visuals were generated using Python libraries such as `matplotlib` and `seaborn`. The creation of the visuals is documented and explained in the GitHub repository (Speidel, 2025)

1.3 Code

The simulation uses multiple open-source Python libraries such as `mesa, numpy, pandas`, their implementation is documented in the Methodology section ?? and the referenced GitHub repository.

1.4 Technology

The thesis was typeset using the standard LaTeX thesis template provided by the university, with additional formatting packages such as `fancyhr, tikz` for formatting preferences. References were managed using BibTeX and LaTeX's built-in bibliography environment. Zotero was used as a reference manager. Generative models such as GitHub's Copilot, Claude and ChatGpt were used for harsh feedback on personal created text and code. The content was not directly copied; instead used as a valuable tool to generate feedback and point out room for improvement. All conceptual, experimental, and implementation work was done by the author, with inspiration from the documentation of the mentioned libraries.

2. Introduction

Wildfires pose an escalating global threat, driven by climate change and human activity, with 96% of wildfires being human-induced (Cañizares et al., 2017). These events cause ecological, economic, and societal damage (Saffre et al., 2022), emitting over 2,000 megatons of carbon emissions globally in 2023 alone (Lelis et al., 2024). The UN Environment Program (UNEP2) forecasts a 50% increase by the end of the century in extreme wildfires if no countermeasures are taken (Sullivan et al., 2022). Escalating wildfire frequency also threatens agricultural productivity (Intergovernmental Panel on Climate Change, 2023) and poses significant health risks through smoke exposure (Finlay et al., 2012). These combined effects make wildfires one of the most urgent environmental and societal challenges today.

Wildfire research traditionally employs different methodological approaches with different advantages and limitations. Historical analysis creates the foundation of wildfire research. Researchers examine fire records, satellite imagery and climate data to identify patterns, trends and correlations between environmental factors and fire behavior (Jones et al., 2024; Intergovernmental Panel on Climate Change, 2023). These studies offer valuable insights into long-term fire cycles and climate relationship, but their retrospective nature limits their adaptability in the accelerating climate change.

Field studies including controlled burns present another critical research approach (Santoni et al., 2011). While these approaches offer scientists valuable real-world data about fire physics and suppression in a controlled environment, they are inherently limited by safety concerns, high costs and their impossibility of testing extreme scenarios or comparing multiple suppression strategies simultaneously.

Traditional aerial firefighting and data collection relies heavily on manned aircraft such as Helicopters or fixed-wing planes. For decades this has been the backbone of wildfire suppression (Janney, 2012). These aircraft deliver water or fire retardant directly to the fire zones, often in dangerous conditions such as limited visibility. Their effectiveness comes with safety constraints, high operational cost and substantial carbon emissions (Spicer et al., 2009).

Recent technological advancements have sparked growing interest in autonomous drone systems for wildfire suppression. Modern drone technology potentially offers operation in extreme conditions without risking human life while being lower in cost and emissions. Research done by Yan and Chen (2024) effectively demonstrates the possibility of using coordinated swarm behavior to detect forest fires. Current research presents promising applications such as new suppression techniques like the "fireball" by Aydin et al. (2019).

While the development is promising especially with more applied drone applications being tested, scientists have also turned to simulation studies as they provide evidence for fire spread behavior at a lower cost. One of the earliest tools in this domain was the fire area simulator FARSITE (Finney and Andrews, 1999), which established a baseline for future work. This laid the groundwork for more advanced systems, such as the model proposed by Hu and Ntaimo (2009), which integrates fire simulation with optimization-based analysis. This is where Agent-Based Modeling (ABM) plays an important role.

Based on Wilensky and Rand (2015), ABM is defined as a methodology for conducting computer-based experiments that enables the study of complex systems by simulating the actions and interactions of autonomous agents within natural, social, or engineered contexts. These dynamic interactions generate complex, system-level patterns, commonly referred to as *emergent behavior*. In wildfire research, ABM enables researchers to model fires, suppression vehicles, and environmental factors as independent agents with distinct behaviors and decision-making capabilities. This approach captures the emergent properties of complex firefighting scenarios that would be difficult or impossible to study through traditional analytical methods or real-world experiments. ABM provides evidence through the analysis of emergent behavior, which can inform real-world firefighting strategies.

ABM is particularly suited for wildfire suppression research because it allows for the modeling of dynamic, spatially distributed systems where multiple autonomous agents must coordinate to achieve common objectives. The framework enables systematic comparison of different suppression strategies under controlled conditions while varying key parameters such as swarm size, resource allocation, and path-finding algorithms.

As wildfires grow in intensity and frequency, traditional suppression methods face increasing limitations. Agent-Based Modeling (ABM) presents a powerful tool for simulating complex scenarios involving autonomous firefighting drones. However, there is limited research directly comparing different suppression strategies, such as drone swarms, hybrid systems, and traditional aircraft, within the same simulation environment.

This research aims to fill this gap by asking:

Research Question "How can agent-based modeling be used to evaluate and optimize autonomous aerial wildfire suppression strategies across drone, plane, and hybrid systems, using path-finding algorithms to assess effectiveness, efficiency, and sustainability?"

Given the research question the following sub-questions arise and will guide this study:

1. "How do drone swarms, hybrid systems, and planes compare in wildfire suppression?"

2. "What are path-finding algorithms and how do they influence the performance autonomous drone swarms in wildfire scenarios?"

3. "What trade-offs emerge among suppression effectiveness, efficiency and sustainability?"

The strength of this thesis is that it presents a robust open-source agent-based simulation framework developed in Python using the Mesa library. Its object-oriented and well-documented architecture promotes interdisciplinary research. Presenting the possibility of an easy integration for different algorithms such as Ant Colony Optimization and Artificial Bee Colony underlines its strengths. The framework provides researchers and relevant stakeholders such as policymakers, emergency response planners, and environmental scientists, with a flexible tool to build on top of and evaluate custom aerial vehicle models and coordination strategies across a range of simulated scenarios. Its public availability offers societal benefit, especially in resource-limited regions, by enabling access to advanced simulation and planning tools.

In the scope of this research different wildfire suppression methods, namely traditional aerial firefighting, autonomous drone swarms and a hybrid system are modeled. These approaches have been simulated and compared focusing on cost, emissions, and water usage. The work combines agent-based modeling, swarm properties, and environmental sustainability. While drone technology has advanced tremendously in both hardware and software, practical evaluations in firefighting contexts remain limited, especially when compared directly. Current systems heavily depend on manned aircraft's despite the growing need for scalable, efficient, and sustainable alternatives.

3. Related Work

3.1 The Importance of preventing Wildfires

As already mention wildfires are increasing, creating devastating destruction. Additionally, the economic damage from wildfires is immense, while the annual cost of wildfire management in the U.S. is estimated to be \$7.6 billion to \$62.8 billion, the economic damage is estimated between \$63.5 billion to \$285.0 billion Afghah et al. (2019). This highlights the importance of this research topic and the need for practical, cost-effective and quick solutions. Aiming for a sustainable approach should be emphasized as traditional methods are costly and emit a lot of CO_2 Saffre et al. (2022). The ecological impact especially on the agricultural sector is seen as a societal threat as several sources report (Steiner et al., 2020; Intergovernmental Panel on Climate Change, 2023).

3.2 Traditional Methods

(Traditional) Aerial firefighting using manned planes has been employed since the 1950s, originating from repurposed military aircraft's (Janney, 2012). Important advancements in the 1960s introduced specialized tactics and retardants, which significantly improved effectiveness (Struminska and Filippone, 2024). These methods made access to remote areas feasible and led to the development of aircraft specifically for firefighting roles (Struminska and Filippone, 2024; Corporation, 2018). Modern firefighting-fleets include a range of aerial vehicles for specific operational tasks (Aviation, 2018).

Despite their effectiveness, these methods are costly and "dangerous and risky for the crew involved" (Struminska and Filippone, 2024, p. 1896). Struminska and Filippone (2024) also pointed out that aerial firefighting is fast and capable but economically and operationally demanding. Additionally, emissions from aircraft like the C-130 Hercules are immense and difficult to quantify (aviationzone, 2022; Spicer et al., 2009), highlighting the need for lower-emission alternatives. Traditional aerial firefighting faces limitations regarding coordination and situational awareness, which motivate the development of autonomous alternatives. Current operations rely heavily on human pilots making real-time decisions in dangerous, low-visibility conditions due to smoke, wind and turbulence (Struminska and Filippone, 2024). These complex situations present challenges for human operators, which can result in suboptimal suppression strategies and safety risks. Autonomous systems offer the potential for real-time data sharing, coordinated swarm behavior and quick adaptation to changing fire conditions, forming the foundation for more effective suppression strategies. With multiple sources reporting that the frequency and intensity of wildfires are increasing (Jones et al., 2024; Intergovernmental Panel on Climate Change, 2023; Steiner et al., 2020), the development of more responsive and autonomous strategies is of high importance.

3.3 Emergence of Drone-Based Solutions

With advancement of global technologies in recent years, drone systems, including both hardware and software components, went through significant development in terms of functionality and operational capabilities. Unmanned Aerial Vehicles (UAV) are increasingly integrated across a range of industrial sectors, including agriculture, healthcare, logistics, and military operations (Emimi et al., 2023). Their main advantages being their adaptability, precision and cost-efficiency. However, these benefits go in line with by persistent regulatory, operational, and ethical challenges (Emimi et al., 2023). In the context of firefighting, drones are establishing themselves as promising tools, offering new approaches to increasing problems in wildfire management. Research conducted by Saffre et al. (2022) demonstrates that autonomous drone swarms are capable of effectively containing wildfire while also reducing greenhouse gas emissions compared to traditional methods (Saffre et al., 2022). In addition, drones are increasingly recognized for their energy efficiency, making them a promising solution for sustainable disaster response strategies (Stolaroff et al., 2018).

Emerging drone-specific firefighting techniques further expand the potential of UAV's in this domain. For example, the "Firefighting Ball" represents a novel condemning technology designed specifically for aerial deployment via drones (Aydin et al., 2019). Building upon this, an autonomous system that integrates the fireball concept into a coordinated drone-based suppression framework got introduced (Alkhatib et al., 2024).

The effectiveness of drone-based firefighting systems is evident, specifically in terms of cost-efficiency and their potential to reduce environmental impact through lower emissions. However, for these systems to achieve optimal performance, early wildfire detection is crucial. Fast and confident identification of fire outbreaks is one of the most critical factors in minimizing damage, especially during the initial stages of a wildfire event (Sudhakar et al., 2020). In comparison, Traditional risk assessment measures are delayed and have low confidence, especially in remote areas (Afghah et al., 2019), highlighting the potential for improvement in autonomous data collection (Lelis et al., 2024) with drones.

The relatively low cost and compact size of drones also make simultaneous deployment of multiple units possible, therefore enabling coordinated swarm behavior which is a logical progression in UAV-based wildfire management (Hocraffer and Nam, 2017). Swarm behavior supports the application of bio-inspired algorithms, such as Ant Colony Optimization (Cañizares et al., 2017) and Artificial Bee Colony algorithms (Karaboga and Basturk, 2007), which increase in effectiveness as swarm size increases. These algorithms allow drones to efficiently compute optimal paths to fire sites, managing speed and resource use. Hocraffer and Nam (2017) identified that, interest in swarm-based UAV systems is growing rapidly, and this area of research is expected to become increasingly important in addressing complex real-world challenges such as wildfire detection and suppression.

While the physical and algorithmic capabilities of drones develop rapidly, coordinating a swarm of autonomous UAVs in uncertain, large-scale environments, especially extreme ones such as wildfire zones, remains a significant challenge. These systems involve many interacting agents reacting to various parameters. This introduces a level of behavioral and environmental complexity that is difficult to model using top-down or deterministic approaches. As a result, Agent-Based Modeling (ABM) has emerged as a promising computational framework to explore and test swarm coordination strategies, especially in complex domains such as wildfire detection and suppression.

3.4 Agent-Based Modeling

Agent-Based Modeling (ABM) is a computational methodology used for conducting experiments that enable the study of complex systems by simulating actions and interactions of autonomous agents within different domains (Wilensky and Rand, 2015). Each Agent follows a set of simple, rule-based behaviors, and through repeated interaction with other agents and their environment "sustainable patterns can emerge in systems that are completely described by simple rules" (Macal and North, 2005, p.5). These dynamic interactions generate complex, system-level patterns, commonly referred to as emergent behavior. These emergent patterns reveal dynamics that are difficult to predict analytically, providing valuable insights for informed decision-making. ABM is grounded in the principles of complexity theory, which studies how individual agents interact within a system, leading to emergent behaviors and patterns. As Wilensky and Rand (2015) explain, complexity theory provides a framework for understanding systems in which "order emerges without central control," making is specifically relevant for wildfire management, where conditions are dynamic and decisions must be made in real time without centralized control. By modeling planes and drones as autonomous agents, ABM provides a framework where each agent is equipped with its own sensors, movement capabilities and objectives (e.g., resource management or fire suppression). The simulated environment can be defined and modeled to represent real-world elements such as terrain, vegetation and fire spread mechanics, making it a powerful tool for investigating wildfire response strategies. ABM has been widely applied in wildfire research. Early models such as the NetLogo Forest Fire simulation demonstrated how simple ignition and spread rules can mimic the dynamic growth of wildfires (Wilensky and Rand, 2015). Recent implementations of ABM for wildfire management have demonstrated the capabilities of this approach for simulation complex environments and testing different suppression strategies to understand forest fires. For instance, Moreno-Espino et al. (2025) applies ABM through the GAMA platform (Taillandier et al., 2019) to simulate wildfire propagation by modeling fire cells, vegetation, and weather as interacting agents. Their approach integrates geographic data to reflect real-world terrain, highlighting how environmental variables like wind speed and fire outbreaks influence fire spread and intensity. Similarly, Dorrer and Yarovoy (2020) presented an agent-based model which integrates a simulated environment onto actual terrain data, combining both fire agents and firefighting agents. Their model provides insights into fire control strategies by demonstrating how emergent behaviors from the agents' interaction with the spreading fire can give evidence for informed resource allocation and decision-making.

These studies demonstrate the relevance of ABM in capturing the dynamics of wildfire events. Building on this foundation, this thesis takes a comparative approach to evaluate coordination strategies in UAV-based wildfire response by contrasting autonomous drone systems with plane only and hybrid models. However, the effectiveness of autonomous drone swarms in ABM simulations for wildfire suppression depends on the path-finding algorithms which dictate the agents movement and coordination strategies.

3.5 Nature-inspired Path-finding Algorithms

Path-finding algorithms are computational methods designed to find efficient routes between two points in a space, often while avoiding obstacles or minimizing costs (such as time, distance or energy). These algorithms often use heuristics, which are informed problem-solving techniques to efficiently explore potential solutions in a solution space under the premise that exploring every possible solution is computationally infeasible. When the heuristic is admissible, it guarantees that the algorithm will find an optimal path (Hart et al., 1968). In the context of autonomous drone swarms for wildfire suppression, these algorithms must balance competing objectives: minimizing travel time to fire sites, avoiding collisions with other agents, optimizing resource consumption, and adapting to dynamic fire spread.

A* Search The A* algorithm, introduced by Hart et al. (1968), is the foundation of modern heuristic pathfinding, It calculates:

$$f(n) = g(n) + h(n) \tag{1}$$

where $g(n)$ represents the actual cost from the start node to node n, and $h(n)$ is the heuristic estimate of the cost from node n to the goal. When the heuristic $h(n)$ is admissible (never overestimates the true cost) and consistent, A* guarantees finding the shortest path while expanding fewer nodes than uninformed search methods (Hart et al., 1968). While A* performs well in known environments, it faces limitations in dynamic scenarios where conditions change rapidly and multiple agents must coordinate simultaneously. This is where nature-inspired algorithms offer an alternative. Nature-inspired pathfinding algorithms draw their inspiration and theoretical concepts from biological systems that exhibit efficient collective navigation and optimization behaviors. These approaches are specifically valuable in wildfire suppression contexts because they enable decentralized decision-making, adaptive behavior, and emergent coordination, making them essential for effective swarm operations in unpredictable environments.

Ant Colony Optimization (ACO) mimics the foraging behavior of ant colonies, where individual ants leave pheromone trails to guide other ants towards food sources (Dorigo et al., 1996). The original ACO algorithm, developed by Dorigo et al. (1996), has since been applied across various optimization domains (Dorigo and Stützle, 2019). In drone applications, virtual pheromones can represent fire intensity levels or success suppression paths. This mechanism enables drones to converge on high-priority areas while maintaining swarm coordination. Cañizares et al. (2017) demonstrates how ACO can be applied in wildfire scenarios by developing a system that coordinates multiple agents for fire prevention and mitigation. ACOs main advantage lies in its ability to find near-optimal solutions through emergent collective intelligence without requiring centralized control, making it perfectly suitable for wildfire suppression in ABM simulations.

Artificial Bee Colony (ABC) is a swarm-based meta-heuristic algorithm. Inspired by the behavior of honeybee swarms, the algorithm simulates the decision-making processes of honeybee colonies during nectar foraging (Karaboga and Basturk, 2007). The algorithm divides the swarm into three types of bees: employed bees that exploit existing food sources, onlooker bees that select among these sources based on information shared by employed bees, and scout bees that search for new food sources randomly when existing ones are exhausted (Karaboga and Basturk, 2007). In wildfire suppression contexts, this translates to drones that can exploit known fire locations (employed behavior), explore new fire areas based on information from other drones (onlooker behavior), and conduct random searches when no fires are detected (scout behavior). This behavioral division enables effective load balancing between exploitation of current fire sites and exploration of potential new outbreaks. This property highlights the strength of ABC, which lies in its inherent balance of exploration and exploitation, making it particularly useful for dynamic environments where fire conditions and resource availability change rapidly.

These nature-inspired algorithms provide the needed computational foundation for autonomous coordination. However, as demonstrated in the following sections the integration of human oversight with the mentioned autonomous capabilities can further enhance system performance and adaptability-

3.6 Human-Drone Teaming

As the complexity of drone systems is increasing, maintaining effective coordination presents a growing trade-off between autonomy, control, and performance. Human drone teaming (HDT) offers a promising middle ground by balancing centralized oversight with distributed decision-making. Integrating humans into the loop, enhances strategy flexibility while reducing cognitive load. Chen and Barnes (2014) demonstrate that system where human operators oversee multiple UAVs and intervene only when necessary, enhance both situational awareness and mission reliability. This supervised control enables operators to take strategic decisions without managing each drone independently, thus reducing cognitive load and improving the flexibility of the operation. Sunar

The comparison of differnt systems remains largely under explored

4. Methodology

5. Results

6. Discussion

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