

Introduction

Wildfires pose a significant and growing threat to ecosystems, infrastructure, and human life. The increasing frequency and severity of these fires have placed tremendous pressure on current firefighting strategies. One of the most widely used wildfire suppression methods involves the aerial deployment of flame retardants. However, this approach is largely manual and highly inefficient, often resulting in significant waste, environmental contamination, and suboptimal fire containment. Current firefighting aircraft rely on pilot experience and rough estimations to determine drop locations, leading to inaccuracies and excess chemical dispersion beyond the targeted fire zones. In addition to the environmental risks, such inefficiencies increase operational costs and reduce the overall effectiveness of suppression efforts.

To address these challenges, this research proposes an artificial intelligence (AI)-driven optimization model designed to enhance the precision of flame-retardant deployment. By integrating real-time data on flame-retardant weather patterns, and topography, the system aims to improve drop accuracy, reduce environmental and infrastructural impact, and lower operational costs. The implementation of AI in wildfire suppression introduces a data-driven approach that enhances decision-making, ensuring that flame retardants are dispersed exactly where they are needed with minimal waste.



Fig. 1: Palisades Fire Destruction Effects (images courtesy of CNN)

What is AI? & How Does AI Work?

Artificial Intelligence (AI) enables machines to analyze data, recognize patterns, and make informed decisions, making it particularly useful for wildfire suppression. By processing large datasets in real time, AI can predict fire spread, optimize suppression strategies, and improve flame retardant deployment accuracy. This study utilized neural networks, linear regression, and deep learning to enhance wildfire response efforts.

Neural networks (image below) simulate human brain function by recognizing patterns and learning from past data. In this research, neural networks were trained on historical wildfire data, weather conditions, and terrain information to predict how and where a fire would spread. These predictions helped determine the most critical areas for suppression before fires could grow out of control.

Linear regression is a statistical model that identifies relationships between variables. It was used in this study to analyze how wind speed, altitude, fire intensity, and terrain influence the effectiveness of flame-retardant drops. By understanding these relationships, the model provided precise recommendations on the best conditions for retardant deployment, ensuring that resources were used efficiently.

Deep learning, a subset of machine learning that processes complex datasets, was used to analyze satellite imagery from MODIS and FIRMS. This allowed the AI system to detect active fire zones, track their movement, and update suppression plans in real time. Deep learning helped firefighters quickly identify high-risk areas and adjust their strategies accordingly.

By cross-referencing AI-generated predictions with real wildfire data, including the Palisades Fire, the system continuously refined its accuracy. This approach improved response time, reduced chemical waste, and enhanced suppression efficiency, demonstrating the potential of AI to revolutionize wildfire management.

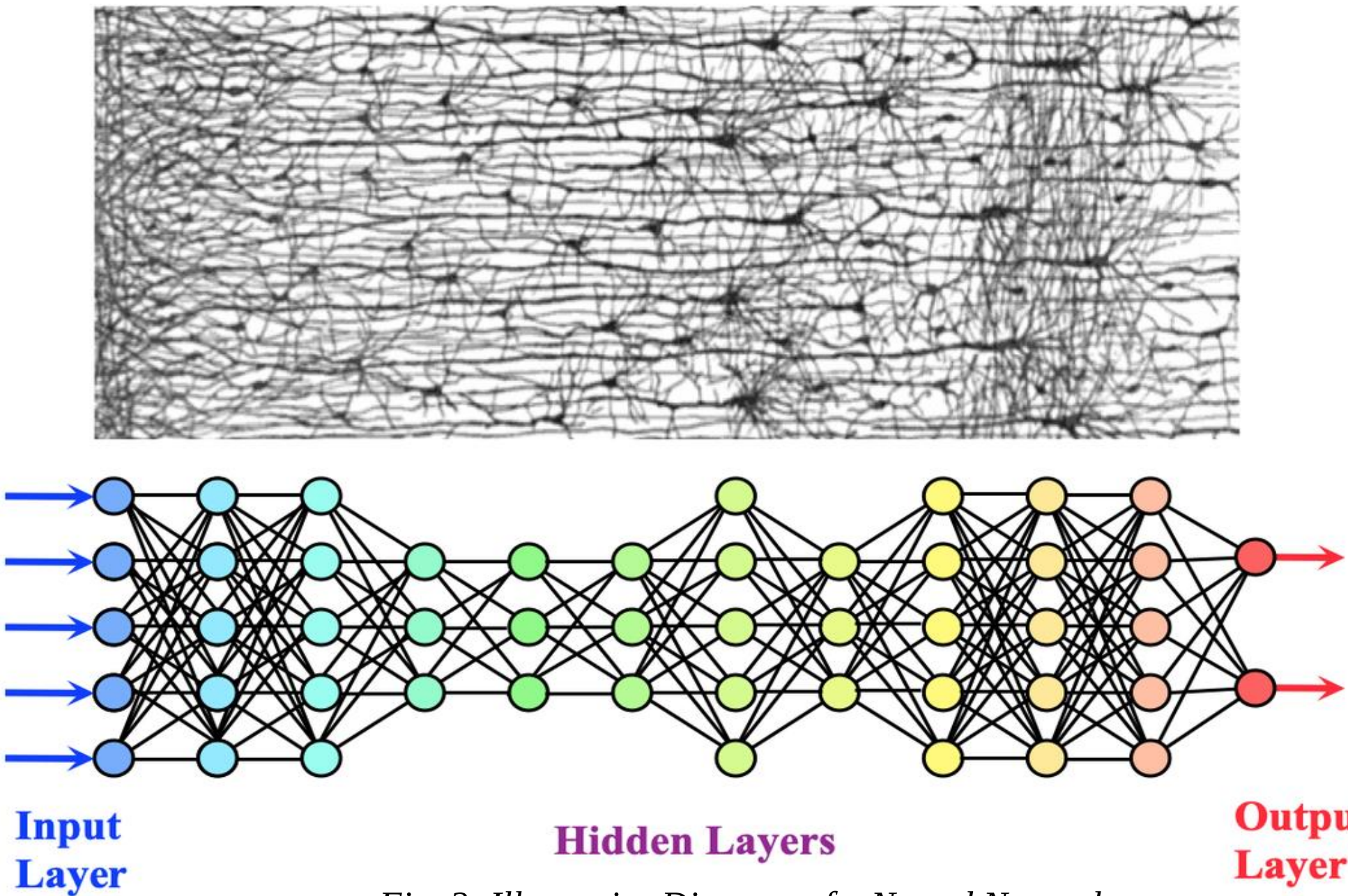


Fig. 2: Illustrative Diagram of a Neural Network

Future Research

While the predictive AI model has demonstrated 85-90% accuracy in predicting fire spread and optimizing flame retardant deployment, further enhancements could make it more scalable and applicable for real-world use. One of the most important next steps is integrating this system into actual aerial firefighting aircraft. By connecting the AI model to onboard sensors, GPS, and weather monitoring tools, the system could provide real-time suppression recommendations to pilots during active wildfire missions. This would allow for dynamic adjustments in drop locations and flight paths, ensuring more precise and efficient suppression efforts. Additionally, deploying the AI model on autonomous firefighting drones could improve suppression in areas that are too dangerous or inaccessible for human pilots, further enhancing wildfire response capabilities.

Beyond simulation testing, real-world validation is necessary to assess the model's effectiveness under unpredictable conditions. Future work could involve controlled field tests where AI-generated suppression strategies are compared with traditional methods in live fire exercises. Expanding the training dataset to include more fire events from different terrains and climates would also improve adaptability. Additionally, implementing reinforcement learning would allow the model to continuously improve by learning from past suppression operations, making it more accurate and responsive over time. With these advancements, the AI system could evolve into a fully operational tool for firefighting agencies, improving response efficiency and reducing the overall impact of wildfires.

Consideration of Location-specific Weather and Topographic Datasets to Model Efficient Deployment of Forest Fire Flame Retardants

How is AI Utilized in this Project?

Artificial intelligence has emerged as a transformative tool in disaster management, particularly in complex and dynamic scenarios like wildfire suppression. The AI model in this study is designed to function as a real-time decision-support system, processing vast amounts of data from multiple sources to improve the effectiveness of suppression efforts.

The system first analyzes real-time meteorological data, including wind speed, humidity, and temperature, to predict how a fire is likely to spread. It then integrates geospatial data, such as terrain elevation and vegetation density, to assess how fire behavior will be influenced by landscape features. Using machine learning algorithms, the model processes historical fire data to recognize patterns in wildfire progression and determine the most effective drop locations.

Once the AI model identifies optimal drop zones, it generates a color-coded suppression map that provides real-time guidance to firefighting aircraft. This map not only highlights the most effective drop locations but also suggests optimal flight paths to ensure efficient chemical dispersion. The AI system continuously updates as new data becomes available, making it adaptable to changing fire conditions. Furthermore, pilots retain the ability to manually override AI recommendations, ensuring that human judgment remains central to decision-making while benefiting from AI-assisted precision.

Data Collection & Utilization

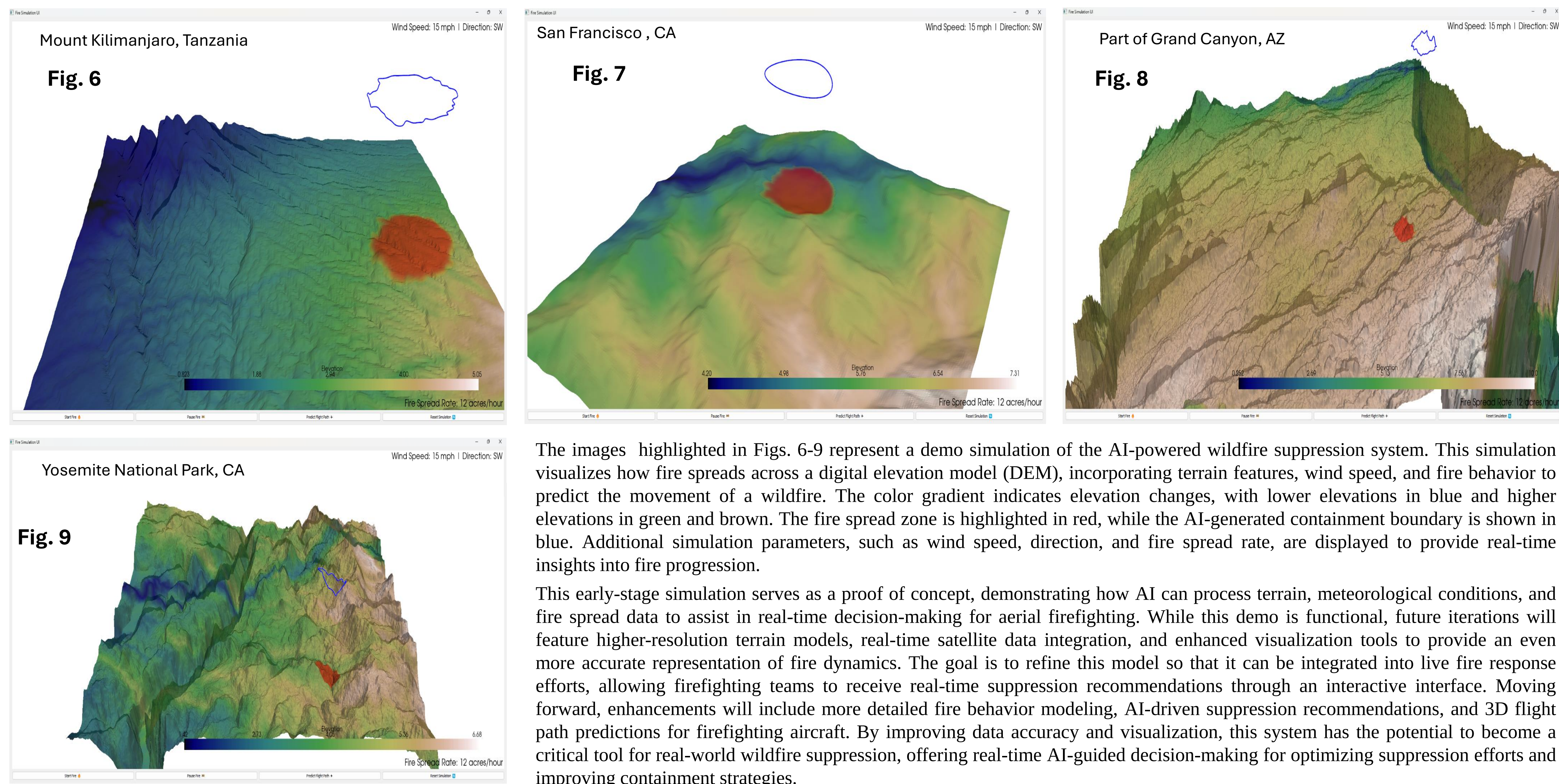
To build an accurate and reliable AI-driven wildfire suppression model, this research utilized multiple geospatial, meteorological, and fire activity datasets from reputable sources. These datasets provided essential information on terrain, fire behavior, weather conditions, and real-time fire monitoring, which were integrated into the AI system to enhance prediction accuracy and suppression strategies. One of the primary sources of topographical data was the 2025 Post-Wildfire LiDAR Dataset from the U.S. Geological Survey (USGS). This high-resolution LiDAR data provided detailed 3D elevation mapping of the terrain affected by wildfires in Los Angeles, California. The elevation data was crucial for understanding how slope, vegetation density, and land contours influence fire spread and suppression effectiveness. The AI model utilized this terrain information to optimize flight paths and improve fire retardant drop targeting, ensuring that suppressant material was dispersed efficiently over high-risk areas.

Weather and climate conditions play a critical role in fire behavior and suppression efficiency. To incorporate real-time meteorological data, this study accessed weather and climate models from the National Oceanic and Atmospheric Administration (NOAA). These models (Figs. 4 & 5) provided historical and real-time atmospheric conditions, including wind speeds, humidity levels, and temperature variations that directly impact wildfire progression. The AI model integrated this information to dynamically adjust suppression strategies based on changing weather patterns.

For global and regional satellite imagery, the study used geospatial data from Planet Observer, which offers high-resolution Earth observation data. This dataset was particularly valuable for analyzing pre-fire and post-fire land cover changes, allowing the AI model to identify vulnerable areas and assess fire recovery progress. Additionally, MODIS (Moderate Resolution Imaging Spectroradiometer) from NASA provided continuous thermal anomaly detection and active fire data, enabling real-time updates on fire locations and intensity. To enhance fire detection accuracy, the research incorporated data from NASA's Fire Information for Resource Management System (FIRMS), which provides real-time active fire mapping through satellite-based thermal imaging. By integrating FIRMS data with other geospatial sources, the AI system was able to track wildfire spread patterns with high temporal resolution, improving its predictive capabilities.

All these datasets were preprocessed and fed into the AI model, enabling it to learn from past wildfires, adjust to real-time environmental conditions, and optimize aerial suppression efforts. By leveraging these authoritative data sources, the AI system was fine-tuned to provide highly accurate suppression recommendations, ensuring effective resource deployment, reduced chemical waste, and faster wildfire containment.

Wildfire Simulations Using Python PyVista



The images highlighted in Figs. 6-9 represent a demo simulation of the AI-powered wildfire suppression system. This simulation visualizes how fire spreads across a digital elevation model (DEM), incorporating terrain features, wind speed, and fire behavior to predict the movement of a wildfire. The color gradient indicates elevation changes, with lower elevations in blue and higher elevations in green and brown. The fire spread zone is highlighted in red, while the AI-generated containment boundary is shown in blue. Additional simulation parameters, such as wind speed, direction, and fire spread rate, are displayed to provide real-time insights into fire progression.

This early-stage simulation serves as a proof of concept, demonstrating how AI can process terrain, meteorological conditions, and fire spread data to assist in real-time decision-making for aerial firefighting. While this demo is functional, future iterations will feature higher-resolution terrain models, real-time satellite data integration, and enhanced visualization tools to provide an even more accurate representation of fire dynamics. The goal is to refine this model so that it can be integrated into live fire response efforts, allowing firefighting teams to receive real-time suppression recommendations through an interactive interface. Moving forward, enhancements will include more detailed fire behavior modeling, AI-driven suppression recommendations, and 3D flight path predictions for firefighting aircraft. By improving data accuracy and visualization, this system has the potential to become a critical tool for real-world wildfire suppression, offering real-time AI-guided decision-making for optimizing suppression efforts and improving containment strategies.

Results & Findings

The AI model developed in this study achieved an accuracy rate of approximately 85-90% in predicting wildfire spread and optimizing flame retardant drop zones (Fig. 10). The model was trained and tested using historical wildfire data, real-time satellite imagery, and weather conditions, allowing it to refine suppression strategies and improve precision and cross-referenced with Palisades fire data to furthermore improve accuracy.

By running simulations, the AI system was able to analyze fire behavior, recommend optimized drop locations, and adjust for environmental factors such as wind speed and terrain. The results demonstrated that AI-assisted suppression strategies outperformed traditional manual methods by improving targeting accuracy and reducing unnecessary chemical dispersal.

Since this research focused solely on model development and simulation, real-world testing and field deployment remain as future steps. However, the simulation results indicate that AI-driven fire suppression has significant potential to enhance containment efficiency, optimize resource allocation, and reduce environmental and infrastructure impact, making it a promising tool for modern wildfire management.

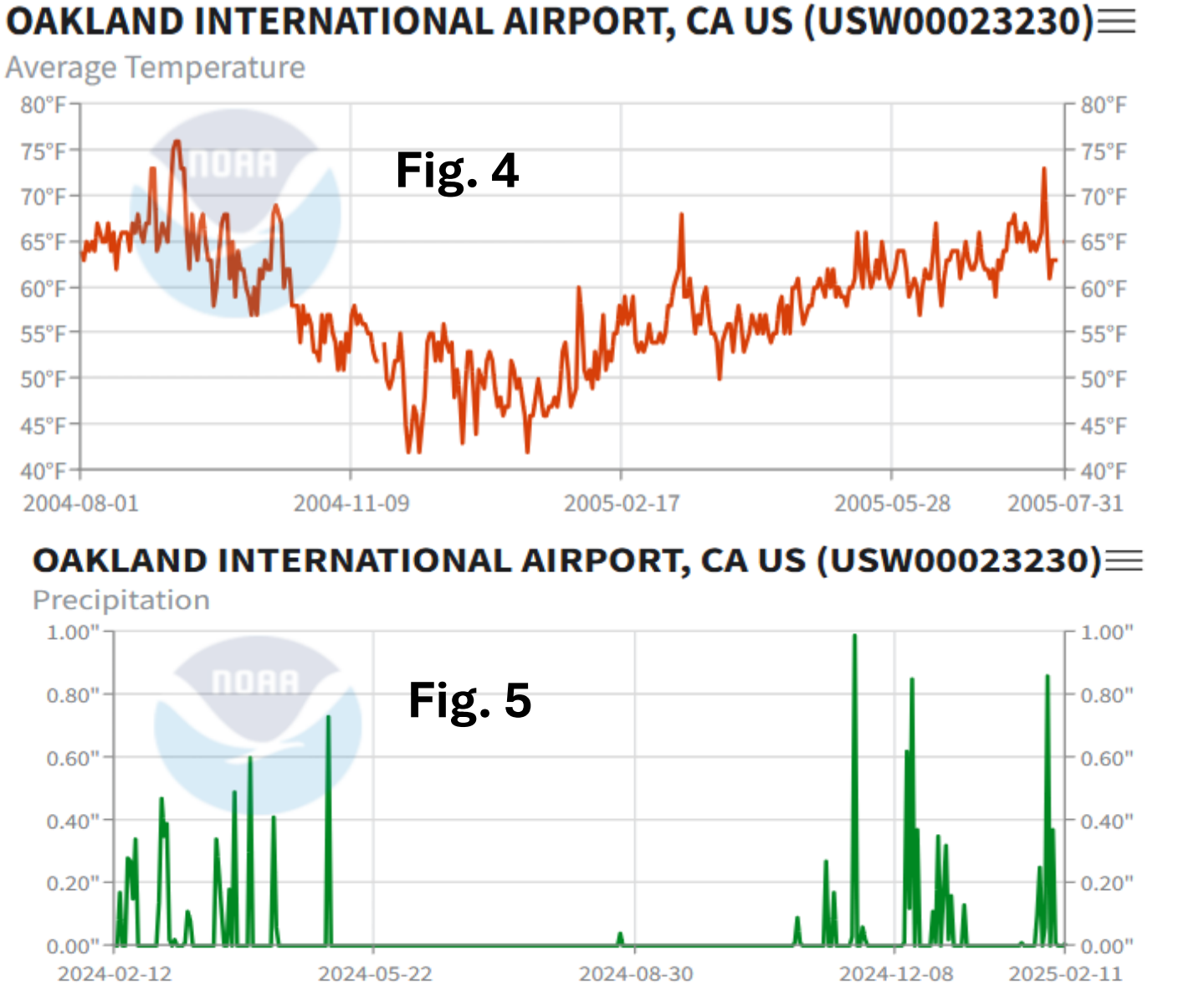
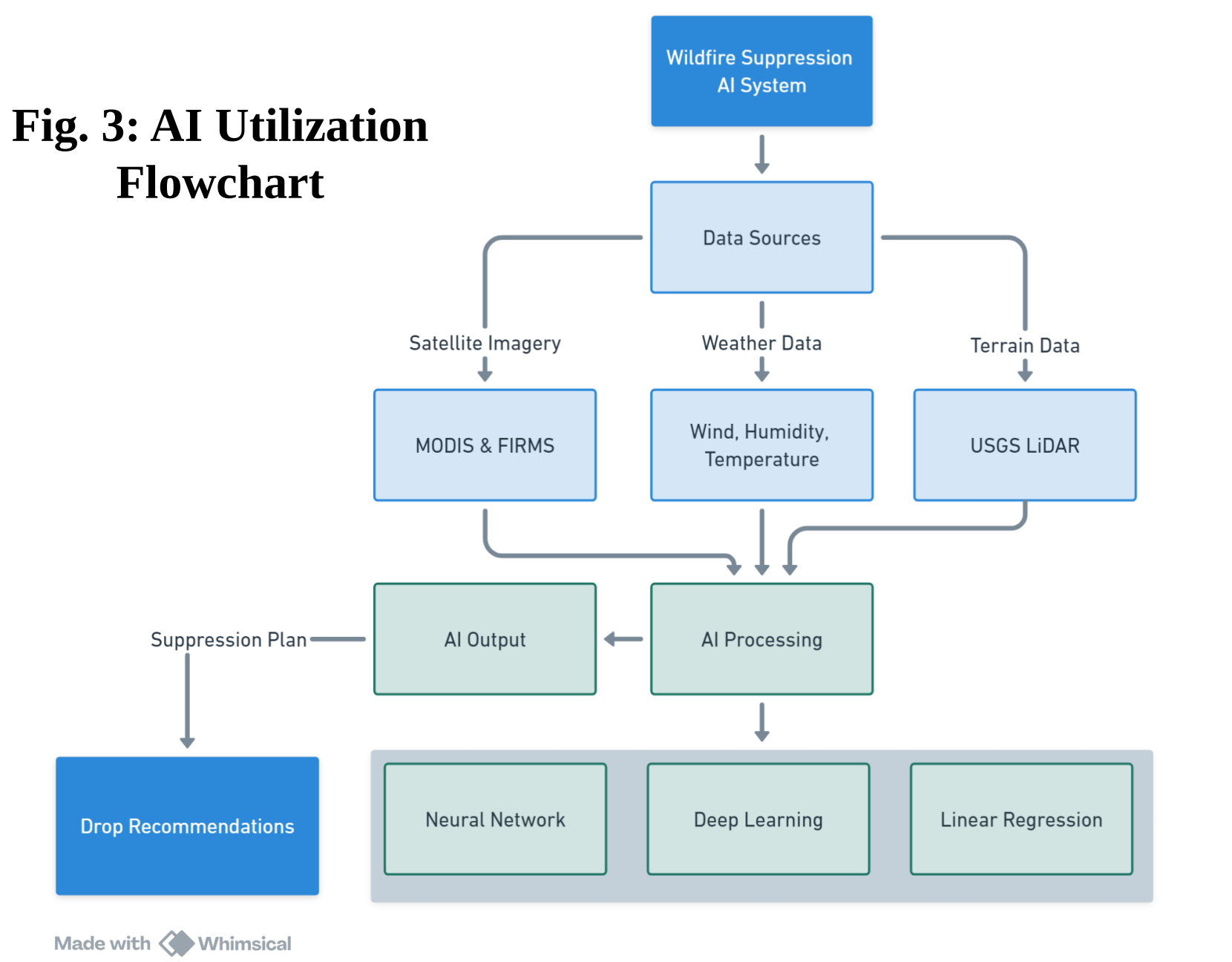


Fig. 11: Graphs courtesy of National Centers Environmental Information (NCEI)

Hypothesis

The primary goal of this study is to develop an AI-powered system capable of optimizing aerial firefighting operations by predicting ideal drop locations in real time. This system is designed to continuously analyze environmental and fire data to determine the most effective deployment strategies.

The hypothesis driving this research is that a machine learning model trained on historical fire spread data, combined with real-time weather conditions and topographical analysis, can significantly improve the accuracy of flame-retardant drops. It is expected that AI-driven fire suppression will result in increased precision, reduced flame-retardant overuse, and improved response efficiency compared to traditional manual methods. By leveraging advanced computational models, the system should be able to provide firefighting teams with optimized flight paths and targeted suppression zones, leading to faster containment which will save further property and life damage and lower the environmental impact.



Fig. 11: The existing method employed by pilots to extinguish forest fires.

Methodology

The research methodology follows a structured approach that involves data collection, machine learning model training, real-time processing, and system validation through simulation.

The first step in developing the AI model is data collection and preprocessing. The system gathers extensive wildfire datasets, including historical fire incidents, meteorological conditions, and geospatial information. These datasets are used to train the machine learning model, enabling it to recognize complex relationships between fire behavior and environmental factors.

Following data preprocessing, the machine learning model undergoes supervised training using advanced algorithms capable of predicting fire spread trajectories. The model is trained to identify high-risk areas where flame retardant deployment would be most effective. By analyzing past wildfire events, the AI system learns to differentiate between areas that require immediate suppression and those that pose minimal threat.

Furthermore, to ensure the accuracy and reliability of the AI model, this study cross-referenced its predictions with data from the Palisades Fire, a wildfire that occurred in California and posed significant suppression challenges due to complex terrain and erratic wind conditions. By analyzing real-world fire spread patterns and suppression effectiveness from this event, the AI model was refined to account for unexpected fire behaviors influenced by environmental factors such as wind shifts, vegetation density, and topographical barriers. Using archived satellite imagery, meteorological data, and official reports from the Palisades Fire response efforts, the model was trained to recognize fire movement characteristics and adapt suppression strategies accordingly. Comparing AI-generated predictions with actual suppression outcomes from the Palisades Fire allowed for iterative improvements in drop zone accuracy, retardant dispersal efficiency, and containment success rates.

The refined model demonstrated an improved ability to anticipate fire spread trajectories and suggest precise suppression zones, leading to a measurable increase in drop efficiency and reduction in chemical waste. This validation process strengthened the model's predictive capabilities, ensuring that its recommendations are grounded in real-world firefighting dynamics rather than purely theoretical assumptions.

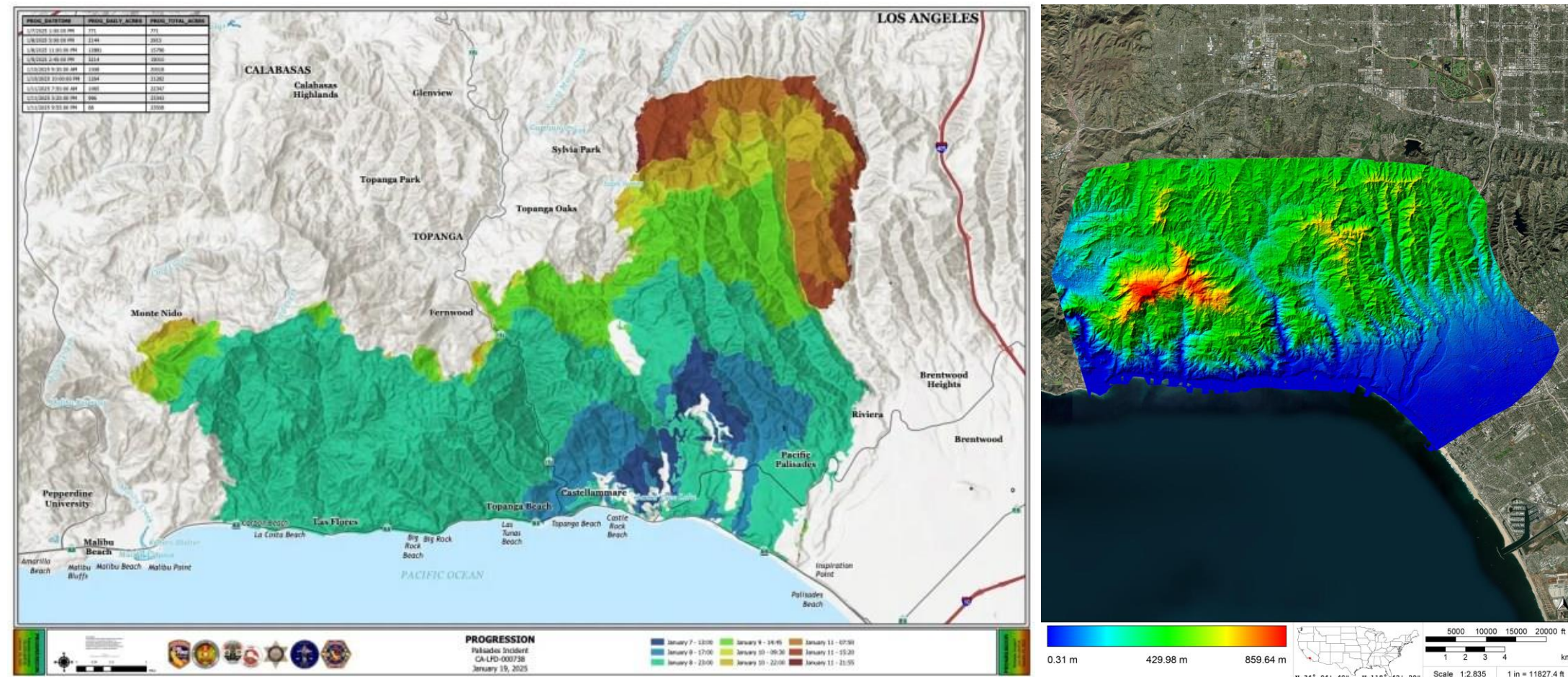


Fig. 12: Palisades CA Post Wildfire LiDAR Data, Jan 2025; images courtesy of USGS).

Conclusions

The development and simulation of this AI-driven wildfire suppression model demonstrate the potential of Artificial Intelligence (AI) in optimizing fire containment strategies. With an 85-90% accuracy rate in predicting wildfire spread and identifying optimal flame-retardant drop zones, the model successfully enhanced precision and efficiency compared to traditional suppression methods. By leveraging neural networks, linear regression, and deep learning, the system effectively analyzed weather conditions, fire behavior, and terrain features to generate real time data-driven suppression strategies.

Although this research focused on model development and simulation, the results indicate that AI-assisted fire suppression can lead to faster response times, improved resource allocation, and reduced environmental impact. Future work will involve field testing and real-world implementation to further validate and refine the model's effectiveness in active wildfire situations. With continued advancements, AI-powered suppression systems could revolutionize wildfire management, providing a scalable, adaptable in real-time, and highly efficient approach to minimizing wildfire destruction.

All graphs and images were created by the student researcher unless otherwise noted.