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

Name: Kai Speidel
Student number: U627621

**THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF SCIENCE IN COGNITIVE SCIENCE & ARTIFICIAL INTELLIGENCE
DEPARTMENT OF COGNITIVE SCIENCE & ARTIFICIAL INTELLIGENCE
SCHOOL OF HUMANITIES AND DIGITAL SCIENCES
TILBURG UNIVERSITY**

Thesis Committee:
Supervisor: Dr. Travis J. Wiltshire
Second Reader: Natalie Ranzhi Wei, Msc.

Tilburg University
School of Humanities and Digital Sciences
Department of Cognitive Science & Artificial Intelligence
Tilburg, The Netherlands

May 2025

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 especially favorable.

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 technological advancements 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 makes 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 effectivity as swarm size increases. These algorithms allow drones to efficiently compute optimal paths to fire sites, managing speed and resource use. Hofcraffer & Nam (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.

3.4 Agent-Based Modeling

3.5 Nature-Inspired Path-finding Algorithms

3.6 Human-Drone Teaming and Human-Swarm Interaction

–> what are path-finding algorithms

4. Methodology

5. Results

6. Discussion

References

Afghah, F., Razi, A., Chakareski, J., and Ashdown, J. (2019). Wildfire monitoring in remote areas using autonomous unmanned aerial vehicles. *arXiv*. No. arXiv:1905.00492.

Alkhatib, A. A., Mohammad Jaber, K., and Al-Madi, M. (2024). A Proposed Automatic Forest Fire Extinguishing and Prevention System Using Drones. In *2024 IEEE International Humanitarian Technologies Conference (IHTC)*, pages 1–6.

Aviation, C. (2018). Fleet information of firefighting.

aviationzone (2022). Lockheed C-130 Hercules - The Aviation Zone.

Aydin, B., Selvi, E., Tao, J., and Starek, M. J. (2019). Use of Fire-Extinguishing Balls for a Conceptual System of Drone-Assisted Wildfire Fighting. *Drones*, 3(1):17.

Cañizares, P. C., Núñez, A., Merayo, M. G., and Núñez, M. (2017). A hybrid ant colony based system for assist the prevention and mitigation of wildfires in forests. In *IEEE Conference Publication*. IEEE Xplore.

Corporation, L. M. (2018). C-130j super hercules: Proven, ready, reliable, and affordable. https://www.lockheedmartin.com/content/dam/lockheed-martin/aero/documents/C-130J/MG180389_C-130Brochure_NewPurchase_Final_Web.pdf. Brochure.

Emimi, M., Khaleel, M., and Alkrash, A. (2023). The Current Opportunities and Challenges in Drone Technology. *International Journal of Electrical Engineering and Sustainability*, pages 74–89.

Finlay, S. E., Moffat, A., Gazzard, R., Baker, D., and Murray, V. (2012). Health impacts of wildfires. *PLoS Currents*, 4:e4f959951cce2c.

Finney, M. A. and Andrews, P. L. (1999). FARSITE - a program for fire growth simulation. *Fire Management Notes*, 59(2):13–15.

Hocraffer, A. and Nam, C. S. (2017). A meta-analysis of human-system interfaces in unmanned aerial vehicle (UAV) swarm management - ScienceDirect.

Hu, X. and Ntaimo, L. (2009). Integrated simulation and optimization for wildfire containment. *ACM Trans. Model. Comput. Simul.*, 19.

Intergovernmental Panel on Climate Change (2023). *Weather and Climate Extreme Events in a Changing Climate*, pages 1513–1766. Cambridge University Press, Cambridge.

Janney, T. (2012). Airtankers: An historic overview. Version 2, Airtanker. Accessed: 2025-05-13.

Jones, M. W., Kelley, D. I., Burton, C. A., Di Giuseppe, F., Barbosa, M. L. F., Brambleby, E., Hartley, A. J., Lombardi, A., Mataveli, G., McNorton, J. R., Spuler, F. R., Wessel, J. B., Abatzoglou, J. T., Anderson, L. O., Andela, N., Archibald, S., Armenteras, D., Burke, E., Carmenta, R., Chuvieco, E., Clarke, H., Doerr, S. H., Fernandes, P. M., Giglio, L., Hamilton, D. S., Hantson, S., Harris, S., Jain, P., Kolden, C. A., Kurvits, T., Lampe, S., Meier, S., New, S., Parrington, M., Perron, M. M. G., Qu, Y., Ribeiro, N. S., Saharjo, B. H., San-Miguel-Ayanz, J., Shuman, J. K., Tanpipat, V., van der Werf, G. R., Veraverbeke, S., and Xanthopoulos, G. (2024). State of Wildfires 2023–2024. *Earth System Science Data*, 16(8):3601–3685.

Karaboga, D. and Basturk, B. (2007). A powerful and efficient algorithm for numerical function optimization: artificial bee colony (abc) algorithm. *Journal of Global Optimization*, 39(3):459–471.

Lelis, C. A. S., Roncal, J. J., Silveira, L., De Aquino, R. D. G., Marcondes, C. A. C., Marques, J., Loubach, D. S., Verri, F. A. N., Curtis, V. V., and De Souza, D. G. (2024). Drone-based ai system for wildfire monitoring and risk prediction. *IEEE Access*, 12:139865–139882.

Saffre, F., Hildmann, H., Karvonen, H., and Lind, T. (2022). Monitoring and cordoning wildfires with an autonomous swarm of unmanned aerial vehicles. *Drones*, 6(10).

Santoni, P.-A., Filippi, J.-B., Balbi, J.-H., and Bosseur, F. (2011). Wildland fire behaviour case studies and fuel models for landscape-scale fire modeling. *Journal of Combustion*, 2011(1):613424.

Speidel, K. (2025). Simulation code for wildfire response models. Accessed: 2025-05-15.

Spicer, C. W., Holdren, M. W., Cowen, K. A., Joseph, D. W., Satola, J., Goodwin, B., Mayfield, H., Laskin, A., Lizabeth Alexander, M., Ortega, J. V., Newburn, M., Kagann, R., and Hashmonay, R. (2009). Rapid measurement of emissions from military aircraft turbine engines by downstream extractive sampling of aircraft on the ground: Results for C-130 and F-15 aircraft. *Atmospheric Environment*, 43(16):2612–2622.

Steiner, J. L., Wetter, J., Robertson, S., Teet, S., Wang, J., Wu, X., Zhou, Y., Brown, D., and Xiao, X. (2020). Grassland wildfires in the southern great plains: Monitoring ecological impacts and recovery. *Remote Sensing*, 12(619).

Stolaroff, J. K., Samaras, C., O'Neill, E. R., Lubers, A., Mitchell, A. S., and Ceperley, D. (2018). Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. *Nature Communications*, 9(1):409.

Struminska, A. and Filippone, A. (2024). Flight performance analysis of aerial fire fighting. *The Aeronautical Journal*, 128(1327):1895–1923.

Sudhakar, S., Vijayakumar, V., Sathiya Kumar, C., Priya, V., Ravi, L., and Subramaniyaswamy, V. (2020). Unmanned aerial vehicle (uav) based forest fire detection and monitoring for reducing false alarms in forest-fires. *Computer Communications*, 149:1–16.

Sullivan, A., Baker, E., Kurvits, T., Popescu, A., Paulson, A. K., Cardinal Christianson, A., Tulloch, A., Bilbao, B., Mathison, C., Robinson, C., Burton, C., Ganz, D., Nangoma, D., Saah, D., Armenteras, D., Driscoll, D. A., Hankins, D. L., Kelley, D. I., Langer, E. R., et al. (2022). Spreading like wildfire: The rising threat of extraordinary landscape fires. Technical report, United Nations Environment Programme. https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires.

ter Hoeven, E., Kwakkel, J., Hess, V., Pike, T., Wang, B., Rht, and Kazil, J. (2025). Mesa 3: Agent-based modeling with python in 2025. *Journal of Open Source Software*, 10(107):7668.

Wilensky, U. and Rand, W. (2015). *An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo*. MIT Press, Cambridge, Massachusetts.

Yan, X. and Chen, R. (2024). Application strategy of unmanned aerial vehicle swarms in forest fire detection based on the fusion of particle swarm optimization and artificial bee colony algorithm. *Applied Sciences*, 14(11).