COST Action CA22164 · X-Fire 2025

1st International Workshop on Extreme Wildfire Events

X-Fire 2025

1st International Workshop on Extreme Wildfire Events

Nicosia, Cyprus · 23–25 September 2025

Book of Abstracts

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Preface

The **X-Fire 2025 – 1st International Workshop on Extreme Wildfire Events** marks an important milestone for the NERO network and for the broader communities of researchers and practitioners working on wildland fire behavior.

Extreme wildfire events are not just bigger fires and they are no longer rare anomalies. They are events that challenge our understanding, overwhelm operational capacity, and test the limits of preparedness and response. Addressing them requires not only scientific progress but also genuine collaboration between researchers, practitioners, and decision-makers.

With this spirit, the **COST Action NERO (CA22164 – european Network on Extreme fiRe behaviOr**) launched X-Fire as a series of workshops designed to bridge science and practice, share knowledge across disciplines, and strengthen our collective capacity to anticipate and respond to extreme wildfires.

The first edition of X-Fire, held in Nicosia (Cyprus) from 23 to 25 September 2025, brought together experts and practitioners from across Europe and beyond to discuss advances in data and modeling, observations, forecasting, and operational challenges. It also served as platform for honest dialogue on how we can transform scientific knowledge into operational readiness and response.

This **Book of Abstracts** captures the diversity of perspectives and research presented during the workshop. It reflects the shared commitment of our community to move from understanding to preparedness, and to ensure that knowledge continues to serve those who face the fires on the ground.

I would like to express my sincere appreciation to the **European University of Cyprus**, and personally to Prof. Dr. Georgios Boustras, for hosting X-Fire 2025; to the **COST (European Cooperation in Science and Technology) Association** for financially enabling this event; and, of course, to **all contributors** that made it a reality.

Let this first X-Fire workshop be the foundation for continued dialogue, stronger collaborations, and lasting progress toward safer and more resilient landscapes in the era of extreme wildfires!

Dr. **Theodore M. Giannaros**
Chair, COST Action NERO (CA22164)
National Observatory of Athens
15.10.2025

Workshop Overview

Background and Objectives

The **X-Fire 2025 – 1st International Workshop on Extreme Wildfire Events** was organized under the framework of the **COST Action NERO (CA22164 – european Network on Extreme fiRe behaviOr)**.

It aimed to serve as a **focused international forum** for advancing knowledge on the unique challenges of extreme wildfire events through the **exchange of scientific and operational insights**.

The workshop's objectives were to:

- Showcase emerging tools, data, and modeling approaches for forecasting and analysis.
- Identify gaps and priorities for improving preparedness, response, and resilience.
- Promote dialogue between research and practice.

- Strengthen international collaboration across scientific and operational communities.

Structure and Format

X-Fire 2025 took place from **23 to 25 September 2025** at the **European University of Cyprus (EUC)** in Nicosia, Cyprus.

The workshop programme included:

- **Three keynote presentations**, addressing forecasting, fundamentals of wildland fire behavior, and observational challenges.
- **Four thematic sessions**, covering topics from modeling and observing extreme wildfires, to studies of their drivers and management challenges.
- A **panel discussion** entitled "*From Research to Practice*", exploring pathways to translate scientific advances into operational and policy contexts.
- **Networking and social activities**, including a workshop dinner and informal exchanges among participants.

Participation

The workshop brought together **39 participants** from **15 countries**, representing a diverse mix of institutions, including **Universities**, **Research Centers**, and **Fire Management Agencies**.

This diversity underscores NERO's mission to bridge science and operations in addressing the growing challenges of extreme wildfire events.

Acknowledgements

NERO acknowledges the **European University of Cyprus (EUC)** for hosting the event and the **COST Association** for its financial support.

Special thanks are extended to the **Local Organizing Team** (Georgios Boustras, Cleo Varianou Mikellidou, Pierantonios Papazoglou, and Klelia Vasiliou) and the **Core Group** of NERO for their contributions to the workshop's scientific and logistical success.

X-Fire 2025

Abstracts

Session 1
Numerical Modeling of Extreme Wildfire Events

Wildfire Modeling by an Advection-Dispersion-Reaction (ADR) Approach Enriched with Empirical Knowledge

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Summary

Wildfires are severe natural hazards with profound impacts on society and the environment. Accurate forecasting requires adaptive, multi-fidelity simulations that integrate weather, fuel, and terrain variability. This work presents a data-and physics-based wildfire spread model that incorporates key thermal and chemical mechanisms alongside empirical knowledge and CFD-inspired insights. The model employs a thermal energy equation with dispersion, advection, reaction, and environmental losses. Simulated cases align with benchmarks, capturing fuel heterogeneity, slope-driven spread, and wind-driven dynamics. The framework is designed as the core of a real-time, data-informed decision support system for wildfire prediction and management.

Keywords: Physics-Based Modeling, Fuel Heterogeneity, Slope Effects, Byram Number, Rate of Spread

1. Introduction

The frequency of wildfire-disasters has escalated in recent years, a trend expected to persist due to climate change and human interventions. Wildfires are fast-moving fires that spread across vegetation-rich areas, with significant social, environmental, and economic consequences [1]. Between March 2023 and February 2024, wildfires consumed approximately 8,400 km^2 across Europe, resulting in the loss of at least 44 lives directly attributed to these events.

Wildland fires are among the most complex environmental phenomena, combining the physics of fluid flow with the chemistry of combustion across a wide range of spatial and temporal scales [2]. Broadly, three categories of models aim to predict key aspects of fire evolution. At the simplest level, empirical models, such as Rothermel's model [3] use functional correlations between the rate of spread (ROS) and variables like wind speed and humidity, leveraging observations and experiments to forecast fire behavior. At the other end of the spectrum, high-fidelity CFD simulations [4], such as FIRETEC, capture detailed physical interactions between fire and the atmosphere, across multiple scales. Despite their accuracy, these models are computationally expensive and impractical for real-time prediction. To address this gap, our approach combines empirical knowledge with CFD-inspired physics to produce a computationally efficient model that preserves key mechanistic details while enabling near real-time, operational wildfire predictions.

The objective of this research is to develop a wildfire simulator capable of predicting flame propagation, designed as a core component of a broader decision support tool for wildfire management. This framework integrates advanced physics-informed fire modeling with empirical knowledge of standard fuel models, allowing the model to account for both mechanistic fire behavior and landscape-specific characteristics. The novelty of the approach lies in formulating mathematical correlations within different parts of the model, combining physics and empirical data to produce accurate, computationally efficient predictions that can serve as the foundation for operational wildfire risk assessment and management.

2. Data and Methods

The employed interpretable, physics-based wildfire model simulates temperature evolution and fuel consumption (moisture and combustible material) using a coupled system of differential equations. It accounts for key physical processes, including: (i) first-order Arrhenius kinetics for water evaporation and wood combustion, with the latter modulated by oxygen limitation; (ii) advective heat transfer driven by canopy drag and wind dynamics; (iii) turbulent and radiative heat transfer near the flame, represented through a velocity-dependent dispersion coefficient; and (iv) heat losses via free convection and radiation. The system is discretized with an explicit finite difference scheme, employing first-order upwinding for advection and second-order central differences for dispersion, and is solved with a stable time step ensuring accuracy and numerical stability across processes. The cutting-edge properties of this paper can be summarized below:

i. **Fuel Heterogeneity:** Our approach incorporates existing fuel models [3], including the 13 standard fire behavior models by Anderson and the 40 models by Scott and Burgan, in a practical, integrative way. Using topographic maps categorized by these fuel models, the wildfire simulator accounts for fuel heterogeneity via spatially varying inputs such as packing ratio, reaction velocity, and dead fuel moisture content.

ii. **Slope Effects:** The influence of topography is examined and validated against benchmark results by incorporating slope effects through Nelson’s formulation [6], which adds a buoyant velocity component to the advection term to represent updraft airflow and enhanced wind over upslope terrain.

iii. **Wind-Driven Dynamics:** The wind speed profile around and within the canopy is analyzed, as energy transfer depends strongly on mean gas-phase velocity, which is influenced by above-canopy wind and vegetation-induced resistance. To quantify the interaction between streamwise wind and buoyancy, we use the Byram number [5] to characterize fireline behavior as wind-driven or plume-dominated.

iv. **Fireline Dynamics:** To evaluate the buoyant velocity, it is essential to estimate the fireline intensity, which quantifies the heat released per meter of fire front. In addition, we propose a novel method for estimating available fuel loading by tracking fuel consumption along the actual fire spread direction over discrete time intervals. This formulation also enables our model to provide estimates of the ROS, linking fuel dynamics and fireline intensity to fire propagation behavior.

These developments mark critical progress toward capturing the essential physics of wildfire behavior and realistically simulating flame propagation. Building on validated empirical models, such as Rothermel's, we embed their insights into a physics-based advection-dispersion-reaction framework, reformulating key correlations to bridge empirical knowledge with multi-fidelity processes. This integration yields a computationally efficient yet physically grounded model, advancing toward real-time wildfire simulation and management applications.

3. Results and Discussion

Some of the key baseline results include the following:

i. **Fuel Heterogeneity:** Figure 1 shows fireline perimeter expansion under different fuel settings [3]. In Figure 1a, the domain contains only heavy fuel ("Fuel 1"), while Figure 1b combines both heavy ("Fuel 1") and light fuel ("Fuel 2"), representing a heterogeneous configuration.

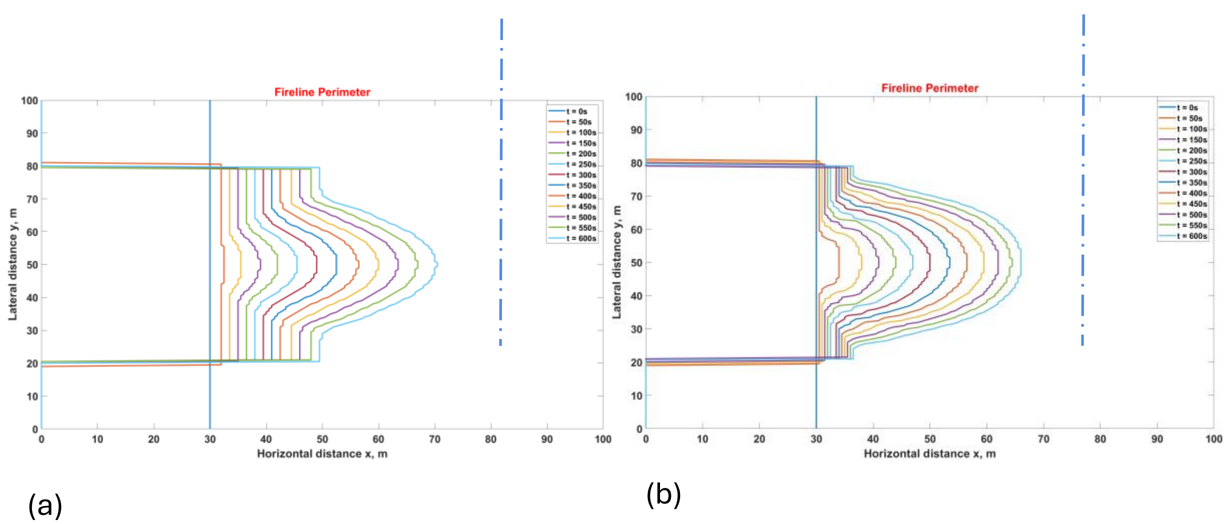

Figure 1: Fire front progression across: (a) uniform fuel configuration; (b) heterogeneous fuel configuration.

ii. **Slope Effects:** Figure 2 depicts fireline perimeter expansion under different topographies. In Figure 2a, the fire spreads over flat terrain, whereas in Figure 2b, an inclined slope accelerates fire spread, highlighting the model's ability to capture slope-driven behavior [6].

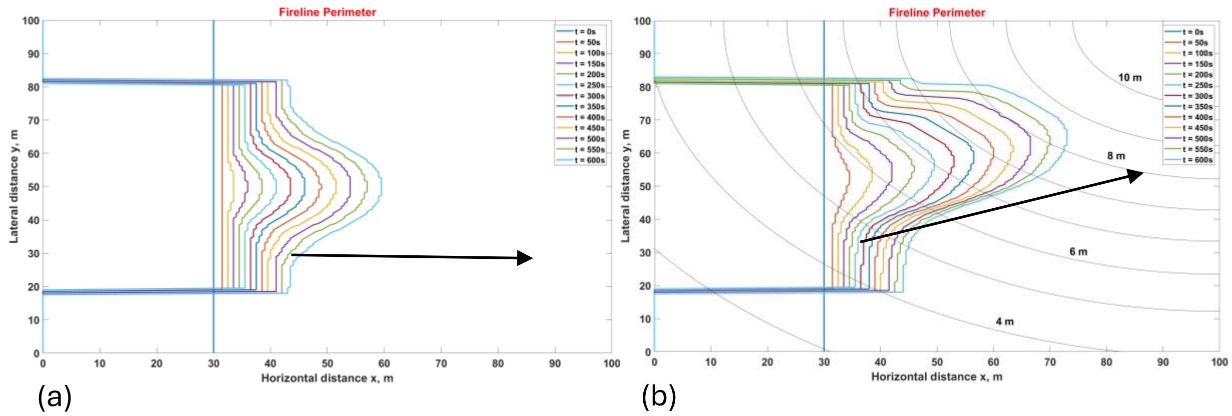

Figure 2: Fire front progression across: (a) flat terrain; (b) inclined terrain.

iii. **Wind–Driven Dynamics:** The model differentiates between plume-dominated and wind-driven fire behavior. Figure 3a illustrates a plume-dominated case, whereas Figure 3b shows a wind-driven scenario, with classification based on the Byram number [5].

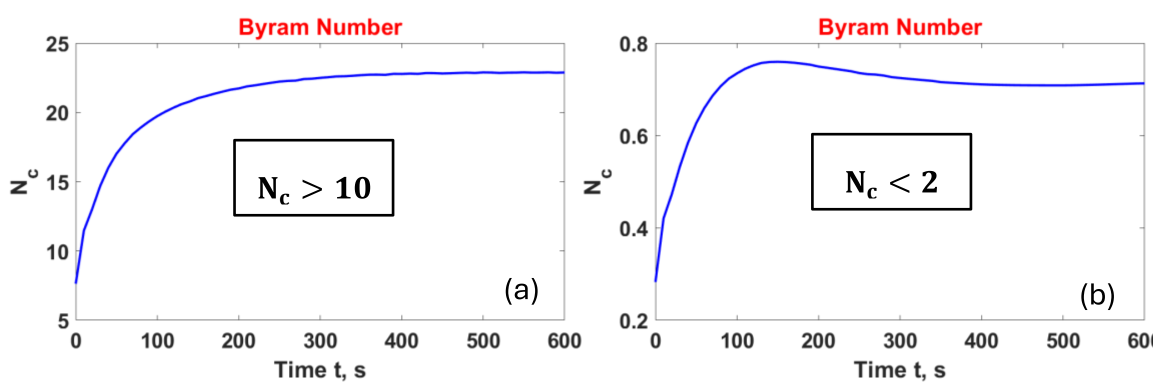

Figure 3: Fire behavior classification based on Byram number: (a) plume-dominated fire; (b) wind-driven fire.

4. Conclusions

The proposed model introduces a novel physics-based framework that integrates heterogeneous fuel mixtures, terrain-driven acceleration, and distinct fire spread regimes. By simulating scenarios with diverse fuel types (light and heavy), varying topographies (flat and sloped), and dynamics (plume- and wind-driven), it provides a flexible tool that realistically captures wildfire behavior and validates established empirical and theoretical observations.

A key next step is validation against real-case data, such as thermal imagery from actual wildfires, to demonstrate practical applicability in operational settings. Future work will also refine wind-canopy interactions and employ parallel computing to further enhance predictive performance.

Acknowledgements

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ForestSphere: A Digital Twin Approach for Monitoring and Managing Forests and Wildfire Risk

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Summary

This work presents the main concept behind ForestSphere, a forest digital twin that will leverage accurate real-time data obtained from ground, airborne, and spaceborne sources. Advanced sensing techniques shall be employed to enable precise, high-resolution forest mapping. The open, scalable, and modular Digital Twin architecture will then possess real-time data processing for dynamic updates. AI-supported predictive wildfire models will provide valuable insights on fire dynamics and user-centric tools for decision support shall be developed to assist firefighting teams, researchers and policymakers. Challenges include managing high computation costs, ensuring real-time data synchronization, and effectively integrating diverse data sources.

Keywords: digital twins, wildfires, remote sensing, decision support, fire modeling

1. Introduction

While the concept of Digital Twin (DT) originated in industry [1], its potential to optimize decision-making and effective action through faithful representations and forward-looking models built from physical-virtual integration of historical and real-time data [2], has pushed the boundaries of DT use to other areas, including natural resource management [3]. While many recent studies have focused on the development of DTs for agricultural and livestock applications [4], only a limited number of works have focused on using DTs for forest management [5]. Most of these studies use ground-level data to build a DT aimed at supporting forestry applications or climate change monitoring [6]. Only two studies specifically targeted wildfires. In [7], the authors created a simulated forest environment from typical variables of forest species and applied a model for calculating the combustion time. The results approximate those of a natural environment. In [8], the authors proposed a wildfire prediction model based on the JULES-INFERNO land surface model [9]. The DT can greatly improve the computational efficiency of the physical model by embedding the input into a low-dimensional space before prediction. This research laid the foundations for efficient methods to deal with the computing costs of high-dimensional dynamical systems. However, there is still a gap in the literature concerning the creation of a Forest DT: 1) built from the combination of multimodal and multi-scale real-world data, both historical and current, obtained from ground-based, airborne and spaceborne sensors and 2) capable of integrating advanced fire and smoke spread models [10] to support wildland fire management. These are the objectives of ForestSphere, which is proposed by a consortium of academic, SMEs and public entities, aiming to create a digital twin of a large, forested area in the central region of Portugal, to support firefighting teams, researchers and policymakers.

2.Data and Methods

ForestSphere is a forest DT, combining multimodal data captured through several platforms and sensors at ground, air and space level. Furthermore, available real-time data on weather, topography, land cover and fire occurrences will be fetched, as the first three are the main driving factors of wildfires. Table 1 summarizes the main types, sources, spatial and temporal resolutions, and formats of the data to be imported into the digital twin.

Table 1. Data to be imported into the digital twin.

Category	Data	Source	Sensor Platform	Spatial Resolution	Temporal Resolution	Format
Weather	Wind speed/direction Temperature Rainfall Atm. pressure	IPMA[*1]	Ground Weather Stations (WS)	Discrete (WS locations)	Hourly (Actual/Historical) Forecast up to 72h	Raster table
		REN	Ground Weather Stations (WS)	Discrete (WS locations)	Minutely	Raster table
	Smoke concentrations	CAMS[*2]	Satellite	10 km	Hourly	GRIB, NetCDF
	Global Climate Trends	C3S[*3]	Satellite	28 km	Hourly Historical / Actual / Forecast	GRIB
Topography	DTM (Digital Terrain Model)	DGT[*4]	Airborne Lidar	0.5 m	Data captured between April 2024 and March 2025	GeoTIFF
	DSM (Digital Surface Model)			2 m		GeoTIFF
Land Cover	Land Cover (9 classes)	DGT[*4]	Airborne Lidar	0.3 m	Data captured between April 2024 and March 2025	Labeled Point Cloud
	Soil occupation (83 classes)		Airborne Multispectral	1 ha	Data captured in 2019	Vectorial Map
	Land Cover	Copernicus CORINE, CLCplus…	Satellite	10 to 100 m	2 to 3 days	Raster GeoTIFF, vector

	Vegetation	Forest Sphere Consortium	UAV Lidar/Multispectral	5 to 10 cm	On demand	Labeled Point Cloud
	Ground-level vegetation Canopy base height		UGV and ground level sensors Lidar/Multispectral	1 to 5 cm	On demand	Labeled Point Cloud
Fire	Burned Areas	ICNF[*5]	Satellite; Ground validation	1 ha	Yearly	Vector
		EFFIS[*6]	Satellite	30 ha	Daily	Vector
	Ignitions	ANEPC[*7]	Airborne, Multispectral	N/A	On demand	Text (coordinates)
	Firefighting means on site		Ground sensors	Discrete (sensor location)	On demand	Text (coordinates)

[*1] Instituto Português do Mar e da Atmosfera (https://api.ipma.pt/)
[*2] Copernicus Atmosphere Monitoring Service (CAMS) Portal (https://atmosphere.copernicus.eu)
[*3] Copernicus Climate Change Service (C3S) Portal (https://climate.copernicus.eu)
[*4] Direção-Geral do Território Portal (https://www.dgterritorio.gov.pt/cartografia/cartografia-topografica/modelos-digitais?language=en)
[*5] Instituto da Conservação da Natureza e das Florestas (https://geocatalogo.icnf.pt/catalogo.html)
[*6] European Forest Fire Information System - EFFIS (https://forest-fire.emergency.copernicus.eu/apps/data.request.form)
[*7] Autoridade Nacional de Emergência e Proteção Civil Portal (https://prociv-portal.geomai.mai.gov.pt/)

The data, processed and shown through interactive user interfaces, designed in close collaboration with main stakeholders and civil protection end-users, which will be used to obtain valuable insights on the forest structure, health, and the wildfire risk exposure of the forest and the valuable assets located in it, such as the electrical, gas, telecommunication and transport infrastructures. Such data can also be generated or leveraged by intelligent means for forest management, including advanced fire behaviour prediction models and autonomous robotic mulchers or firefighting robots [11]. Figure 1 depicts the proposed ForestSphere architecture.

3. Results and Discussion

Challenges such as the computational costs associated with high-dimensional dynamical systems require the development of ad-hoc methods and the employment of HPC resources to support the proposed development. Temporal and spatial synchronization of data, updates and feedback is another challenge for the integration and fusion of heterogeneous data obtained from different sensor modalities and observation sources. Strategies to overcome this include data Resampling and interpolation, use of convolutional neural networks (CNNs) capable of handling multi-resolution inputs, implementing fusion frameworks (e.g., spatial-temporal fusion models) designed for heterogeneous data sources, downscale coarse data using statistical models or machine learning to generate finer-resolution estimates where needed and validation of fused datasets with ground truth measurements. A compromise between accuracy and operability should be found, leveraging soft-synchronization and decision-level fusion approaches. Furthermore, real-world testing shall be required to ensure the platform interoperability, AI-driven models' accuracy and adaptability and final system validation by main stakeholders.

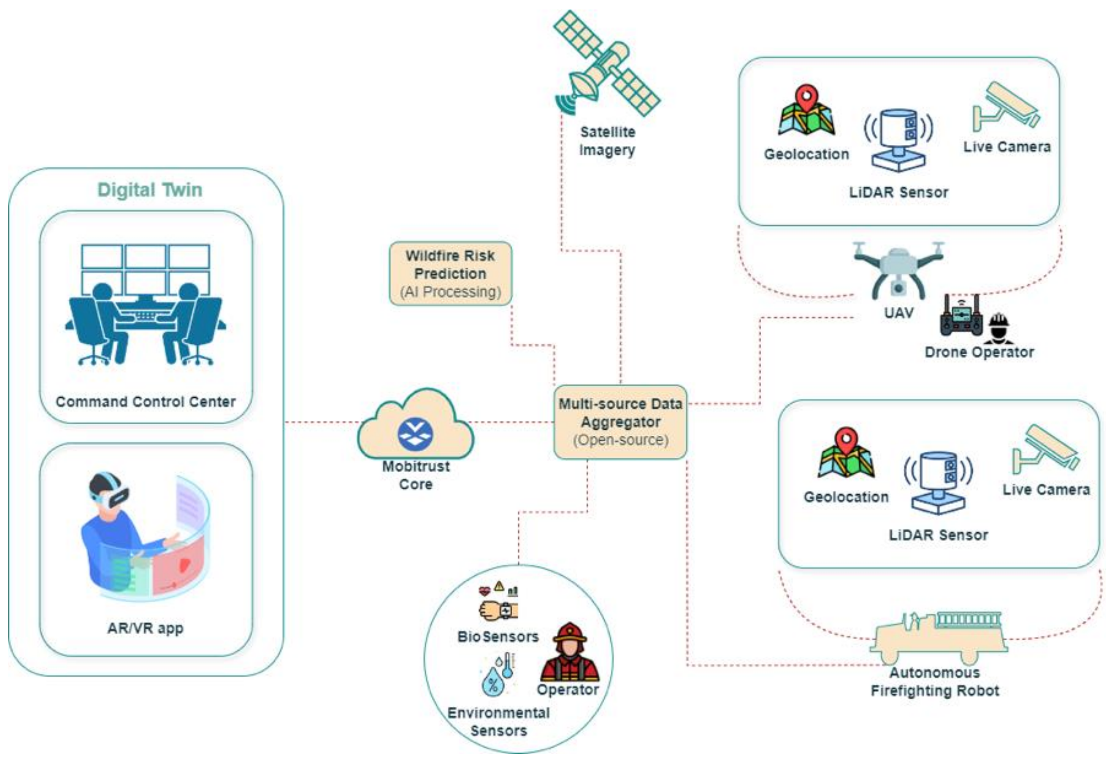

Figure 1. ForestSphere Digital Twin architecture.

4. Conclusions

Research to develop technological solutions that contribute to forest resilience and protection of human lives and assets is required and has the potential to be quickly assimilated, as we witness an increase in wildfire frequency and extent, exacerbated by the effects of climate change and rural land abandonment. ForestSphere shall contribute both to the resilience of the territory and the forestry industry, with clear socio-economic benefits. Real-time data on vegetation structure and location can be leveraged by the authorities and infrastructure owners to assess wildfire risk exposure. Forestry enterprises can leverage this information for thinning and harvesting activities. Companies responsible for large critical infrastructures such as power distribution, can monitor the growth of trees in the vicinity of powerlines and predict the need for pruning or tree removal actions in advance, facilitating the planning of operations. Civil Protection Authorities will have a digital platform aggregating current and historical multimodal data concerning forests and wildfires. Historical data on wildfire occurrences can support fire preparedness and prevention actions, such as fuel break locations, firefighting means allocations, fuel management strategies and more. Advanced fire spread simulators applied to the interactive DT environment can be leveraged for the training of civil protection teams. During fire occurrences, data can be used to perceive the wildfire behavior and estimate its potential spread, with the help of dedicated models and AI algorithms. Additionally, the platform will facilitate collaboration between firefighting teams, civil protection authorities, and infrastructure managers, ensuring coordinated responses to wildfire emergencies.

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iFire AI: AI-powered Wildfire Simulation and 3D Immersive Visualisation

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Summary

Wildfires, especially extreme wildfires in the urban/rural interface, cause irreversible damage to ecosystems, human lives and economies globally. To reduce such losses, understanding wildfires is crucial for effective preparedness and response by first responders. We introduce iFire AI, aimed at developing the world's leading wildfire visualisation system by integrating AI with wildfire simulation and 3D immersive visualisation for first responders. We propose a deep learning-based wildfire simulation model, providing high-fidelity extreme wildfire behaviour data for our visualisation system. Such data will then be reconstructed using the Unreal Engine 5 and rendered on 3D immersive visualisation platforms, providing dynamically evolving hyper-realistic extreme fire landscapes. By offering life-like visualisations for dynamic wildfire scenarios at the urban/rural interface, we hope iFire AI can enhance first responder risk perception, situational awareness and collaborative decision-making, and thereby reduce risks due to extreme wildfires and promote strategic readiness.

Keywords: Wildfire Visualisation, Wildfire simulation, Deep Learning, Emergency preparedness

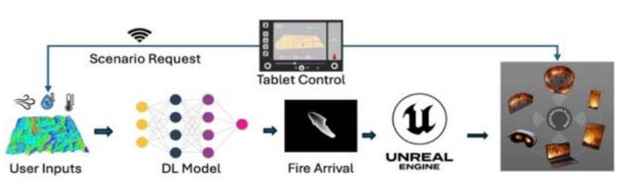

Figure 1 Overview of iFire AI System

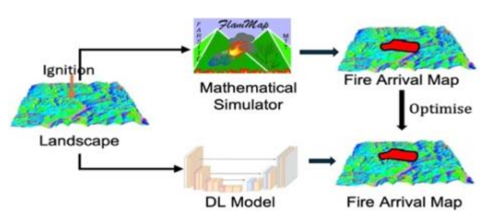

Figure 2 Pipeline of Training a DL Model

1. Introduction

Wildfires are unplanned, unpredictable, and erratic fires that affect vast open areas and urban interfaces [1]. Extreme wildfires at the urban/rural interface (URI) cause irreversible damage to both natural and urban environments and pose risks to life and property [2]. During 2019-20, Australia experienced its largest bushfires, which burnt 19 million hectares, killed at least 34 people and three billion wild animals, affected 450 people from smoke inhalation, and caused up to 100 billion US dollars in economic losses. To mitigate such losses, it is essential to understand wildfire behaviour by offering education and training sessions for firefighters, enhancing their risk perception, situational awareness and collaborative decision-making against wildfires [2]. With the development of computer technologies, researchers have been exploring enhanced wildfire simulation and immersive wildfire visualisation [3], enabling users to safely experience diverse wildfire scenarios without exposing them to real-life dangers.

In this study, we propose *iFire AI*, an AI-powered wildfire simulation and 3D immersive visualisation system. *iFire AI* is built upon the iCinema Research Centre's current system *iFire*, which translates the 2D wildfire scenarios into a first-person perspective using Unreal Engine 5 (UE5) and visualises them in our design-registered 3D immersive visualisation system AVIE and AVIE-SC [4], along with any type of smart screen (Figure 1). In particular, *iFire AI* has its *AI-powered wildfire simulation*, which uses advanced deep learning (DL) techniques to simulate the fire spread given the terrain information, ignition and weather conditions. We also propose the *FARSITE-8K***,** a simulation dataset used to compare the capability of feature extraction from the landscape data.

Compared to existing 2D and 3D visualisation systems, *iFire AI* allows a more intuitive and visceral engagement with wildfires by allowing full immersion inside a fire ground with a better sense of how extreme fires interact with different landscapes and environmental conditions [5]. Unlike other immersive visualisation platforms such as head-mounted virtual reality systems [5], *iFire AI* allows users to physically interact and collaborate with each other in wildfire scenarios, reflecting the real-world conditions of first responder team interaction. Finally, by learning from a large amount of wildfire data, our deep learning-based wildfire simulation model can generate higher-fidelity wildfire scenarios at the urban/rural interface than those produced by mathematical models.

2. Data and Methods

The role of wildfire simulation in *iFire AI* is to provide realistic wildfire scenarios to our visualisation system. Existing fire simulators [6], [7] are usually conducted via mathematical models, which solely rely on handcrafted physical rules and are thus often limited by their lack of scalability for complex landscapes involving interaction between ground and atmospheric processes. With the rapid advancement of artificial intelligence (AI) and, particularly, deep learning (DL), it has become increasingly feasible to incorporate AI methods for extreme event visualisation [8].

Our DL model follows a similar architecture to image segmentation models [6], [7], where the inputs and the outputs are 2D maps. Specifically, the inputs of the model are the landscape data[1], including eight maps describing the terrain, tree canopy, and surface fuel. These maps are cropped into a constant size (e.g., 512x512) with the ignition as the centre and sent into the DL model to generate the 2D fire arrival map, with each pixel representing the time (in minutes) of the fire arrival at the location. To simplify the model training, we use a Sigmoid function to normalise the outputs, so that each pixel has a float value from 0 to 1. The model is optimised using an L1 loss function with an ADAM optimiser.

The integration of the DL model in *iFire AI* follows the pipeline shown in Figure 1. A tablet interface is designed to allow users to select the scenarios and adjust ignitions. Then, it sends the request to the database to obtain the required input data and uses the DL model to generate the fire arrival maps. These inputs and outputs are further reconstructed into a 3D space using UE5, the most advanced 3D computer graphics game engine. The terrain information is built using pre-designed materials in UE5 based on the landscapes. Meanwhile, the renderings of flames, smoke and embers are built upon the particle effect with hard-coding to simulate their behaviours.

Finally, we visualise the wildfire scenarios using the immersive simulation. As a system capable of taking users into a full-body 1:1 scale on a virtual experience of a wildfire in an exact geo-location, *iFire AI* involves using our 3D cinema AVIE and AVIE-SC, a 360-degree and 130-degree 3D immersive and interactive cinema (Figure 1: Top centre and top left). These systems exhibit wildfire scenarios on panoramic screens at 4K resolution. Users wear 3D glasses to enable a tangible experience of the fire ground. They support up to 30 users to interact simultaneously and directly with each other and the virtual environment, with no occlusions of the views. It is a promising visualisation system that has previously been successfully deployed for multiple first responder projects [9], [10]. Therefore, AVIE and AVIE-SC can be ideal visualisation systems to optimally visualise and experience wildfires.

FARSITE-8K. To build a reliable wildfire simulation model, it is essential to evaluate the capability of extracting features from the landscape data among different model architectures. However, it is currently impractical to obtain such data from real-world sources to support our task. To mitigate this problem, we propose the FARSITE-8K dataset. We first sample 8,000 different regions across the US, each having an area of $15.36 \times 15.36 km^2$. Then, for each region, we download the landscape data from the LANDFIRE (https://landfire.gov/). Each map contains 512×512 pixels with a spatial

[1] https://landfire.gov/fuel/landscape

resolution of 30 meters. To obtain the fire arrival maps, we use FARSITE to simulate fire spread for 144 hours. The simulated fire spread starts from ignition at the centre of the region and follows constant weather conditions with a temporal resolution of one hour as parameters. This setting allows the DL model to consider only the landscape features once trained on this dataset.

3. Results and Discussion

Evaluation Metrics. In our method, we select Mean Intersection of Union ($MIoU$) to evaluate our model, which calculates the average of the ratio between the intersection and the union of predicted P and ground truth GT arrival time maps lying in short time slots $MIoU = \frac{1}{12}\sum\frac{(t_i \leq P \leq t_{i+1}) \cap (t_i < GT \leq t_{i+1})}{(t_i < P \leq t_{i+1}) \cup (t_i < GT \leq t_{i+1})}$ where $t_i \in \{0,12,24,\dots,144\}$. We also calculate $IoU_{all} = \frac{(P \leq 144) \cap (GT \leq 144)}{(P \leq 144) \cup (GT \leq 144)}$, evaluating the overall burning areas.

Results. In this part, we test the capability of existing segmentation models on the FARSITE-8K Dataset.

Table 1 Performance of models on the FARSITE-8K dataset

	UNet++ [11]	PSPNet [12]	DeepLabv3+ [13]	SegFormer [14]	SegFormer-MiT [14]
$MIoU$	**19.47%**	18.00%	17.94%	18.90%	19.26%
IoU_{all}	**64.43%**	62.59%	60.44%	60.12%	60.56%

DL models are trained using 80% the dataset following the pipeline in Figure 2 and validated on 5%. Finally, they are tested using the remaining 15% of the dataset. In Table 1, all models achieve above 60% of IoU_{all} scores. Also, UNet++ performs best among all models, followed by PSPNet. Surprisingly, SegFormer only performs slightly better than DeepLabv3, indicating that MLP may not outperform CNN for decoders on wildfire simulation. Finally, the Mixed Transformer (MiT) encoder outperforms ResNet34 on SegFormer, indicating that Transformer-based decoders are potentially better than CNNs. Finally, all models achieve around 18% of $MIoU$, indicating that generated fire arrivals do not well match the ground truth, suggesting future improvements.

For the immersive visualisation system, we have demonstrated our prototype version of *iFire*, using a hypothetical Australian pine plantation fire, a grasslands fire in the Australian state of Victoria in 2022 and the Bridger Foothills Fire in Montana, USA in 2021. We received positive comments and feedback from our stakeholders. Currently, the *iFire* visualisation system is being deployed by FRNSW for its Emergency Services Academy to train incident commanders and fire station commanders and the Australian Broadcasting Corporation (ABC) for its online news divisions to educate its 12M+ audience. More details can be found on our iFire project page.

4. Conclusions and Future Work

This study introduces *iFire AI*, aimed at developing the world's leading wildfire visualisation system by combining DL-based wildfire simulation and 3D immersive visualisation. The DL model provides realistic wildfire scenarios for our visualisation system. These scenarios are then reconstructed into 3D space using UE5 and are finally rendered on 3D immersive visualisation systems AVIE and AVIE-SC, providing dynamically evolving hyper-realistic URI landscapes in extreme fires. We also design a FARSITE-8K dataset, with collected landscape maps from LANDFIRE and simulated fire arrival maps with constant weather conditions, to explore the capability of the feature extraction on landscapes among different DL models. By offering life-like visualisations for dynamic URI wildfire scenarios, we hope *iFire AI* can enhance first responder risk perception, situational awareness and collaborative decision-making and thereby reduce vulnerabilities due to extreme wildfires and promote long-term readiness.

At the current stage, our DL model is successfully built upon the simulation dataset FARSITE-8K, illustrating its capability to learn from the data. To maximise the advantage of deep learning, future studies will explore improving the model by using real-world data, e.g., model fine-tuning. We will also integrate dynamic weather conditions to enable users to see how the same fire may evolve under future climate conditions. Furthermore, the DL model can generate extra outputs, such as smoke and flame behaviour, to enhance 3D modelling.

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Path to Extreme Wildfire Modeling via Highly Resolved Vegetation Structures

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Summary

Wildfire spread – in small and large scale – is heavily driven by complex flow structures interacting with the vegetation. In this work, understanding of the path to extreme wildfire events is progressed by modeling small and larger scale vegetation structures in highly resolved simulations. In particular, the flow field in a wind tunnel setup with distributed needles is evaluated in detail, and large-scale, highly resolved trees are simulated. These simulations can give insight into the development of extreme situations which later can be used for informing reduced models based on Lagrangian particles or porosities.

Keywords: CFD, turbulence, needles, trees, fire whirls

1. Introduction

In wildfire modeling, one faces challenges of different physical scales and multiple levels of uncertainties. It is known from experimental and numerical observations at different scales that details of vegetation fuel structure, and its role in heat transfer from the gas to the solid, can heavily impact ignition and therefore fire spread [1, 2]. Typically, this detailed structural information is not available for the wide range of real tree structures found in nature. However, highly resolved models of representative trees, branches, their needles and other small-scale vegetative structures can provide valuable insight into the controlling phenomena of wildfire spread in general. This can be important, for example, in extreme wildfire situations where global and local flow structures can cause extreme outcomes that usually cannot be modeled in detail. Local turbulent flow structures influence convective and radiative heat transfer as well as species distribution which itself directly influences flame and fire spread – methods based on Lagrangian particles or porous media are not yet able to describe the effect of these detailed structures on the flow field. Further the continuous improvement of coarser fuel structures relies on detailed knowledge of detailed vegetation structures [3].

The objective of this work is to provide insights of the impact of highly resolved vegetation structures on local fluid dynamics. Detailed modeling, informed by high quality experiments, can be used to improve the more practical coarse resolution (e.g. particle) methods so that detailed turbulent flows and oxygen and soot distribution can be modeled more accurately when considering large-scale extreme fire behavior. Here, the focus is on pine needles, where studies have demonstrated the importance of fuel distribution and arrangement on flame and fire spread due to complex intra-bed convective and radiative heat transfer (e.g. [4, 5]). Moreover, it is highlighted that this highly resolved modeling approach can also be transferred to larger scales where trees shapes are resolved in detail and are evaluated with different models. The results show that highly resolved tree simulations reveal the development of complex turbulent flow phenomena. In addition to affecting horizontal fire spread, these complex flow phenomena can support surface-to-crown fire transition – a key step for incipient extreme fire behavior. They may also play a role in the development of extreme fire whirls.

2. Data and Methods

The simulations of pine needle (Pinus rigida) beds were based on previously reported wind tunnel measurements of pressure and velocity in beds of different packing density (Mueller et al. [m2]). In this case, detailed geometrical models of the fuel structure were generated via a computer tomography approach. The samples were loosely filled into a plastic cylinder of 12 cm diameter and 10 cm height, with an overall bulk density of 20 kg/m^3 (sample porosity of ~97%). Rotating this cylinder between an X-ray source and a detector led to a series of images that were converted to be used as a solid grid in Computational Fluid Dynamics (CFD) simulations. Figure 1 shows on the left the arrangement of the x-ray source and the detector which is converted to a three-dimensional description of the needles (see Figure 1 on the right) with a Stereolithography (STL) format, which can be further used for the volume mesh with different refinement levels in the wind tunnel.

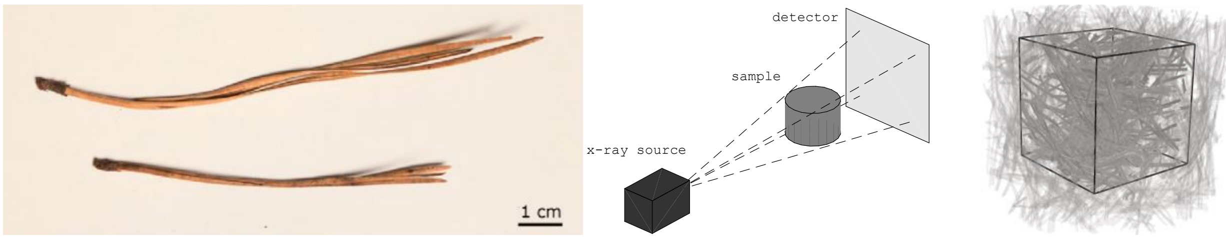

Figure 2 Needle size and extraction of needle geometry from computer tomography [6]

For the replication of the wind tunnel experiment, the cylindrical arrangement cannot be directly transferred to the simulation. Rather, a (5x5x5) cm region is extracted from the cylindrical bulk needle representation, as highlighted in black in Figure 1 on the right. The need for this extraction becomes clearer when looking at the actual wind tunnel setup shown in Figure 2 on the left. The setup consists of a 375 mm long, 100 mm high, and 150 mm wide wind tunnel where only a section is filled with pine needles (density 20 kg/m^3). The section is 50 mm high and starts at position x=0 mm up to the end of the wind tunnel at position x=300 mm. The filling of this needle section is done via multiple copies of the originally extracted box region; this copied arrangement is highlighted in Figure 2 on the right via the blue box shapes.

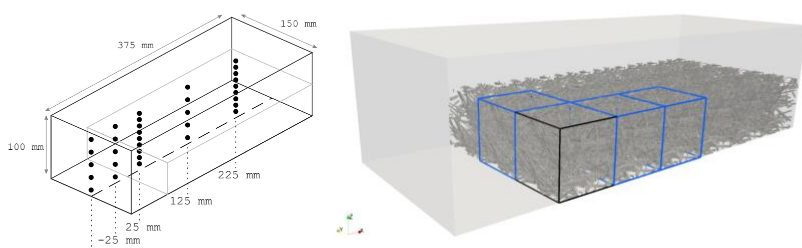

Figure 3 Wind tunnel setup [2], simulation domain and arrangement of extracted needles

The simulation is done with OpenFOAM, applying a cold inflow and an inlet velocity of 0.5 m/s. The post-processing includes velocity profiles, pressure drop, flow uniformity and wall shear stress as an estimate for heat transfer. The mesh study includes a wide range of total cell numbers, starting with only 5 million cells and ranging up to about 50 million cells (see Figure 3). The smallest cell size is 0.3 mm at local refinements around the needles and at the interface of the needles to the remaining flow region. The setup for the tree simulation is done with – for now – only 54 million cells in a domain of size 20x6x8 m; in total, 4 trees of size 5 m are evaluated in a non-symmetric setup.

Figure 4 Mesh setup with different refinements around position x=0mm (left: around 5 million cells, middle: around 25 million cells, right: around 50 million cells)

3. Results and Discussion

For the small-scale wind tunnel simulation, the x-velocity is compared for 4 different mesh setups to experimental measurement by Mueller et al. [6].

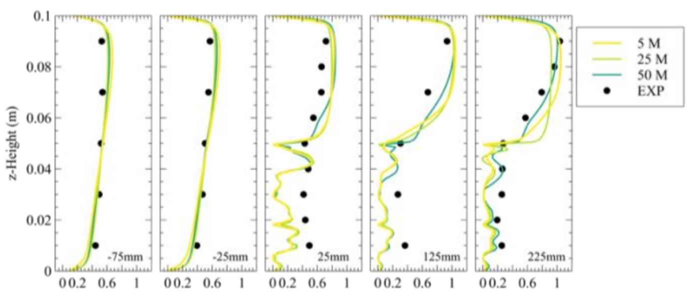

Figure 5 x-Velocity distribution on x axes of each subplot in (m/s)

Both the differences in velocity between the different meshes, as well as the ones between the simulation data and the measurements, are small. The most significant discrepancies are within the fuel bed at the 25 mm position. This is near the leading edge where the flow field is more sensitive to the individual placement of needles (and the X-ray model is representative of only the average structure, not the exact arrangement in the wind tunnel). It is expected that the differences will further increase when applying Large Eddy Simulation (LES) models which reduce the overall turbulent viscosity. The flow field – here velocity magnitude – in the symmetry plane (y=0.075 mm and about 50 million cells) of the wind tunnel is shown at Figure 5. It is seen that the needles deflect a large part of the volume flow to the upper part of the mesh; inside the needle bed the flow is much more complex and would impact any heat transfer or species concentration in an interesting way. The impact on convective heating and radiation, through flame structure, will be critical for understanding how marginal burning behavior in surface fuels can transition into more extreme fire behavior.

These small-scale needle simulations give a first impression of the importance of detailed modeling of flow structures in wildfires. Once again, these detailed simulations are not directly applicable for any larger extreme fire scale, but these will be used to improve methods based on Lagrangian particles and/or porous modeling approaches. An important next step will include evaluating the implications of using average (superficial) velocities to submodel intra-bed physics driving flame spread (e.g. Mueller et al. [6]) and quantifying differences when compared to the fully resolved flow structure shown here.

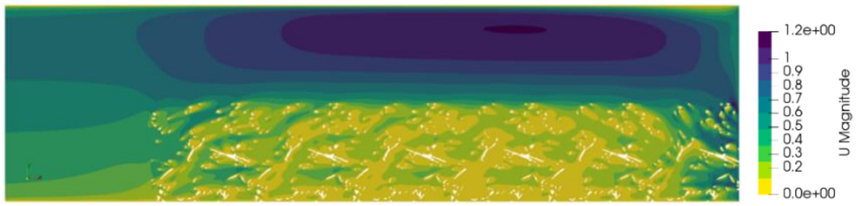

Figure 6 Velocity distribution

At larger scale – here at tree scale – the impact can be even stronger. Figure 6 shows, for the selected setup, the arrangement of trees and highlights the complex flow structures around one of the trees.

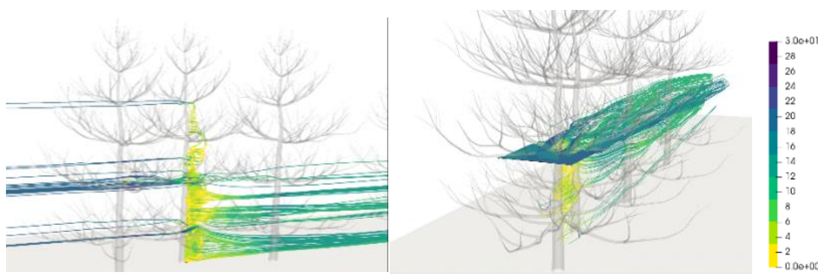

Figure 7 Large scale example of highly resolved flow structures

It is seen that in the wake region of the tree(s) strong vortices occur which potentially lead to stronger generation of firebrands in that region of the trees. This is also seen in large scale experiments. Further investigations are ongoing which apply different arrangements of trees and different modeling settings to evaluate the flow region. In addition to these qualitative descriptions of the flow via streamlines, further post-processing will be done to evaluate the different flow properties e.g. forces on the trees, flow uniformity, pressure drop and wall shear stresses as a proxy for heat transfer, but also to gain better insight to firebrand generation. The objective is also to evaluate the importance of fire whirls and their role in surface-to-crown fire transitions. In addition to the effects of detailed flow structures for fire spread, the simulation can give further insight to the shear layer of the forest canopy and larger atmospheric flow interactions.

4. Conclusions

Highly resolved vegetation structures are simulated on two different scales. The wind tunnel setup shows good agreement with the experimental results.

Future research will focus on the path from needle to tree scale based on highly resolved structures and well-resolved Large Eddy Simulations. On the small scale, other wind tunnel setups will be evaluated with varying boundary conditions and needle distributions. On the tree scale, special emphasis will be given to fluid dynamics relevant for surface to crown fire transition and turbulent shear layer development in the crown region. The aim is to get insights into local fluid dynamics and connect its impact on global flow phenomena relevant for extreme fire situations.

Acknowledgements

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Modeling the largest wildfire using FARSITE in the Czech Republic: National Park Bohemian Switzerland 2022

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Summary

In July 2022, Bohemian Switzerland National Park experienced Czechia's largest recorded wildfire, burning over 1,060 hectares. We used FlamMap (respective FARSITE) to simulate fire behavior under various scenarios combining fuel types and weather conditions. Results indicated that the fire could have reached a similar extent under alternate settings, though healthy, closed-canopy forests would have notably limited its spread. This study enabled the first FARSITE calibration in Central Europe, confirming its relevance for regional wildfire modeling. The findings support improved forest management, highlight the role of vegetation structure, and inform future wildfire preparedness under climate change.

Keywords: Czech Republic, modeling, FARSITE, FlamMap, wildfire

1. Introduction

The wildfire in Bohemian Switzerland National Park in the summer of 2022 was the largest recorded in the modern history of the Czech Republic, burning over 1,060 hectares on the Czech side and approximately 113 hectares on the German side. The event, which occurred in a landscape heavily affected by bark beetle-induced spruce dieback, introduced new challenges for fire risk assessment and fire modeling in Central Europe [1]. While fire behavior models are commonly used in North America, the Mediterranean, and other parts of the world, their applicability under Central European conditions has remained limited.

This study aimed to simulate the 2022 event using the FARSITE model [2] (part of the FlamMap tool [3–4]) and to evaluate various scenarios combining alternative vegetation structures and climatic-meteorological conditions, including variables such as fuel moisture, wind, drought, and forest composition. The study provides insight into wildfire dynamics in temperate European climates, where not only fuel structure but also weather and climate variability play crucial roles. Moreover, it offers valuable knowledge to improve fire management and preparedness strategies.

Importantly, this exceptional event provided a unique opportunity to verify and calibrate the development of high-resolution (5 m) input layers for fire behavior modeling, which are typically not available for the territory of the Czech Republic.

2. Data and Methods

The simulation framework was based on a combination of high-resolution spatial data and advanced modeling tools for predicting fire behavior. Terrain was represented using a 5 m resolution digital elevation model, supplemented with forest structure derived from airborne LiDAR data, including stand height, canopy bulk density, canopy base height and canopy cover. Fuel characteristics were classified according to standardized models [5], while meteorological inputs were taken from observations during the actual wildfire event in July 2022. To account for local wind flow in complex terrain, the WindNinja model was applied [6].

Fire behavior was simulated using the FlamMap system (FARSITE model). In addition to the real-case scenario, a set of seven hypothetical scenarios was developed, reflecting different combinations of vegetation structure (e.g., bark beetle-affected dead stands, healthy spruce forests, natural mixed forests, clearings) and environmental variables (e.g., reduced temperature, varying wind intensity, different levels of drought and fuel moisture). This scenario-based approach allowed for the evaluation of the relative influence of individual factors on fire spread and intensity under Central European conditions. It also provided a unique opportunity for the first calibration of the FARSITE model based on a real wildfire event in the Czech Republic and Central Europe, increasing its relevance and transferability to similar regions.

3. Results and Discussion

The FlamMap model proved to be an effective tool for simulating wildfire spread under Central European conditions. The simulations accurately captured the spatial dynamics of the fire and highlighted the key role of forest structure, fuel condition, and meteorological factors—particularly wind [1].

Scenario analyses revealed that natural mixed forests or healthy spruce stands significantly limited fire spread compared to dead spruce monocultures. In contrast, removing deadwood led to faster, though less intense, fire propagation. These findings underscore the importance of forest species composition and suggest that fuel reduction alone may not be sufficient to limit fire extent [1].

The model also confirmed that inaccurate input data—especially wind measurements—can strongly affect the reliability of simulations. Overall, FlamMap demonstrates strong potential as a decision-support tool for planning prevention and response strategies to future extreme wildfire events in a changing climate.

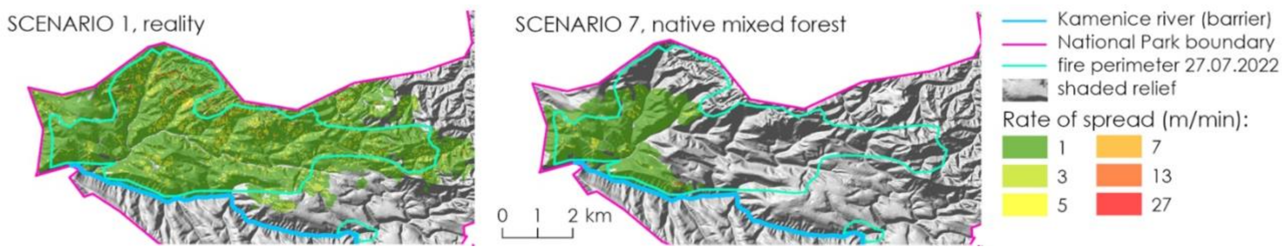

Figure 1. Simulated rate of spread (m/min) for Scenario 1 (Reality) – the July 2022 wildfire in Bohemian Switzerland National Park, Czech Republic (FARSITE model) [1].

4. Conclusions

This study demonstrated the effectiveness of the FARSITE model (part of FlamMap) for simulating wildfire behavior in Central Europe [1]. It represents the first calibration of the FARSITE model based on a real fire event in the Czech Republic. The findings highlight the importance of forest species composition in mitigating fire spread and confirm the potential of scenario-based modeling for forest management planning. Future research could focus on expanding validation datasets, testing additional model parameters, and gradually integrating modeling into decision support for forest protection and crisis management—serving, for example, as a complementary tool for fire and rescue services or protected area authorities.

Acknowledgements

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Clim4Cast (study about forecasting drought, heatwave, and fire weather in central Europe—Clim4Cast; CE0100059), PERUN TAČR Project (SS02030040) and program Transadapt.

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Session 2
Observing Extreme Wildfire Events

Mapping wildfire progressions and measuring rate of spread from "line scans" in Australia

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Summary

We have developed a prototype database containing over 9,000 fire progressions and 727 individual rate of spread (ROS) measurements from Australian wildfires. 237 spread faster than 1 km/h, and 66 spread > 3 km/h, with a maximum of 18.4 kmh. Progressions are mapped from aerial line scans and satellite imagery. While created for an ongoing Bayesian ROS modelling project, the database has the potential to become a widely accessible resource for wildfire researchers. It currently has the largest set of wildfire spread observations currently available in Australia.

Keywords: line scan, wildfire spread, database

1. Introduction

Wildfires can spread too rapidly and intensely to allow for detailed, systematic observations of their progression. In Australia, the most accurate way to map these fires is through the use of multi-spectral scanners mounted on aircraft, which capture geo-referenced images of active fires [1]. These images—known as "line scans"—and the resulting GIS progression polygons have a wide range of applications, including model development and validation, identifying extreme fire behaviours, analysis of suppression effectiveness, and post-fire reviews by fire agencies. Much of this data is held by fire agencies, but it is not always stored consistently, making it difficult to access and process for research purposes. Improving access to this data would significantly support research to better understand wildfire behaviour.

As part of a project to develop a Bayesian rate of spread (ROS) model, we have collected and processed more than 9,000 line scan and satellite images of wildfires, including extreme fires, across Australia. We have mapped fire progressions from this data (some progressions were provided by fire agencies) and measured ROS for many fires. Additionally, we are developing a prototype ROS database to store the data in a structured format and enable efficient searching. We have also created an initial R package [2] that automates tasks such as database queries, satellite data retrieval, fire progression mapping, and matching ROS measurements to weather data.

The next part of our project will use this database to develop the Bayesian wildfire rate of spread model [3,4]. This model will generate predictions that explicitly incorporate and communicate uncertainty in wildfire spread. However, a major goal of the overall project is to continue to explore the establishment of a publicly accessible, consistently maintained database of wildfire spread in Australia.

2. Data and Methods

The main source of fire observations in our database is from aerially acquired **"**line scans**".** These scans are produced by sensors mounted on aircraft flown over active fires. In most cases, the resulting images clearly show the active fire boundary and burnt areas. However, cloud cover can obstruct the view, and burnt areas may be difficult to distinguish depending on vegetation type. While the scanners are capable of capturing multiple spectral bands, typically only a subset is provided to fire agencies—either a single thermal infrared band (with high values artificially coloured red in the final image) or a combination of three bands (one blue and two shortwave infrared), where active fire appears as yellow-orange (Figure 1).

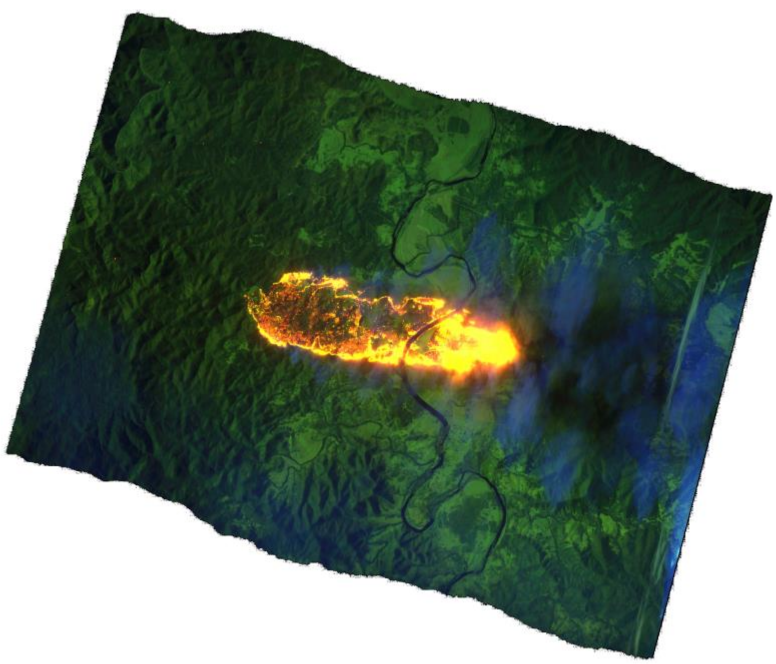

Figure 1. Example of a 3-band line scan image from a fire in 2019-2020 in south-eastern Australia. Most intense fire in yellow, recently intense fire in orange. Dark green vegetation is forest and light green is grass.

To generate GIS fire progression polygons from these images, the process usually involves manual mapping in ArcGIS by fire operations staff. The accuracy of these manually created progressions can vary depending on the time available to the mapper—who may be under pressure during major fire events—and whether any post-fire analysis was conducted. Detailed post-event mapping is usually more accurate.

For our project, we were provided with both line scans and some mapped progression polygons. Where progressions were missing, we manually mapped them ourselves. We also reviewed and corrected polygons provided by fire agencies, including DEECA (Victoria), RFS (NSW), and DFES (WA). For most scans, we mapped fire progressions where line scan pairs were available between 20 minutes and 5 hours apart. This time window allowed us to calculate rate of spread (ROS) during periods of likely continuous fire activity, avoiding stretches where fire behaviour may have paused or slowed significantly. For the 2019–2020 wildfires in southeastern Australia, we mapped fire progressions from all available scans as part of work conducted for the NSW Bushfire Inquiry. In some cases where no line scan data existed, we used supplementary satellite data (VIIRS, MODIS, HIMAWARI, Landsat, and Sentinel-2) to map fire progression. The choice of satellite source depended on factors such as timing relative to line scans, fire size, image resolution, and cloud cover.

We developed a prototype Postgres database to store fire progression polygons. Each entry in the database includes geometry, progression time, a link to the AWS-hosted line scans used, fire type (main or spot), and fire name. We also developed an associated R package that includes functions to automate ROS measurement from two progression polygons (Figure 2), query the database, download line scan and satellite data, sample local reanalysis weather data and extract fire areas from line scans using Meta's Segment Anything algorithm [5] for efficient polygon mapping. Both the database and the R package are still under development, but we aim gain support to develop them into a widely accessible and regularly updated resource for fire behaviour research.

3. Results and Discussion

Our project is still in progress; however, there are already some initial results in terms of data and database development. Our database currently contains over 9,000 unique fire progression times. Our automated approach to measuring rate of spread (implemented as a function in our R package) has so far produced 727 unique ROS measurements (Figure 3). Most of these measurements are from fires in New South Wales and Victoria. Of the total, 33% exceed 1 km/h, while 9% exceed 3 km/h. The maximum recorded ROS was 18.3 km/h, observed in a fire in Western Australia. Many images reveal extreme fire behaviours, including mass spotting, which could be coded in the database and extracted for future research.

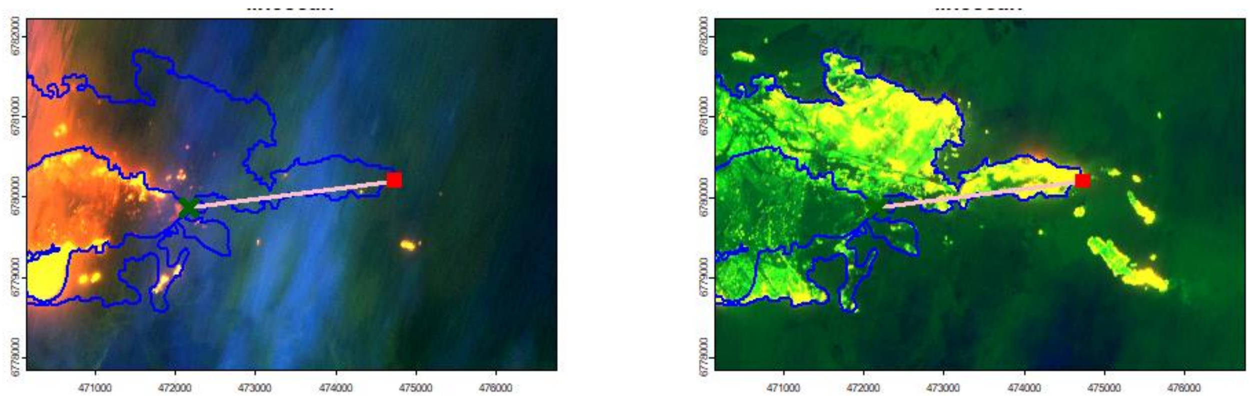

Figure 2. Example of a rate of spread (ROS) measurement using two line scans (day left, night right). Blue polygons are the fire edges mapped from both scans (overlaid on both images). Pink line is an automatically generated line of maximum spread from an R package function, red square is end of line. Spread line = 2.6 km, spread time = 41 minutes, ROS = 3.8 km\h Spot-fires not included in ROS measurement.

We are continuing to develop our R package, but the functions added so far work well and integrate effectively with the Postgres database. The database serves as a straightforward prototype that demonstrates the advantages of structured data storage. However, further development of the database is needed in the future, and funding for this work is still needed.

We have conducted some initial testing of the "Segment Anything" approach in R for mapping polygons. The early results are promising—many progressions can be mapped and saved to a GeoPackage from a scan in just one to two minutes. In contrast, the previous approach, which relied entirely on manual mapping in ArcGIS, takes at least five to ten minutes per scan, as each scan must be manually loaded, mapped, and saved. Manual mapping time can increase significantly depending on the fire's complexity and size. The Segment Anything algorithm captures burning edges extremely well but can struggle with previously burnt edges that are not clear to the user, or with dense smoke or cloud cover. Our process includes a step for manual oversight and correction of the automated polygons to ensure accuracy.

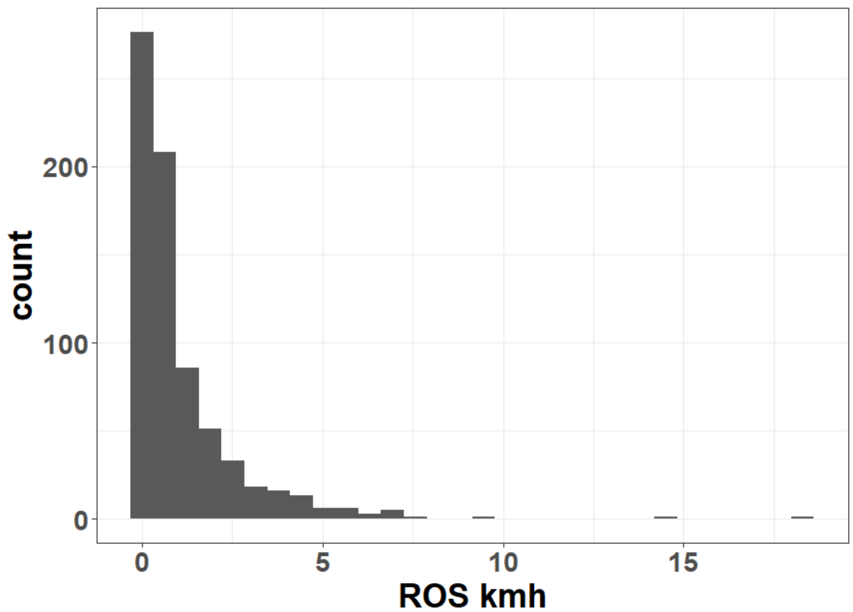

Figure 3. Histogram of rate of spread (ROS km/h) measurements extracted from fire progression polygons.

4. Conclusions

To date, we have produced a large set of wildfire progressions and rate of spread measurements. We have demonstrated a structured storage approach for this data through our prototype database. We have also shown how data can be produced more easily and quickly using our R package and image segmentation. In addition to contributing to our Bayesian ROS model, our aim is to further develop the database and tools to provide a method for generating and storing ROS data, and to allow easy access. This will help remove a significant roadblock in Australia (finding spread data) which can hinder fire behaviour research.

Acknowledgements

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Pyroconvection Analysis and Data Gathering from Extreme Wildfire Events

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Summary

This study presents the analysis of pyroconvection phenomena and the harmonised data gathering process developed within the EWED project. Data from extreme wildfire events (EWEs) in Greece, Spain, and other regions are analysed using radiosonde atmospheric profiling and surface fire behaviour metrics. Key findings show strong correlations between vertical air movements and increased fire spread rates, supporting the need for standardised data to improve predictive modelling and decision-making.

Keywords: Extreme Wildfire Events, Pyroconvection, Radiosonde, Data Standardisation, Fire Behaviour

1. Introduction

The past few decades have witnessed a profound shift in global wildfire regimes, with Extreme Wildfire Events (EWEs) emerging as the 'new normal'. This concerning trend signifies a geographical expansion of wildfire risk, now extending beyond traditional fire-prone regions in Southern Europe towards its northern counterparts. EWEs are characterised by high intensity, a high rate of spread and pyro-convective activity that release large amounts of energy, and unpredictable fire behaviour, frequently overwhelming the control capacities of emergency services [1] and posing unprecedented challenges to fire management. The imperative, therefore, is to move beyond reactive suppression and cultivate a deeper, anticipatory understanding of EWEs to bolster both the efficacy and safety of firefighting operations.

The EWED project directly addresses this critical need. Its core objective is to advance our comprehension of EWEs through a unique co-production approach, fostering collaboration between academics and practitioners to gather and analyse empirical fire and atmospheric data. This collaborative effort is crucial for generating actionable knowledge and refining predictive models, with a view to analysis of ongoing extreme fire events with atmospheric coupling. Ultimately, EWED aims to enhance Europe's protection against these events by fostering knowledge sharing across diverse stakeholders, innovating how emerging risks are addressed, building competencies for civil protection, raising awareness among decision-makers, and boosting the preparedness of those fighting, or soon to face, extreme fire behaviour.

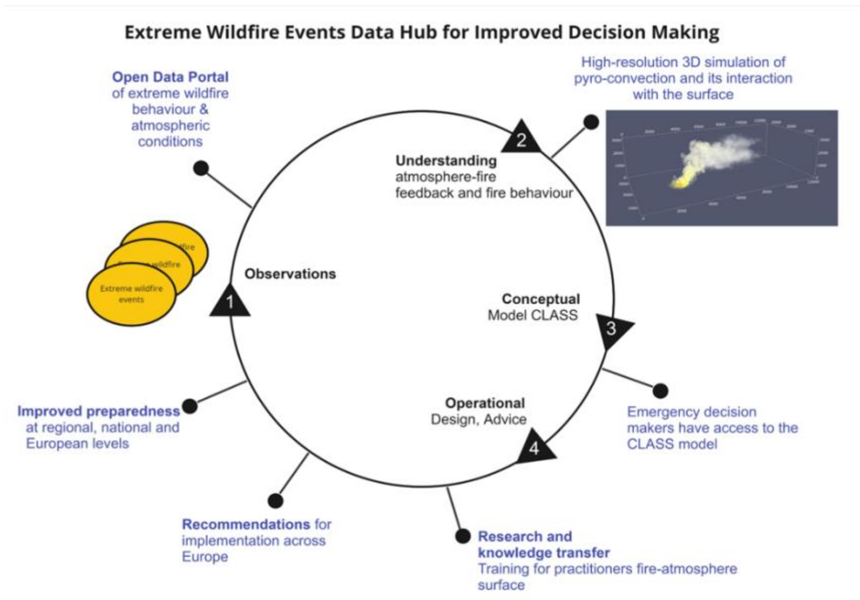

Figure 8. EWED project concept.

The resultant knowledge and tools, including a dedicated Wildfire Data Portal, are designed to serve as an open resource, complemented by targeted training events aimed at disseminating findings, addressing ongoing challenges, and facilitating continuous learning within the wildfire community. This abstract focuses on pyroconvective behaviour documented in the Varnavas fire (Greece, 2024) and outlines the data collection process initiated by Catalan Fire and Rescue Service (CFRS).

2. Data and Methods

To achieve its objectives, EWED systematically collects two primary datasets: detailed surface fire behaviour data and atmospheric vertical profile data. Surface fire behaviour observations, including rate of spread, flame height, fire front dimensions, and growth rate, are derived from diverse sources such as direct observations, measurements, frontline personnel imagery, aerial photographs, and post-processed satellite images. Concurrently, atmospheric vertical profile data are collected using meteorological radiosondes. These small, reusable, and portable devices are strategically launched both within and outside the smoke plume to capture real-time atmospheric conditions. Each radiosonde is equipped with sensors for meteorological variables and a GPS, providing precise atmospheric conditions and flight trajectory at various altitudes. Depending on the launch location (be it the fire head, flanks, back, under the plume, or outside its direct influence (control sondes)) these data offer unique insights for understanding and validating specific aspects of pyroconvection.

Data acquisition is standardised through robust protocols developed from the extensive experience of the Catalan Fire and Rescue Service (CFRS) [2]. These protocols are now implemented by EWED's operational partners, in Greece, The Netherlands, Spain and Norway, and collaborating entities, such as CONAF in Chile, ensuring data homogeneity, maximised volume, and geographical representativeness across diverse regions globally. Once collected, raw data undergo post-processing using specialised software to translate them into a more user-friendly format. This facilitates a clearer understanding of the fire's dynamics, enabling more informed strategic decision-making for fire suppression operations. Furthermore, by comparing atmospheric data collected within and outside the fire's influence, enables empirical data-driven analysis of fire-atmosphere interactions, and their operational consequences.

3. Results and Discussion

During the Varnavas fire in Greece (August 2024), the Hellenic Fire Service (HFS) team, following the methodology and protocol established by the project, successfully gathered detailed data on both surface fire behaviour and the vertical profile of the atmosphere.

Analysing the radiosonde data from Varnavas revealed crucial findings. It showed relative humidity (RH) above 80% at over 1500 m and air rising at over 7 m/s. This indicated the accumulation of water vapour at the top of the Atmospheric Boundary Layer (ABL), coming from the combustion. The data showed that due to a stable and dry air layer above the ABL top, the plume has not capacity to grow vertically at the moment of launching the sonde, so it was not expected the formation of a strong vertical plume. As observed, the Lifted Condensation Level (LCL) was not far from the ABL top, which meant that during some of the most intense moments, the fire had the opportunity to reach this level and condensate. It is worth mentioning that the main convection activity was observed during the initial hours of the fire, not in the evening when the radiosonde was launched.

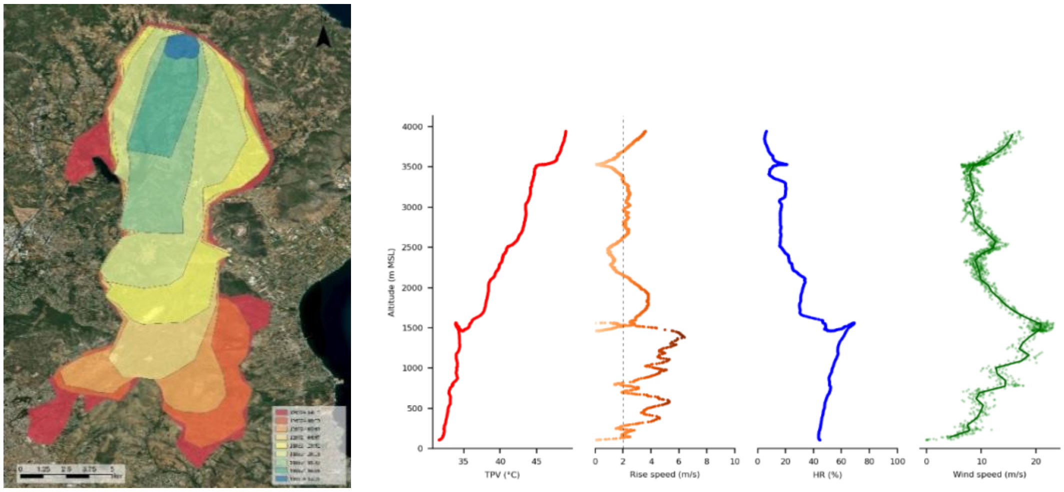

Figure 9. **Left**: Hourly perimeters. **Right**: Atmospheric vertical profile from the radiosonde launched from the back

These observations support what Castellnou et al. [3] found: a direct link between faster rising air and an increased Rate of Spread (ROS). The Varnavas fire was significantly fast, with a maximum ROS of 4,500 m/h, with a burned area exceeding 10,000 hectares. This observation is also evident in the hourly perimeters, where a high ROS was observed specially during the initial hours of the fire due to the surface meteorological conditions (strong winds and low RH values). A high Burn Ratio (BR) was sustained until late at night, with high-intensity fire behaviour, which was not expected. This had a significant impact on the suppression capacity of the firefighting operation. The continuous interaction between the fire and the atmosphere from the early hours into the night significantly helped the fire spread quickly and made it very difficult for firefighters to control. This event was classified as having a convective plume with short-lived overshooting Pyrocumulus activity. These conditions helped explain the high-intensity fire behaviour seen on the ground.

These findings are hugely important for operations. The standardised methods mean we can compare data from different incidents, helping us build a solid, data-driven understanding of EWEs. By providing evidence of how fires and the atmosphere interact, EWED improves situational awareness and helps operational teams make better decisions.

4. Conclusions

The EWED dataset demonstrates the critical value of integrating pyroconvection data from vertical profiling with surface fire behaviour observations. The Varnavas fire exemplifies how gathering this kind of data can unlock a deeper understanding of what drives extreme fire behaviour. A key achievement of the project is the standardisation of data collection across countries. This will significantly improve how we understand and anticipate complex wildfire scenarios.

The future of fire management in Europe hinges on new approaches to better understand extreme fire behaviour dominated by pyroconvection. Fire services need to reduce uncertainty and get better at predicting these EWEs so they can plan more effectively to protect people and the environment.

The synergy between academics and operational personnel is incredibly valuable. Operational crews possess practical insights and the ability to collect data in the field that academics may not. In return, researchers have the capacity to process this data, generate new knowledge, and address the needs identified by those on the ground. This collaborative approach benefits the entire wildfire community.

Crucially, the advancements in this area are not just for countries with a high recurrence of EWEs, like Spain or Greece. They are equally relevant for nations that haven't traditionally dealt with EWEs as often, such as Norway or the Netherlands, but where projections indicate a rising trend of such events. Therefore, it's essential to anticipate these changes and foster two-way collaboration with neighbouring countries, especially those to the south. This allows to capitalise on lessons learned and cutting-edge knowledge, helping to prepare for uncertain scenarios and improve the efficiency of wildfire emergency management.

Ultimately, understanding the physical processes behind wildfires is key to improving our ability to respond and make strategic decisions [4]. The new knowledge gained from EWED is practical and can be directly used in decision-making, offering clear improvements for everyone involved in Disaster Risk Management (DRM).

While EWED builds on the progress of earlier projects like AFAN, FIRE-RES, and FIRE-IN, and has made important advances, there are still challenges to tackle. For the future, we need to focus on integrating data in real-time, studying more diverse fire cases, and including data on suppression strategies. All case studies collected during the project, along with other relevant historical data from CFRS, will be made openly available through the Wildfire Data Portal once the project is finished, maximising its impact for both research and frontline operations.

Acknowledgements

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Estimating the Probability of Pyrocumulus Formation in Extreme Wildfire Scenarios: A Preliminary Approach

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Summary

This study presents a methodology to predict pyrocumulus formation based on the thermal power released by wildfires and atmospheric conditions. By integrating fire behavior simulations with the Pyrocumulonimbus Firepower Threshold (PFT), we evaluate the 2022 El Pont de Vilomara wildfire. Results show that fire power briefly exceeded the PFT, aligning with observed pyrocumulus development, but was insufficient to sustain it. The findings highlight the potential of the proposed framework and emphasize the need to incorporate convective energy losses to improve predictive accuracy.

Keywords: Extreme Wildfire, Pyrocumulus, Wildfire energy, Pyrocumulonimbus Firepower Threshold

1. Introduction

Extreme Wildfire Events (EWEs) represent a growing and critical challenge for societies across the globe. Although they account for a small fraction of all wildfires, their destructive potential and impact on human lives and ecosystems are often disproportionate [1]. These fires exceed the current control capacity, even in well-prepared regions and areas with extensive firefighting experience. Due to climate change, the number and frequency of fires have increased significantly. This has been reflected in devastating fires in Portugal, Greece, and the USA, as well as in large fires in Catalonia, such as Torre de l'Espanyol (2019, 4,281 hectares).

These fires are usually related to extreme phenomena such as the formation of pyrocumulus clouds (clouds generated due to atmospheric conditions and the presence of a large fire), which can generate electrical storms, winds, and sudden changes in the direction of the fire, or other phenomena such as the formation of fire tornadoes and the projection of burning fuel over long distances. Some studies highlight that at this point, the behavior of the fire cannot be simulated by the current fire spread models [2].

Despite the growing recognition of these phenomena, there remains no operational methodology capable of determining in real time whether a fire will remain within expected behavior limits or escalate into an EWE. In particular, the identification of conditions conducive to pyrocumulus or pyrocumulonimbus formation remains a key gap in predictive wildfire science. By combining wildfire thermal power estimates derived from fire spread simulations with atmospheric instability metrics, the method aims to identify critical time intervals during which pyroconvective transitions become thermodynamically favorable. Such capability would support earlier detection of regime shifts in fire behavior, thereby enhancing strategic wildfire management and improving the effectiveness of emergency response protocols.

2. Data and Methods

The formation of pyrocumulonimbus clouds requires specific atmospheric conditions combined with sufficient thermal energy release from wildfire. The methodology proposed in this study aims to quantify this relationship through two complementary techniques:

- To estimate the wildfire energy release through the utilization of a forest fire spread simulator, enabling direct comparison with the calculated PFT values.
- Application of the Pyrocumulonimbus Firepower Threshold (PFT) [3], which establishes the minimum power release required for pyrocumulonimbus development within a given atmospheric condition.

2.1. Estimation of Wildfire Energy Release

The thermal power released by an active wildfire is estimated using an equation derived from Catchpole et al. [4]. formulated an expression that relates wildfire power to the rate of change in burned area over time:

$$P = \int I \ dS = H \omega \frac{dA}{dT}$$

Where P represents the instantaneous wildfire power in watts (W), I denotes the fireline intensity (W/m), S is the perimeter length (m), H signifies the heat released per unit area (J/m^2), ω is the mass flow rate (kg/(m^2/s)), and $\frac{dA}{dt}$ is the rate of area change (m^2/s). H and ω can be obtained in *lcp* data files. And $\frac{dA}{dt}$ can be computed using a wildfire simulator by knowing the total area burned and the time elapsed.

2.2. Pyrocumulonimbus Firepower Threshold (PFT)

The Pyrocumulonimbus Firepower Threshold (PFT) defines the minimum wildfire energy needed to trigger pyrocumulonimbus formation under given atmospheric conditions, based on three key variables.

$$\text{PFT} = 0.3 \cdot z_{\text{fc}} \cdot U_{\text{ML}} \cdot \Delta\theta_{\text{fc}}$$

Where z_{fc} represents the free-convection height (m), U_{ML} denotes the mixed-layer wind speed (m/s), and $\Delta\theta_{\text{fc}}$ signifies the potential temperature difference (K) between the mixed-layer and the free-convection level. These instances correspond to conditions where pyrocumulus formation becomes thermodynamically favorable. Conversely, if the energy released remains below the PFT, the development of pyrocumulus clouds is unlikely, even in the presence of supportive atmospheric profiles.

2.3. Coupled Analysis of Fire Power and Atmospheric Favorability

To predict the risk of pyrocumulus formation, both components, Estimation of Wildfire Energy Release and PFT are compared. When a simulated wildfire power exceeds the calculated PFT for a sustained period, pyrocumulonimbus formation becomes thermodynamically favorable. Conversely, when fire power remains below this threshold, cloud formation is unlikely despite otherwise conducive atmospheric conditions. The combination of these two components provides a simple and fast methodology for assessing the risk of pyrocumulus formation and identifying transitions between fire behavior to extreme fire behavior.

The case study focuses on the wildfire that occurred in El Pont de Vilomara (Catalonia) between 17 and 18 July 2022, with an affected total area of 1,422 hectares. This event is of particular interest because the fire released sufficient thermal energy to initiate pyrocumulus development, but not enough to sustain it over an extended period. Atmospheric data for this study is derived from ERA5.

3. Results and Discussion

The simulation was carried out using the FARSITE fire simulator [5]. Using a temporal discretization of 35 minutes and 35 meters, the results were compared with the PFT values calculated. Figure 1 shows that the power released by the fire exceeded the PFT values during the first hours of the fire, which coincides with the reported formation of pyrocumulus by Bombers de Catalunya [6]. However, as it is noticed in the report, the pyrocumulus clouds disappeared a few hours after their formation, which indicates that the power released by the fire was not high enough to maintain them for a long time. This is consistent with the results obtained from the simulation, which show that, although the power released by the fire was still high, PFT values increased significantly, making it unlikely for pyrocumulus clouds to form again.

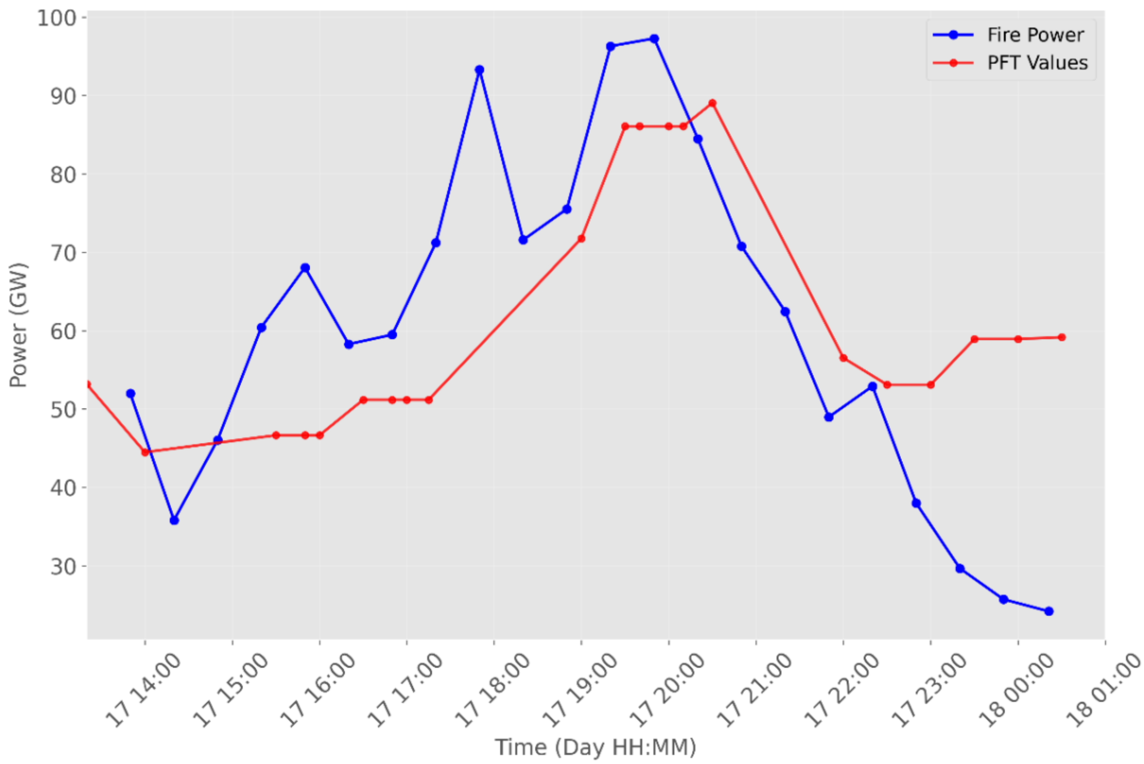

Figure 1: Power released by the fire and PFT values during the fire in El Pont de Vilomara (Catalonia) in 2022.

Figure 1 should be interpreted carefully, as convection losses were not considered when computing the fire power, making the results not directly comparable with the PFT values. Nevertheless, the results demonstrate that the power released was higher during a short period when the PFT was lower; however, this relationship did not persist long enough to sustain pyrocumulus development. During the observed pyrocumulus formation, during the afternoon, our simulation shows higher power values and lower PFT values, while when no pyrocumulus was observed, during the night, fire power decreased as PFT values increased. These findings suggest that the methodology proposed in this study provides a promising foundation for predicting pyrocumulus formation, though further refinements are needed to improve predictive accuracy.

4. Conclusions

The integration of meteorological indices with fire behavior modeling offers a promising approach to predicting pyrocumulonimbus formation. The findings of this study remark on the importance of integrating meteorological indices and fire behavior modeling to enhance predictive capabilities regarding pyrocumulonimbus formation. The 2022 El Pont de Vilomara wildfire demonstrates the effectiveness of the Pyrocumulonimbus Firepower Threshold (PFT) in linking wildfire energy release to atmospheric conditions. While fire power initially exceeded the PFT values during the initial hours of the event, aligning with observed pyrocumulus cloud formation, sustained formation was not achieved due to insufficient energy input over time. These results underscore the importance of accounting for convective energy losses and highlight the need for further research to refine predictive tools and deepen our understanding of fire–atmosphere interactions.

To enhance the accuracy of wildfire power estimates and improve pyrocumulonimbus prediction capabilities, future research should focus on implementing coupled fire-atmosphere models that would provide more realistic simulations. Additionally, incorporating high-resolution meteorological data and real-time fire detection systems would further enhance the operational value of the proposed methodology. The combination of improved power calculations with advanced PFT assessments could lead to the development of an early warning system for extreme wildfire behavior, potentially providing critical lead time for emergency response actions during high-risk fire events.

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Evolution of Extreme WUI Wildfire Incidents Forensic Chrono-Spatial Reconstruction Methodology – Varnavas/Greece 2024 application

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Summary

This work presents the evolution of a forensic digital reconstruction methodology, applied to the August 2024 Varnavas wildfire (Attica, Greece), a high-impact Wildland–Urban Interface event. Integrating satellite imagery, field observations, meteorological data, and geotagged user-generated content, the spatial and temporal progression of fire fronts to be reconstructed. Key outcomes include Rate of Spread (RoS) estimation, burn rate per cultivated plot by crop type and condition, and impact assessment on the built environment. The study supports tactical response analysis, resilience planning, public awareness, and the enhancement of AI wildfire simulation models through reliable data-driven learning inputs.

Keywords: WUI Wildfire, Reconstruction, Fire spread Analysis, Public Safety

1. Introduction

Many extreme Wildland–Urban Interface (WUI) wildfire incidents have been recorded, driving research and policy initiatives at European Union and national levels to adapt accordingly towards mitigating devastating impacts [1]. The August 2024 Varnavas wildfire (Attica, Greece) exemplifies this growing threat: ignited under adverse fire weather conditions, the fire rapidly spread through rural area, breached the urban grid, and resulted in extensive destruction of residential and commercial properties, and ultimately, one fatality. Since response time remains a critical constraint [2], high-resolution spatiotemporal reconstruction at short intervals (10–30 minutes) was deemed essential. This forensic-level reconstruction aimed to identify fire behavior patterns, assess exposure of the built environment, and analyze the influence of agricultural assets on fire front propagation.

The key objective is to demonstrate how digital reconstruction can be leveraged to raise public awareness by providing intuitive visualizations that convey the speed and intensity of

WUI wildfires, which are projected to increase in frequency under climate change scenarios [3]. Furthermore, the study serves to enhance an evolving innovative methodology that identifies temporal fire spread milestones and geospatial pathways using diverse sources of evidence, including satellite data, user-generated content (e.g., social media images and videos), conventional media, leased firefighting aircraft flight paths, and firsthand interviews with incident participants (e.g. residents and voluntary firefighters).

2. Data and Methods

2.1 Method

The methodology used in this study was developed by N. Kamakiotis to analyze Wildland-Urban Interface (WUI) wildfire incidents with a focus on public safety. The process aims to map detailed fire front spread patterns. It includes three main stages: data collection, processing, and the design of isochronous fire front curves [4].

The first step involves identifying fire front milestones—specific times and locations where the fire front was observed, including starting point. Once these are determined, they are manually drawn on recent high-resolution satellite imagery, representing fire fronts as curves corresponding to specific time intervals.

After identifying fire front milestones, intermediate isochronous curves are drawn between them, considering influencing parameters such as wind speed and direction, topography, vegetation types and density, continuity of fuels and physical barriers [5]. Each parameter's local influence is assessed to determine the density and orientation of the isochronous curves.

The exact area within which the isochronous curves are designed is defined via the detailed design of the actual fire scar in reference to multiple satellite pictures after and before each incident. The final step is creating a digital animation that links static curves with their respective timestamps, enabling a visual reconstruction of fire spread over time. The method had already been applied on Arakapas wildfire incident (Cyprus/July 2021) and its outcome has been included in relevant NERO Network's database (Figure 1).

2.2 Data Sources

Fire front milestones are identified using diverse data sources that provide spatial and temporal clues on fire behaviour. These include:

- Site inspections

- Videos and images published by conventional and social media users documenting the fire's progress.

- Interviews with individuals involved in firefighting or who directly observed the incident.

- Satellite imagery showing fire progression and burn scars.

- Web applications (e.g., FlightRadar24) tracking firefighting aircraft paths to infer water drop zones based on changes in altitude and speed.

Each media file undergoes detailed processing to determine the capture location, the visible fire front location, and the date/time of capture. If metadata is missing, investigators estimate locations by comparing visible elements (e.g., terrain, structures) with satellite or Street View imagery.

Time is cross verified by comparing sun position, shadows, and other recordings. When necessary, publishers may be contacted for confirmation. Wind data is sourced from automated weather stations or national services, and if unavailable, archived forecast data may be used. Topography data is gathered using tools like Google Earth, EO Browser, or national land survey services.

Vegetation types, fuel continuity and density are inferred from satellite images and site visits. Burn scars are mapped with precision using multiple satellite products, forming the reconstruction's base layer. These ensure an accurate depiction of fire progression and key barriers that affected its spread.

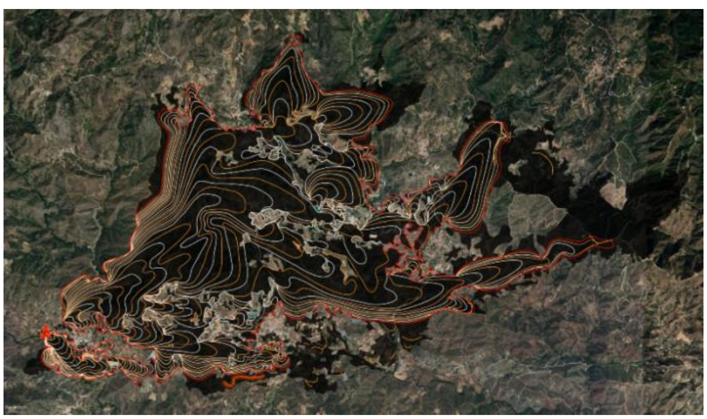

Figure 1. Isochronous curves designed on reconstruction of Arakapas wildfire (Cyprus/2021).

3. Results and Discussion

The Varnavas wildfire incident's reconstruction is in progress, and it is expected to be completed by the end of July 2025.

3.1 Data Collection

Information and visual evidence about the location and time that fire fronts appeared during the incident had already been collected via multiple site visits, surveys across all main

Social Media platforms, conventional media web outlets, satellite imagery, private firefighting aircrafts paths and NASA FIRMS recordings.

By the time of present extended abstract's submission, the process on collection of information and visual evidence from members of voluntary civil protection teams based at the broader incident's area is in progress via teleconferences.

3.2 Data Processing

Having as starting point the fire scar published by Copernicus EMS services the actual scar had been designed in detail by referring to multiple post incident satellite pictures provided by various outlets. All the plots allocated to agricultural activities had been registered via polygons by identifying the general type of cultivation typical in Mid-Southern Greece's mainland (grain, woody crops, & greenhouses) and status at the time of incident (active – abandoned/inactive). Additionally quarries and PV farms were registered accordingly. Private firefighting aircrafts' paths had been registered per day (11 – 13/08/2024) and the points where it is assumed that water bombing occurred had been registered.

3.3 Preliminary findings

Preliminary findings refer to intrusion rate in traditional dense communities (e.g. Varnavas village) is minimal compared to recently built/under development rural communities (e.g. Dioni). In both types of built environment, the rate of structures' destruction is nearly zero due to minimal intrusion and type of structures (multistory concrete structures) respectively. As registered also in Arakapas wildfire analysis, the highest destruction rate occurred on structures built out of pre-existing traditional communities' core.

One of the main Arakapas wildfire analysis findings had been reconfirmed since the active woody crops plots consist of effective obstacles on the spread of fire fronts that stop along their perimeter or bypass them. In contrast, grain crops and abandoned plots consist of areas that fire fronts cross unobstructed and probably accelerated compared to adjacent areas covered by natural vegetation.

3.4 Reconstruction's exploitation

The visual animation to be produced from the reconstruction process to serve both as a post-event analytical tool, training material for emergency services (chrono-spatial mapping of hypothetical scenario to be deployed during large scale exercises), means for raising public's awareness on threats emerging through extreme WUI wildfire incidents, source of technical feedback as for the development of proactive interventions referring to use of cultivated areas as effective fire fronts spread's obstacles and source of information on risk assessment related to the future residential areas development and their wildfire resilience depending on the type and density of structures.

The outcome of the reconstruction will be compatible with specifications of NERO Network's database. One of the goals is the use of the detailed and in dense time intervals reconstruction for the guidance of AI wildfire simulation codes on their learning process allowing enhancement of their accuracy.

4. Conclusions

This spatiotemporal reconstruction of the 2024 Varnavas wildfire demonstrates the power of integrating diverse data sources to understand extreme WUI wildfire dynamics by providing tangible evidence easily conceivable by non-experts. Key outcomes will include:

- Precise RoS quantification at localized scales along the overall affected area allowing incident's overview contrary to current wildfire's public perception based on localized footage which may provide a false view of actual incident's characteristics and threat's magnitude
- Detailed mapping of agricultural impact on fire fronts spread by plot, crop type and actual status depicting the positive effect of active cultivations on passive protection of rural communities
- High-resolution analysis of fire front interactions with built environments (traditional rural communities, recently developed rural communities and dense urban areas)

These results will support improved response strategies, informed land-use planning, and community fire resilience initiatives. Future work should explore introduction of automation on all stages of the method. This innovative process deploying less technologically advanced means may consist of a critical driver as for the improvement of sophisticated wildfire simulation AI codes providing the learning benchmarks emerging through actual past incidents. Automating the individual steps of the process will allow reconstruction of more incidents, thereby facilitating the development of additional AI-based learning modules referring to a variety of landscapes or/and fuels profiles while, in parallel, will ideally allow the fire spread mapping/reconstruction during incidents.

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Integrated Multi-Source Dataset for Spatiotemporal Analysis of the 2024 Skradin Wildfire, Croatia

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Summary

The multi-source, varied, and unsynchronized nature of data related to wildfire events makes comprehension and analysis difficult. To overcome the scatteredness of the data, this study presents a comprehensive multi-source dataset and demonstrates its usage on a case study of the 2024 Skradin wildfire in Dalmatia, Croatia. The dataset integrates satellite fire detections (VIIRS, MODIS), ERA5 meteorological reanalysis, topographic data, and fuel mapping within a unified HDF5 framework. The objective is to create a spatiotemporally aligned resource for analyzing complex wildfire dynamics. Methods involved data processing, temporal synchronization, and spatial alignment using Python-based geospatial libraries. Preliminary analysis revealed wind-driven fire spread patterns and topographic influences, with fire expanding from deeper terrain to higher elevations. Despite meteorological resolution limitations, the dataset captures essential environmental context, demonstrating a robust, generalizable approach for wildfire analysis and modeling.

Keywords: wildfire observing, remote sensing, spatiotemporal analysis, data integration, fire behavior modeling

1. Introduction

Observation of wildfire behavior and analysis of its drivers and effects relies on data such as geospatial information, remote sensing, model outputs, fixed sensor data, as well as testimonies and interviews. The collection, organization, and utilization of these pieces of information are crucial for gaining valuable insights and learning important lessons.

Satellite sensors, like MODIS and VIIRS, are indispensable for active fire detection, offering distinct spatial and temporal resolution trade-offs [1]. While some datasets integrate fire detections with ancillary environmental variables for fire behavior modeling, few coherently align them with critical terrain and atmospheric drivers in a spatiotemporal framework. This integration is paramount for unraveling complex fire dynamics.

ERA5 meteorological reanalysis products have gained prominence in assessing fire weather conditions and ignition potential. Studies show strong correlations between ERA5-based wildfire danger indices and precipitation evaluations with ground observations, despite local resolution limitations [2]. However, comprehensive integration of ERA5 data with high-resolution topographic variables and precise fire detections remains uncommon, especially for regional, multi-day events where such interactions are highly significant.

HDF5 [3] is a practical format for storing multi-dimensional variable data because it provides a flexible and portable way to specify data storage layouts. It's self-describing, allowing efficient I/O and data access. FireTracks [4] and GFED [5] exemplify the utilization of HDF5 for sharing fire data. FireTracks focuses on active fire events, their spatiotemporal components, and associated land cover. GFED emphasizes burned areas, emissions, biosphere fluxes, and ancillary data. A key difference is that FireTracks provides detailed spatiotemporal clustering of individual fire events, whereas GFED offers comprehensive global estimates of fire emissions and burned areas at a coarser resolution. However, neither dataset includes weather data or other auxiliary environmental variables directly within their HDF5 structures, which would provide additional context for understanding fire behavior and impacts.

This research deals with a novel, comprehensive, multi-source dataset, integrating all available sources. The dataset is demonstrated on an item for the recent Skradin wildfire in Dalmatia, Croatia (July 30 - August 2, 2024).

2. Data and Methods

For this demonstration we collected geospatial, remote sensing and auxiliary data related to wildfire that emerged near Skradin on July 30. 2024. This fire event was one of the most media covered since it emerged near protected area of national park Krka and lasted for unusually long time. The location of fire is shown on figure 1.

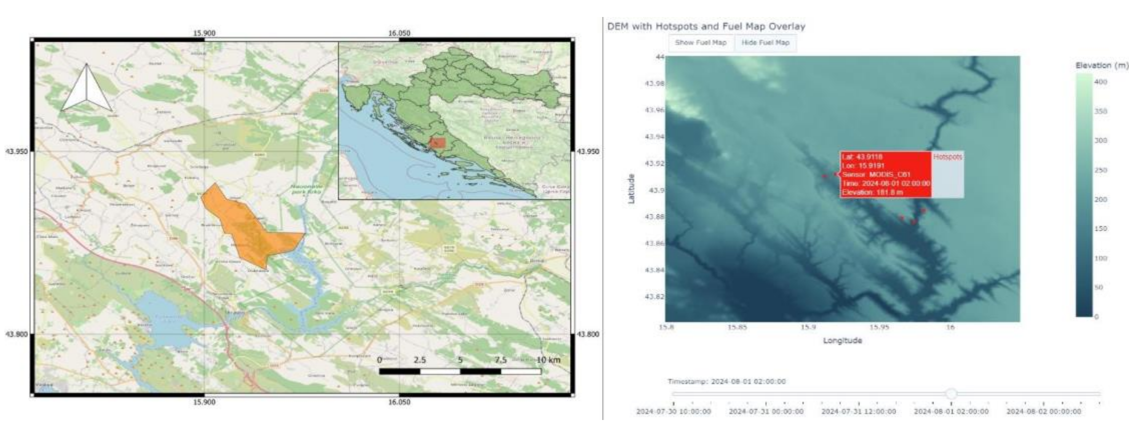

Figure 1 Study Area (left) and Skradin wildfire visualization (right)

The Skradin wildfire dataset (July 30 - August 2, 2024) integrates active fire detections, meteorological reanalysis, high-resolution topography, and a regional fuel map.

Hotspot data came primarily from 375m VIIRS (SUOMI C2, J2 C2, J1 C2) and 1km MODIS C6.1 satellite sensors, systematically grouped as a single 'hotspots' entity. Occasional spatial gaps occurred due to satellite overpass limitations.

Hourly meteorological variables from the Copernicus Climate Change Service's ERA5 global atmospheric reanalysis included:

- 10m u and v components of wind (used to derive wind speed and direction)
- 2m dew point temperature
- 2m temperature
- Surface pressure
- Total precipitation
- A 90m resolution Digital Elevation Model (DEM) from the Copernicus GLO-90m product was incorporated to capture the fire's interaction with terrain. From this DEM, the slope was derived to provide additional topographic context crucial for understanding fire spread patterns.
- A 100m resolution fuel map, based on FirEUrisk project downscaled for Croatian territory [6][7], was integrated to characterize the vegetation and fuel types across the fire-affected area, serving as a critical input for fire behavior assessment.

Raw datasets were stored in their original Coordinate Reference Systems (CRS) within a structured HDF5 format for efficient and organized access.

A crucial preprocessing step involved synchronizing VIIRS and MODIS hotspot detections by snapping timestamps to the nearest full hour, aligning them with hourly ERA5 meteorological data for spatiotemporal consistency.

To ensure spatial accuracy, all layers, including the Digital Elevation Model (DEM), were reprojected on-the-fly into a common WGS84 (LatLon) system during processing and visualization. Raster datasets underwent affine transformations to correct for misalignment and enable precise overlay.

Data processing, manipulation, and analysis were conducted using Python, leveraging multiple libraries. These included geopandas for efficient handling of vector-based geospatial data, xarray for managing and operating multi-dimensional labeled arrays, rasterio for raster data operations and shapely for geometric operations.

For interactive visual analysis and exploration of the dataset, plotly was utilized, enabling dynamic overlays of all integrated layers in a user-friendly projection. The structured organization within the HDF5 file enabled seamless integration and accessibility of all components for analysis.

3. Results and Discussion

Our initial exploration of the Skradin wildfire dataset highlights the power of a multi-source, spatiotemporally aligned approach in revealing key dynamics of wildfire behavior. The integration of satellite fire detections and meteorological reanalysis into a unified structure enables a more coherent understanding of how environmental factors shape fire progression.

Analysis of active fire detections shows a rapid dual-direction spread from a central ignition zone. By the time of the first satellite detection at 10:00 AM on July 30th, the fire had already advanced significantly, suggesting early ignition and an intense initial burn phase. The progression of hotspots closely follows dominant wind directions retrieved from ERA5 reanalysis, underlining the strong influence of wind on fire trajectory.

Topographic influence is also evident in the fire's behavior. Initially confined to a lower-elevation basin, the fire gradually expanded upslope, with spread patterns suggesting terrain channeling and slope - driven propagation. These interactions, while often hard to isolate in disconnected datasets, are more readily discernible through integrated analysis within a common spatial and temporal frame. Fire spread can be seen on figure 1.

The impact of vegetation and fuel types, represented by the downscaled FirEUrisk-based fuel map, has yet to yield clearly identifiable patterns in this early phase of analysis. Future work will focus on quantifying these relationships more rigorously, potentially using simulation or classification-based modeling techniques.

This early case study already demonstrates the practical strength of combining disparate geospatial, meteorological, and thematic layers into a single, accessible HDF5 dataset. It provides not only a foundation for historical fire inspection but also foundation for simulations and scenario analysis if coupled with robust models.

4. Conclusions

This extended abstract presents format and use of a unified, multi-source dataset capturing the 2024 Skradin wildfire in Dalmatia, Croatia. This fire represents a complex, multi-day event shaped by topography and meteorological conditions. By integrating satellite-based fire detections (VIIRS, MODIS), ERA5 reanalysis, high-resolution elevation data, and detailed fuel map into a cohesive HDF5 structure, this work delivers a robust foundation for spatiotemporal analysis of a wildfire.

Multi facet visualization of data reveal clear wind-driven spread patterns and terrain-driven behavior, demonstrating how aligned spatiotemporal datasets can uncover environmental drivers not easily observable in isolation. While fuel-type influences remain under investigation, and the coarse resolution of meteorological input presents limitations, the dataset already supports meaningful interpretation of fire-environment interactions.

This work underscores the importance of merging satellite and atmospheric observations into a spatially and temporally coherent format. The HDF5-based approach not only enables efficient storage of multidimensional data but also promotes accessibility and scalability for future case studies. Next steps include enhanced visualization of wind vectors, interoperability with fire simulation software and application of this framework to additional regional fires

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Calibration of a Thermal Tunnel to Analyse the Effect of Atmospheric Structure on Fire Spread

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Summary

Forest fires are influenced by complex interactions between fire and atmospheric conditions, particularly by temperature and wind velocity vertical profiles. These "fire-atmosphere interactions" affect fire behaviour, especially the vertical air movement driven by heat. Atmospheric stability, characterized by vertical temperature gradient, can either suppress or intensify fire spread. To study this problem, CEIF | ADAI at the University of Coimbra developed a Thermal Tunnel capable of simulating different air temperature and velocity vertical profiles. This work focuses on calibrating the Thermal Tunnel to examine how atmospheric conditions that affect the rate of fire spread can be replicated in the laboratory.

Keywords: Fire Behaviour, Forest Fires, Dynamic Fire Behaviour, Fire and Atmosphere Interaction, Fire atmosphere coupling, Physical Modelling.

1. Introduction

Forest fires often exhibit complex and dynamic fire behaviour resulting from interactions between the fire and the surrounding environment. These interactions, known as "fire-atmosphere interactions" or "fire atmosphere coupling," can cause instantaneous increases or decreases in the rate of fire spread (ROS), creating critical safety issues [1,2].

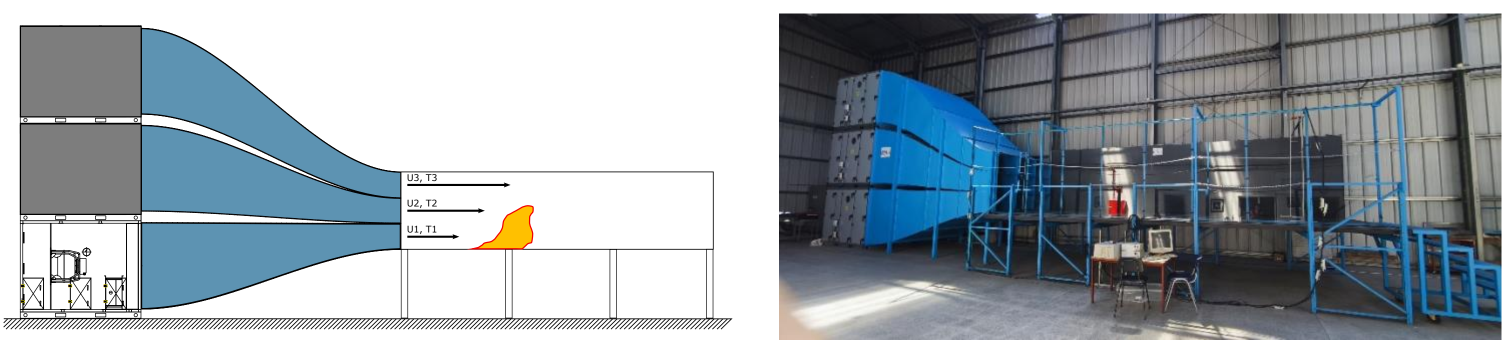
The vertical structure of the atmosphere, specifically temperature and wind velocity profiles, plays a significant role in fire dynamics. The heat generated by a wildfire primarily causes vertical air movement, the intensity of which is affected by air density in the lowest layer of the atmosphere (the troposphere) [3-6]. Atmospheric stability, characterized by the vertical temperature gradient, determines whether vertical mixing is suppressed or intensified:(i) Stable Atmosphere (Temperature Inversion): Occurs when temperature increases with height. This structure resists vertical movement, inhibiting vertical mixing, and potentially trapping smoke near the surface, which may lead to higher ground-level temperatures that affect fire behaviour; (ii) Unstable Atmosphere: Occurs when temperature decreases rapidly with height. This condition promotes vertical mixing, allowing hot gases to rise more easily, which can lead to rapid plume development, increased fire intensity, and erratic fire behaviour (such as that observed in the large Portuguese wildfires of 2017) [7, 8].

To isolate and analyse these specific effects, experimental studies in controlled environments like thermal tunnels are essential. This work focuses on calibrating the Thermal Tunnel created by CEIF | ADAI to investigate the properties of the flow inside its test chamber and analyse how atmospheric conditions affecting the rate of fire spread can be reliably replicated in a laboratory setting.

2. Data and Methods

2.1 Thermal Tunnel

The Thermal Tunnel is located at the Forest Fire Research Laboratory of the University of Coimbra in Lousã, Portugal, see Figure 10. The tunnel has a working area of 8x2m^2 with a cross-section of 1.5x2m^2 and is open on the top to avoid flow stratification and smoke accumulation in the combustion area. The tunnel is open on the top to prevent flow stratification and smoke accumulation in the combustion area. Tempered glass side walls facilitate observation within the test chamber. the wind flow is produced by three independent channels or ducts of rectangular cross-section. The flow velocity in each channel can be controlled independently.



a) b)

Figure 10: Thermal Tunnel of the Forest Fire Research Laboratory of the University of Coimbra in Lousã (Portugal). a) Schematic view; b) View of the combustion thermal tunnel in the laboratory.

Two high-power heat pumps produce water (ranging between 6 °C and 45 °C) to either heat or cool the air in the upper and lower channels. The mid channel works with air at ambient temperature. This design allows the facility to blow air in three distinct layers at different temperatures and velocities, crucial for simulating various atmospheric stability regimes.

2.2 Air velocity and temperature measurements

The calibration aimed to investigate the flow properties within the test chamber. The HT-400 series system, including a hot-sphere-type thermal anemometer probe (HT-41x), a transducer unit (HT-42x), and a multichannel power supply (HT-430), was used for air velocity and temperature measurements. The probe includes an omnidirectional velocity sensor (enamelled copper wire, 3mm sphere) and a temperature sensor (thin nickel wire), both covered with a special AL coating to reduce the effect of thermal radiation Figure 11.

During the calibration of the Thermal Tunnel, 10 sensors (S_i where i range between 1 to 10) were used to measure the air flow velocity and temperature. For each air duct 3 sensors ($S_1 = (0, 100, 125)cm,\ S_2 = (0, 100, 75)cm,$ and $S_3 = (0, 100, 25)cm$) were fixed in their geometric centre. The other seven sensors ($S_4 = (dis, 50, 125)cm,\ S_5 = (dis, 50, 25)cm,$ $S_6 = (dis, 100, 125)cm,\ S_7 = (dis, 100, 75)cm,\ S_8 = (dis, 100, 25)cm,\ S_9 =$ $(dis, 150, 125)cm$ and $S_{10} = (dis, 150, 25)cm$) were placed on a structure to calibrate the thermal tunnel at various distances. Thus, the following distances were considered $dis =$ $100, 300, 500$ and 700cm. For each distance 4 different flow velocities were considered, and the potential difference was 1.5V, 2V, 3V and 4V. The Figure 3 represent the schematic view for the position of each sensor.

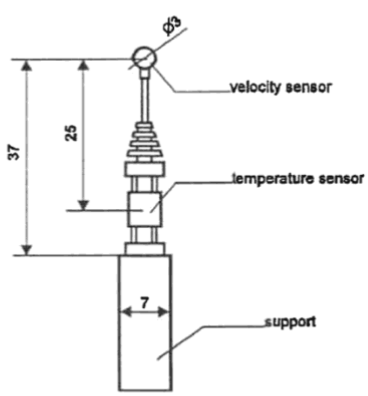


Figure 11: The probe is schematically shown. The dimensions of the velocity sensor and the temperature sensor is presented in this figure.

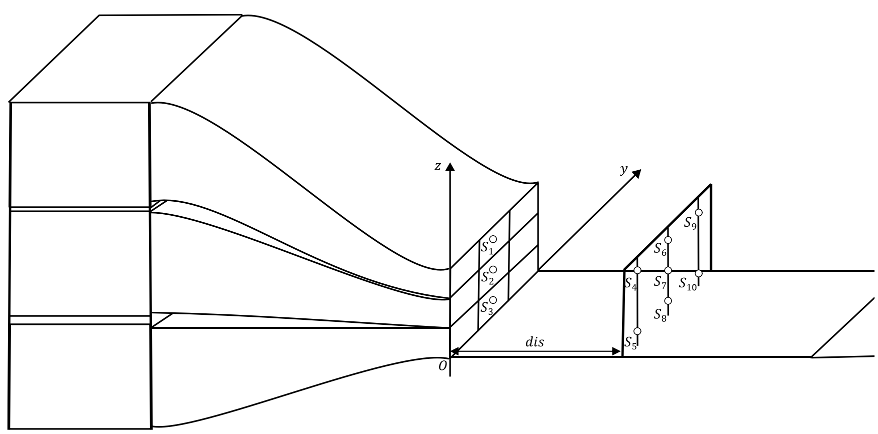


Figure 12: Schematic view of the sensors to measure the air flow velocity and temperature.

3. Results and Discussion

3.1 Air flow rate as a function of potential difference

The calibration results characterized the tunnel's capabilities regarding airflow control linearity, sensitivity, flow uniformity, and the successful generation of stability regimes. The analysis evaluated the linearity and sensitivity of the fan systems (UTA1, UTA2, UTA3) in response to changes in input voltage, *Figure 13*. All three datasets demonstrated a strong linear correlation between voltage and airflow rate, as indicated by high coefficients of determination ($R^2 > 0.99$).

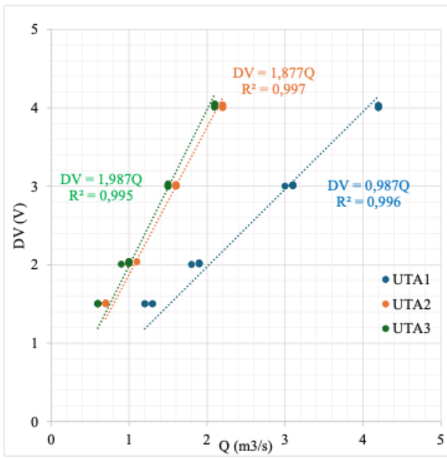


Figure 13: Relationship between airflow rate (Q, in m^3/s) and the potential difference (DV, in Volts) for three different air ducts under test (UTA1, UTA2, and UTA3) within the Thermal Tunnel.

3.2 Wind Flow Velocity Profiles

Understanding the wind flow velocity profile is essential for characterizing the environment's impact on fire behaviour. *Figure 14* presents the wind flow velocity profiles for four different set velocities, measured at various distances ($dis = 1, 3, 5$ and 7m) along the tunnel.

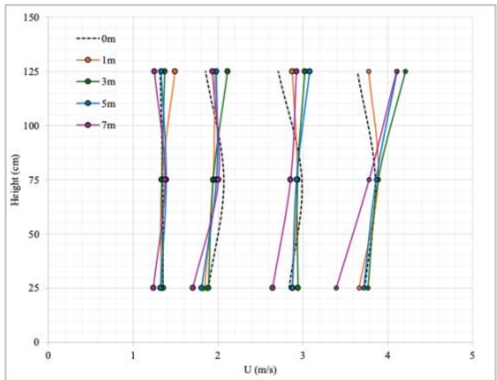


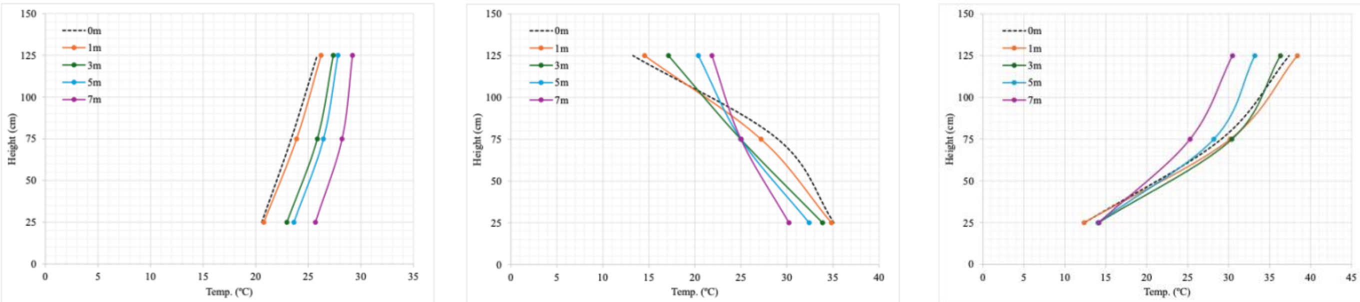
Figure 14: Wind Flow Velocity Profiles.

The profiles were measured at various distances (1m, 3m, 5m, and 7m). While the profiles change slightly as the flow moves down the tunnel due to factors like wall friction and turbulence, the uniformity of the flow is essentially maintained across the entire test chamber. The tunnel demonstrated its ability to generate a range of flow conditions with great uniformity, as the flow velocity profile tends to remain almost constant throughout the test chamber.

3.3 Vertical Temperature Profiles

The capability to establish controlled atmospheric conditions is crucial for accurately assessing the impact of atmospheric structure on the fire rate of spread. The Thermal Tunnel successfully achieved three distinct stability regimes: *Figure 15a* Ambient Temperature Profile (Neutral Stability): Represents a baseline condition where the temperature is relatively uniform throughout the height of the tunnel. This simulates a neutrally stable atmosphere where vertical mixing is neither enhanced nor suppressed, serving as a control for comparison; *Figure 15b* Temperature Inversion (Stable Atmosphere): Established by having temperature increase with height. This simulates a stable atmospheric condition that inhibits vertical mixing; and *Figure 15c* Unstable Atmosphere: Established by having temperature decrease with height. This promotes vertical mixing, potentially leading to rapid plume development and increased fire intensity.

These analyses demonstrate the Thermal Tunnel's capability of generating a range of atmospheric stability conditions. By systematically varying the temperature profiles, it becomes possible to investigate the specific influence of atmospheric stability on various aspects of fire behaviour.



a) b) c)

Figure 15: Vertical Temperature Profiles: a) Ambient Temperature Profile; b) Temperature Inversion and c) Unstable Atmosphere.

4. Conclusions

This study confirmed the thermal tunnel's suitability for conducting controlled experiments on fire behaviour under varying atmospheric conditions.

The calibration successfully demonstrated the tunnel's ability to generate controlled and repeatable vertical temperature profiles, simulating stable, neutral, and unstable atmospheric conditions. Furthermore, the characterization of the fan systems showed excellent linearity and provided a comprehensive understanding of the uniform flow dynamics within the tunnel.

By allowing researchers to manipulate both temperature and wind velocity profiles, the Thermal Tunnel enables the isolation and analysis of specific fire-atmosphere interactions, addressing a critical need in fire research. Future work will utilize this calibrated environment to investigate the rate of spread of head fires under stable and unstable atmospheric conditions to contribute to improved fire behavior prediction and mitigation strategies.

Acknowledgements

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Session 3
Drivers, Trends, and Future Projections of Extreme Wildfire Events

Hydroclimatic Rebound Drives Extreme Fire in California's Non-Forested Ecosystems

The catastrophic Los Angeles Fires of January 2025 underscore the urgent need to understand the complex interplay between hydroclimatic variability and wildfire behavior. This study investigates how sequential wet and dry periods, hydroclimatic rebound events, create compounding environmental conditions that culminate in extreme fire events. Our results show that a cascade of moisture anomalies, from the atmosphere to vegetation health, precedes these fires by around 6–27 months. This is followed by a drying cascade 6 months before ignition that results in anomalously high and dry fuel loads conducive to fires. These patterns are confirmed when analyzing recent (2012–2025) extreme fire events in Mediterranean and Desert Californian biomes. We find hydroclimatic rebound as a key mechanism driving extreme wildfire risk, where moisture accumulation fuels vegetation growth that later dries into highly flammable fuel. In contrast, extreme fires in the fuel-rich Forested Mountain regions are less influenced by the moistening cascade and more impacted by prolonged drought conditions, which typically persist up to 11 months prior to fire occurrence. These insights improve fuel-informed operational fire forecasts for the January 2025 Los Angeles fires, particularly when year-specific fuel conditions are included. This underscores the value of incorporating long-memory variables to better anticipate extreme events in fuel-limited regions.

McNorton, J., Moreno, A., Turco, M., Keune, J. and Di Giuseppe, F., 2025. Hydroclimatic Rebound Drives Extreme Fire in California's Non-Forested Ecosystems. *Global Change Biology*, *31*(9), p.e70481.

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Cross-country correlations in fire weather enhance the danger of extremely widespread fires in Europe

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Summary

Wildfires increasingly threaten European ecosystems, with spatially compounding events characterized by synchronous wildfires across multiple regions posing major challenges for shared resource mechanisms. This study investigates these events using daily burned area and Fire Weather Index (FWI) data. Our results show that cross-country fire weather correlations amplify widespread fire danger, with a recent increase in such events linked to decreasing relative humidity and rising temperatures. Using CMIP6-based detrending of FWI, we distinguish changes due to internal variability from those driven by human-induced climate change. These findings enhance our understanding of European fire risk, supporting response strategies to these high-impact events.

Keywords: Spatially compounding wildfires events, Fire Weather Index (FWI), Climate change, CMIP6 climate simulations

1. Introduction

Fire is a natural component of the European forested ecosystems, and in recent years, an increase in destructive wildfires has led to major ecosystem and socioeconomic impacts[1-3]. In Europe, the response to these extreme wildfire events is coordinated by the European Protection Agreement[4], which enables the mobilization of resources—such as airplanes and firefighters—when a member country faces a major fire. This mechanism is challenged when multiple countries experience wildfires simultaneously due to the limited resources available to cope with widespread impacts, potentially leading to greater cumulative impacts than isolated events occurring at different times. An illustrative example is the 2021 fire season, during which widespread fires across Europe challenged cooperative response capacities[5]. Such events are known as *spatially compounding wildfires*, and understanding the drivers and characteristics of these events is at the core of the present work.

2. Data and Methods

To advance our understanding of spatially compounding wildfires, we use the daily-scale Burned Area dataset from the Global Fire Emissions Database (GFEDv4) for the period 2001-2015 and the Canadian Fire Weather Index (FWI) derived from ECMWF Re-Analysis version 5 (ERA5) data for 1940-2023[6]. We also use simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6)[7] climate models to disentangle FWI changes driven by internal variability from those led by human-induced climate change.

The first part of the analysis consists of a study of the link between extreme FWI conditions and real burned area events over Europe. To inspect the effect of the spatial dependency between FWI in multiple countries on continental-scale FWI extremes, we apply a shuffling-based approach. Based on ERA5 weather reanalysis and FWI, the meteorological drivers of extreme FWI events are also studied, deepening the understanding of the weather drivers of widespread continental-scale FWI extremes. Recomputing the FWI based on individually detrended weather time series and comparing the spatially compounding events among the simulations allows us to underpin which of the weather drivers explains the long-term trends in the extreme FWI events[8,9]. We also investigate further these long-term trends by combining ERA5 reanalysis with CMIP6 climate model simulations.

3. Results and Discussion

By combining burned area with FWI data, focusing on the May-October fire season, we find that the top 20% of days with the highest European area under FWI > 50 account for 40% of the total European burned area, all fires considered. By focusing on FWI data, we reveal that cross-country dependencies in fire weather enhance the likelihood of days affected by a larger fraction of Europe under extreme fire danger. Similar cross-country dependencies are observed for burned areas. The spatial dependencies in FWI can be linked to large-scale atmospheric patterns that favor fire-prone weather over different regions simultaneously. Typical meteorological conditions profiles for the most extreme FWI events across the continent indicate that persistent high-pressure systems, characterized by increasing temperature and decreasing relative humidity prior to the events, are key drivers for widespread FWI extremes. Based on detrending individual FWI drivers, we reveal that a decrease in relative humidity and an increase in temperature are the key drivers of the recent increase in the severity of these spatially compounding FWI extreme events. The use of a similar method based on the CMIP6 climate model simulation allows us to disentangle the effect of climate variability and human-induced climate change in the observed long-term trend of FWI. Even though these results focus solely on the weather component of the fire risk in Europe—without accounting for fuel availability or socioeconomic factors—they provide a valuable basis for evaluating continental-scale wildfire risk. These findings can also help inform response strategies to high-impact events in the context of shared resources.

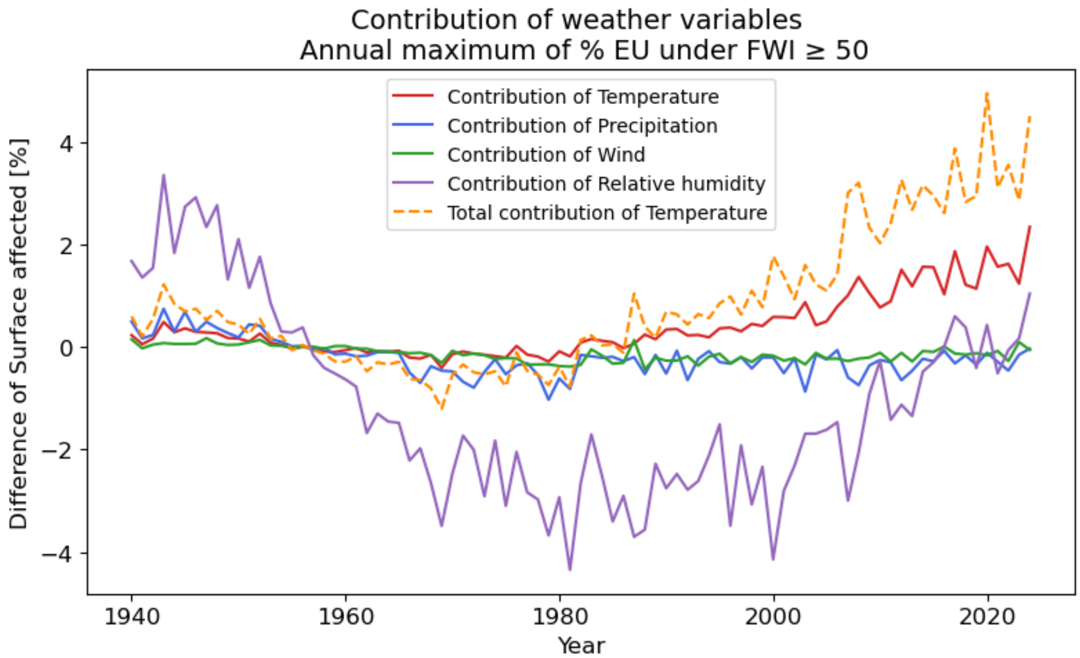

Figure 16 Contributions of individual meteorological variables to the trends in extreme FWI area, quantified by recomputing FWI after detrending each driver separately. The dashed orange line represents the combined contribution of temperature, accounting for both its direct effect and its indirect influence via relative humidity.

Conclusions

Our results highlight a strong link between fire weather conditions and extreme wildfire events, as well as clear spatial compounding effects across European countries. Relative humidity and temperature emerge as the main drivers of recent increases in fire danger, trends that are likely to intensify under continued climate change. Future work could make use of the CMIP6 climate models simulations to assess the projected evolution of spatially compounding wildfires events in the future and to improve the current understanding of the underlying drivers of these changes, thereby informing preparedness and adaptation strategies.

Acknowledgements

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European fire synchronicity more likely due to overlapping fire seasonality and atmospheric blocking

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Summary

In this work, we use satellite-derived fire observations to detect significant synchronous wildfires at regional to continental scales in Europe. We link the occurrence and spatial scale of synchronous wildfires in spring, summer and fall to weather regimes and fire seasonality. Our results reveal significant fire synchronicity among many European regions and show that the spatial scale of fire synchronicity is amplified by European Blocking, which promotes warm and dry weather conditions. Since weather regimes are predictable on a sub-seasonal timescale, our work improves the predictability of synchronous wildfires and provides guidance for firefighting resources distribution within Europe.

Keywords: fire synchronicity, weather regimes, Europe, compound events, drivers

1. Introduction

In recent years, Europe has been increasingly impacted by extreme wildfire seasons. To ensure effective wildfire emergency response, European countries share essential firefighting resources according to the European Union Civil Protection Mechanism. The distribution of firefighting resources is challenged by the co-occurrence of multiple wildfires at different locations within a short time window (i.e., synchronous wildfires). The frequency of such fire emergencies is likely to increase with intensified wildfire activity in Europe under climate change, however, it is largely overlooked by ongoing wildfire research. Specifically, observation-based evidence of synchronous wildfire occurrences, spatial extents and their large-scale atmospheric drivers is missing.

In this work, we focus on synchronous wildfires across different European regions within a weekly time window. We aim to: (1) identify regions with synchronous wildfire occurrences, (2) explain their occurrences from the perspectives of overlapping fire seasons and weather regimes, and (3) quantify the dependence of their spatial scale on weather regimes.

2. Data and Methods

We extract fire observations from the satellite-derived fire event dataset FRY_v2.0_FireCCI51_6D [1]. This dataset aggregates fire patches based on burned area and active fire detections, including start date, size, and shape information for each fire patch. To reduce the anthropogenic influence of agricultural fires, we filter these fire events based on land cover information to focus on wildfires occurring in near natural vegetation. A fire polygon should have least 80% of natural vegetation coverage to be considered in our analysis. It should be noted that prescribed burning, if occurred in natural vegetation we define, may still be included this analysis. For climate data, we use: (1) a year-round daily weather regime classification scheme in the European-Atlantic sector [2–4]; (2) daily outputs of temperature, relative humidity and wind speed from the climate reanalysis CERRA [5].

To detect fire synchronicity, we extract daily fire time series from 2001 to 2020 for each of the ten European regions and apply a statistical framework of event synchronicity [6] to identify significant fire synchronicity between these regions in each season. To link synchronous fire events to weather regimes, we calculate the relative conditional probability [7] of synchronous wildfires co-occurring with weather regimes in spring, summer and fall. We further analyze the relationship between the spatial scale of synchronous wildfires and weather regimes by defining five levels of synchronicity – no, regional (wildfire(s) occurred within a region), low (2-3 regions co-experienced wildfires), medium (4-5 regions co-experienced wildfires) and high synchronicity (>5 regions co-experienced wildfires).

3. Results and Discussion

We detect significant fire synchronicity between multiple European regions with seasonal variations. Regions with overlapping fire seasons are more likely to co-experience fires within these seasons. For example, regions with spring fires (British Isles, Middle Europe, and Northeastern Europe) show significant fire synchronicity in spring, whereas southern regions with summer fire activity show significant fire synchronicity in summer. These findings indicate that European regions with strongly overlapping fire seasons have reduced opportunities to share firefighting resources in case of synchronous wildfire emergency.

Further, we compare atmospheric conditions on regional fire days versus synchronous fire days and find that these two types of days are featured by warm and dry weather conditions. Synchronous fire days co-occur with even warmer and drier conditions than regional fire days. The frequency of compound warm and dry events is likely to increase in coming decades, suggesting higher synchronous fire danger under climate warming.

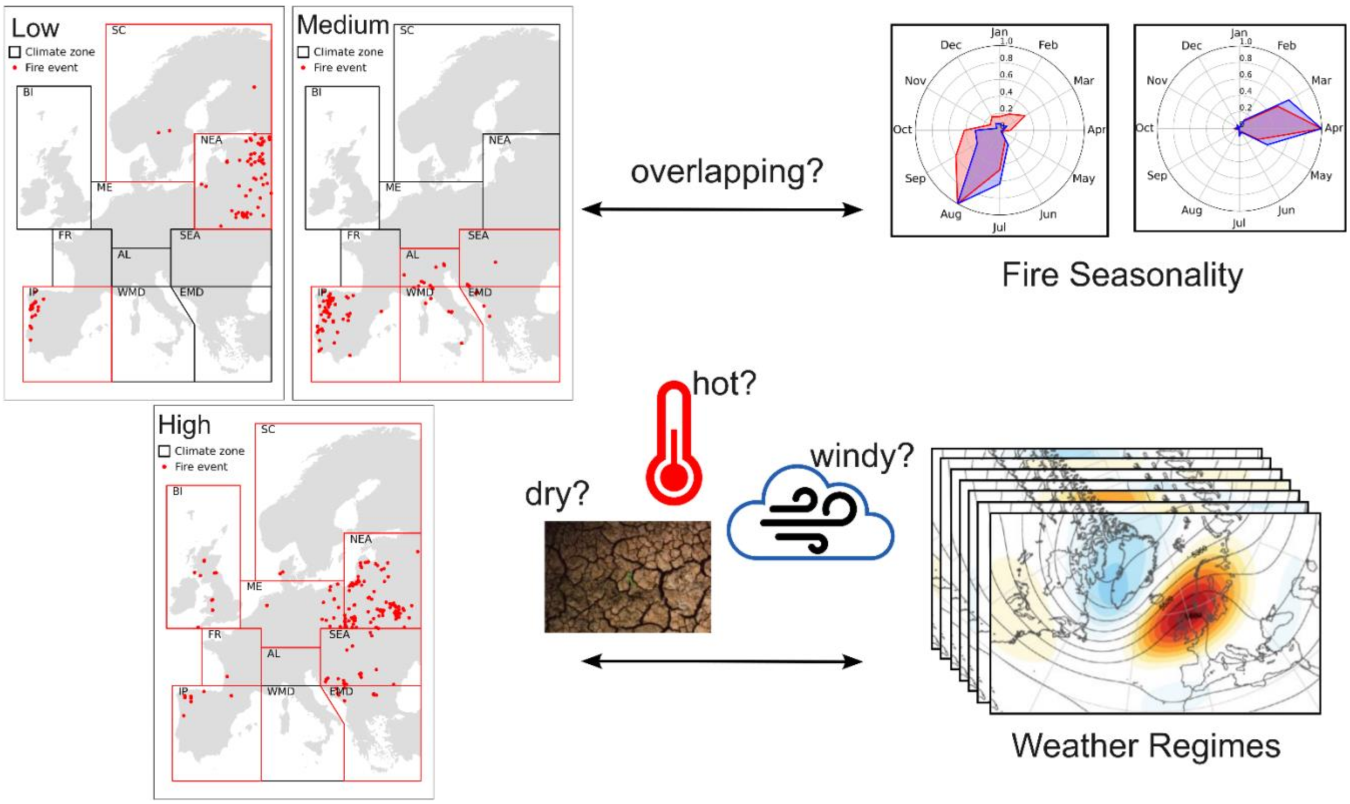

Figure 1. A schematic overview of two driving processes of synchronous wildfires.

Synchronous wildfires in Europe are significantly modulated by weather regimes. Weather regimes featured by a high-pressure center above the European continent, such as European Blocking and Scandinavian Blocking, increase the likelihood of synchronous wildfires by driving warm and dry weather conditions. Further, extreme synchronous wildfires with more than five regions involved are the most likely to co-occur with European Blocking. Conversely, when a low-pressure center develops above the continent, synchronous wildfires are suppressed. As weather regimes are predictable on a sub-seasonal timescale, these findings may help to develop a synchronous wildfire early warning system for Europe.

Conclusions

We detect seasonally varying patterns of significant fire synchronicity between different European regions. We reveal that fire seasonality and persistent weather regimes co-regulate the occurrence of synchronous wildfires. Compound warm and dry weather conditions co-occurring in several regions have the potential to trigger synchronous wildfires at regional to continental scales. European blocking can trigger synchronous wildfires over large spatial extents by promoting warm and dry conditions.

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Increasing likelihood of fire-conductive conditions in a warming Europe

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Summary

Recent extreme wildfire seasons in Europe, particularly in 2017 and 2018, were driven by compounding fuel, drought, and fire weather conditions. By using the CESM2-Large Ensemble, we assess how the likelihood of such wildfire months—characterized by FWI, SPEI, and GPP—has changed from pre-industrial times to present climate and future warming scenarios. Fire-promoting conditions become substantially more likely in the future, with return periods of observed events dropping below three years in Southern Europe and reaching decadal levels in Central and Northern Europe. These results highlight increasing wildfire risks and the need for coordinated climate-adaptive fire management across Europe.

Keywords: climate change, wildfires, compound events

1. Introduction

In recent years, various regions in Europe experienced unprecedented wildfire extremes, including the Iberian Peninsula and the Mediterranean in 2017 and Central Europe, the British Isles, and Scandinavia in 2018. These wildfire extremes consisted of multiple large wildfires that occurred in close temporal proximity in the case study regions and led to the most severe months ever recorded in terms of burned area and damage to ecosystems, livelihoods, and infrastructure. All case study months are characterized by pronounced drought conditions, which promote fuel aridity and high fire danger levels. While climate change likely promoted the extreme conditions that led to the extreme fire events in the Iberian Peninsula in October 2017, the Mediterranean in July 2017, the British Isles and Scandinavia in July 2018, and Central Europe in September 2018, the degree to which drought conditions, fire weather, and fuel availability have changed compared to pre-industrial levels is not yet fully understood. Here, we use the Community Earth System

Model version 2 Large Ensemble (CESM2-LE)[2] to investigate how the likelihood of extreme wildfires and their drivers in different regions of Europe compare to pre-industrial levels and explore how these likelihoods change in a Europe that is 2° or 3° warmer.

2. Data and Methods

We first identify case studies of extreme wildfire seasons between 2001 and 2020 in different climate regions of Europe, i. e. Iberian Peninsula, Mediterranean, British Isles, Scandinavia and Central Europe. Extreme wildfire seasons are defined as the top three years with the largest burned area observed between June and November in each region. Within these extreme seasons, we identify the month with the largest burned area (derived from FireCCI[1]) and evaluate how extreme these months were in terms of burned area (derived from FireCCI[1]), FWI and SPEI-3M (derived from CERRA reanalysis[3]) and GPP (derived from MODIS[4]). To illustrate the likelihood of these events in observed climate, we fit a GEV distribution to burned area and FWI and a log Gamma distribution to SPEI and GPP summer and fall monthly mean values in the 20-year observation period. Next, we map the likelihoods of the observed extremes to respective likelihoods in pre-industrial climate, present climate (2001-2020) and future climate, i. e. 2°- and 3°-degree warming levels for Europe, which we derive from the CESM2-LE. We map the likelihoods of the observed events in terms of FWI, SPEI and GPP to assess how the preconditions of extreme wildfire months change across climates. Burned area information form CESM2-LE does not compare consistently across seasons and regions with observational records and is therefore omitted from the climate change analysis.

3. Results and Discussion

We identified 2017 and 2018 as the most severe wildfire seasons in multiple regions. For example, 2017 was the worst fire season in terms of burned area in the Iberian Peninsula and the third worst in the Mediterranean. Meanwhile, 2018 was the worst fire season in terms of burned area in the British Isles, Scandinavia, and Central Europe. Within these seasons, the peak monthly burned area was observed in October 2017 in the Iberian Peninsula and in August 2017 in the Mediterranean. In 2018, July was the worst month in the British Isles and Scandinavia, and September was the worst month in Central Europe.

The wildfires in the British Isles and Scandinavia (Northern Europe) in 2018 co-occurred with the highest observed FWI and the strongest observed drought (SPEI) indicator values. In these regions, GPP was higher than average. In Central Europe, FWI conditions were less extreme, while GPP conditions were below average under severe drought conditions. The FWI conditions were average for the Iberian Peninsula wildfires in October 2017. In the Mediterranean, the FWI conditions were among the five highest observed values in 2017. In both regions (further Southern Europe), drought conditions in the SPEI represent moderate drought, while GPP is lower than average in the Iberian Peninsula and average in the Mediterranean.

We map the probabilities of these conditions under pre-industrial, present, 2, and 3-degree warmer climate conditions within the CESM2-LE and find that, in comparison to the pre-industrial climate, the observed FWI and SPEI extremes became at least twice as likely in all regions under present climate conditions. Increasing warming will make FWI extremes, such as those observed during our identified extreme wildfire months, four times more likely in a 2° warmer Europe and at least five times more likely in a 3° warmer climate. SPEI extremes are even more likely to occur. For example, in Southern Europe, SPEI conditions will be three times more likely under 2°C warming and five times more likely under 3°C warming. In Northern and Central Europe, extreme drought conditions will be ten times more likely under 2°C warming and more than fifteen times more likely under 3°C warming.

Our findings imply that the preconditions for wildfires will worsen significantly across different European climate regions. The likelihood of such wildfire-promoting extreme conditions will rise especially in Central and Northern Europe, suggesting that these regions will become more fire-prone in the future. Though these extremes will increase significantly in Northern and Central Europe, their return levels will remain above a 10-year return period under different warming levels. In the Mediterranean, however, the conditions of the observed extreme months will become much more frequent, i.e., occur every two to three years.

4. Conclusions

Our study shows that the likelihood of preconditions, i.e., FWI and SPEI-3M, for severe wildfire months increases drastically under climate change conditions in all European regions. As extreme drought and SPEI conditions approach annual and decadal return levels, respectively, in Southern, and Northern and Central Europe, it is crucial to emphasize the need for Europe-wide wildfire management and preparedness that addresses the pressure that climate change puts on fire-prone regions and those that will become fire-prone in the future.

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Eruptive Fire Early Warning System

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Summary

One of the most dangerous forms of extreme wildfire behavior is undoubtedly eruptive fire spread. Eruptive fire spread is a frequent cause of wildfire accidents in which numerous firefighters have been injured or killed. For this reason, we believe that prediction of possible eruptive fire spread should be included in wildfire risk assessments as a specific indicator of propagation potential, referred to as the Potential Eruptive Fire Spread Indicator. The system described in this paper was implemented successfully in Croatian advanced wildfire surveillance system used by Croatian firefighters in daily practice enhancing the firefighter's safety.

Keywords: eruptive fire, early warning, wildfire surveillance

1. Introduction

One of the most dangerous forms of extreme wildfire behavior is undoubtedly **eruptive fire spread**. Fire does not spread uniformly as assumed in the essential Rothermel model, but rather accelerates - this acceleration depends on wind speed and terrain slope. This phenomenon is known as Eruptive Fire or Blow-Up Fire. Eruptive fire spread is a frequent cause of wildfire accidents in which numerous firefighters have been injured or killed. The worst firefighting tragedy in Croatia occurred in 2007 on the island of Kornat, in the Šipnate canyon, where 12 firefighters lost their lives. According to many indicators, the tragedy was triggered by eruptive fire spread [1].

For this reason, we believe that prediction of possible eruptive fire spread should be included in wildfire risk assessments as a specific indicator of propagation potential, referred to as the Potential Eruptive Fire Spread Indicator. In Croatia, firefighters use the advanced STRIBOR OiV Fire Detect AI wildfire surveillance system [2] in daily operations. In addition to early fire detection, the system integrates various tools that support firefighting efforts, such as micro-location fire risk prediction and simulation of potential fire spread from a specific ignition point [3]. One of the embedded tools is the prediction of potential eruptive fire spread included as an Eruptive Fire Early Warning System, which is the focus of this paper. In the following sections, we will describe the methodology for determining this indicator, based on mathematical models of eruptive fire behavior, along with the results obtained.

We hope that this contribution will help improve firefighter safety in Croatia. Index is calculated dynamically based on actual weather data, as well as on weather prediction for the next 12 hours using Croatian official weather prediction model ALADIN. Therefore, when the firefighter clicks on map showing Potential Eruptive Fire Spread Indicator two times a day (12:00 and 24:00) it shows indicator based on real weather data and between them prediction based on ALADIN model in time resolution of 2 hours.

2. Related Work

Any wildfire could experience accelerated, eruptive spread if conditions related to slope and terrain shape, as well as wind direction and speed, are met. Therefore, it may be more accurate to use the term eruptive fire spread effect. Rothermel's equation assumes that a grassland fire reaching a slope of 14%, with wind blowing upslope (in the direction of fire spread) at a speed of 5.5 m/s at 10 meters height, will spread upslope at approximately 20 meters per minute. According to Rothermel, the speed would remain the same at both the bottom and top of the slope, regardless of its length. In other words, the rate of spread determined by the equation depends solely on three factors: terrain slope, vegetation, and meteorological conditions. The eruptive effect is essentially an extension of Rothermel's base fire spread model, incorporating the effect of fire acceleration when terrain and wind conditions are favorable. In the previously mentioned example, when the fire reaches a sloped incline, its speed will not be the same at the beginning and end of the slope. As it moves uphill, the speed will accelerate and can become ten times greater at the top compared to the base. This behavior has been observed in both experiments and real fires, making the eruptive effect a more accurate representation of how fires spread.

According to the FirEUrisk Extreme Fire Handbook [4], eruptive fire behavior is associated with a very rapid acceleration of the fire, which can be compared to an eruption - hence the name. The destructive force of such eruptions is significant and can catch people by surprise. Most fatal wildfire accidents are linked to this type of fire behavior. While closely associated with canyons and steep slopes, the underlying physical processes can also occur in more typical situations. In the literature, such events are sometimes referred to as "blow-up fires", although the term "explosive" can be misleading, as there is no actual detonation. The increase in spread rate is a continuous process, not a sudden flare-up, which is why the term eruptive or accelerated fire spread is more appropriate.

This type of extreme fire behavior was first systematically studied by Viegas et al. in 2002 [5], who found that eruptive behavior is linked to fire-induced airflow, amplified by the concave shape of canyon terrain. In laboratory experiments, a tabletop canyon model composed of two sloped planes was used to systematically analyze this behavior. The shape of the canyon was defined by the angles of inclination of the two slopes and the overall base angle. Higher values of these angles result in greater fire acceleration.

There are two types of eruptive fire behavior: slope-driven eruptive fire and wind-driven eruptive fire. Since slope-driven eruptive fire occurs more frequently, the term eruptive fire is commonly used to refer specifically to this type of accelerated fire spread caused by terrain slope. However, it is important to note that the eruptive effect can also be triggered by wind. Viegas [6] demonstrated this duality and the possibility of treating the influence of both wind and slope in a unified manner when assessing the potential for eruptive fire development.

The fundamental equation of eruptive fire spread, as proposed by Viegas and his co-authors [6,7,8], is a semi-empirical equation that relates the increase in the rate of fire front spread to the speed at which the fire would spread if the eruptive fire effect were not present. It should be noted from the outset that these equations were derived for fire spread on inclined planes, not for canyon-shaped terrain. In canyons, all these effects would be even more pronounced and the spread rates even higher - something that has also been confirmed experimentally [5,6].

3. Data, Methods, Results and Discussion

Our research on the Potential Eruptive Fire Spread Indicator starts during the EU IPA Adriatic Holistic project [9]. Here, we present an improved version developed during work on H2020 FirEUrisk project [10]. The results are mostly based on the work of Viegas from 2004 [6] and the study by Charleton et al. from 2015 [11]. The main difference compared to the earlier version is the introduction of one additional class (see Figure 1). In this improved version, we propose a total of five classes:

Slope-driven Eruptive Fire:

- **Class I** – Potential for eruptive fire spread caused by terrain slope. Class I is for those regions where slope $S \geq 25^0$, regardless of wind. Based on [11, p.1356] and [4, Fig.10].

Wind- and Slope-driven Eruptive Fire:

- **Class II** – Potential for eruptive fire spread caused by wind and slope. Class II is for those regions where corrected midflame wind speed considering slope and aspect is MFWS_S_A ≥ 2 m/s [4].

- **Class III** – High potential for eruptive fire spread caused by wind and slope. Class III is for those regions where MFWS_S_A ≥ 2 m/s and aspect A ∈ [135°, 225°] (south-facing). Increased solar exposure dries fuel faster.
- **Class IV** – Very high potential for eruptive fire spread caused by wind and slope. Class IV is for those regions where MFWS_S_A ≥ 2 m/s, A ∈ [135°, 225°], and vegetation is grass/shrub type. According to [11], low-buoyancy, light vegetation promotes rapid spread.
- **Class V** – Extreme potential for eruptive fire spread caused by wind, slope, and meteorological conditions. Class V is for those regions where MFWS_S_A ≥ 2 m/s, A ∈ [135°, 225°], grass/shrub vegetation, high air temperature (Ta ≥ 35°C), and low relative humidity (RH ≤ 20%). Per Charleton et al. (2015), extreme conditions accelerate ignition and spread. Temperature thresholds are: ≥ 30°C – dangerous; ≥ 35°C – very high risk; ≥ 40°C – extreme (common in Mediterranean). Humidity thresholds are: < 30% – increased fire risk; < 20% – very unfavorable; < 15% – extreme risk.

MFWS_S_A is Combined Wind-Slope-Aspect Effect calculated as follows:

$$MFWS\_S\_A = MFWS\_S * rWDA \tag{1}$$

where MFWS_S is slope correction calculated from midflame wind speed (MFWS):

$$MFWS\_S = MFWS + k * 0.447 \tag{2}$$

where midflame wind speed (MFWS) is scaled from standard 10-m height taking into account vegetation type and k depends on slope S[^{0}]: k = 0 for S < 20^0; k = 1 for $20^0 \le S < 40^0$; k = 2 for $40^0 \le S < 60^0$; k = 3 for S ≥ 60^0

rWDA is Wind and Aspect Correlation – If Wind Direction (WD) and Aspect (A) match, rWDA = 1. If WD and A are opposite, rWDA = 0. For all other cases: rWDA = 0.5 + 0.5 * cos(WD - A).

Figure 1 presents a map of part of Dalmatian coast showing potential eruptive fire spread indicators. for earlier version that had four classes. Improved version described in this paper includes a fifth class, representing extreme eruptive fire spread potential.

4. Conclusions

Eruptive fire spread is extremely dangerous for firefighters and has been the cause of numerous accidents to date. Motivated by the desire to improve firefighter safety, we have developed Potential Eruptive Fire Spread Indicator System that had been integrated into an advanced wildfire surveillance system STRIBOR OiV Fire Detect AI that is now actively used by firefighters in Croatia.

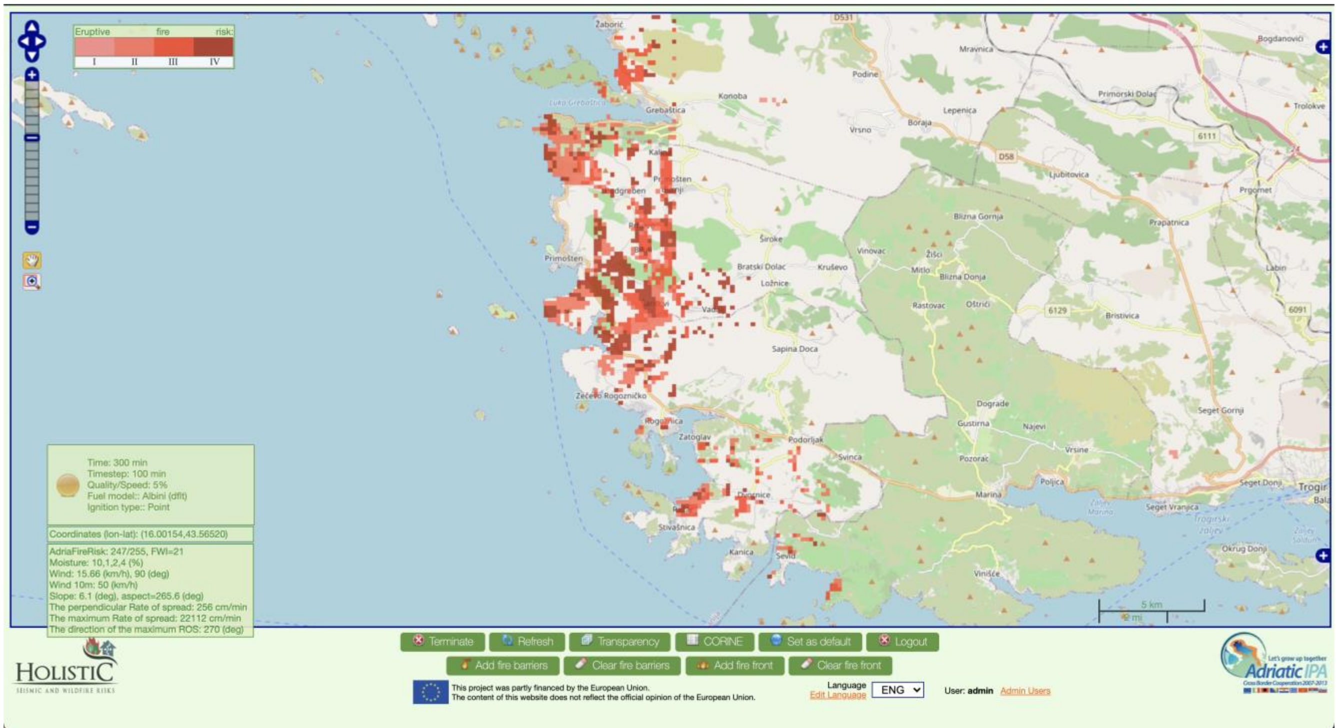

Figure 1. Part of the Dalmatian coast showing indicators of potential eruptive fire spread for old version with four classes. The new one will have five classes including extreme danger.

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Thinking Like the Locals: Expert-Laypeople Mental Model's Dissonances on Fire Hazards from Leisure Activities

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Summary

This research explores dissonances between experts' and laypeople's mental models regarding wildfire risk from leisure activities. Using the CMU mental models' approach, qualitative interviews and confirmatory surveys revealed significant gaps in public understanding, especially on ignition sources beyond fire-based activities. Findings underline the need for socially attuned communication strategies grounded in both scientific evidence and cultural context.

Keywords: Risk Communication; Mental Models; Leisure Activities

1. Introduction

Wildfires increasingly threaten forest-urban interfaces, often due to leisure-related ignition sources. However, risk communication strategies are typically expert-driven and may not resonate with public understanding. This research investigates divergences in mental models between experts and laypeople, aiming to enhance the design of targeted and effective wildfire risk communication strategies.

2. Data and Methods

The CMU Mental Models methodology was used to explore mental representations of fire risks. Semi-structured interviews elicited expert and laypeople's perspectives, which were translated into influence diagrams. The dissonances identified were then tested through a confirmatory survey administered to a statistically representative sample in Portugal.

3. Results and Discussion

Key dissonances were identified between expert and laypeople's mental models. While laypeople acknowledged fire-related leisure risks (e.g., barbecues), they overlooked factors like motorized recreation or structural fire drivers (e.g., fuel accumulation, weather).

Additionally, cultural narratives (e.g., blaming eucalyptus or government inefficiency) shaped public perception. These gaps suggest current communication strategies may fail to address the public's actual beliefs and informational needs, undermining fire prevention efforts.

4. Conclusions

The study highlights significant gaps between expert and lay perceptions of wildfire risk linked to leisure activities. While laypeople acknowledge direct fire use as hazardous, they often disregard less obvious ignition sources and structural contributors. Their understanding is shaped by cultural narratives and institutional mistrust. These dissonances suggest current risk communication is insufficient. To be effective, strategies must be evidence-based, culturally sensitive, and behaviorally informed. Addressing these gaps is essential for improving public awareness and enhancing wildfire prevention efforts.

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