FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

Grant Agreement Number: 101003890 **Call identifier:** H2020-LC-CLA-2018-2019-2020	
Topic:	LC-CLA-15-2020 Forest Fires risk reduction: towards an integrated fire management approach in the E.U.
Instrument:	RIA

D2.7 – Report analysing destructive fires with a protocol to collect feedback from next fires

Deliverable Identifier:	D2.7
Deliverable Due Date:	31/03/2024
Deliverable Submission Date:	14/06/2024
Deliverable Version:	Final version
Lead partner:	ADAI
Authors:	Miguel Almeida (ADAI), Luís Mário Ribeiro (ADAI), Domingos Xavier Viegas (ADAI), Tiago Rodrigues (ADAI)
Work Package:	WP2 – Risk reduction to improve protection
Task:	Task 2.4 Reduce communities' vulnerability
Dissemination Level:	☒ CO: Confidential

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

Revision History

Version	Date	Edited by	Description
v.0.1	18/01/2024	Miguel Almeida (ADAI)	Document Content outline / structure
v.0.2	09/03/2024	Miguel Almeida (ADAI)	Draft version
v.0.3	11/03/2024	Miguel Almeida (ADAI)	Complete version formatted according to template
v.0.4	09/05/2024	Miguel Almeida (ADAI)	Complete version with Annexes (Appendix B uncomplete)
v.0.5			Complete draft review by WP2 Leader
v.0.6	08/06/2024	Juli Pausas (CSIC), Vasileios Kazoukas (KEMEA), Christopher Marrs (TUD); Michele Salis (CNR)	Internal review of the Complete version
v.0.7	13/06/2024	Miguel Almeida (ADAI)	Version integrating the internal review comments

Quality Control

Type	Date	Reviewed by	Approved/Comment
Internal/Peer/External	08/06/2024	Juli Pausas (CSIC), Vasileios Kazoukas (KEMEA), Christopher Marrs (TUD); Michele Salis (CNR)	Approved after minor revisions

Copyright © FirEURisk Consortium. All rights reserved.

Executive Summary

The FirEUrisk project, which brings together a very large consortium involving 38 institutions from 17 countries is an ambitious project addressing the problem of integrated wildfire management, particularly those occurring under extreme conditions that endanger human lives and expose assets to risk.

Among the objectives of the FirEUrisk project, “Objective 8” stands out, which consists of " Gather, formalise, and organise in a functional way, the experience, facts and lessons learned from previous extreme wildfires in the EU and worldwide. Develop protocols to collect and analyse impacts of extreme wildfires on people's health and property, critical infrastructures, as well as the effects of fire on soil, water, fauna, flora and air quality aiming to share knowledge, raise awareness and improve risk perception and preparedness among local populations, stakeholders and policy-makers." In pursuit of this objective, Task "T2.4: Reduce communities’ vulnerability," from the FirEUrisk Project Working Document, integrates Activity "A2.4.1: Lessons learned from past cases," which envisages the analysis "feedback from five or more past large and high-impact wildfires, both in Europe and in partner countries of North America and Australia, with special focus on fire development in the WUI and impacts on the communities. This review will also consider aspects of land planning, community awareness, alert systems, social perception, and structural damages..." and the development of "protocols to collect data for future fire impact analysis."

This deliverable reports the work carried out in Activity A2.4.1, presenting the results of the analysis of 20 wildfires that occurred in Europe in the years 2021 and 2022, and presenting the study of several wildfires that occurred in the year 2023. This includes the wildfires in Canada where the European Union sent a common force to support Canadian authorities. Additionally, this document includes a protocol for the analysis of past wildfires, which benefited from the multidisciplinary nature of the project consortium and its experience, gained from analysing various wildfires within and outside the scope of FirEUrisk.

The results of A2.4.1 provide direct benefits for a better understanding of wildfires, as lessons are drawn from each analysed fire event, based on described facts, enabling learning, validation of other studies and statements, and a critical and constructive analysis of policies followed in the context of wildfire management. On the other hand, the activities of A4.2.1 integrate the flow of information among the various tasks of the FirEUrisk project. For example, the products developed in the tasks of WP1: “Risk Assessment” were relevant for presenting information and maps that helped frame and explain the analysed wildfires. The activities developed in WP1 also allowed the development of methodologies to obtain analysis data that were considered in the development of the protocol for the analysis of past wildfires, included in this deliverable. On the other hand, the lessons learned from past wildfires, following the analysis conducted, allowed the development or refinement of several guidelines developed in WP2: “Risk Reduction”. Unfortunately, the analysed year sequence - 2021-2023 - was not long enough to establish trends or support statistical studies that could be useful for WP3: “Risk Adaptation”. Thus, this methodical and systematic analysis of wildfires occurring in European territory, or outside it, continues, so that we can develop a consistent wildfire history, enabling society to better understand how to prepare for the future. We believe that this set of wildfire studies can be a source of inspiration and information, and the suggested protocols can be a valuable ally for future studies.

Copyright © FirEUrisk Consortium. All rights reserved.

Disclaimer

The content of the publication herein is the sole responsibility of the publishers, and it does not necessarily represent the views expressed by the European Commission or its services.

While the information contained in the documents is believed to be accurate, the authors(s) or any other participant in the FirEUrisk consortium make no warranty of any kind with regard to this material including, but not limited to the implied warranties of merchantability and fitness for a particular purpose.

Neither the FirEUrisk Consortium nor any of its members, their officers, employees or agents shall be responsible or liable in negligence or otherwise howsoever in respect of any inaccuracy or omission herein.

Without derogating from the generality of the foregoing neither the FirEUrisk Consortium nor any of its members, their officers, employees or agents shall be liable for any direct or indirect or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

Copyright message

© FirEUrisk Consortium, 2021-2025. This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both. Reproduction is authorised provided the source is acknowledged.

Table of Contents

1 Introduction 7
1.1 Purpose of the document 8
1.2 Structure of the Document 8
2 Lessons learned from past wildfire events 8
3 Protocols to collect data for future wildfire impact analysis 10
4 Conclusions 12
5 References 14

Copyright © FirEUrisk Consortium. All rights reserved.

List of Figures

Figure 1. Wildfires analysed and described in the 2021 Fires Report (Appendix A1). The numbers in the red circles represent the number of fatalities registered in the respective wildfire.....9
Figure 2. Wildfires analysed and described in the 2022 Fires Report (Appendix A2). The pink colour used for Ukraine highlights that the respective chapter did not describe a specific wildfire event but rather the country's situation in times of war, within the context of wildfires. 9

Copyright © FirEUrisk Consortium. All rights reserved.

1 Introduction

The FirEUrisk project epitomises collaborative efforts in confronting the escalating threat of extreme wildfires. With 38 international partners synergizing their expertise, it represents a unified endeavour to comprehend and reduce the impacts of catastrophic wildfire events. Acknowledging wildfires' transboundary nature and broad societal ramifications, the project aims to ensure accessibility and efficacy of its solutions across diverse potential end users, including the citizens. This inclusive approach encompasses a diverse consortium comprising researchers, policymakers, forest and wildfire managers, civil protection and weather services, companies, and NGOs.

At the heart of the FirEUrisk initiative lies its integrated approach, considering the interplay between society, economy, and policies in wildfire risk management. By crafting an evidence-based strategy, the project endeavours to strengthen resilience against wildfires while streamlining and fortifying existing European strategies. This comprehensive approach recognises the socio-economic drivers of wildfire occurrence alongside biophysical factors such as vegetation and climate, amalgamating diverse perspectives to grasp community vulnerabilities and develop optimal adaptation strategies. Critically, the project scrutinises wildfire risk from multiple vantage points, encompassing risk assessment, risk reduction, and risk adaptation, thus ensuring an integrated and holistic and proactive wildfire management approach.

The deliverable D2.7 focuses on the FirEUrisk component dedicated to risk reduction, specifically Activity A2.4.1: “Lessons learned from past cases”. Key objectives of this activity include analysing feedback from five or more significant past wildfires, with a special focus on fire development in the Wildland-Urban Interface (WUI) and its impacts on communities. The analysis considers aspects like land planning, community awareness, alert systems, social perception, and structural damage, alongside developing a protocol for future wildfire impact analysis.

While laboratory and field experiments are crucial to improve wildfire knowledge, they often face limitations due to scale and the challenge of representing real wildfire conditions. Numerical and simulation studies encounter difficulties in acquiring quality input data and validating outputs without real-world measurements. Real wildfire event analysis research is constrained by the occurrence, limiting the data obtained. Emerging methodologies, such as artificial intelligence-based wildfire behaviour prediction, require datasets conducive to deep learning processes. Therefore, real wildfire case studies are vital for advancing and consolidating existing research programs. Harmonising analysis methodologies is crucial for enabling the comparison of results from studies across different wildfire events at different conditions.

Moreover, wildfire analysis enables the discovery of new wildfire-related phenomena and mechanisms, paving the way for deeper understanding of this complex hazard. Historical wildfire records not only contribute to historical narrative but also serve as invaluable resources for future utilisation amidst expected technological, methodological, and modelling advancements. The FirEUrisk project analysed 20 major wildfires in Europe from 2021 and 2022, spanning 10 countries. The experience garnered from studying these wildfires, combined with previous expertise, facilitated the development of a protocol that could serve as a reference for other researchers analysing wildfires. This paves the way

Copyright © FirEUrisk Consortium. All rights reserved.

for establishing a consistent, comprehensive, and harmonised European database of major wildfire events, and a standardised development methodology for their analysis.

1.1 Purpose of the document

This document reports the outputs obtained regarding the two previously mentioned main components of Activity A2.4.1: "Lessons learned from past cases," namely: 1) the analysis of past wildfire events, presenting the studies conducted on the analysed wildfires and compiling some of the main conclusions, and 2) the development and presentation of a protocol to collect data for future wildfire impact analysis.

1.2 Structure of the Document

Based on the presentation of documents independent of each other, this deliverable is quite particular in that its most interesting parts are referred to as appendices, namely, the two reports on the analysis of the wildfires from 2021 and 2022, and the document outlining the protocol to collect data for future wildfire impact analysis. Thus, following this introduction, Chapter 2 provides a brief description of the analysed wildfire reports and their main facts. In Chapter 3, a brief presentation of the developed wildfire analysis protocol will be provided, with the complete document available in Appendix B. The fourth and final chapter will offer a summary of the document and provide some recommendations as conclusions.

2 Lessons learned from past wildfire events

The heterogeneity of nationalities and fields of expertise within the consortium allowed for the analysis of several of the major wildfires that occurred in Europe in the years 2021 and 2022, resulting in two reports presented in Appendix A1 and Appendix A2 of this document. The selection of wildfire events analysed considered three essential factors: 1) the burned area and the wildfire impacts; 2) the international nature of the wildfires, both in terms of the wildfire perimeter involving more than one country and the cooperation between countries, both directly affected and those not, and 3) the occurrence of wildfires in regions or countries historically less prone to wildfires. Figure 1 and Figure 2 present the wildfires that were analysed and reported in these two reports.

Copyright © FirEUrisk Consortium. All rights reserved.



Figure 1. Wildfires analysed and described in the 2021 Fires Report (Appendix A1). The numbers in the red circles represent the number of fatalities registered in the respective wildfire.



Figure 2. Wildfires analysed and described in the 2022 Fires Report (Appendix A2). The pink colour used for Ukraine highlights that the respective chapter did not describe a specific wildfire event but rather the country's situation in times of war, within the context of wildfires.

Copyright © FirEUrisk Consortium. All rights reserved.

Each wildfire was analysed by a team of researchers, both internal and external to the FirEUrisk project Consortium. To harmonise the studies and reporting of the analysed cases, a reference set of topics to be addressed in each chapter was proposed as follows:

- General description
- Characterisation of the affected area
- Wildfire conditions (meteorology, fire risk, alert, etc.)
- Wildfire behaviour (and smoke dispersion)
- Wildfire impacts (particularly at WUI)
- Cascading effects (post-fire)
- Conclusions and lessons learned

Given the situation of war in Ukraine and considering the potential changes in the context of wildfires that this situation may lead to, such as an increase in ignitions and greater difficulties in fire suppression, a special chapter was written in the 2022 Fires Report (Appendix A2) to address this context. Due to its specificity, this chapter did not follow the previously chapter's structure.

Each report was initiated by a framing chapter of the work and another chapter framing the meteorological conditions and the overall wildfire situation in Europe and the world for each year.

Given the European interest generated by both reports, an agreement was established with the Joint Research Centre (JRC) for their publication in the European Commission's Library – JRC Publications Repository. The 2021 Fires Report (Appendix A1) has already been published (Almeida et al., 2023). The 2022 Fires Report (Appendix A2) is still under editorial review at the JRC, with its publication expected soon.

Aware that the analysis of the most impactful wildfires for Europe requires an annual report, the FirEUrisk Consortium decided to continue with these studies. Thus, the wildfire events of 2023 with the greatest relevance to Europe are being analysed and reported with expectations to be published during the year 2024. In this report, in addition to the European wildfires with the most prominence, a specific chapter will be included to evaluate and learn from the support operations provided by European countries integrated into the European Union Civil Protection Mechanism (EUCPM) to Canada, during the massive and devastating wildfires that ravaged the country last summer. This report will be based on interviews conducted with the main stakeholders from each European countries involved – Portugal, Spain, and France –, the EU Civil Protection Mechanism, and the Canadian counterpart. The study will focus on three main perspectives: political, coordination, and command of the operations. Its main objective is to analyse the difficulties encountered in this process, the things that went well and those didn't go so well, both at the national and European levels, as well as the cooperation issues between countries for joint civil protection operations. It is hoped that this study will improve the efficiency of similar future interventions, sharing the experience gained with other European countries and beyond.

3 Protocols to collect data for future wildfire impact analysis

The advantages of analysing the wildfires studied during the project are self-evident and it's essential to continue this work. While there are various studies across Europe, they are reflected in reports that show some lack of

Copyright © FirEUrisk Consortium. All rights reserved.

harmonisation. To create a reference for conducting these studies and to facilitate access to available information, which is essential for wildfire reporting, a protocol has been developed that can provide support and facilitate harmonisation for conducting studies and reporting on major wildfires. Due to its size, this report is presented as an appendix to this document – Appendix B.

Naturally, this is not a rigid protocol but rather a report that provides flexibility to the researcher to apply their style to the study and report, adapting it to the study's objectives and the intended audience. At the same time, it allows for updates over the years, as the realities of wildfires, methodologies and doctrines used, and sources of information change over time.

Copyright © FirEUrisk Consortium. All rights reserved.

4 Conclusions

In this document, the results of the analysis conducted on 20 wildfires that occurred in 2021 and 2022 across 10 European countries are presented. Additionally, it highlights the developments in the wildfires of 2023, with special emphasis on the support operation provided by European countries, integrated into a joint force of the European Union, during the major wildfires that ravaged Canada that year.

The outcomes of the activity that led to this document, Activity A2.4.1 - Lessons learned from past cases, positioned itself in a central area of the work structure of the FirEURisk project. On one hand, in characterising the conditions in which the wildfires developed, various products developed in WP1 – Fire Risk Assessment were utilised, particularly concerning the use of fuel maps and WUI (Wildland-Urban Interface) risk, among other products developed within that work package. On the other hand, the lessons learned from the analysis of the selected wildfires enabled the framing of objectives and the development of guidelines for wildfire risk management, primarily used in WP2 – Fire Risk Reduction and WP3 – Fire Risk Adaptation.

Among the various conclusions drawn from the analysis of the selected wildfires, the following aspects stand out:

- Europe exhibits two levels of readiness to face wildfires: Southern countries, with a long history of wildfires, present a good level of preparation to confront the current reality of wildfires and are developing strategies to adapt to the exacerbated wildfire scenarios expected due to climate change and anticipated social changes. Northern countries, with a weak history in terms of wildfires, are still poorly equipped to deal with the increasing wildfire risk that is already a reality. Cooperation and knowledge-sharing between these two European regions are urgently needed.
- Although the Civil Protection Systems of Southern European countries perform well and have a high level of sophistication, this capacity does not have true alignment with other national and European policies – for example, the increase in the exposure of buildings in WUI areas is concerning and poses a growing challenge.
- Cross-border wildfires are naturally fought by entities from the different countries affected. Although there is intercommunication between entities of different nationalities, it is observed that the wildfires end up being fought independently, as if they were restricted to an individual event in each of the involved countries, instead of being treated as a single event in a cooperative effort between different entities from different countries.
- The activation of the civil protection mechanism for countries in need of reinforcement of resources works well and is of great interest. However, some countries/regions receiving these resources, due to their lack of experience in these processes, still have a significant potential for improvement and increasing their capacity for receiving assistance.
- Citizens are still inadequately aware or involved in the collective effort required in wildfire management. Several of the impacts recorded in the wildfires analysed could have been avoided if citizens were better prepared, evacuation plans were more well-defined and practiced, and fuel management in WUI areas, close to homes, communities and roads, was more carefully handled.

Considering the importance of these analyses of major wildfires, not only as a source of information and monitoring/evaluation of policies and strategies pursued but also as a historical record that should be part of the European project, a reference protocol for the analysis of major wildfires that will surely occur in the future has been developed. For this reason, we believe that an effort should be made to produce a report each year on the wildfires

Copyright © FirEURisk Consortium. All rights reserved.

with the greatest impact in Europe or in which European countries have intervened. It would be of interest to establish a group of experts distributed across various European countries who could provide these scientifically characterised studies, which would be aggregated into the more common operational reports.

Copyright © FirEUrisk Consortium. All rights reserved.

5 References

Almeida, M., Ribeiro, L.M., Alves, D., Viegas, D.X., Vaz Pinto, V., Marques, R., Gomes, A., Ballereau, D., Lahaye, S., Matile, R., M., Salis, M., Arca, B., Bacciu, V., Canu, A., Del Giudice, L., Duce, P., Pellizzaro, G., Stroppiana, D., Ventura, A., Cabiddu, S., Casula, A., Cuccu, G., Pinna, T., Vaccargiu, M., Campesi, S., Casule, F., Chessa, M., Cinus, S., Massidda, P., Peddes, M., Soi, F., Tola, F., Usai, A., Castiglia, C., Dessy, C., Delitala, A., Trudu, P.L., Angotzi, S., Murtas, F., Barone, A.V., Erriu, N., Fresu, G., Melis, G., Fiorucci, P., Pampanoni, V., Laneve, G., Eftychidis, G., Varela, V., Gkotsis, I., Petrou, K., Boustras, G., Senekkis, I., Kirschner, J., Pandey, P., San-Miguel-Ayanz, J., Durrant, T., Liberta`, G., Boca, R., Maianti, P., Branco, A., Jacome Felix Oom, D., De Rigo, D., Roglia, E., Scionti, N. and Suarez-Moreno, M., Analysis of 2021 critical wildfire events in the Mediterranean region, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/562495, JRC133972.

Other references of the document are provided directly in the three appendices, which constitute the central part of the content.

Copyright © FirEUrisk Consortium. All rights reserved.

Appendix A1: 2021 Fires Report

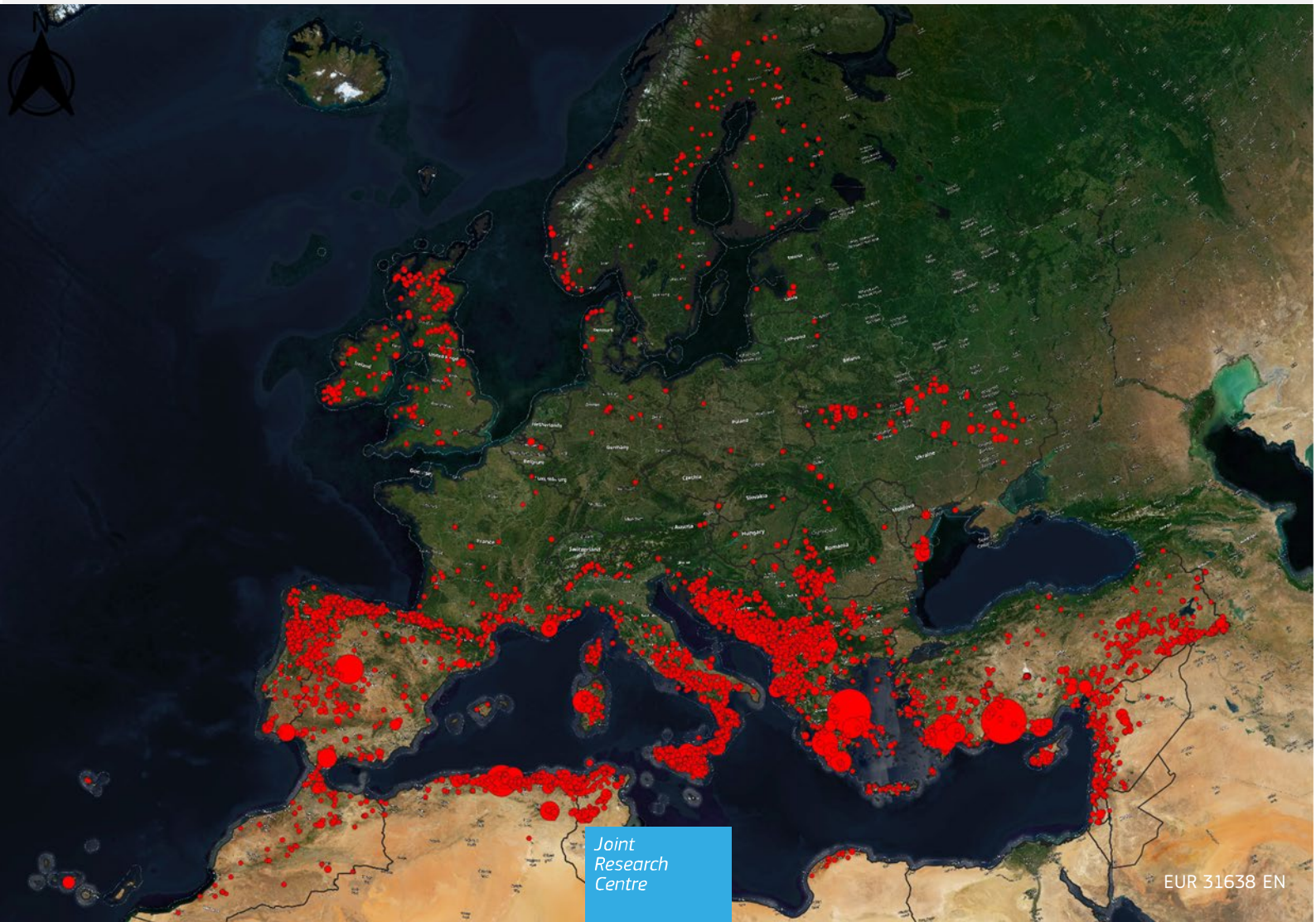
ISSN 1831-9424

European Commission

JRC TECHNICAL REPORT

Analysis of 2021 critical wildfire events in the Mediterranean region

2023



Joint Research Centre

EUR 31638 EN

This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 261, 21027 Ispra (VA), Italy
Email: JRC-EFFIS@ec.europa.eu
Tel.: +39 0332 78 6138

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC133972

EUR 31638 EN

PDF ISBN 978-92-68-06759-8 ISSN 1831-9424 doi:10.2760/562495 KJ-NA-31-638-EN-N

Luxembourg: Publications Office of the European Union, 2023

© European Union, 2023



The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union permission must be sought directly from the copyright holders. Unless otherwise stated, all images in the chapters of individual case studies are owned by the authors of the chapters.

How to cite this report: Almeida, M., Ribeiro, L.M., Alves, D., Viegas, D.X., Vaz Pinto, V., Marques, R., Gomes, A., Ballereau, D., Lahaye, S., Romain, M., Salis, M., Arca, B., Bacciu, V., Canu, A., Del Giudice, L., Duce, P., Pellizzaro, G., Stroppiana, D., Ventura, A., Cabiddu, S., Casula, A., Cuccu, G., Pinna, T., Vaccargiu, M., Campesi, S., Casule, F., Chessa, M., Cinus, S., Massidda, P., Peddes, M., Soi, F., Tola, F., Usai, A., Castiglia, C., Dessy, C., Delitala, A., Trudu, P.L., Angotzi, S., Murtas, F., Barone, A.V., Erriu, N., Fresu, G., Melis, G., Fiorucci, P., Pampanoni, V., Laneve, G., Eftychidis, G., Varela, V., Gkotsis, I., Petrou, K., Boustras, G., Senekkis, I., Kirschner, J., Pandey, P., San-Miguel-Ayanz, J., Durrant, T., Liberta`, G., Boca, R., Maianti, P., Branco, A., Jacome Felix Oom, D., De Rigo, D., Roglia, E., Scionti, N. and Suarez-Moreno, M., *Analysis of 2021 critical wildfire events in the Mediterranean region*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/562495, JRC133972.

Cover image: EFFIS – Distribution of burnt areas mapped in 2021

Authors – Case studies

Fire of Castro Marim (Portugal)	
Miguel Almeida, Luís Mário Ribeiro, Daniela Alves, Domingos Viegas	Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI)
Vítor Vaz Pinto, Richard Marques, Abel Gomes	Autoridade Nacional de Emergência e Proteção Civil (ANEPC)
Fire of Gonforon (France)	
Damien Ballereau, Sébastien Lahaye	SAFE
Romain Matile	Warucene
Fire of Montiferru (Italy)	
Michele Salis, Bachisio Arca, Valentina Bacciu, Annalisa Canu, Liliana Del Giudice, Pierpaolo Duce, Grazia Pellizzaro, Daniela Stroppiana, Andrea Ventura	Consiglio Nazionale delle Ricerche (CNR)
Salvatore Cabiddu, Antonio Casula, Gabriella Cuccu, Tiziana Pinna, Massimo Vaccargiu	Sardinia Forest Service
Stefano Campesi, Fabio Casule, Michele Chessa, Salvatore Cinus, Pietro Massidda, Michele Peddes, Fabrizia Soi, Francesco Tola, Antonio Usai	Sardinia Civil Protection
Carluccio Castiglia, Carlo Dessy, Alessandro Delitala, Pier Luigi Trudu	Sardinia Envir. Prot. Agency
Salvatore Angotzi, Filippo Murtas	Sardinia Forest Agency
Andrea Vittorio Barone, Natascia Erriu, Giovanni Fresu, Giuseppe Melis	Vigili del Fuoco
Paolo Fiorucci	CIMA Foundation
Valerio Pampanoni, Giovanni Laneve	University of Rome
Fires of Attica and Evia (Greece)	
George Eftychidis, Vassiliki Varela	Kentro Meleton Asfaleias (KEMEA)
Ilias Gkotsis	SATWAYS
Fire of Arakapas (Cyprus)	
Klelia Petrou, George Boustras, Iasonas Senekkis, Judith Kirschner, Pooja Pandey	European University Cyprus (EUC)

Authors – European report

JOINT RESEARCH CENTRE

Directorate E: Space, Security & Migration

Disaster Risk Management

EFFIS TEAM

Jesús San-Miguel-Ayanz[1]
Tracy Durrant[2]
Roberto Boca[3]
Pieralberto Maianti[3]
Giorgio Libertà[1]
Duarte Oom[1]
Alfredo Branco[1]
Daniele de Rigo[3]
Davide Ferrari[2]
Elena Roglia[3]
Nicola Scionti[3]
Maria Suarez-Moreno[3]

1 European Commission, Joint Research Centre (JRC),
Directorate for Space, Security and Migration, Disaster Risk Management Unit,
Ispra (VA), Italy

2 External consultant for the European Commission
(Engineering Ingegneria Informatica S.p.A.) Piazzale dell'Agricoltura (RM), Italy

3 External consultant for the European Commission
(ARCADIA SIT s.r.l) Vigevano (PV), Italy

Contents

Abstract 1
Foreword 2
1 Introduction 3
2 The Fire Event of Castro Marim (Portugal) 11
2.1 General description 11
2.2 Characterization of the affected area 12
2.3 Fire conditions 14
2.3.1 Fuel moisture content of dead fine fuels 15
2.3.2 Fire danger 16
2.4 Fire development and operational response 17
2.5 Fire impacts 18
2.5.1 Damage to buildings 19
2.5.1.1 Cortelha 19
2.5.1.2 Faz Fato 1 and Faz Fato 2 21
2.5.1.3 Faz Fato 3 and Faz Fato 4 23
2.5.1.4 Corte António Martins 24
2.5.2 Fire risk management in animal facilities 25
2.5.2.1 Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António 25
2.5.2.2 Private kennel next to the A22 26
2.6 Conclusions and lessons learned 27
3 The Fire Event of Gonfaron (France) 28
3.1 General description 28
3.2 Characterization of the affected area 29
3.2.1 Fire History 29
3.2.2 Environmental and Socio-economic issues 30
3.2.3 Topography, fuel cover, and WUI characterization 30
3.3 Fire conditions 31
3.3.1 Meteorology 31
3.3.2 Fire risk & alert 32
3.3.3 Allocated resources 32
3.4 Fire behavior 33
3.5 Fire impacts 36
3.5.1 Fatalities & loss of property 36
3.5.2 Post-fire impactsnimals 37
3.6 Conclusions and lessons learned 37
4 The Wildfire Event of Montiferru (Sardinia, Italy) 38
4.1 General description 38
4.2 Vegetation and topography of the affected area 40
4.3 Fire weather conditions 41
4.4 Fire development and operational response 48
4.5 Smoke emissions and dispersion 52
4.6 Fire impacts 53
4.7 Conclusions and lessons learned 58
5 The Varybobi Fire Event, Attica (Greece) 59
5.1 General description 59
5.2 Characterization of the affected area 59
5.2.1 Fuel conditions 62
5.2.2 Fire ignition 62

5.3 Fire conditions 63
5.3.1 Meteorological conditions 63
5.3.2 Fire Risk 63
5.4 Fire behavior 65
5.5 Fire impacts 67
5.5.1 Air pollution 70
5.5.2 Fatalities 71
5.6 Conclusions and lessons learned 71
6 The Limni Fire Event, North Evia (Greece) 72
6.1 General description 72
6.2 Characterization of the affected area 73
6.2.1 Vegetation characteristics 74
6.2.2 Fire ignition 75
6.3 Fire conditions 75
6.3.1 Meteorological conditions 75
6.3.2 Fire Risk 78
6.4 Fire behavior 79
6.4.1 Resources operating on site 81
6.5 Fire impacts 82
6.5.1 Damage to properties 83
6.5.2 Impact on the atmosphere 86
6.5.3 Fatalities 88
6.6 Conclusions and lessons learned 88
7 The Fire Event of Arakapas (Cyprus) 90
7.1 General Description 90
7.2 Characterization of the affected area 90
7.3 Fire conditions 93
7.4 Fire behavior 94
7.5 Fire impacts 95
7.6 Conclusions and lessons learned 97
8 References 99
9 List of Figures 101
10 List of Tables 106
11 List of Acronyms 107

Abstract

This report presents an overview of the 2021 wildfire season in the Mediterranean region on the basis of the data that are available in the European Forest Fire Information System (EFFIS[1]), which is complemented with a specific analysis of some of the most damaging fires during this campaign, performed by the FirEURisk[2] project. For the analysis of these fires, information on the pre-fire conditions is provided to determine wildfire danger at the time of ignition. Furthermore, evolution and damage of each of the fires is described with as much detail as possible, looking into the possibility of learning from the experience gathered from these fires for the management of future critical wildfire events. It is foreseen that this report is repeated for the forthcoming fire seasons as a collaboration between the FirEURisk project and the EFFIS team at the Joint Research Centre.

[1] https://effis.jrc.ec.europa.eu/
[2] https://fireurisk.eu/

Foreword

This report emerges from the collaboration of the Joint Research Centre (JRC) and its collaboration with the EU funded project FirEURisk. The aim of both the European Forest Fire Information System (EFFIS), developed and managed by the JRC, and the FirEURisk project, is to provide information to support science and policy making in the European Union to prevent and minimize the devastating effects of wildfires in the pan-European region. Since the year 2000, EFFIS has supported EU policy making and has been, since 2015, part of the European Union Copernicus Emergency Management Services fulfilling this role. For its part, the FirEURisk project, funded by the EU, aims to assess wildfire risk and propose better ways to reduce it, in order to prepare Europe to face new challenges in wildfire management in future scenarios. To learn from past situations, the FirEURisk Project planned to "*Analyze feedback from five or more past large and high impact fires, both in Europe and in partner countries of North America and Australia, with special focus on fire development in the WUI and impacts on the communities.*" This review, which considers aspects of land planning, community awareness, alert systems, social perception, and structural damage, is presented in this report.

During the summer of 2021, an important number of very high impact fires occurred in Europe. This report provides an overview of the 2021 wildfire season in Europe on the basis data in EFFIS and analyzes some of the major fires that occurred in this season in the context of the FirEURisk project.

In a Webinar held on December 2nd, 2021, available at https://youtu.be/fcLqxESfAxg, preliminary results of the analysis of critical fires in Europe during 2021 were presented, including an overall perspective of the fires of 2021 in the World and Europe.

1 Introduction

Year after year, catastrophic fires have become more recurrent. Southern European countries, the United States and Australia are some of the countries where major tragedies have been registered, with forest fires destroying buildings, devastating communities, and, frequently, causing fatalities. If fire spreading in wildlands causes such great apprehension in society, when the fire reaches the Wildland Urban Interface (WUI), the general concern increases even more since it is in these situations that the most valuable assets and the lives of people and domestic animals are most at risk.

In Europe, 2021 was another year of large fires with huge impacts. The most serious period was between August 1st and 18th, with several catastrophic fires following a heatwave in southern Europe. The first part of this report presents an overview of wildfires in the area covered by the European Forest Fire Information System (EFFIS), which now comprises 43 countries in Europe, the Middle East and North Africa. It is followed by a detailed analysis of some of the major fires occurring this year in a number of Mediterranean countries.

Assessment of wildfires in the European Forest Fire Information System (EFFIS)[3]

The Rapid Damage Assessment module of EFFIS was set up to provide reliable and harmonized estimates of the areas affected by forest fires during the fire season. The methodology and the spatial resolution of the satellite sensor data used for this purpose, from the MODIS sensor, at 250 metre spatial resolution, allowed fires of about 30 ha or larger to be mapped. This methodology was enhanced in 2018 through the use of Sentinel 2 imagery, at 20 metre spatial resolution, which allowed the mapping of fires of about 5 ha or larger. In order to obtain the statistics of the burnt area by land cover type, the data from the European CORINE Land Cover database were used. Therefore, the mapped burnt areas were overlaid with the CLC data, making it possible to derive damage assessment results comparable for all the EU countries.

EFFIS Rapid Damage Assessment is based on the analysis of MODIS satellite imagery. The MODIS instrument is on board both the TERRA (morning pass) and AQUA (afternoon pass) satellites. MODIS data has 2 bands with spatial resolution of 250 metres (red and near-infrared bands) and 5 bands with spatial resolution of 500 metres (blue, green, and three short-wave infrared bands). Mapping of burnt areas is based mainly on the 250 metre bands, although the MODIS bands at 500 metres resolution are also used, as they provide complementary information that is used for improved burnt area discrimination. This type of satellite imagery allows detailed mapping of fires of around 30 ha or larger. Although only a fraction of the total number of fires is mapped (fires smaller than 30 ha are not mapped), the analysis of historical fire data has determined that the area burned by wildfires of this size represents in most cases the large majority of the total area burned. On average, the area burned by fires of at least 30 ha accounts for about 85% of the total area burnt every year in the Southern EU. As mentioned above, since 2018, through the use of Sentinel 2 imagery nearly about 95% of the total burnt area is mapped in EFFIS. The results for each of the countries affected by forest fires are given in the following paragraphs in alphabetical order, followed by a section on the MENA countries.

The total area burned in 2021, as shown by the analysis of satellite imagery, is shown in Table 1. These figures may also include agricultural and urban areas that were burned during the forest fires. Figure 1 below shows the scars caused by forest fires during the 2021 season.

In 2021, fires were mapped in 43 countries and a total burnt area of 1 113 464 ha was mapped, a similar total to that mapped in 2020. In total, 500566 were burnt in the EU, 417807 ha in other European countries and 195091 in Middle East and North Africa. Out of those, 102598 ha were burnt in Natura2000 and other protected sites.

Table 1. Areas mapped in 2021 estimated from satellite imagery.

Country	*Area (Ha)*	*Number of Fires*	*Country*	*Area (Ha)*	*Number of Fires*
Austria	82	2	Albania	31275	329
Belgium	659	2	Bosnia & Herzegovina	63284	294
Bulgaria	4261	80	Kosovo under UNSCR 1244	7580	92
Croatia	10074	113	Montenegro	43469	198
Cyprus	6339	24	North Macedonia	21511	136
Denmark	369	19	Norway	991	22
Finland	2793	42	Serbia	7708	139
France	34986	587	Switzerland	12	2
Germany	285	27	Turkey	206013	612
Greece	131254	222	Ukraine	27866	128
Hungary	573	8	United Kingdom	8098	234
Ireland	3609	50	**Non-EU total**	**417807**	**2186**
Italy	159537	1422	Algeria	134273	295
Latvia	312	6	Iraq	25	1
Lithuania	65	5	Israel	4021	32
Poland	51	12	Jordan	2	1
Portugal	31582	749	Lebanon	2360	50
Romania	20957	121	Libya	377	11
Slovakia	115	1	Morocco	6083	81
Slovenia	81	2	Palestinian Territory	143	2
Spain	91295	901	Syria	18798	118
Sweden	1287	48	Tunisia	29009	98
EU27 total	**500566**	**4443**	**MENA total**	**195091**	**689**

Total burnt area 1113464 ha	**Total number of fires 7318**

[3] Information in this section is taken from "Forest Fires in Europe, Middle East and North Africa 2021" (https://effis.jrc.ec.europa.eu/reports-and-publications/annual-fire-reports)

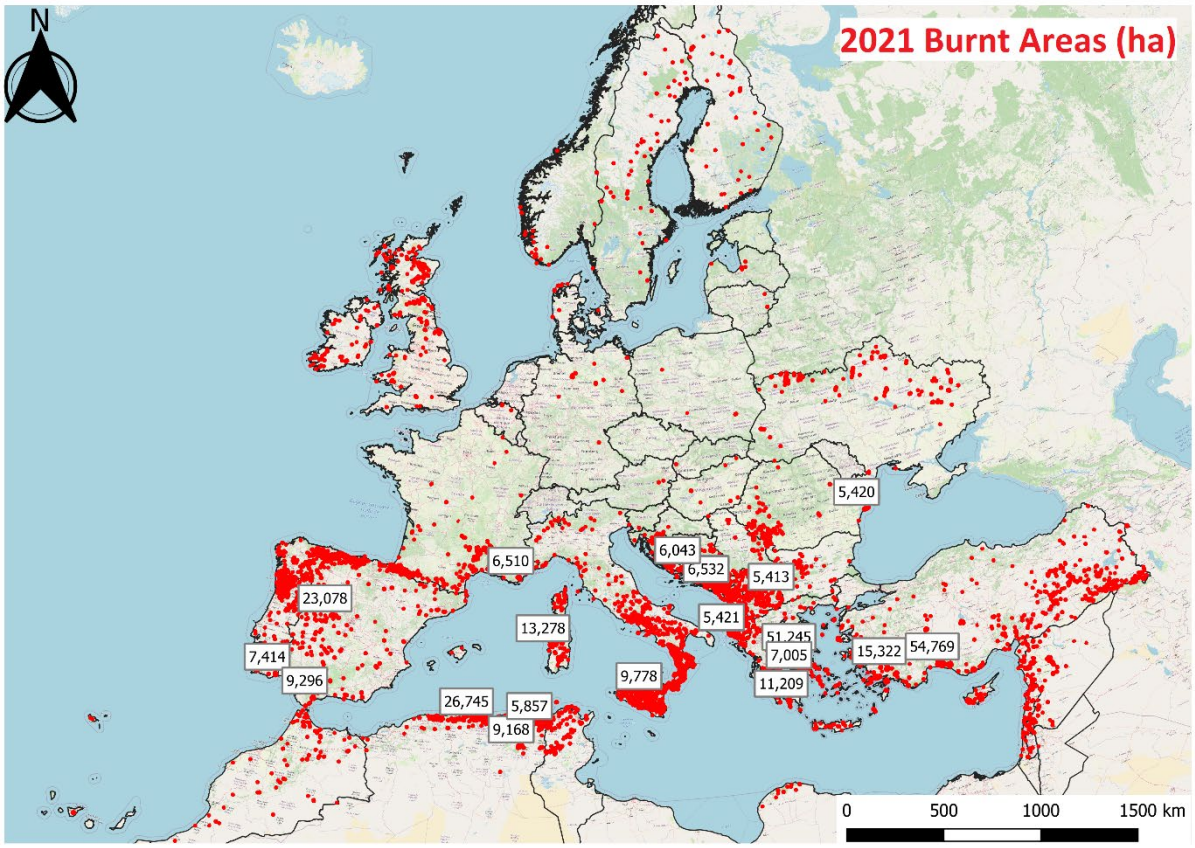


Figure 1. Burnt areas mapped during the 2021 fire season. Largest fires are indicated in ha.

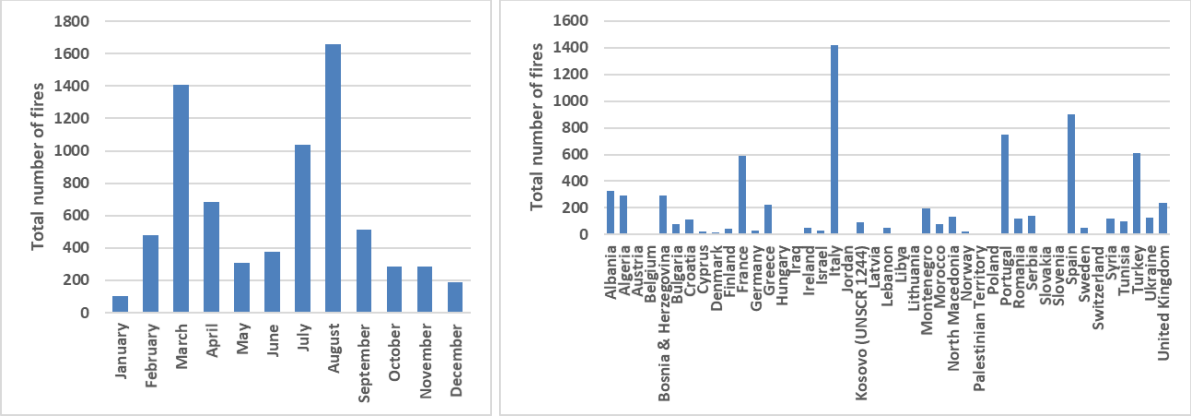


Figure 2. Total number of fires mapped by month and country in 2021.

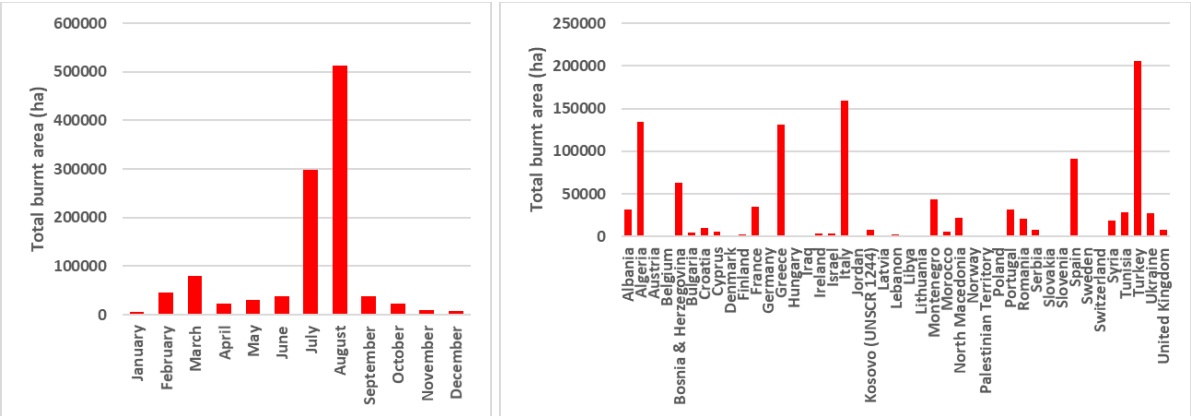


Figure 3. Total burnt area of fires mapped by month and country in 2021.

Damage to Natura2000 and other protected sites

Of particular interest is the analysis of the damage caused by fires to the areas protected within the Natura2000 network, as they include habitats of especial interest which are home for endangered plant and animal species.

The category of Natura2000 areas only exists in the countries of the European Union. Information on other protected areas outside the EU is presented for those countries for which the information is available. The area burnt within the Natura2000 and other protected sites is presented below.

Country	*Area (Ha)*	*% of Natura2000 Area*	*Number of Fires*
Austria	72.0	0.005846	1
Belgium	643.1	0.167338	2
Bulgaria	1937.1	0.051546	20
Cyprus	196.3	0.120738	3
Denmark	230.0	0.059806	4
France	9277.2	0.135198	164
Germany	118.8	0.002167	3
Greece	10453.5	0.292012	35
Finland	1605.1	0.03295	5
Hungary	563.9	0.028311	5
Ireland	2209.4	0.242724	9
Italy	25222.6	0.437154	206
Latvia	218.9	0.029986	2
Poland	40.0	0.000658	1
Portugal	7902.0	0.41354	91
Romania	15289.3	0.359062	36
Slovenia	76.0	0.01065	1
Spain	21668.0	0.157953	142
Sweden	447.2	0.007855	2
EU27 total	**98170.4**		**732**
Albania	6.9	0.70516444	1
Algeria	2737.7	1.64471275	15
Morocco	544.0	0.07587772	3
United Kingdom	1139.1	0.06466358	15
Non-EU total	**4427.7**		**34**
TOTAL	**102598.1**		**766**

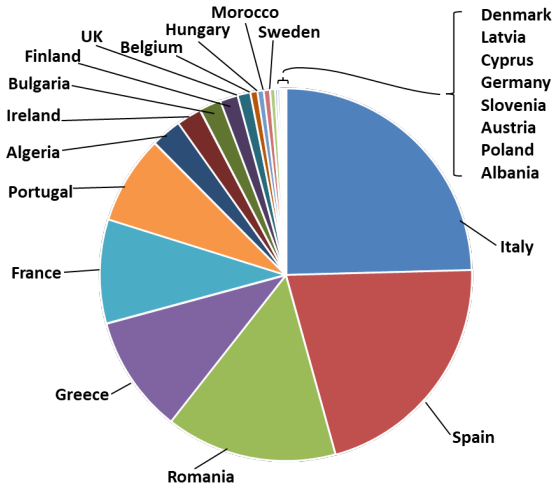


Figure 4. relative proportions of burnt area mapped in protected areas in 2021, ordered by size.

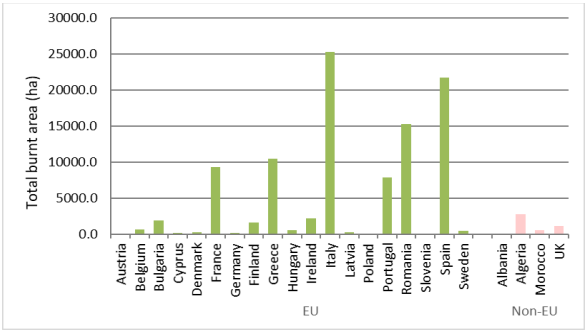


Figure 5. Burnt area in Natura2000 sites and other protected areas in 2021.

Fires were mapped in 18 of the 27 EU member states and four non-EU countries that have information on protected areas. The total burnt area in protected areas in 2021 was 102 598 ha, less than in the last two years and slightly below the average of the previous 10 years. The most affected country in 2021 was Italy, followed closely by Spain. These two countries accounted for 45% of the total burnt in protected areas.

Affected land cover types

In 2021, the vegetation types were classified into more detailed categories than used in previous years, as follows:

Category	Description
Broadleaved forest	Vegetation formation composed principally of trees, including shrub and bush understoreys, where broad-leaved species predominate.
Coniferous forest	Vegetation formation composed principally of trees, including shrub and bush understoreys, where coniferous species predominate.
Mixed forest	Vegetation formation composed principally of trees, including shrub and bush understoreys, where neither broad-leaved nor coniferous species predominate.
Other Natural	Other natural land not included in the other categories
Sclerophyllous	Bushy sclerophyllous vegetation, includes maquis and garrigue.
Transitional	Bushy or herbaceous vegetation with scattered trees. Can represent either woodland degradation or forest regeneration/recolonization.
Agriculture	Cultivated crops
Artificial	Includes urban and industrial areas, mine, dump and construction areas.
Other	Other land types not included in the above categories

A detailed description of all the land cover types used can be found in:

Bossard, M., Feranec, J., Otahel, J., Steenmans, C., 2000. **CORINE land cover technical guide - Addendum 2000**. Report No. 40. *European Environment Agency*. https://www.eea.europa.eu/ds_resolveuid/032TFUPGVR

In 2021, around a quarter of the total burnt area was in the Agriculture land type. Forest (comprising Broadleaved Forest, Coniferous forest and Mixed Forest) together accounted for 28%, and other natural land types (Sclerophyllous, Transitional and Other Natural Land) accounted for most of the remainder (nearly one half) of the total.

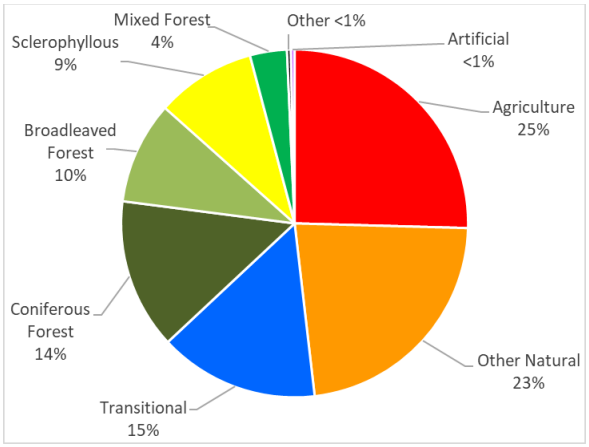


Figure 6. Proportions of land cover types affected in 2021 (all countries, ordered by total burnt area).

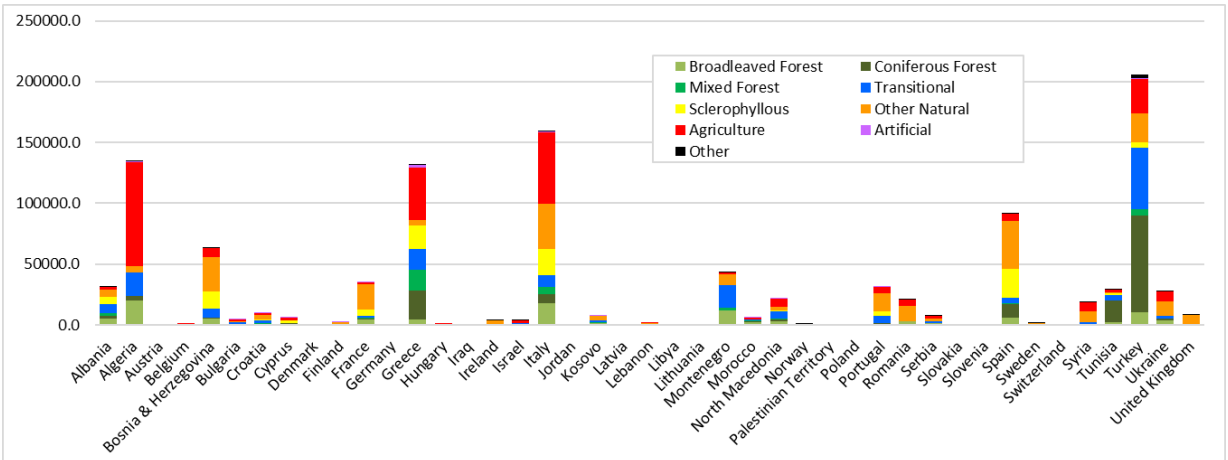


Figure 7. Burnt area in each country in 2021 by CORINE land class.

European countries (EU27)

In 2021, fires were mapped in 22 of the EU27 countries in 2021: (Austria, Belgium, Bulgaria, Croatia, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden), burning 500 566 ha in total. This is above the amount recorded in 2020. August was the month when a significant proportion of the damage occurred, particularly in Greece.

Of this total, 102 598 ha occurred on Natura2000 sites. This amounts to 20% of the total, a smaller proportion than in 2020.

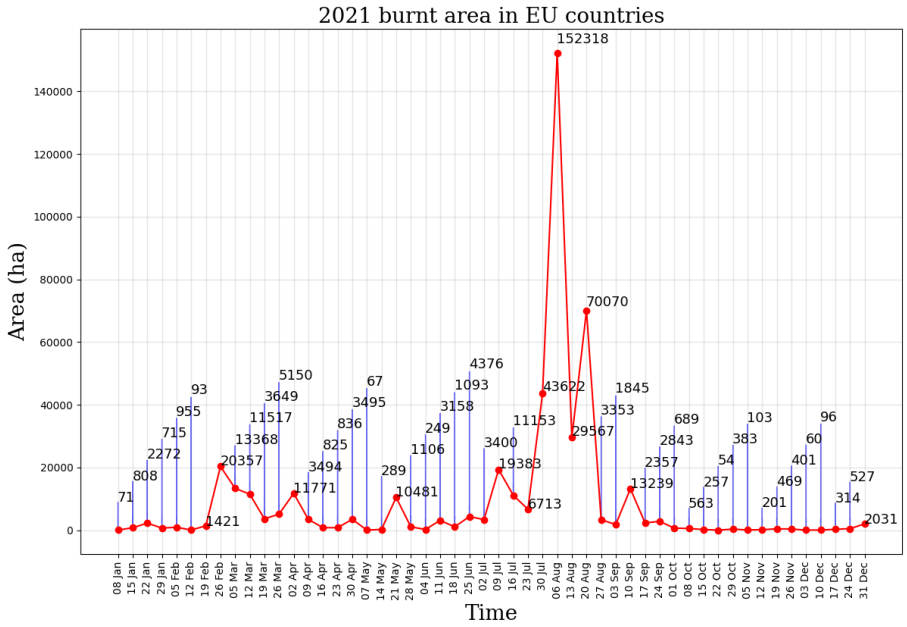


Figure 8. Burnt area weekly evolution in 2021 (European Union countries).

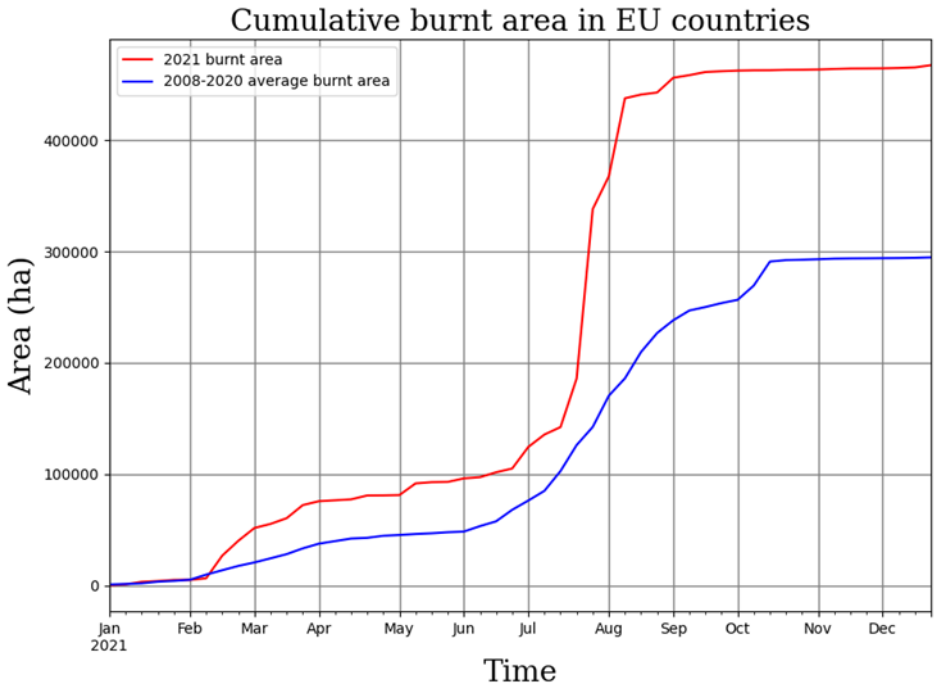


Figure 9. Cumulative burnt area in 2021 (European Union countries).

Largest fires mapped by EFFIS in the 2021 fire season

The following table presents the fires over 5000 ha that were mapped by EFFIS in 2021, in order of size. All but three of them occurred in July or August. Those that are included as case studies in later sections are indicated.

Table 2. Largest fires mapped by EFFIS in 2021.

Country	Initial date	Final date	Total mapped burnt area (ha)	
Turkey	28/07/2021	07/08/2021	54769	
Greece	03/08/2021	11/08/2021	51881	Limni fire, page 72
Algeria	09/08/2021	15/08/2021	26745	
Spain	14/08/2021	20/08/2021	23078	
Greece	04/08/2021	12/08/2021	18400	
Turkey	31/07/2021	08/08/2021	16157	
Turkey	29/07/2021	10/08/2021	15860	
Turkey	02/08/2021	08/08/2021	15322	
Italy	24/07/2021	29/07/2021	13278	Montiferru fire, page 38
Turkey	29/07/2021	05/08/2021	11548	
Greece	03/08/2021	11/08/2021	11209	
Turkey	29/07/2021	12/08/2021	10366	
Greece	16/08/2021	23/08/2021	10175	
Algeria	10/08/2021	16/08/2021	9887	
Italy	04/08/2021	11/08/2021	9778	
Spain	08/09/2021	12/09/2021	9296	
Algeria	04/07/2021	10/07/2021	9168	
Bosnia and Herzegovina	05/08/2021	16/08/2021	8909	
Greece	03/08/2021	07/08/2021	8454	Varybobi fire, page 59
Turkey	28/07/2021	01/08/2021	7795	
Portugal	16/08/2021	17/08/2021	7414	Castro Marim fire, page 11
Algeria	09/08/2021	14/08/2021	7342	
Italy	04/08/2021	20/08/2021	7096	
Greece	19/05/2021	23/05/2021	7005	
Montenegro	08/08/2021	23/08/2021	6532	
France	16/08/2021	19/08/2021	6510	Gonfaron fire, page 28
Algeria	11/08/2021	16/08/2021	6324	
Algeria	09/08/2021	14/08/2021	6262	
Bosnia and Herzegovina	07/08/2021	11/08/2021	6043	
Algeria	11/08/2021	14/08/2021	5857	
Albania	30/07/2021	11/08/2021	5421	
Romania	08/03/2021	09/03/2021	5420	
Macedonia	02/08/2021	10/08/2021	5413	

This study reports some of the large fires that occurred during that year. As shown in Table 1, there were other fire events of great relevance, but due to a natural limitation of the scope of this report, only eight selected fire events are described – all of them in the European Mediterranean basin (Figure 10). The selection of these events was based on the occurrence of fatalities, the registration of large impacts, or the extension of the burnt area. Naturally, the availability of information was also a determining factor in the choice of the fires to be described.

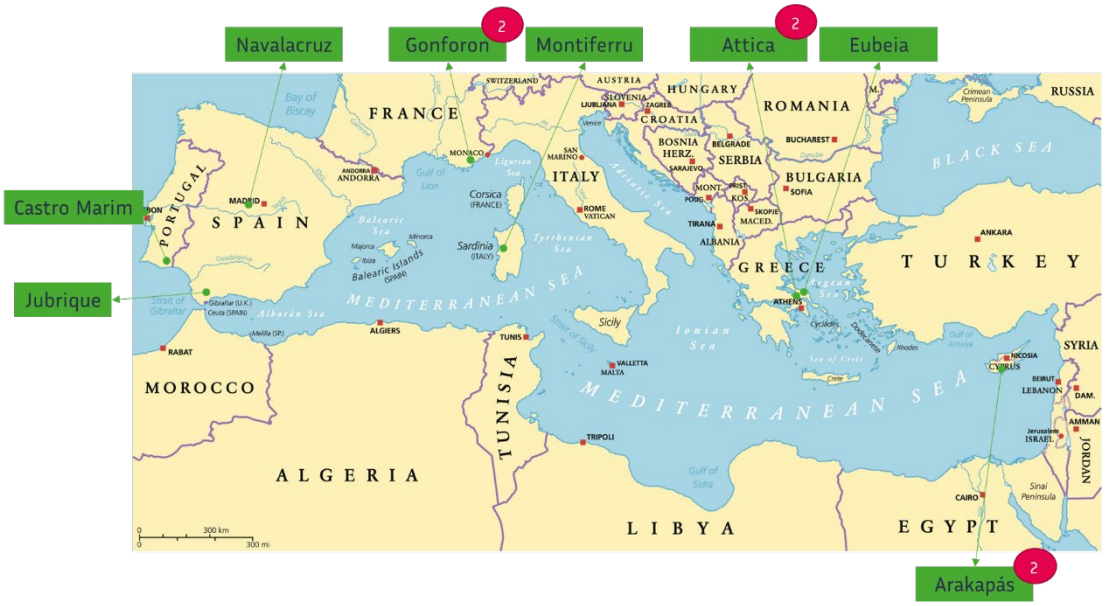


Figure 10: Fire events addressed in the study. The circles in red indicate the number of direct fatalities recorded in the respective event. (Background image adapted from REMPEC / Copernicus)

In the perspective that a present without a past has no future, the main objective of the present study is to extract lessons from the analysis of past fire events. It is not the intention of this study to point out failures or to attribute responsibilities regarding the occurrences of the impacts registered. Rather, it is intended to explain the development of the fires analyzed and, according to the reflection made by the authors, point out ways to reduce the possibility of such events, episodes, or impacts happening again. The main focus of this study is the impacts on the wildland-urban interface considering aspects such as land planning, community awareness, alert systems, social perception, and structural damages.

In this report, following this first introductory note, a brief analysis will be made of the major fires that occurred in the World during 2021, paying special attention to the general situation that was experienced in Europe. Then, a description of each of the selected fire events, (Figure 10) – the sequence of presentation followed was from west to east so starting with the Fire of Castro Marim (Portugal) and ending with the description of the Arakapás Fire (Cyprus). In general, each chapter of each fire event presents a factual description of the region, the affected populations, the history in terms of fires, the fire developments, and the conditions associated, as well as the explanation of some of the episodes that deserved more emphasis. At the end of each description, a reflection is made on the lessons that can be drawn from the episode described.

NOTE: To simplify the text exposition, all dates refer to the year 2021, except when another year is explicitly mentioned. The times mentioned are local times in the countries concerned – Portugal: UTC+01h; Spain, France, Italy: UTC+01h; Greece and Cyprus: UTC+03h.

FIRE OF CASTRO MARIM

Authors

Miguel Almeida	ADAI
Luís Mário Ribeiro	ADAI
Daniela Alves	ADAI
Domingos Viegas	ADAI
Vitor Vaz Pinto	ANEPC
Richard Marques	ANEPC
Abel Gomes	ANEPC



2 The Fire Event of Castro Marim (Portugal)

2.1 General description

This event started in the locality of Pernadeira, in the municipality of Castro Marim, District of Faro, in the Eastern region of Algarve, in southern Portugal. The ignition occurred in the early hours of August 16th and the alert was given at 1.05 a.m. of that same day. With a burnt area of 6 648ha, this was the largest fire recorded in Portugal in the year 2021. Fortunately, there were no human victims to mourn, but among the impacts are several damaged buildings, besides several animals that were caught by the flames. It should also be noted that the Algarve is a summer seaside touristic area, so the fire caused great concern among tourists.

The Castro Marim wildfire raged for seven days, spreading by seven parishes of three municipalities (Figure 11a), namely Castro Marim (2 121ha), Tavira (2 671ha), and Vila Real de Santo António (1 168ha). However, about 95% of the burnt area was reached during the first 30 hours of the fire, i.e., until around 7 a.m. on August 17th. Thus, the description of this report focuses mainly on this period. As can be seen in Figure 11b, the area of the fire is predominantly high/very high danger, which indicates the difficulty of fire management that was felt.

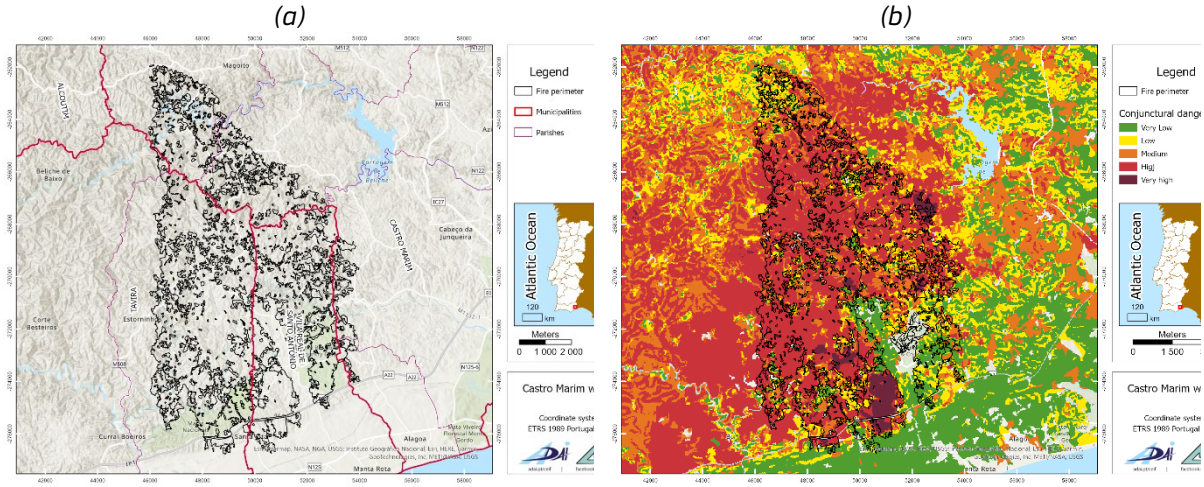


Figure 11 – a) Geographical setting of the Castro Marim Fire; b) Conjunctural danger for 2021 (Source: ICNF [1]).

In October 2021, a team from the Association for the Development of Industrial Aerodynamics (ADAI) visited the area affected by the fire to collect data necessary for the completion of this description. The locations mentioned hereby were visited and first-hand testimonies were collected, both from popular and civil protection agents who were directly involved in this event.

2.2 Characterization of the affected area

The Algarve region knows two different realities. The area to the south and west, in the Atlantic Ocean coast, is mainly exploited by the tourism sector, with high standards of living and a high population density. In most inland regions, the population density decreases exponentially and land use is mainly represented by agricultural land, bushland and forest. This regional heterogeneity extends to the three municipalities where the characteristics of the coastal area are clearly distinguished from the inland areas.

The resident population in the region is very heterogeneous. On the one hand, there is a large number of people who come from foreign countries and who decided to live in the Algarve. This is a fraction of the population with higher education and financial capacity than the local average, but who are not normally used to dealing with wildfires and rarely speak Portuguese. On the other hand, we have the native population that, especially in the northernmost regions (inland) is aged and with a low level of education. We present some socio-economic indicators of the four parishes most affected by the fire.

Table 3: Some socio-economic indicators of the parishes most affected by the Castro Marim fire.

Municipality	Residents (Var. 10yrs)*	Residents/km²*	Age > 65yrs⁺	University education⁺
Odeleite	574 0(-24.8%)	4.0	54%	1%
Azinhal	479 (-8.2%)	7.0	42%	4%
Conceição	3 431 (+36.2%)	49.4	25%	11%
VN de Cacela	3 872 (-0.8%)	87.1	23%	11%
ALGARVE	467 495 (+3.7%)	94.3	19%	13%
PORTUGAL	10 347 892 (-0.2%)	112.4	19%	15%

⁺*Census 2011 [2](INE); *Census 2021 [3](INE)*

The area affected by the fire is almost entirely inland. According to the land use map produced by the National Directorate for the Territory [4] the burnt area is distributed by forest (31%), bush (53%), agricultural land (13%), and other types of occupation (3%). The dominant species are Stone pine (*Pinus pinea*), Gum Rock Rose (*Cistus ladanifer*), Carob Tree (*Ceratonia síiqua*). The cistus is a species with great flammability during the summer months [5] and which contributed decisively to the rapid and intense spread of fire. The existing agricultural lands are composed of family farms and intensive agriculture, with emphasis on fig, avocado, carob, and olive trees. These last plantations were those where the greatest losses were registered. In Figure 12, we present the fuel map of the burnt area and a photo that allows us to have an idea of the type of vegetation in that area.

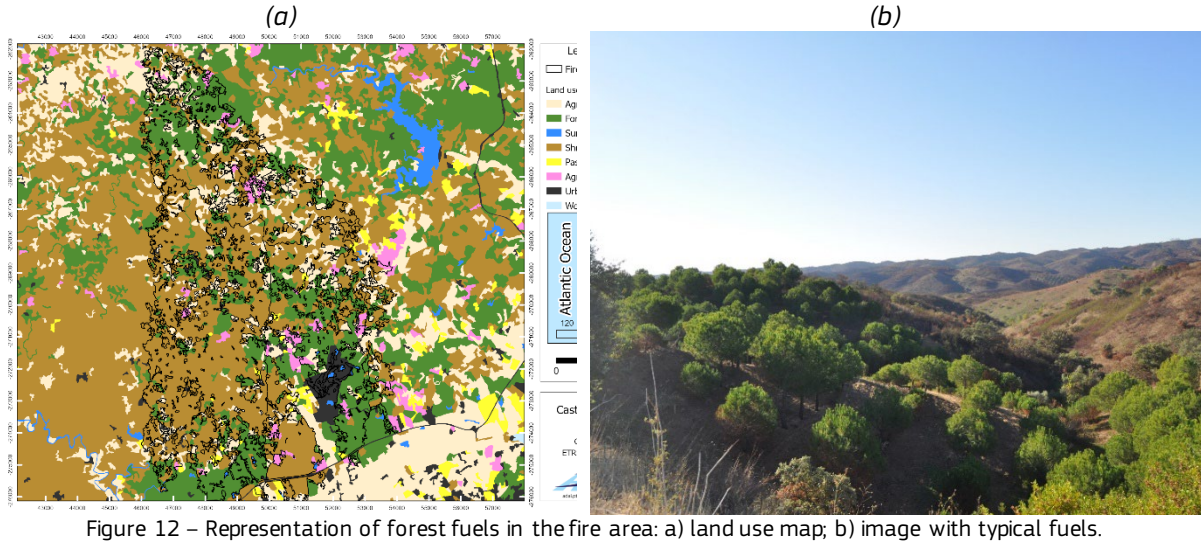


Figure 12 – Representation of forest fuels in the fire area: a) land use map; b) image with typical fuels.

The orography of the region was also decisive for the fire behavior. Although there are no large mountains or deep valleys, the area where the fire developed is characterized by having many small hills that are distributed continuously throughout the territory (Figure 13 and Figure 12b, above). Thus, the final perimeter of the fire is very fragmented, with a tapering pattern from North to South, which is characteristic of a wind-driven fire.

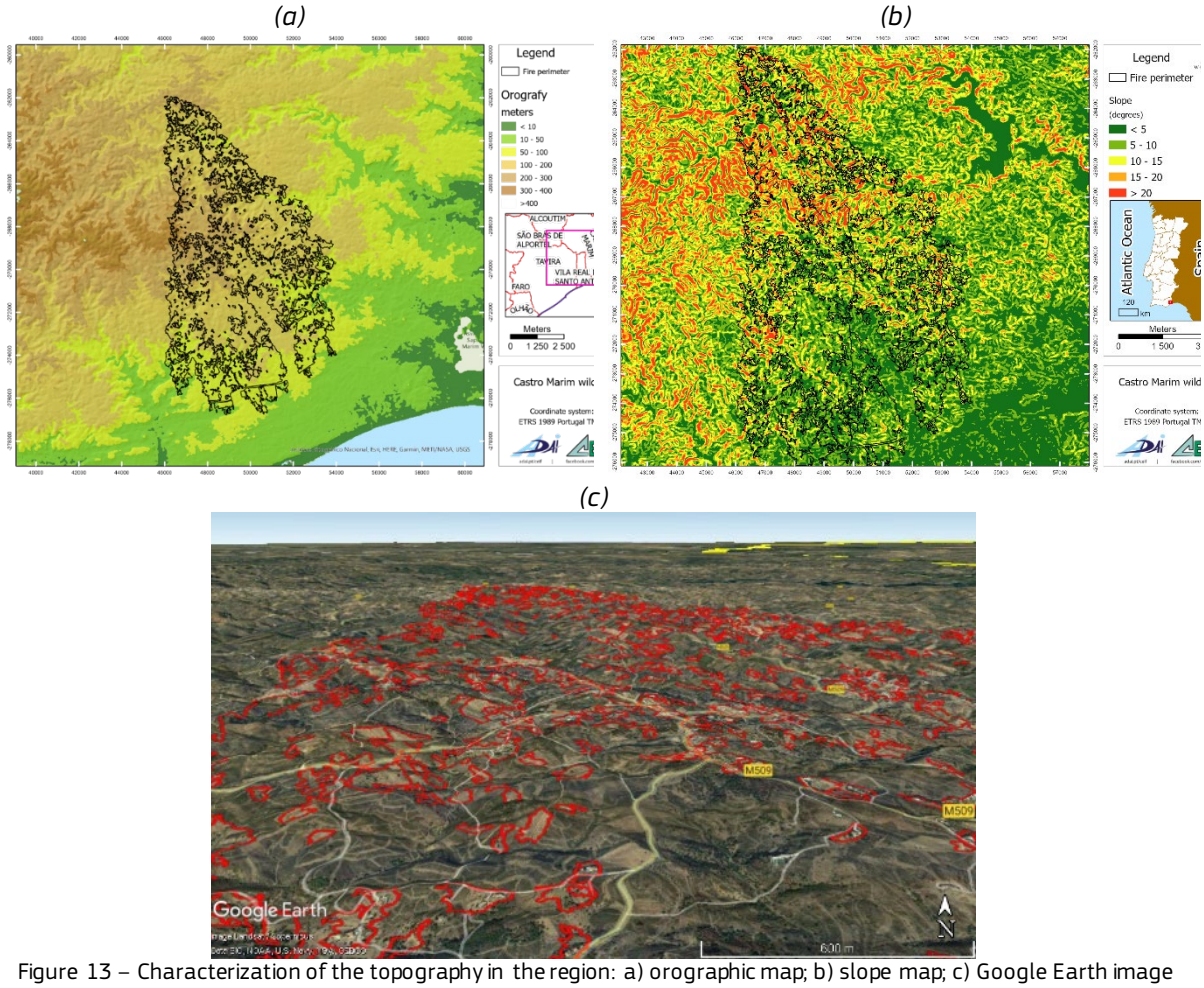


Figure 13 – Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern.

As mentioned before, this territory has a low population density. In addition, the existing communities do not typically present themselves as clusters of buildings demarcating a clear boundary of the wildland-urban interface, but rather as scattered constructions in the landscape. This dispersion of buildings greatly complicated the fire management operations, which naturally did not have sufficient resources to respond to all the isolated requests for help that were made. Moreover, many of the existing buildings in this region belong to foreigners who were not always present on the day of the fire and often do not clearly understand what procedures should be taken in such situations.

Figure 14 shows the final perimeters of the three largest fires that have occurred in this region since 2000. It can be seen that fire behavior in the large fires follows a behavioral pattern from north to south, being interrupted in the southern part where the combat is more favorable due to lower slopes, large agricultural areas, and higher population density organized in communities with concentrated built-up areas. The Castro Marim Fire (2021) defined an area very close to the Eastern Algarve Fire in 2004.

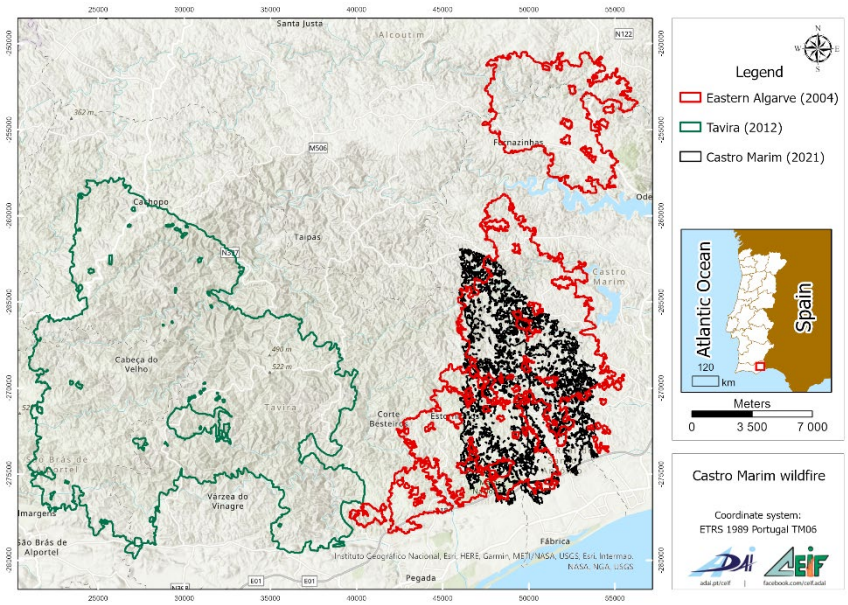


Figure 14 – Final perimeter of the largest fire events that occurred in the region since 2000.

2.3 Fire conditions

As mentioned in the Introduction, during August, Europe was hit by a heat wave directed from the East, which led to several large fires like those described in this report. Portugal was hit late by that heat wave which only arrived at the beginning of the second half of August. As can be seen, by the records of the weather station of the Portuguese Institute of Sea and Atmosphere (www.ipma.pt [6]) located in Castro Marim (Figure 15), the temperature values exceeded 40ºC and the relative humidity reached values below 5%. It should be noted that on the nights of August 15th and 16th the high temperature and low relative humidity remained - only on the night of August 17th these meteorological parameters became more favorable for firefighting, which was important for the consolidation phase of operations.

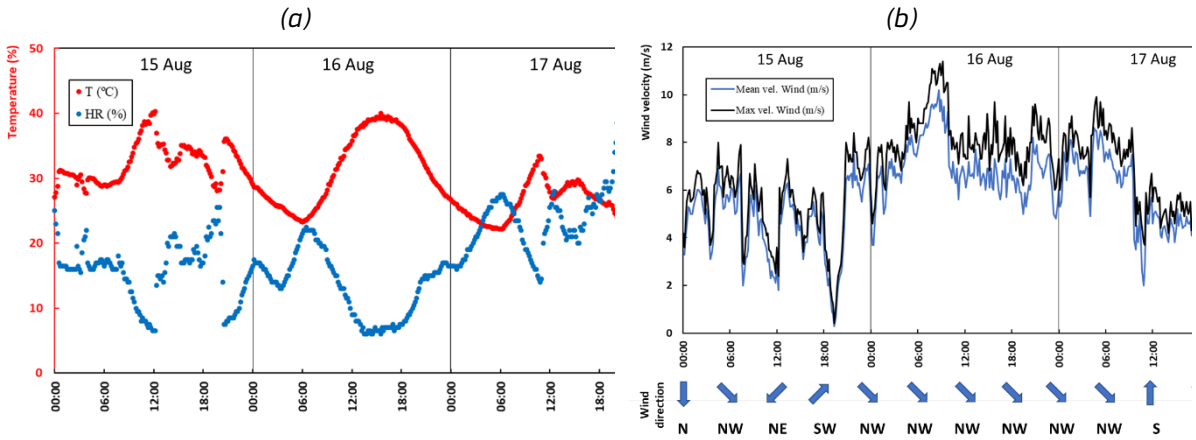


Figure 15 – Meteorological conditions registered by the Meteorological Station of Castro Marim between August 15th and 17th, 2021 (source: IPMA [6]): a) temperature and relative humidity variation; b) wind variation.

The wind also played an important role in the events. As can be seen in Figure 15b, on August 16th, the wind blew invariably from the north quadrant, with gusts that exceeded 11 m/s (~36km/h). On August 17th, the wind decreased in intensity providing better conditions for the consolidation of fire management operations.

2.3.1 Fuel moisture content of dead fine fuels

The fuel moisture content of dead fine fuels (m_f) as they are in the wildland is relevant for the analysis of the ignition conditions, the potential of spotting, and the understanding of the initial propagation of the fire.

ADAI has been coordinating a national project – MCFire (www.adai.pt/mcfire) – in which the m_f is regularly measured in several regions of Portugal. This research project covers Algarve, where the m_f values are determined in the municipality of Faro, for the following fuels: a) dead pine needles of *pinus pinaster*, b) dead pine needles of *pinus pinea, c)* dead leaves of *Eucalyptus globulus*; and d) live tips of Gum Rockrose (*Cistus ladanifer)*. The sample collection is done around (12:00) noon (local time). In Figure 16 the variation of the moisture content of fuels in the Algarve, throughout the year 2021, is presented.

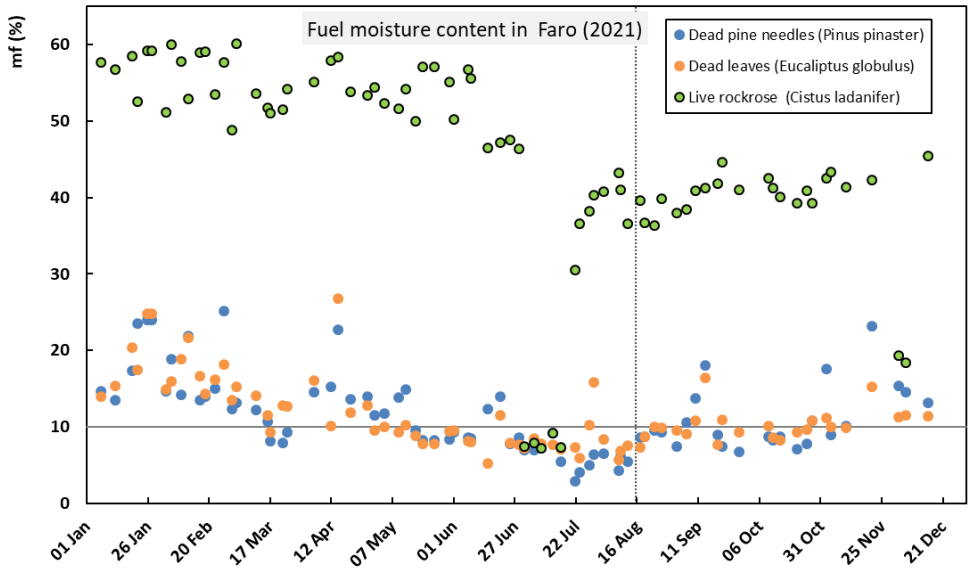


Figure 16 – a) Fuel moisture content (mf) for dead Pinus pinaster needles and dead Eucalyptus globulus leaves during 2021 in Faro (Algarve). Data source: MCFIRE/ Univ. Algarve).

As can be observed, the m_f values for dead fuels are inferior to 10% and the m_f values for live Gum Rockrose are around 35%. Several studies carried out by ADAI indicate that dead fuels m_f values lower than 10% are associated with highly danger conditions and m_f values of around 6 to 7% are associated with extreme danger conditions (Viegas et al., 2019). This is what was observed in Castro Marim during the period of the wildfire.

2.3.2 Fire danger

In Portugal, as in many other countries, it is common to use the Canadian Fire Weather Index System to evaluate the daily wildfire danger conditions. The mathematical structure of the system requires as input the daily meteorological parameters, namely: temperature, relative humidity, precipitation, and wind velocity (Van Wagner, 1987).

An analysis of the fire behavior indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) of the Canadian system, allows us to verify that on August 15th, 16th, and 17th they assumed extreme values, as shown in Table 4a. The values can be interpreted on a danger scale (Table 4b) where an increase in the index corresponds to an increase in fire danger. The magnitude of those values (Table 4a) indicates that any eventual wildfire is characterized by exceptional intensity with the extreme difficulty of control (IPMA, 2021) [6].

Table 4. a) Fire behavior indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) in Castro Marim weather station between August 15th and 17th; b) Danger scale for ISI, BUI, and FWI.

(a)

Day	15th Aug	16th Aug	17th Aug
ISI	21.4	38.7	11.6
BUI	400.9	406.4	409.6
FWI	64.4	91.3	44.0

(b)

	Fire Danger scale						
ISI	0	2.0	6.0	12.0	17.0	23.0	30.0
BUI	0	50.0	100.0	150.0	200.0	250.0	325.0
FWI	0	8.5	17.2	24.6	38.3	50.1	64.0

The final output of the system is FWI which indicates the expected fire front intensity. Figure 17 presents the FWI variation between 2018-2021 in the Faro weather station and the FWI daily values on August 15th, 16th and 17th in Castro Marim.

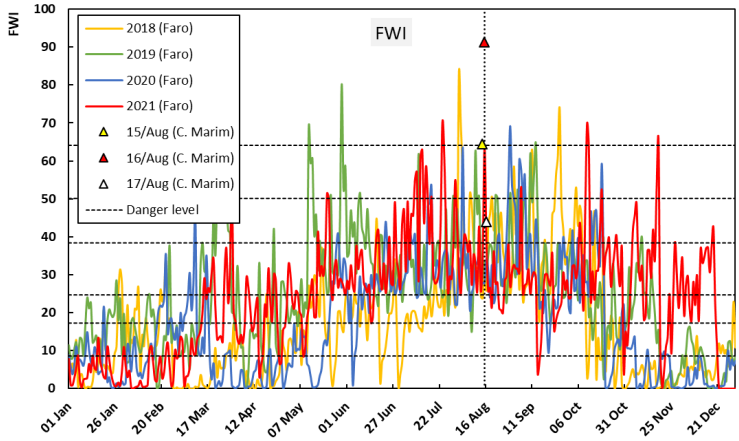


Figure 17 – a) Fire Weather Index (FWI) determined by the observed meteorological data from the weather station of Faro between 2018 and 2021 and the weather station of Castro Marim between August 15th and 17th (data source: IPMA).

FWI values on August 15th (FWI= 64.4) and 16th (FWI=91.3) crossed the highest threshold level of danger, being exceptionally extreme on August 16th where a record value was observed.

Due to its territorial marginality, there is some historical difficulty in reinforcing firefighting operations in Algarve, since a substantial part of the reinforcement means takes several hours to travel the long way to the Algarve. Therefore, it has been usual over the last few years to allocate firefighting resources in advance whenever the forecasted conditions indicate the need for them. Thus, the observed fire danger levels presented in Figure 17 motivated the pre-allocation of firefighting means in strategic areas. We will see below how this pre-allocation of means influenced the way operations were conducted.

2.4 Fire development and operational response

Figure 18 presents an estimate of the fire propagation according to the information provided by the National [Portuguese] Authority for Emergency and Civil Protection (ANEPC). In Figure 19 the level of destruction is presented. Next, a detailed analysis of some periods considered as a determinant in the course of the event will be made.

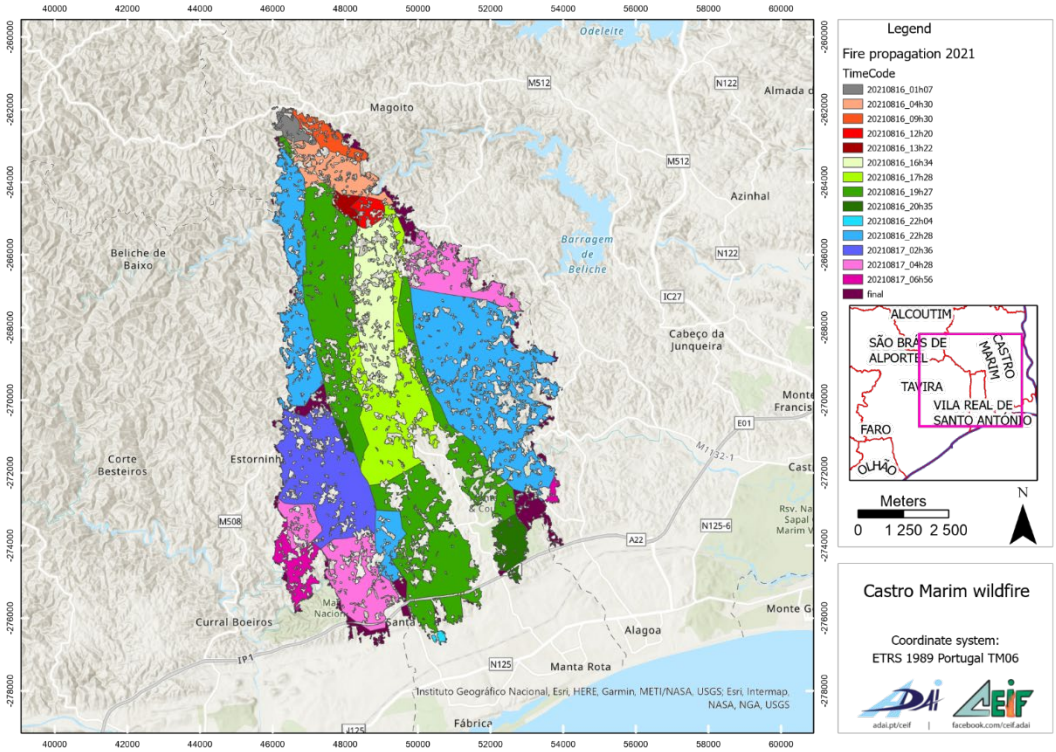


Figure 18 – Representation of the estimated fire behavior according to the indications from ANEPC.

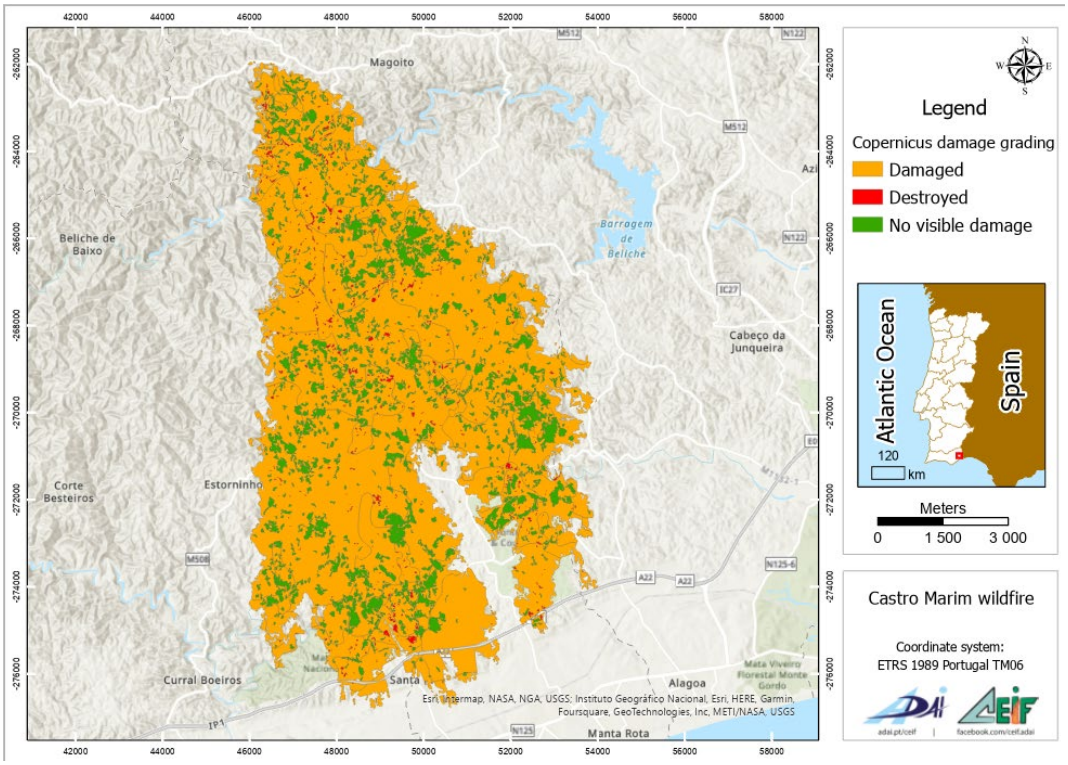


Figure 19 – Damage grading of the burned area (image adapted from Copernicus).

The fire started in Pernadeira in an area next to road M512, close to the village of Alta Mora (37.307518°/-7.612846°). Considering the previously mentioned early allocation of firefighting means, a firefighting team was placed close to Azinhal, about 21 km from the ignition location. This was the first team to arrive at the theatre of operations, which happened around 30 minutes after the alert – the sinuosity of the narrow road they followed and the fact that it was nighttime delayed their arrival. It should be noted that if this prepositioning had not taken place, the arrival time would naturally have been much longer, as the nearest fire station is more than 30km from the ignition site. Due to the wind (~15km/h) and favorable conditions for fire spread, when the first team arrived, the fire already had a considerable perimeter, so it was quickly concluded that reinforcement of means would be necessary.

Around 10.10 a.m., the fire was considered stabilized and the fighting resources remained in the theatre for surveillance and consolidation. In the following two hours, five reactivations were promptly fought by the means in the field. At 12.23 a.m., a sixth reactivation occurred in an area of complex topography, when the wind speed exceeded 20km/h. The control of this new reactivation was lost, giving origin to a new fire front that progressed southwards with great speed. In the following seven hours, the fire advanced about 12km and damaged several buildings, among other impacts (c.f., Chapter 3.5). It was also during this period that the public water and electricity supply collapsed at several points, limiting the people's ability for self-protection. With the failure of the water pressure from the public network, the fighting vehicles had to be supplied by other water sources; however the main water reserves were far away so reducing the efficiency of the fighting operations.

Around 6 p.m., the fire started to threaten the A22 motorway, which is a major road crossing the entire Algarve in an east-west direction. In anticipation, on the sections of road threatened, the A22 was closed to the public. The closure of the second busiest road in Algarve – the EN125 – and the railway line was also considered to potentially be closed but it was only kept under surveillance, with no need for its closure.

During the night of August 17th, the weather conditions, the orography, and fuel characteristics were much more favorable, creating opportunities to fight the fire. Around 07.00 a.m. on September 17th, the fire was definitively stabilized. At 4 p.m. on the same day the fire was considered under control and at 9 p.m. on August 23rd it was considered extinguished.

In the theatre of operations, 1 034 agents from 122 entities, 395 vehicles, 15 bulldozers, 9 aircrafts, and 6 helicopters were used. It should be noted that occasionally, the great intensity of the fire complicated the effectiveness of the aerial means.

2.5 Fire impacts

Besides the general extensive impacts resulting from the fire event, there were several specific impacts that we highlight with the description below. During the field visit, together with technicians from the Municipality of Castro Marim, nine buildings were visited, six of which were dwellings in good state of conservation, two dwellings in poor maintenance conditions, and a warehouse/agricultural enterprise. Naturally, several ruins or constructions without great urbanistic value were affected by the fire, but we did not consider them to be part of this study. Several other episodes are also of great interest – e.g., the “Mata da Conceição” forest that was affected; a storage area for gas cylinders that was threatened although the fire had not reached this area; a golf resort that was hit by a fire that destroyed a small building. In order not to make the report too exhaustive, these episodes will not be detailed.

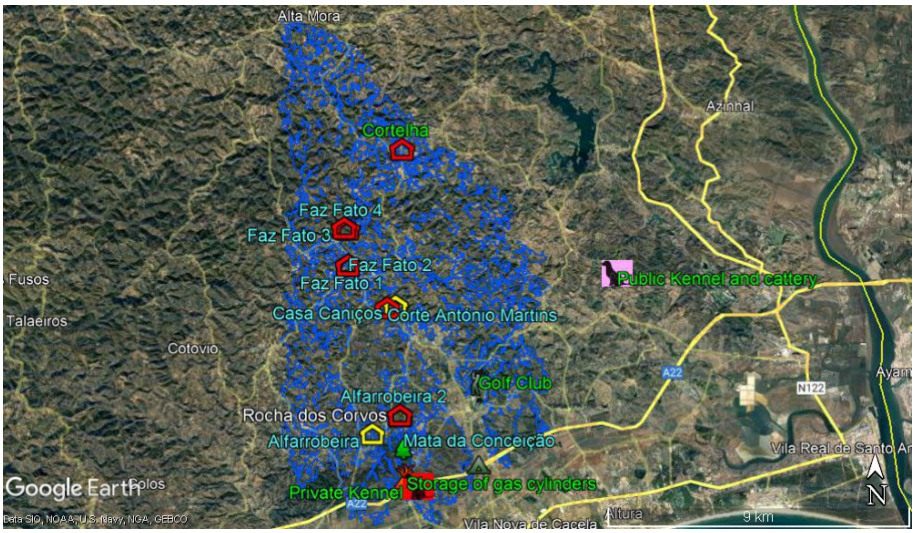


Figure 20 – Location of wildland-urban interface elements damaged or threatened by fire, considered to be of greatest interest for the study.

2.5.1 Damage to buildings

Of the nine buildings with the highest value analyzed, only six episodes will be described in this chapter because they were those from which the most lessons can be learned. Some of these buildings are neighbors and so are presented together in order to establish a comparative analysis. The name given to each case is associated with the locality of implantation of those buildings followed by the numbering in a sequence from south to north. In Figure 20 these buildings are highlighted in red.

2.5.1.1 Cortelha

This episode was the only case of building damage analyzed in the municipality of Castro Marim, as the remaining cases were registered in the municipality of Tavira. This building was used to store agricultural products that were commercialized by its owner who managed this buying and selling family-run business.

The fire reached this building by its back side as presented in Figure 21a. In Figure 21b is presented an image of the back of the building where the proximity of many trees that projected their branches on the building's roof can be seen. Furthermore, next to the building there were several man-made fuels such as vehicles and other implements.

(a) (b)



Figure 21 – a) General view of the building damaged – the yellow arrows indicate the provenience of the fire front; b) photo of the back of the building where it is possible to see the proximity of forest fuels such as trees.

According to the witnesses' account, before the flame front reached the building, a eucalyptus tree on its northern façade started to burn, spreading the fire to the building. As can be seen in Figure 22, beneath the eucalyptus, attached to the building, was a pile of man-made fuels. It is believed that early-stage firebrands fell on this pile of fuels that ignited, spreading the fire to the eucalyptus crown and then to the construction. As can be seen in Figure 22, the fire on that façade was so intense that it destroyed the cladding of that wall. The roof collapsed and the building was virtually destroyed.

(a) (b)



Figure 22 – Images before (a) and after (b) the destruction of the building by the fire. The red arrow in image (a) indicates the eucalyptus tree where the witnesses point to have seen the first flames next to the building.

About 30m from the building that was destroyed there is a sheepfold that due to the intervention of its owner, was not caught by the fire. During the period of greatest distress and fire intensity, the owner of the sheep opened their doors and tried to flush them outdoors in the hope that their survival instinct would save them. However, the sheep stubbornly remained in the sheepfold where they felt safer. In the past, there have been other episodes where people have died while trying to herd the sheep out of the fold (e.g., Viegas 2019). Also, in that time, the sheep ended up staying in the sheep pen showing a behavioral pattern that should be known in order to change the emergency procedures of those dealing with these situations.

(a) (b)



Figure 23 – Images of the sheep pen. The red arrow in image (a) indicates the location of the sheep pen. The blue arrow (b) points to the location of the building destroyed by the fire.

Lessons learned

Two generic lessons can be drawn from this episode. On the one hand, the importance of managing the surrounding space near the house with regard to natural and man-made fuels was confirmed. On the other hand, the obstinate refuge behavior of the sheep in the fold was highlighted, which makes the actions of those who try to remove them from the sheepfolds useless.

2.5.1.2 Faz Fato 1 and Faz Fato 2

In the village "Faz Fato" we analyzed four houses damaged by the fire. Two of these houses were adjacent to each other and were therefore caught at roughly the same time. According to the popular witnesses, the fire was moving rapidly to SE, as a surface fire. As can be seen in Figure 24, the fire was developing in a gorge of about 250 m and with slopes of approximately 35%. At the end of the terrain where the fire was spreading there was a small slope of approximately 45º, rising about 2m to the road. At the base of the slope, there was a large eucalyptus tree (*Eucalyptus globulus*).

(a) (b)



Figure 24 – Overview of the location where the episodes "Faz Fato 1" and "Faz Fato 2" took place. The yellow circle highlights the eucalyptus tree, which was relevant in the ignition of the houses.

The intensity of the fire did not make the citizens assume that the houses were threatened, because they were on the opposite side of the road, about 8m away. When the fire front reached the edge of the road, the fire transited to the canopy of the eucalyptus tree causing a "rain" of firebrands towards the houses on the other side of the road.

The ignition of the house related to the episode "Faz Fato 1" occurred after the breaking of the glass of an entrance door with wooden frames (Figure 25). The glass of this door was a single pane with dimensions of 1.75x0.75m^2 – the glass thickness is unknown.

(a) (b)



Figure 25 – General view of the building related to the "Faz Fato 1" episode: a) before the fire event (Google Earth image) and b) after the fire event (photo courtesy of Tavira Câmara Municipal).

After the door glass was broken, several firebrands entered the house, igniting it and causing damage to the entrance hall. The existing vegetation at the entrance of the house was not ignited and the window panes of the same façade, which had smaller glass panels, did not break.

A reflection on this episode allows us to conjecture that the entry of the fire into the canyon caused high-velocity convective air flows which, in association with the strong meteorological wind, were directed toward the door. When the fire reached the canopy of the eucalyptus tree this effect was aggravated. The hot and high velocity combined airflow caused a strong vibration of the door glass triggering it to break, thus allowing the entry of the firebrands. The windows in the same façade, although larger in size, did not break due to several factors such as the protection provided by the immediate vegetation and due to the smaller size of the glass panel as the window had an intermediate frame, so reducing the vibration.

In the second house – Faz Fato 2 – a wooden marquee with glazing was burnt down, as shown in Figure 26. In this case, the glass was also single pane but its size was much smaller than the neighboring house. Therefore, we suspected that the ignition was not due to the breakage of the glass because these smaller panes vibrate less and consequently have a lower tendency to break when subjected to strong airflows. Since no hints of carbonization of the vegetation adjacent to the house were found, the ignition is believed to have been started in the marquee itself. The accumulation of firebrands on the wooden frame of the marquee could have been associated with its ignition.

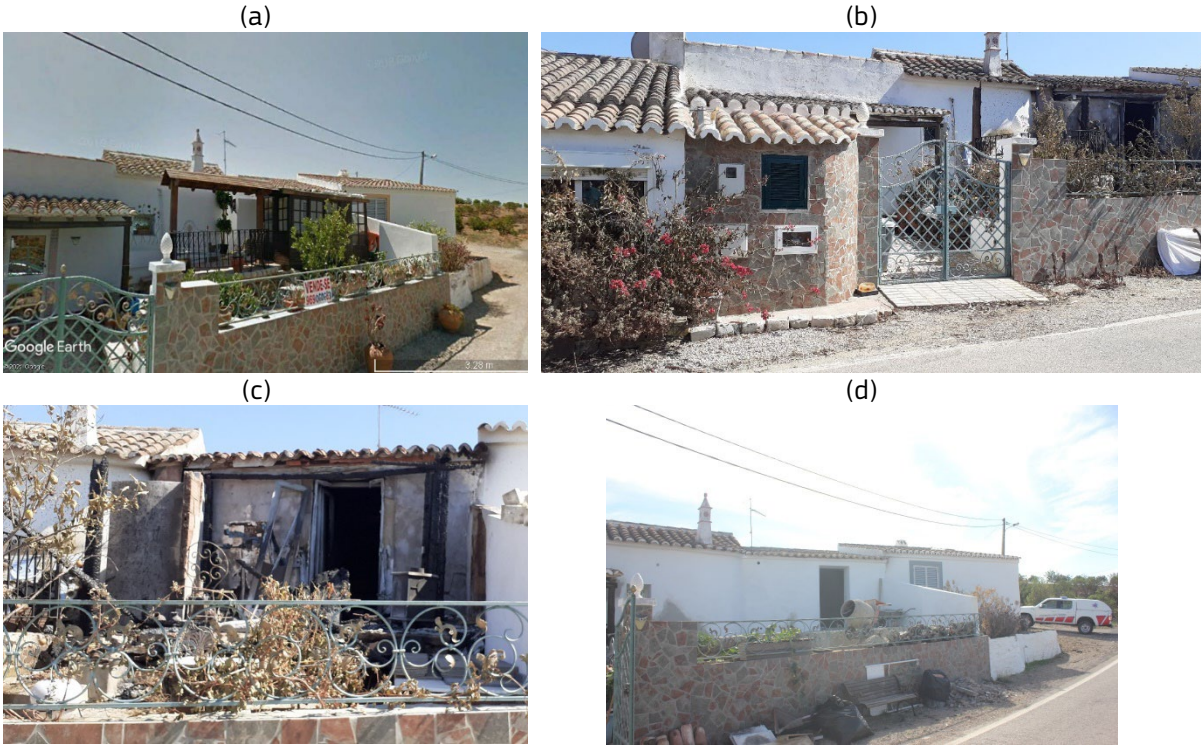


Figure 26 – General view of the building related to the "Faz Fato 2" episode: a) before the fire event (Google Earth image); b and c) after the fire event (photos courtesy of Tavira Câmara Municipal); and d) image of the house during its reconstruction.

The visit we made to the house four months after the fire allowed us to verify that in the reconstruction of the house, the wooden marquee was eliminated, so we believe that the house is now less vulnerable to eventual new wildfires.

Lessons learned

The establishment of houses at the top of canyons is a factor of major risk for wildfires. This risk is aggravated when the construction elements of the house are vulnerable, such as wooden structures or large single-glazed panels.

2.5.1.3 Faz Fato 3 and Faz Fato 4

The other two cases that we analyzed near Faz Fato refer also to two neighboring buildings, describing also the situation of construction that was not damaged by the fire. As we can see from Figure 27, the situation of the three houses is quite similar, i.e., they are all located on top of canyons with parallel alignment. The fire came from the East and South, where it aligned with the canyons. To the authors' knowledge, the fire did not enter inside the houses but, apart from the walls, only affected their immediate surroundings and nearby fittings. Figure 28 shows some photographs of the main impacts.



Figure 27 - General view of the integration of the three houses in the landscape. The yellow arrows point to the place where the fire front hit the constructions.

(a)



(b)



Figure 28 –Photographs of some of the impacts caused by the fire in the Faz Fato 3 (a) and Faz Fato 4 (b) case studies. The images from (a) were kindly provided by the Municipal Council of Tavira / Volunteer Firefighters of Tavira.

Analyzing the Google Earth images well, we can see that the house that was not damaged by the fire was the one with the best fuel management. This was also noted during the field visit. Therefore, the proximity of the houses to the natural vegetation with higher fuel load was the main difference in the three situations with the remaining characteristics very similar.

The fuel management in the immediate surroundings of the houses (about lower than 5m) was not entirely inadequate, with low flammability plants (e.g., cactus) and ceramic flooring. However, the location of the houses on the top of canyons had a twofold effect: 1) increased the fire intensity; and 2) channeled convective hot gases toward the houses and the fuels in their immediate surroundings. Thus, when the fire front approached the house, directly or by firebrands, the fuels were already dehydrated and therefore highly flammable.

Lessons learned

Like before, the location of houses on top of canyons has been shown to be highly dangerous. However, one of the houses that were in this situation ended up not being damaged by fire because it had a more favorable fuel management condition. Thus, although houses should not be located in canyons, if they are, additional efforts should be made to manage fuel in the surrounding area.

It is also mentioned that several man-made fuels (air conditioning, vehicle, shading awning, etc.) were ignited, demonstrating that the focus on fuels management in the surroundings of buildings should go beyond the focus on vegetation management and extend to man-made fuels, besides the construction accessories (e.g., wooden pergolas).

2.5.1.4 Corte António Martins

This episode does not have much to tell, but it highlights a constructive aspect that was decisive in the damage that the fire caused in the house. The management of fuels in the surroundings was reasonable, given the generality of situations. In fact, the fire did not reach the house directly by the flames but through spotting when the fire front was still some tens of meters from the house.

In Algarve, the construction of roofs in reeds under the tiles is widely used. This technique cools naturally the house, is traditional, and is followed by many people, including foreigners, who appreciate it. However, it causes major problems related to fire as it ignites easily. What happens is that the wind, whether meteorological or convective, lifts the tiles, even if slightly, exposing the highly flammable reeds to incoming firebrands. This is what happened in this case that led to the partial destruction of the house, causing the fire to enter its interior. Figure 29 presents some images that help to understand this episode.

(a) (b) (c)



Figure 29 – Images regarding the case study of Corte António Martins: a) photograph of a reed roof; b) general image of the house where is possible to see the roof area that was damaged by the fire; c) indoor image of the roof that was damaged by the fire, where we can see the reed roof where the fire started.

2.5.2 Fire risk management in animal facilities

In the description of the Cortelha episode, the difficulties of protecting/rescuing sheep during a wildfire were highlighted. Other animals such as dogs or cats have an instinctive reaction to fire that is different from that of sheep, usually seeking to move away from the fire to safer areas. For this reason, the owners of cats and dogs often release their animals in the hope that their instinct will guarantee their survival in a fire event. However, this procedure is not always possible. For example, in the case of kennels and/or catteries, the release of animals is not recommended because of the number of animals besides other social implications such as the eventual aggresseness or the loss/disorientation of the animals.

In Portugal, this issue has been much debated, especially after the death of several dogs in kennels during past wildfires. These tragic episodes revolted citizens who considered that the lives of these animals should have been protected. Next, two episodes of the Castro Marim fire involving kennels/catteries will be described.

2.5.2.1 Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António

At the time of the fire, the Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António was homing about 80 dogs and 110 cats. The rapid and uncontrolled progress of the fire caused concern that it could reach these facilities and affect several animals. Therefore, the decision to evacuate the kennel/cattery was taken in due time.

In this process, the more aggressive dogs were separated from the other animals, having been displaced to a pavilion in the surroundings where they were kept until the threat of fire ceased. The solution for the remaining animals was primarily based on voluntary temporary shelter. Thus, using social networks and direct contacts, an appeal was launched for families and for the "Friends of the Kennel" to home these animals during this period of fire threat. The response was very positive with several Portuguese and Spanish families responding positively to the challenge. Some animals that did not find a family, were moved to other pavilions, but being fewer animals, this management was highly facilitated. In the end, the fire did not reach the kennel/cattery, but we consider that the decision to evacuate it beforehand was the right one. In addition to the survival of all the animals, we are happy to highlight that, in the end, 30 animals did not return to the kennel/cattery because they were adopted permanently.

Although all went well, if the fire front had reached the kennel/cattery it could have caused a high level of destruction as the availability of fuels present was very large (Figure 30). Due to the nuisance, these facilities cause in the neighborhood, kennels are often installed in areas with low heritage value. These areas are often remote and sometimes subject to little maintenance care, which increases the fire danger. In this case, the kennel/cattery was located in an area with a high wild fuel load and next to a park of abandoned vehicles. Thus, if the fire had reached this area, it would have been difficult for the facility not to be seriously impacted. If this happened, the consequent economic losses would be added to the social losses, because it would not be easy to quickly rehome so many dozens of animals.

(a) (b)



Figure 30 – Images of the Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António.

Lessons learned

This episode allows us to understand how complex it is to deal with wildfire risk management in this type of facility. Therefore, it is important that preventive actions are well defined, namely: location of these facilities in areas of lower fire risk, adequate management of fuels in the surroundings and inside the facilities; the existence of intervention plans before, during, and after fires.

2.5.2.2 Private kennel next to the A22

This episode is much more dramatic than the previous one since 14 dogs died in the fire. This was a kennel of which the authorities reported previously no knowledge of its existence, so it was apparently illegal. When the authorities became aware of it, the access to the kennel was too risky and the dogs were left to themselves. Some employees of the previously described Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António also went to the area to support this rescue operation, but the authorities did not allow them to access the kennel because the safety conditions were not assured.

The kennel was about 100m away from the A22 motorway at the top of a canyon's versant. When the authors of this study went to the site, the debris from the kennel had already been removed. However, it was possible to see the high wild fuel load on the hillside below the kennel. Therefore, the intensity of the fire at that location spreading in dense vegetation surely was very high.

(a) (b)



Figure 31 – Images of the private kennel that was destroyed by fire.

Lessons learned

As in the previous case, these spaces must be subject to adequate fuel management in their surroundings, complying with the same criteria as if they were a dwelling house. Furthermore, the location of the kennel at the top of a canyon slope is totally inadvisable. It is believed that the convective heat flow resulting from the combustion gases drives survival conditions very difficult, even before the flames got there. The use of self-protection systems (e.g., water sprinklers) for this type of installation with very difficult evacuation operations should be considered.

2.6 Conclusions and lessons learned

Throughout this chapter, the context in which the Castro Marim Fire occurred was described, as well as the main characteristics and impacts resulting from its propagation. It was verified that the fire occurred in very unfavorable conditions for firefighting and that it would have been difficult to avoid the impacts verified.

Many citizens complained that there were not enough firefighting means in the theatre of operations, but the number of means in the field was in line with what is normally used in similar situations, even though Algarve is in a peripheral region of Portugal where reinforcement means have difficulty in reaching. It is considered that the pre-positioning of means on the ground was fundamental for the combat to be carried out with many means from its initial phase. However, the wide dispersion of houses and settlements made the operations difficult. in particular the capacity to respond to all situations. Given this scenario, it is essential that constructions have conditions of survival without the intervention of public firefighting means, namely: a) implantation in less exposed areas (e.g., not in canyons or steep slopes); b) use of good construction practices, both in the architectural design (e.g., roofs with fire-resistant under-tile) and in the choice of construction materials; (c) appropriate fuel management in the building surrounding areas; (d) autonomy in terms of water and energy); e) the existence of self-protection systems such as water sprinklers.

Episodes of threatening animal installations have also been described. This is a matter that deserves reflection in order to define the best evacuation and protection measures for these infrastructures. The feeling is that the construction of these facilities of such great social importance does not present effective prevention and emergency plans that would clearly define the measures to be taken in a fire situation. After the fire, the conclusions can be more or less positive with the statement that the civil protection agents did their best within the existing capabilities and conditions. However, the management of these situations requires prior planning by the citizens and by the private and public entities, which is not always what really happens.

FIRE OF GONFARON

Authors

Damien Ballereau	SAFE Cluster
Sébastien Lahaye	SAFE Cluster
Romain Matile	Warucene



3 The Fire Event of Gonfaron (France)

Before 1975, a forest fire was already "an old problem in Provence and particularly in the Var department which... held the lead in national statistics for burned areas" [7], However, the Gonfaron fire of 2021 is not in line with previous fires, as its intensity and speed of spread are different and more impactful.

3.1 General description

The fire that took place in the summer of 2021 in Provence, France, highlights all the issues related to large fires in our current society: an area with a continuity of vegetation, environmental issues, many Wildland-Urban Interface areas, and extreme meteorological conditions favoring very rapid-fire spread.

On August 16th, by 5.45 p.m., this wildfire started on a highway rest area on Gonfaron and quickly grew due to drought and wind conditions, despite reinforced surveillance and prevention measures [8]. During the first night, it traveled 21km in six hours. By comparison, in 2003 another major fire was also declared on this territory and had progressed in a similar direction, but it had progressed only 10km in 36 hours! The Gonfaron fire of 2021 has therefore relatively progressed very quickly compared to the usual fires in the territory. This wildfire event burned nearly 7 000ha, including half of the national nature reserve of the Plaine des Maures, a highly protected natural area causing a large crisis by having to evacuate thousands of people and protect hundreds of homes and human infrastructures. Two inhabitants died in this event.

The prevalence of forest fires in the Mediterranean region, and more particularly in the Var department, is not new. The area of this specific fire is the sad holder of the largest burned areas in France.

Despite the fire prevention planning that exists since 1980, requiring the inhabitants to clear brush around their houses, providing the forests with cleared roads and hydrants for the firefighters, installing lookouts, pre-positioning firefighters on the ground, and establishing a strategy of massive attack of fire starts, it happens that some fires overtake the committed rescue services.

3.2 Characterization of the affected area

3.2.1 Fire History

Since the 1970s, five fire seasons were particularly severe and destructive in the Var department (1979, 1986, 1990, 2003, and 2021) – the fire of August 2021 is officially the most extensive fire in metropolitan France for 31 years. The fire history indicates that this area of the Maures has had the highest recurrence of large fires in recent decades, with multiple fires that have ravaged tens of thousands of hectares in total (Figure 32).

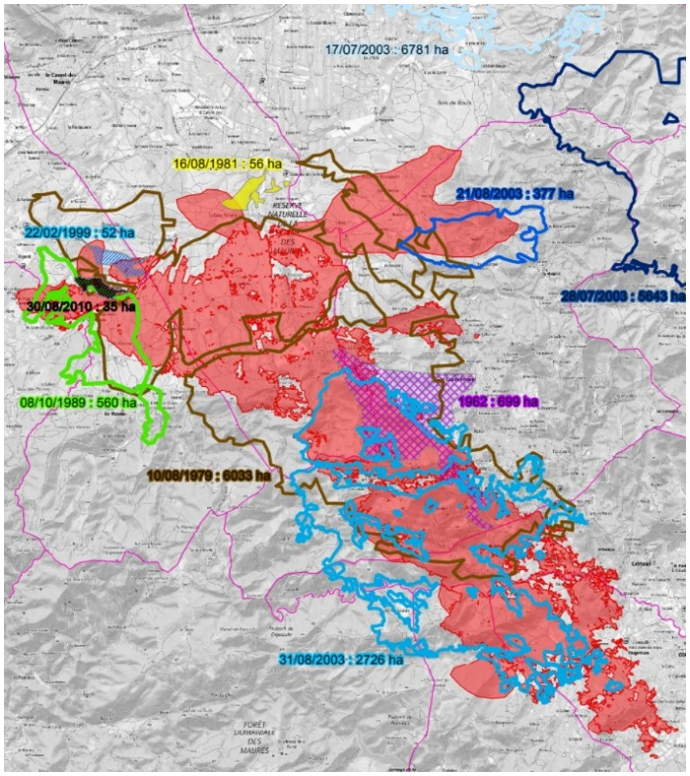


Figure 32 – Map of the history of fires on the impacted territory (source: National Forestry Office).

During the summer of 1979, two major fires affected the Var department during the second week of August: one in the Verdon, in Ginasservis (North of Var) affecting 1 ,200ha; and the other, much larger, starting at Le Luc (Maures area), burning 5 880ha with several injured among the rescue forces.

The summer of 2003 is also remembered for the dry meteorological conditions with a heat wave that affected the entire metropolitan territory. Large-scale forest fires then broke out in the Var department, and in particular in the Maures massif, resulting in ten deaths, including three firefighters [9] On July 17th, 2003, a fire began in the town of Vidauban, traveling 25km up to the coast, crossing the towns of Saint-Aygulf and Issambre, and destroying dozens of vehicles, homes and campsites, 6 744ha of wildland area and triggering the evacuation of more than 5 000 people. This fire lasted a week, until July 24th.

The fire of 2021 has taken the same direction as its predecessors, but faster and more intense. Lahaye et al. [10] have identified that this Maure area in the Var is one of the most challenging regions for French firefighters, as due to the coastal breeze effect, the wind is frequently shifting, originating adverse fire behavior.

3.2.2 Environmental and Socio-economic issues

The Maures area, made of plains and mountains, is a diversely occupied territory (housing, protected, agricultural, forest, and military areas…) and a very attractive place for tourists and local people. It has, moreover, a large number of natural habitats for fauna and flora with major conservation issues [11].

The land use history is similar to many others in Europe. The agricultural decline triggered by the industrial revolution and then the globalized economy has accentuated the abandonment of the least productive agricultural land. The use of fossil fuels has decreased the demand for charcoal and firewood which were collected for thousands of years. As a result, a few decades later, the territory has become overgrown and the memory of the "old" stakeholders has been lost. In addition, urban expansion has spread, ecological issues have been highlighted and the public's approach to natural spaces has radically changed. It all happened little by little, but the final cocktail is only getting more bitter… by a touch of climate change!

Firstly, concerning ecological issues, the plain and the Massif des Maures are rich in terms of biodiversity. The presence in the Nature 2000 area of numerous protected or endemic plant and animal species makes it an area to be preserved. Created in 2009, this Nature 2000 area covers an area of 5 276ha and lists 30 natural habitats (Xerophilic lawns, wet meadows, scrubland, moorland, suberais (dry and mesophilic), pine groves (pine pine, Mesogean pines), chestnut groves, riparian forests, pine forests (planting and sowing of laricio pine, maritime pine) with original or exceptional natural habitats such as Mediterranean ponds or temporary runoffs, sandy lawns of annual plants (helianthemums, fresh and dense suberaies, dry and scattered.), including 11 habitats of the community of interest and three priorities under the European "habitats-fauna-flora" directive [12]. The reserve also has "a thousand [floral] species inventoried [11] including 89 remarkable species, 57 protected species (24 at national level, 33 at regional level), 32 species inventoried in the regional red book" and 183 protected species of wildlife of which Hermann's Tortoise (*Testudo hermanni hermanni*) is the most popular (The only land tortoise in mainland France on the red list of the International Union for Conservation of Nature (IUCN) and which is, therefore, the subject of a national action plan).

Secondly, the territory concentrates many conflicting socio-economic issues with the development of the territory, and the creation of this Nature 2000 area is the result. Indeed, its creation follows collective actions carried out against, in particular, a project to set up a test center for an automotive equipment manufacturer. The Nature 2000 area is then intended to be "a bulwark against economic projects that consume natural space [...because the] Plaine des Maures is one of the last land reserves in the Var plain in a context of strong demographic dynamics, urbanization and a viticulture in full reconquest" [11]. It integrates a 1/3 public and 2/3 private land mosaic (including 750ha of agricultural land with 490ha of the vineyard), pastoralism with three sheep breeders, a bovine pastoral group, and beekeeping (approximately 1 000 hives). Finally, many outdoor activities (hunting, hiking, mountain biking, horse riding, etc.) take place in this territory, making the WFRM subject to conflicts between different ends such as sustainability, economic use of resources, and nature conservation, in which different stakeholders with different interests and goals clash [13].

3.2.3 Topography, fuel cover, and WUI characterization

The area of the Gonfaron wildfire event covers the Thermo and meso-Mediterranean stages, characterized by hot and dry summers. The geology of this territory is fascinatingly different from the surrounding area. The substrate of the mountains is siliceous and crystalline, while the plain is more volcanic [14] and the amplitude of the elevation of the territory varies from 100m to 650m. These elements contribute to the fact that the fire dynamics are stronger in the "Plaine des Maures" than in limestone areas of Provence.

The burnt area comprises a majority of hardwoods (53.6%) of which 36.1% are in the closed forest and 17.5% are in open forest, approximately 1 000ha are moors and are mainly at the level of the plain. The fire started in the plain of the Maures (Figure 33) where the vegetation included many vineyards and recent plantations. Then, it went into the dense maquis, where the rest of the vegetation was mainly made up of maquis of holm oaks, pine forests of maritime pines, or planted stone pines [15].



Figure 33 – 3D assembly of the propagation of the fire vis-à-vis the reliefs (source: Departmental Fire and Rescue Service of the Var)-

The Maures plain has some rare and isolated habitats (e.g., equestrian center) and the interior of the massif has a few villages (Collobrières, La Môle, La Garde-Freinet, Plan-de-la-Tour, Gassin, Ramatuelle) for a total of more than 13 000 inhabitants (Municipal population) and a few hamlets which are identified as sensitive points by the emergency services. Most of the localities are established on the periphery of the massif such as the commune of Gonfaron which has 4 336 inhabitants (INSEE, 2015) with the presence of campsites and mobile homes.

3.3 Fire conditions

3.3.1 Meteorology

The summer of 2021 was wet in the north of France and abundant pluviosity started in June. However, some Mediterranean regions were an exception by staying away from almost all rainy periods until July as can be seen in figure 27 below.

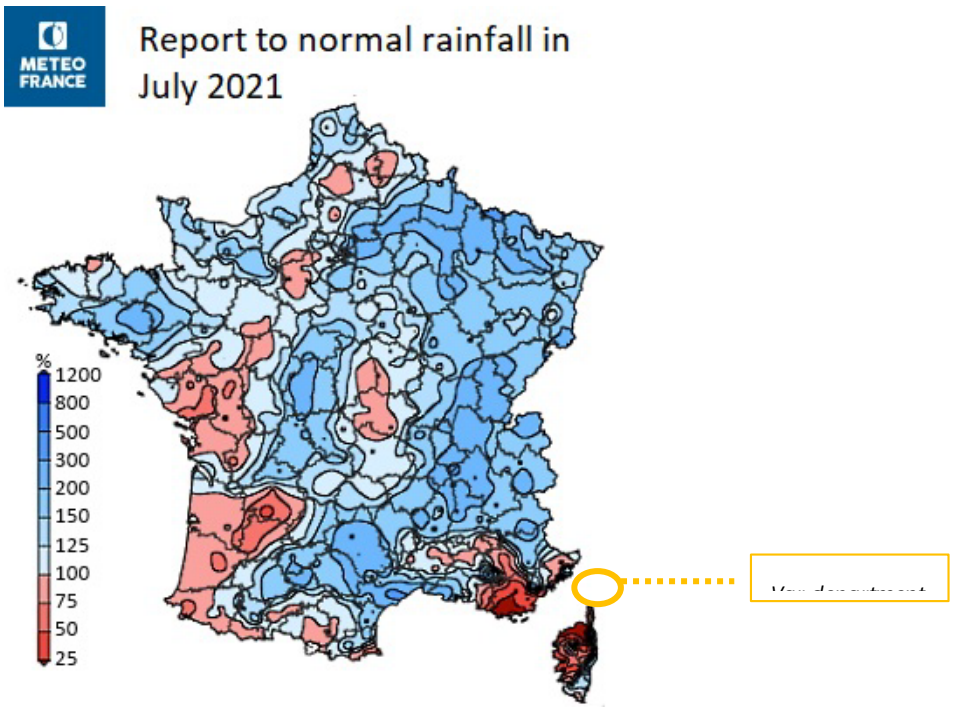


Figure 34 – Cumulative rainfall and ratio to normal in July 2021 (Source: Météo Villes & Météo France).

On the eastern part of the Maures, the last significant rains (<10mm) happened on May 23rd, 2022, i.e., almost three months before the Gonfaron fire. Small storms and rainy episodes then took place on June 8th, 2022, and August 4th, 2022 bringing about 5mm each, but no significant rain occurred.

The evolution of temperatures over the last four days showed maximums close to 40°C (and more particularly the two previous days before the fire started) and temperatures not falling below 23°C during the nights.

When the fire started, the wind changed in the direction from West to North West (270°/280°) with gusts between 70km/h and 95km/h, and an average speed of 45km/h. The average temperature was 32°C and the average relative humidity was 20%. Thus, the announced theoretical propagation speed was 1,500 to 1,800m/h.

3.3.2 Fire risk & alert

On the morning of the fire, MétéoFrance produced its weather report taking into account the impact of climatic conditions on the fire danger (It is based solely on weather conditions, with no adjustment for fuel humidity). Ainsi, the organization had classified the Var department for August 16th as "very severe level, extreme limit", meaning that the area is very sensitive with a high risk of ignition and that any flame or source of heat risks to give a fire propagating at a high speed.

Météo France had also issued a "Special Defense Zone Bulletin" to the attention of the departments of Alpes-Maritimes, Var, and Haute-Corse to report a "yellow heat wave vigilance due to an episode of high heat in the south-east of France".

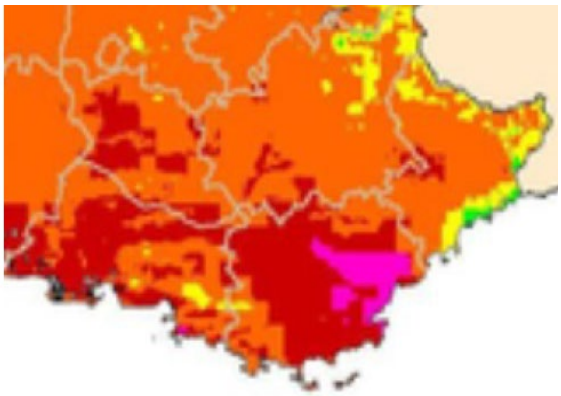


Figure 35 – Dead vegetation: IEP6x planned (purple) (Source: Departmental Fire and Rescue Service of the Var).

Following the experience of the fires in 2020, a sixth level of the Maximum Spread Outbreak Index (IEPx) has been created, representative of dead or dormant vegetation and was being tested this year. On the situation of August 16th, the IEPx reacted by indicating a level six from the center of Var to Esterel and north of the Maures.

3.3.3 Allocated resources

Due to the known risks, the Var Fire and Rescue Department Service (SDIS) and the Zone Operations Center (CoZ) set up a resource pre-positioning system throughout the department (cf. Table 5).

Table 5 – Resources pre-positioned by the SDIS of the Var department and the CoZ on August 17, 2021

Departmental Fire and Rescue Service (SDIS)	Zone Operations Center (CoZ)
9 Forest Fire Intervention Groups (GIFF), i.e., 162 firefighters and 36 Forest Fire Tanker Trucks (CCF)	1 extra-departmental column, i.e., 72 firefighters and 16 forest fire tankers (CCF)
5 Rapid Intervention Modules (MIR), i.e., 40 firefighters and 10 Forest Fire Tanker Trucks (CCF)	4 Bombardier Water Helicopter (HBE)
4 Bombardier Water Helicopter (HBE)	2 Canadair CL-415 (HRS)
A Pelicandrome team, responsible for ensuring the supply of water bomber aircraft	1 Armed Air Watch (GAAR) which is also a water bomber aircraft (ABE)
3 Site Command Group	
1 On-call Cartography	

The fire then broke out at 5.45 p.m. on August 16th in the town of Gonfaron, with black smoke that escaped from it from the start.

3.4 Fire behavior

The fire quickly grew due to the low fuel moisture content and the strong wind, despite the prevention measures put in place. In Figure 36, the smoke emerging after 16 minutes (5.59 p.m.) is shown. At this time, the fire had already traveled about 700m, which represents a fire spread of about 3.5km/h.

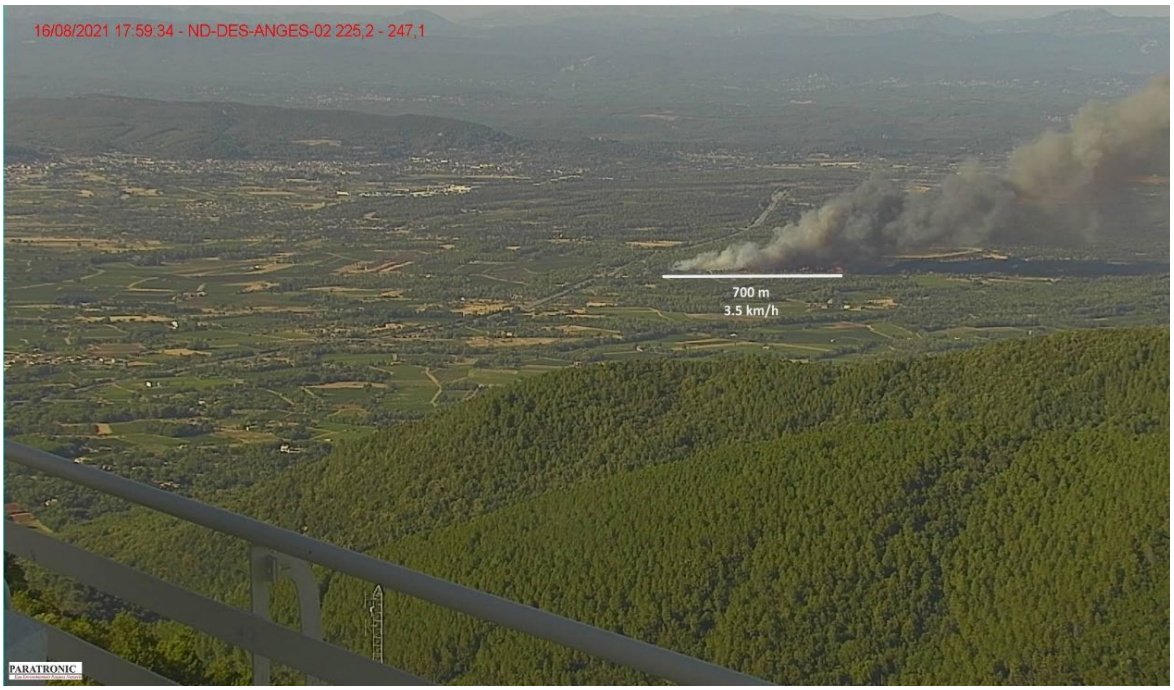


Figure 36 – Initial phase of the fire – photo taken at 5.59 p.m., 16 minutes after its ignition (Source: Departmental Fire and Rescue Service of the Var)

In nearly 46 minutes, the had burned about 100ha in an area of more than 2km long and up to 500m wide. It continued spreading from West to East (270°) for three hours and from Northwest to Southeast (220°) for T+3 hours, despite the intervention of many aerial means (7 Canadairs, 2 dashes, 3 water bomber helicopters, and the command helicopter) in addition to the resources on the ground. We can see the evolution of its smoke in figure 30 below.

At 8.30 p.m., the Var prefect activated the departmental operational center at the Var prefecture and the aerial assets stopped their operations due to the nightfall. Starting from Gonfaron, the fire reached the ridge line to the village of La Garde-Freinet arriving around 10.00 p.m., triggering the evacuation of several campsites. By 02.00 a.m., the fire had burned 4 000 hectares, 750 firefighters were engaged and 12 campsites had been evacuated. The average fire spread is estimated to be 4km/h. We can see in the following Figure 31, the axis of propagation of the fire during this night (until midnight).



Figure 37 : Photo of the fire taken at 6.30pm, 46 minutes after the original ignition (Source: Departmental Fire and Rescue Service of the Var)

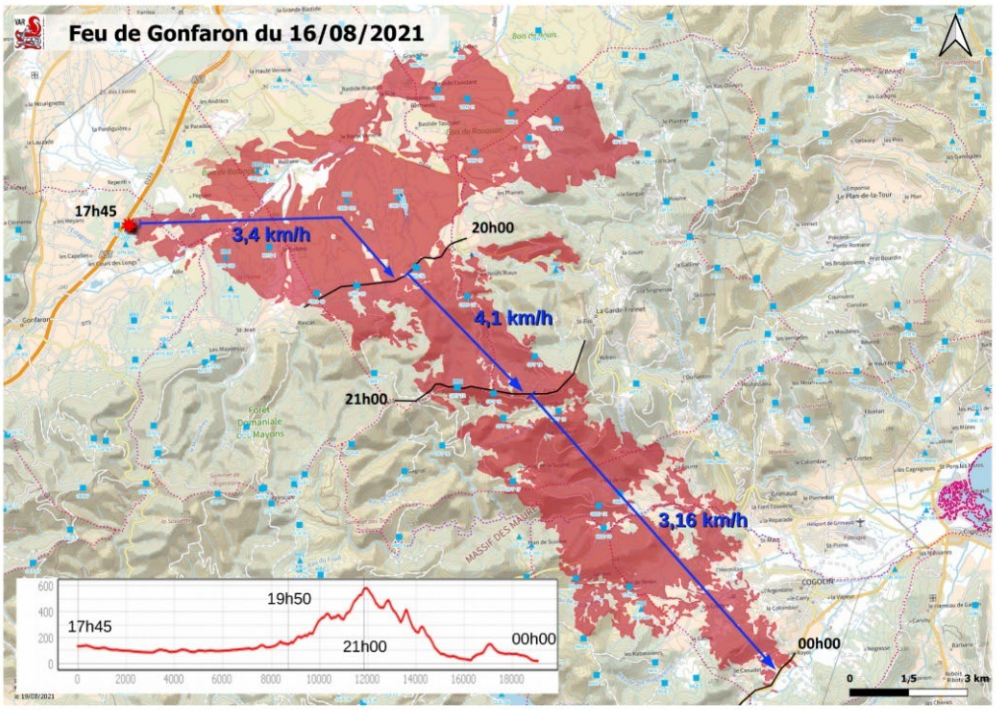


Figure 38 – Course of the fire between 05.45 p.m. and 12.00 p.m. of August 16th (Source: Departmental Fire and Rescue Service of the Var)

By 6.00 a.m. of August 17th, many hot spots persisted in the fire zone mostly in the Plaine des Maures sector. Around 5 000 hectares had burned and approximatively a hundred buildings were damaged.

At 4.00 p.m. the fire was still not under control and was experiencing significant flare-ups. Spot fires of more than 2km appear, due to unfavorable winds with two hot spots, the first in the Cogolin-La Môle sector and the second in Cannet-des-Maures. At this moment, 1 200 firefighters were deployed on the ground. Extra-departmental reinforcements were still expected in order to complete the staff of the rescue centers to allow the firefighters of the Var Fire and Rescue service to be engaged in this fire event. On August 18th, by 9.00 p.m., the fire remained active on these flanks. 6 700 hectares burned so far, despite the commitment of exceptional human and aerial resources. Noticeably, a decisive back-burning operation stopped the main run of the fire, after road D98. Figure 32 below shows the fire propagation axes per days, according to Copernicus data.

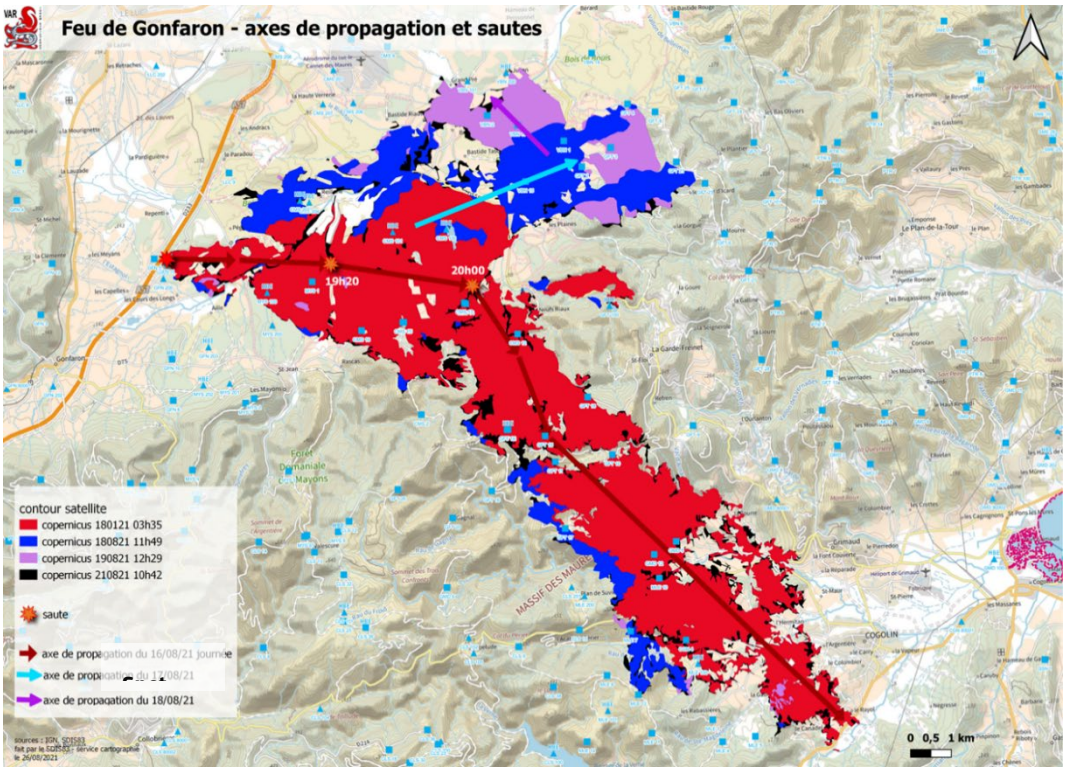


Figure 39 – Fire-covered area, indicating satellite contours, spot fires, and axes of propagation (Source: Departmental Fire and Rescue Service of the Var)

On August 19th, by 7.30 a.m., the fire became less violent and its progress was slowed down even if the risks of a resumption persisted. More than 6 832 hectares have been covered by fire since the start of the event. Aerial operations resumed at daybreak. The extreme south of the fire perimeter was controlled and the main points of attention were located to the northeast of the site, in an area encompassing Le Cannet-des-Maures, Le Plan de la Tour, and Vidauban. Significant work was being done on the edges of the burnt area, which represented more than 80km in length. All of the Var massifs remained to enter very severe fire risk this Thursday, August 19th.

On Friday, August 20th, at midnight., the fire was considered "dominated", i.e., it was no longer progressing. The Prefect, together with the local politicians, also prepared for the post-crisis period with the establishment of a one-stop shop to support those affected by the fire in conjunction with the municipalities, the association of mayors, and the consular chambers. The CO_2 emission generated by the smoke from this fire and the loss of storage capacity that it caused by the destruction of the forest is estimated to be about 2.5 million tons of additional CO_2 in the atmosphere.

3.5 Fire impacts

3.5.1 Fatalities & loss of property

Two inhabitants perished in the fire and seven injuries were registered. 22 civilians were also slightly injured, including 19 for smoke intoxication.

The fire spread was very rapid from the beginning. Starting from Gonfaron the fire very quickly moved towards La Garde-Freinet, Grimaud then towards La Môle. Also, in its path, several campsites were evacuated, namely the Charlemagne Campsite, in Grimaud, and the PachaCaïd Campsite, in La Môle. By the 01.00 a.m. of August 18th, three campsites began preparing for their evacuation in Cavalaire: the CGU Campsite, the BonPorteau Campsite, and the Cros de Mouton Campsite. The Charlemagne campsite ended up being destroyed by the flames as can be seen in the photos in Figure 33 below.

(a) (b)



(c) (d)

Figure 40 – Photos of the Charlemagne campsite destroyed by fire, located in Grimaud

Several equestrian centers and a wine-cellar were also destroyed. Out of 627 buildings investigated by the various state services (forestry, civil security, ecology, agriculture, researchers), 320 buildings were identified as damaged by the fire.

Forest damage is of course to be deplored, including the 6 386 hectares of forests and moors, 5 797 hectares of private forest, and 466 hectares of public forest that were affected. More than 400 hectares of vineyard were damaged.

9 municipalities were impacted: 2 262 hectares in the municipality of Cannet des Maures, 1 802 hectares in the commune of La Garde-Freinet, and 794 hectares in the municipality of Cogolin. Two deaths are registered in the town of Grimaud. Several villages were evacuated always it was possible, and others were confined when more opportune. In total, 10 000 people were evacuated and accommodated in reception centers.

The phone and electricity distribution networks were impacted by the fire: electricity was cut off for 400 people during the fire only partially returning on August 20th.

3.5.2 Post-fire impactsnimals

Post-fire recovery actions were carried out urgently, especially rescue operations for Hermann's tortoises and other protected species, with a large mobilization of volunteers to rehydrate and treat the animals found, and transfer those injured to a recovery care center. More than 391 Hermann's tortoises were found during post-fire ecological assessments, including 251 alive (25 injured) and 140 dead. The survival rate of tortoise populations exposed to fire in the Nature 2000 area has been estimated at 60%, a figure much higher than that observed in particular in the hilly terrain due to the rapidity of the passage of fire and the presence of natural shelters in some areas of the Nature 2000 area.

We can also point out the installation of fascines on certain sites in order to limit the erosion of exposed soils, and the mineralization of temporary pools and oligotrophic environments by leaching.

Considering the rich biodiversity of the massifs and the very great fragility of the natural environments impacted by fire and the habitats of threatened species including the Hermann tortoise, the Prefect of the Var issued a regulation on September 10th, 2021 regulating access to the Nature 2000 area. This prohibits, for a period of one-year, pastoral activities, hunting, fishing, the presence of dogs, the circulation of pedestrians, riders, and cyclists, and other nature sports.

3.6 Conclusions and lessons learned

This extreme event questions the paradigm of public policies investing more in response than prevention. We can see here that the fire services were not able to protect all the citizens, homes, and infrastructures. Faced with extreme fires, measures to prevent building fires (e.g., self-protected buildings), and better preparation of the population seem to be necessary, following the example of the paradigm shift, from suppression to prevention, recommended by the consensus of scientific experts in this field [16].

Prevention and land management: the territory concentrates many conflicting socio-economic issues with the development of the territory and therefore with the WFRM, and these conflicts between wildlife ambassadors and proponents of land management to reduce fire risk led to the destruction of wildlife by fires. Thereby, the WFRM requires here a systemic approach, considering social and economic systems nested within natural systems. Here the question of agricultural abandonment, of the treatment of wasteland is important. We can also note that the investigations showed that the Legal Clearing Obligations were only 35% compliant with the recommendations, of which 17% were incomplete and 20% were not carried out. If additional analyzes are necessary to establish a precise link with the extent of this fire, we know the landscape connectivity and the accumulation of fuels accentuate the intensity of the fires and the speed of spread of the fires [17].

Response phase: fire has shown the effectiveness of certain tools used by French firefighters (e.g., back burning) which deserve to be incorporated more into practices with a less restrictive legal framework. However, it supports the information provided by the scientific community according to which the means of emergency civil protection can find themselves physically ineffective when it comes to fighting against an extreme fire that escaped the initial attack [18]. To answer this challenge, it seems necessary that the techniques for analyzing extreme forest fires are incorporated into the civil protection toolbox, in order to incorporate the scientific knowledge on extreme fire behavior in the analysis of intervention areas carried out by civil protection agents.

Finally, this fire triggered numerous attacks by the press and social networks against the reserve teams employed in charge of the reserve maintenance, accusing the latter of being responsible for the fire, because of the excessive restrictions that they put in place, on the realization of forest fire protection works. However, if the interest in the DFCI works (tracks and firebreaks) in France is twofold, on the one hand, to allow secure access for the firefighters within the framework of the fight and on the other hand, to channel and slow down the fire progression, this is only true for small to medium-sized fires. However, the behavior of this fire showed that it was part of the new European wildfire context defined by «*extreme fire behavior characterized by rapid spread, intense burning, long-range fire spotting and unpredictable shifts*» [16]. Moreover, if the scientific consensus shows that beyond certain environmental conditions, in a context of climate change and increasingly frequent and severe droughts, the behavior of fires changes [19], becoming more frequent and violent [20], challenging the suppression capacities of many wildfires' protection programs across Europe. This media attack seems to show that the new context of megafires is not acquired as knowledge by civil society, whereas «*this trend is the result of unbalanced policies that can be effective in fire suppression in normal weather conditions but are insufficient to prevent extreme event such* as megafires» [16].

FIRE OF MONTIFERRU

Authors

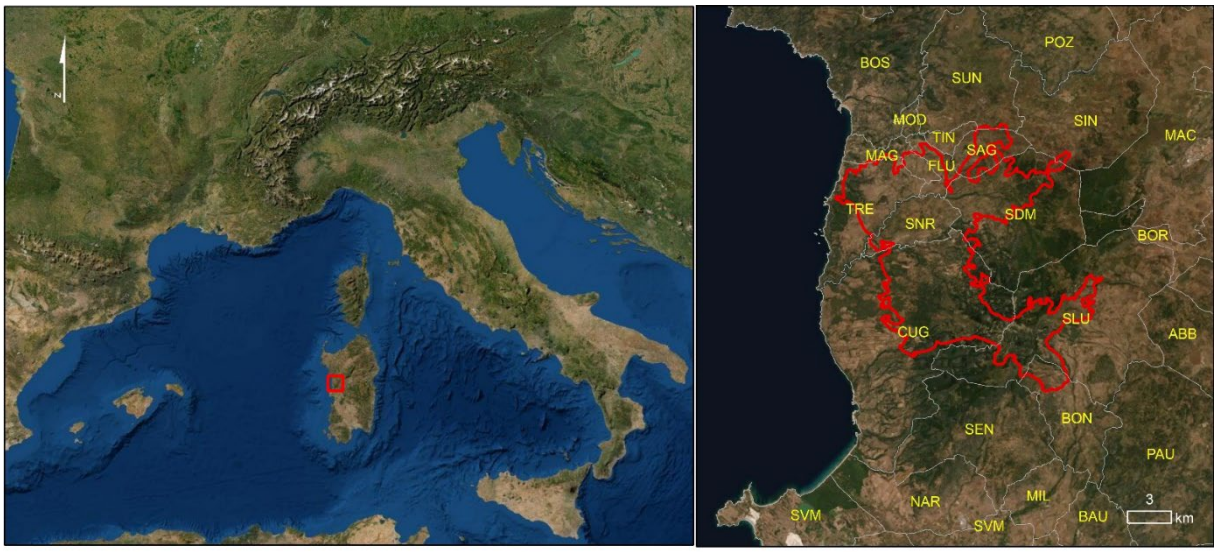
• Michele Salis, Bachisio Arca, Valentina Bacciu, Grazia Pellizzaro, Liliana Del Giudice, Daniela Stroppiana, Pierpaolo Duce, Annalisa Canu, Andrea Ventura	National Research Council
• Salvatore Cabiddu, Antonio Casula, Gabriella Cuccu, Tiziana Pinna, Massimo Vaccargiu	Sardinia Forest Service
• Stefano Campesi, Fabio Casule, Michele Chessa, Salvatore Cinus, Pietro Massidda, Michele Peddes, Fabrizia Soi, Francesco Tola, Antonio Usai	Sardinia Civil Protection
• Carluccio Castiglia, Carlo Dessy, Pier Luigi Trudu, Alessandro Delitala,	Sardinia Envir. Prot. Agency
• Salvatore Angotzi, Filippo Murtas	Sardinia Forest Agency
• Andrea Vittorio Barone, Natascia Erriu, Giovanni Fresu, Giuseppe Melis	Vigili del Fuoco
• Paolo Fiorucci	CIMA Found.
• Valerio Pampanoni, Giovanni Laneve	Univ. of Rome



4 The Wildfire Event of Montiferru (Sardinia, Italy)

4.1 General description

The Montiferru wildfire started on the SP15 road that connects Bonarcado and Santu Lussurgiu, in the Oristano province, western Sardinia, Italy (Figure 41). The ignition occurred in the late afternoon of July 23rd and was due to a vehicle fire. With about 13 200 ha of land burned, this event was the largest wildfire recorded in Sardinia in the last 35 years, and one of the largest at the National level of all time. The Montiferru wildfire was declared fully extinguished about one month after the ignition. This was due to the high frequency of rekindling in the forest areas because of both high ground and surface fuel loads and difficulties to mop up in a so large and topographically complex area.



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 41 – General map of the Montiferru area, including the 2021 wildfire perimeter and the administrative municipal boundaries. ABB=Abbasanta; BAU=Bauladu; BON=Bonarcado; BOR=Borore; BOS=Bosa; CUG=Cuglieri; FLU=Flussio; MAC=Macomer; MAG=Magomadas; MIL=Milis; MOD=Modolo; NAR=Narbolia; PAU=Paulilatino; POZ=Pozzomaggiore; SAG=Sagama; SDM=Scano Montiferro; SEN=Seneghe; SIN=Sindia; SLU=Santu Lussurgiu; SNR=Sennariolo; SUN=Suni; SVM=San Vero Milis; TIN=Tinnura; TRE=Tresnuraghes.

About 70% of the fire's final area, which is approximately 9 000 ha over 13 000 ha, was burned from about 18.00 CET to 24.00 CET on July 24th. The Montiferru wildfire affected a variety of forest and rural ecosystems (including highly valued oak forests, olive groves, and vineyards and about 300 several agro-pastoral farms), wildland-anthropic interface areas, and about 50 buildings, mainly located in the following municipalities: Bonarcado, Santu Lussurgiu, Cuglieri, Scano Montiferro, Sennariolo, Tresnuraghes, Flussio, Sagama, Magomadas. Fortunately, there were no human casualties, but many animals lost their lives in this wildfire.

Overall, the population density in the area impacted by the fire and its surroundings is limited (0.29 inhabitants per km^2 in the municipalities mostly affected by the fire) (ISTAT, 2010) [21]. The average net income (net taxable income/resident population) in the above municipalities is quite low and close to 8 600 € [21]. About 8% of residents people is involved in zootechnical activities (ISTAT, 2010) [21]. In general, the prevalence of scattered buildings in the landscape is due to the relevant number of agro-silvo-pastoral farms, generally of small size.

The final perimeters of the three largest wildfires that occurred in this area since 1980 are presented in Figure 42. A key point in driving large fires in these mountains is represented by the forest area of "Pabarile". This area is located immediately before the mountain chains of Montiferru and is mostly covered by herbaceous pastures. The leverage effect of Pabarile in originating large wildfires is principally determined by the complex combinations of topography, high-load fuels, and strong winds from South and East directions that are the main drivers of fires in this zone.

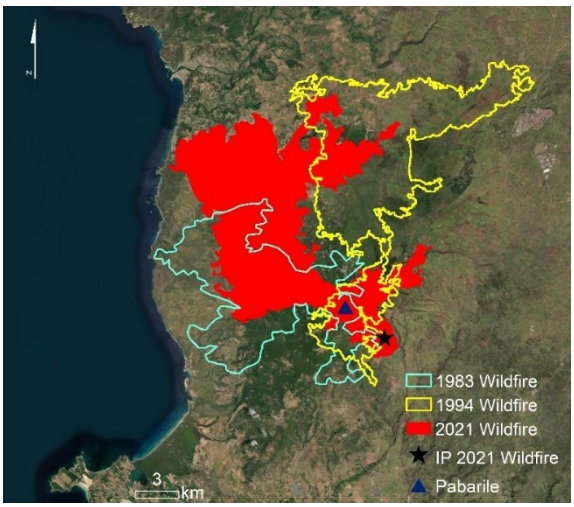


Figure 42 – Perimeters of the largest wildfire events that occurred in the Montiferru area in recent years.

4.2 Vegetation and topography of the affected area

From a phytoclimatic point of view, the area ranges from the Lauretum zone, at lower elevations, to the cold Lauretum zone at the highest elevations. The main forest type is represented by *Quercus ilex* woodlands, which dominate the lands in the altitude range of 400-900 m (a.s.l.). The holm oak is accompanied by *Quercus pubescens*, *Quercus suber*, *Arbutus unedo*, *Erica arborea*, *Pistacia lentiscus*, and in some areas by *Castanea sativa*, *Taxus bacata*, *Ilex aquifolium*, and *Acer monspessolanum*. Overall, the oak forests are often characterized by the presence of liana species, such as *Hedera helix*, *Rubus ulmifolius,* and *Smilax aspera*, which act as ladder fuels and increase fuel load and vertical continuity. The latter phenomenon has been progressively increasing in the last years in conjunction with the reduction of grazing and agro-forest activities in the area. In some zones, the landscape was greatly affected by the reforestation activities started in the early 1970s through mixed plantings of conifers (black pine, maritime pine, and Cedrus spp.) and broadleaf trees. High shrubs are mostly represented by tall *Arbutus unedo*, *Erica arborea,* and *Olea europea* var. *oleaster*. In the areas close to the sea, low shrubs of *Myrtus communis*, Cistus spp, *Rosmarinus officinalis*, Euphorbia spp., and Genistae can be found. Very low shrubs are also located at the top of the mountain areas, in the zones most exposed to wind and tilted. The municipalities of Cuglieri, Scano Montiferro, and Sennariolo present large portions of land covered by olive groves that are present, to a lesser extent, also in the south (Seneghe and Bonarcado municipalities). Vineyards are mainly located in areas closer to the coast.

The area affected by the Montiferru wildfire, according to the fuel map produced for the study site (Figure 43), is mainly represented by herbaceous vegetation (39.5%), low shrubs (24.2%), broadleaf forests (19.1%), olive groves (6.8%), high shrubs (6.7%), and conifer forests (2.9%).



Figure 43 – Main fuel types of the area affected by the Montiferru wildfire. AA=anthropic areas; OG=olive groves; HV=herbaceous vegetation; R=rocks; BF=broadleaf forests; CF=conifer forests; LS=low shrubs; WB=water bodies; HS=high shrubs. On the right, some olive groves were affected by the wildfire in the municipality of Cuglieri.

The wildfire area presents three main morphological domains (Figure 44).

1) The mountain sector (e.g.: Badde Urbara, Monte Urtigu), is characterized by the presence of large volcanic domes, with maximum elevations of about 1 000 m a.s.l. These very jagged reliefs dominate the entire complex and are joined together by rocky ridges without vegetation. The major contribution to the morphology of this sector is certainly made by the type of parent rock, which is represented by andesitic basalts. The zones derived from phonolitic lithologies present softer forms with very steep slopes, with gradients even higher than 45 degrees.
2) The foothill sector is mostly located in the western sector of the basin, where the most erodible lithologies generate hilly and sub-planar forms (basaltic flows), with weak slopes with a domed, rounded, or flattened appearance. The hydrographic network follows the main tectonic lines (E-W and N-S).
3) The flat or low hillside sector, which has very moderate slopes is mostly located in the northernmost portion of the study area.

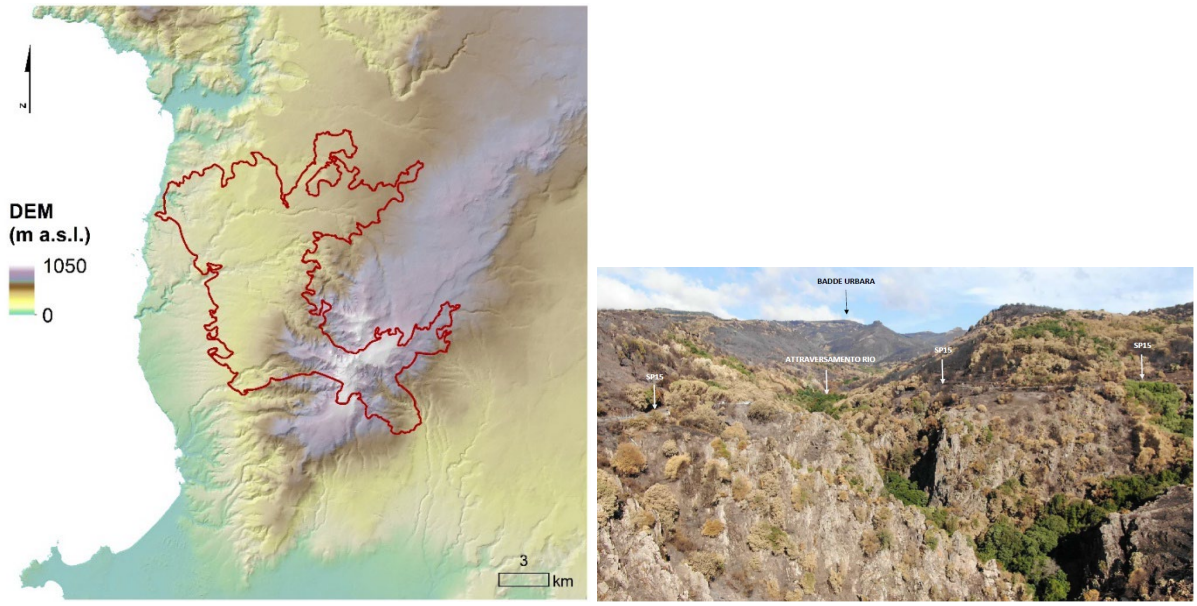


Figure 44 – Digital elevation model of the Montiferru area. On the right, a picture of the southeastern part of the wildfire area (Sos Molinos), from which the Badde Urbara peak can be seen.

4.3 Fire weather conditions

This analysis aims to describe the weather conditions from July 22nd to 26th in the areas affected by the Montiferru wildfire. The large-scale analysis presented is based on Eumetsat satellite images and numerical outputs partly produced by the European Center for Medium-Range Weather Forecasts (ECMWF) and partly processed by the Meteoclimatic Department of the Sardinia Environmental Protection Agency (ARPAS). Observed data were obtained from ground station networks and weather radar managed by ARPAS.

On July 22nd at mid-day, the European synoptic weather situation was characterized by three main baric structures (Figure 45): 1) a perturbation positioned northwest of Spain; 2) a ridge extended from North Africa to the Central Western Mediterranean and the British Isles, with a geopotential height over Sardinia between 588 gpdam and 590 gpdam; 3) a weakening trough stretched over Eastern Europe. Sardinia was affected by flows of relatively warm sub-tropical air and was on the border between a very dry area (that extended in a west-east direction from North Africa to the Eastern Mediterranean) and a cold air mass of polar origin with higher water vapor content that was transiting over Central and Western Europe. The synoptic evolution during the following days was a slow eastward movement of the abovementioned structures. This configuration carried southwestern flows toward Sardinia. This situation basically did not change until the afternoon of July 25th, when the approaching ascending branch of an Atlantic perturbation brought lower temperatures with widespread cloudiness over Sardinia, and convective events over Central Europe.

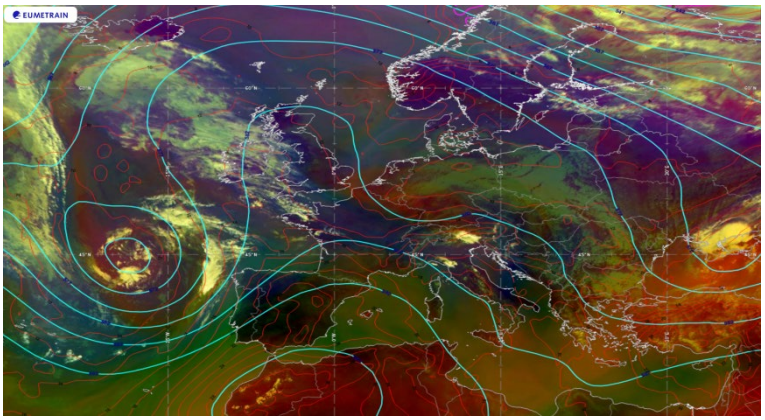


Figure 45 – MSG (Meteosat Second Generation) Air Mass RGB composition with ECMWF analysis of geopotential height (gpdam) and temperature (°C) respectively at 500 hPa and 850 hPa levels on 02.00 p.m. (12.00 UTC) of July 22nd.

The synoptic configuration above described resulted in the advection of warm air masses of African origin first over the Iberian Peninsula and then over Sardinia, as shown in Figure 46. The temperatures at the baric altitude of 850hPa were in the range of 20 to 24°C, over the entire island on July 23rd and 24th, with further increases on July 25th (24-28°C).

To support the fire management operational rooms, ARPAS provides high-resolution weather forecasts based on the WRF (Weather Research and Forecast) limited area model with a horizontal grid step of about 1.8km. Figure 47 shows temperature (2m), wind and relative humidity forecasts, issued the day before, relative to July 24th, 12.00 UTC of the regional-scale weather situation. On July 24th, a synoptic flow from the southeast prevailed over the thermal circulation. In addition, the warming of the 850hPa layer over the entire regional territory resulted in very high ground temperatures (T>37°C) and relative humidity between 20% and 30% for most of the regional territory (light yellow color shades); in the central hours of the day, SE winds were expected, with moderate-high intensity at the local scale (10.8m/s). Moreover, a southwesterly wind rotation for the night of July 24th to July 25th over the areas affected by the wildfire was forecasted. On July 25th, diurnal breeze and nighttime variable winds were expected.

The Weather Sector of the Sardinia Civil Protection issued a weather warning from July 23rd, 10.00 a.m. to July 25th, 06.00 p.m., and reported temperatures locally over 40°C starting from July 24th. Based on all available information, Sardinia Civil Protection published the fire danger bulletins, which highlighted extreme danger conditions in several sectors of the island for July 24th and 25th, as reported in Figure 48.

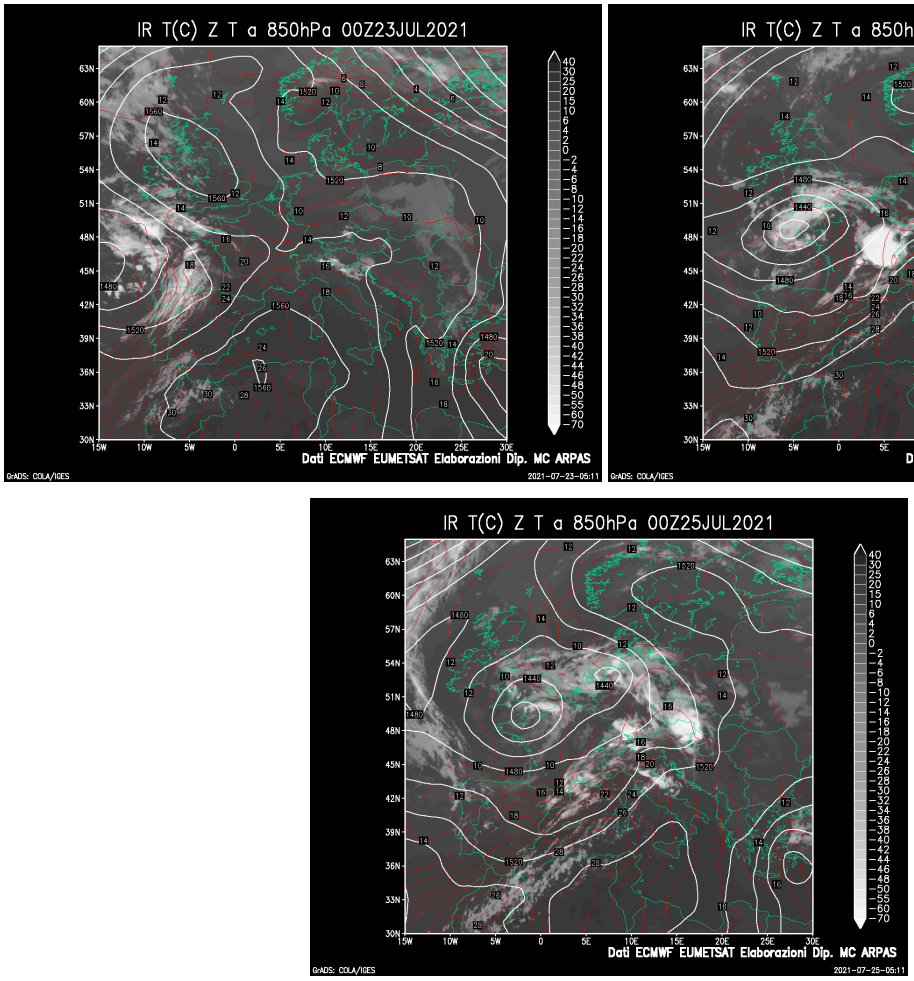


Figure 46 – Superimposed infrared MSG (Meteosat Second Generation) images and ECMWF analysis of geopotential height and temperature at 850hPa on 02.00 a.m. (00.00 UTC) of July 23rd, 24th, and 25th.

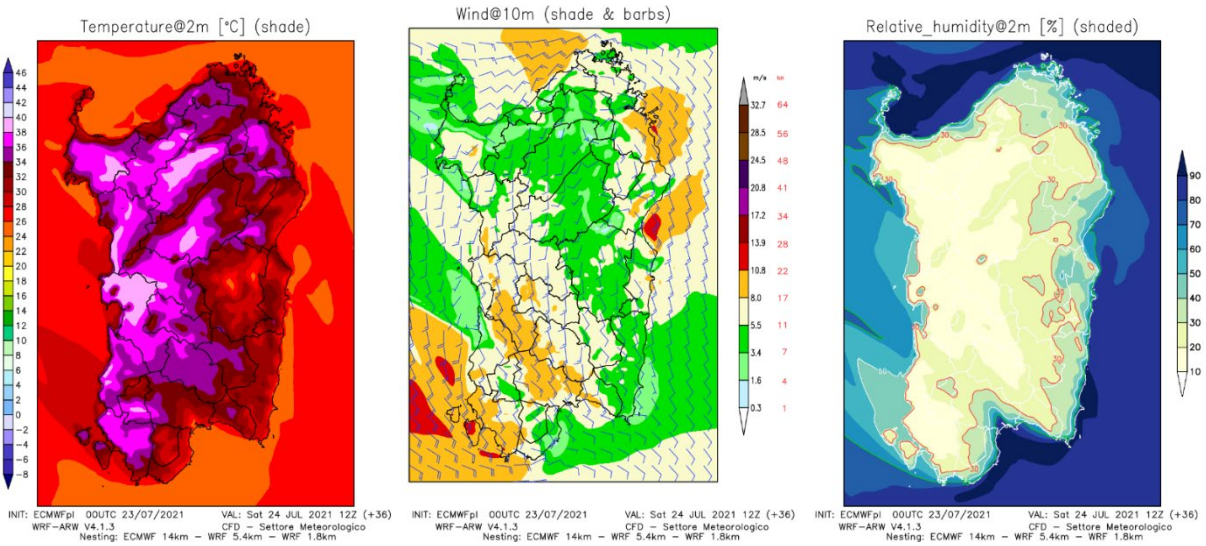


Figure 47 – Temperature, wind, and relative humidity conditions forecasted by the WRF model for 02.00 p.m. (12:00 UTC) of July 24th.

The large and regional-scale weather conditions occurring effectively complied with the forecast document issued the day before the fire. Figure 49 shows the areas with maximum temperatures above 37°C detected from the interpolations of the data observed in the weather stations of the Civil Protection, from July 23rd to 26th. The areas affected by the Montiferru wildfire were overall characterized by very high temperatures, especially on July 24th and 25th (purple regions in Figure 49). In particular, on July 24th the high temperatures were accompanied by strong winds from the southern quadrants (e.g., 11.6m/s in Badde Urbara and Scano Montiferro, 12.5m/s in Bosa).

Figure 50 presents temperature, relative humidity, and wind intensity data for the weather station of Badde Urbara (1 033m a.s.l.), which was directly affected by the wildfire at around 16.00 UTC on July 24th. When the wildfire reached the weather station, a sudden rise in temperature from about 30°C to 44°C was registered; at the same time, the relative humidity dropped to 13%, while the anemometer was damaged and suddenly stopped working. The low relative humidity values overnight (as observed in several weather stations) were a key factor to limit fuel moisture recovery and favor extreme fire spread and behavior in those hours.

Figure 51 provides the hourly data of 10h dead fuel moisture content and fuel stick sensor temperatures recorded in some of the fuel moisture monitoring stations of CNR-IBE, from July 20th to 28th. We focused our analyses on the stations closest to the Montiferru area and located in western Sardinia. On July 24th and 25th, fuel temperatures in the night and early morning hours were much higher than the general trend of previous days. For these days, peak values of the diurnal curve reached temperatures close to 45°C in Ghilarza (yellow line) and Giave (red line). In addition, from July 23rd the typical nighttime recovery of fuel moisture was not observed in Putifigari (green line), Samassi (violet line), and Ghilarza, with values being steadily below 8% from July 23rd at 09.00 a.m. for several hours (until July 25th at 09.00 p.m. in Putifigari, until July 26th at 06.00 a.m. in Ghilarza); albeit with a slight delay (from July 24th at 09.00 a.m. until July 26th at 05.00 a.m.), the Giave station evidenced the same conditions of prolonged low dead fuel moisture.

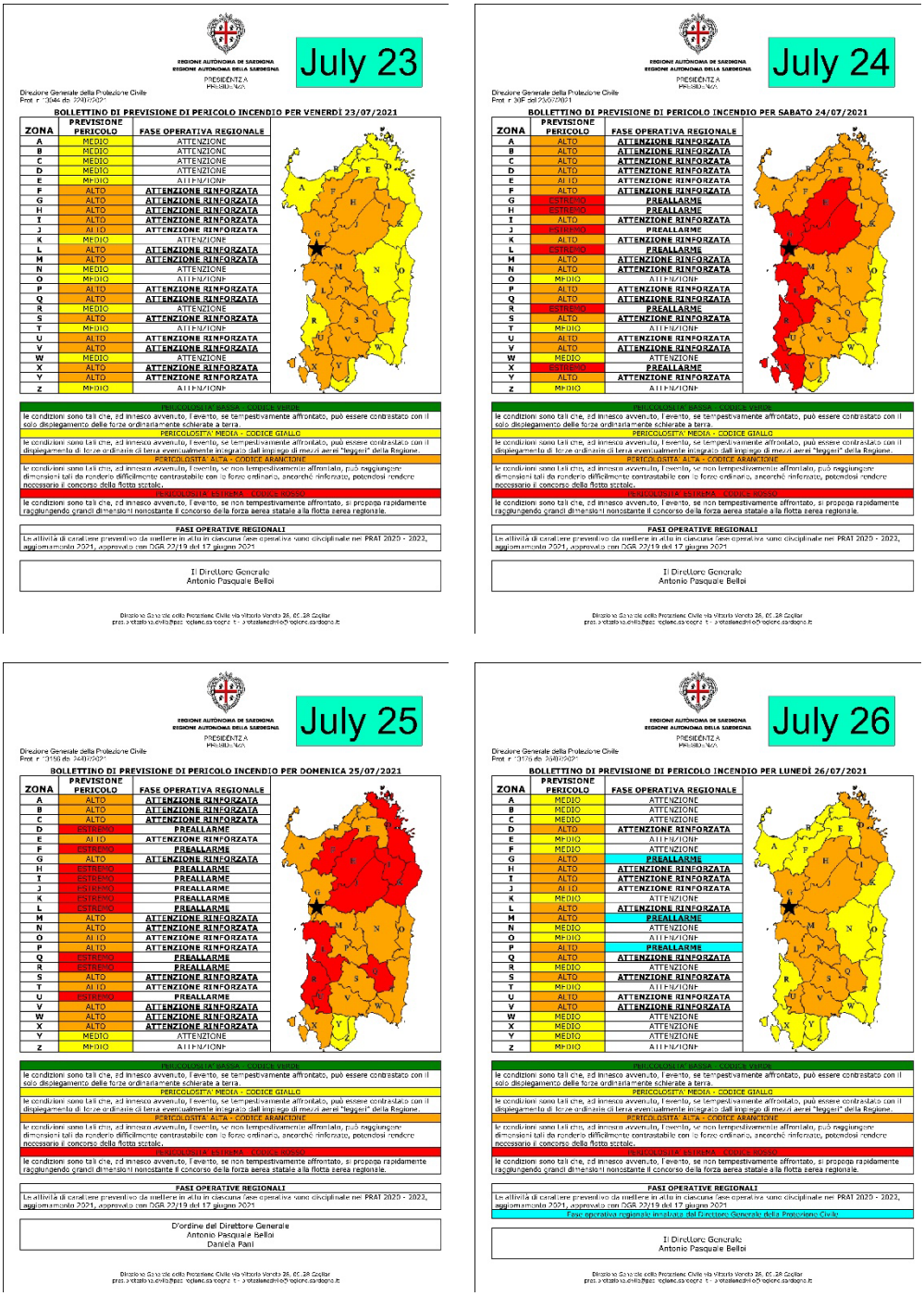


Figure 48 – Fire danger bulletins issued by the Sardinia Civil Protection for the period July 23rd to 26th. Sardinia is split into several homogeneous weather sectors (from A to Z). The black star indicates the Montiferru wildfire ignition.

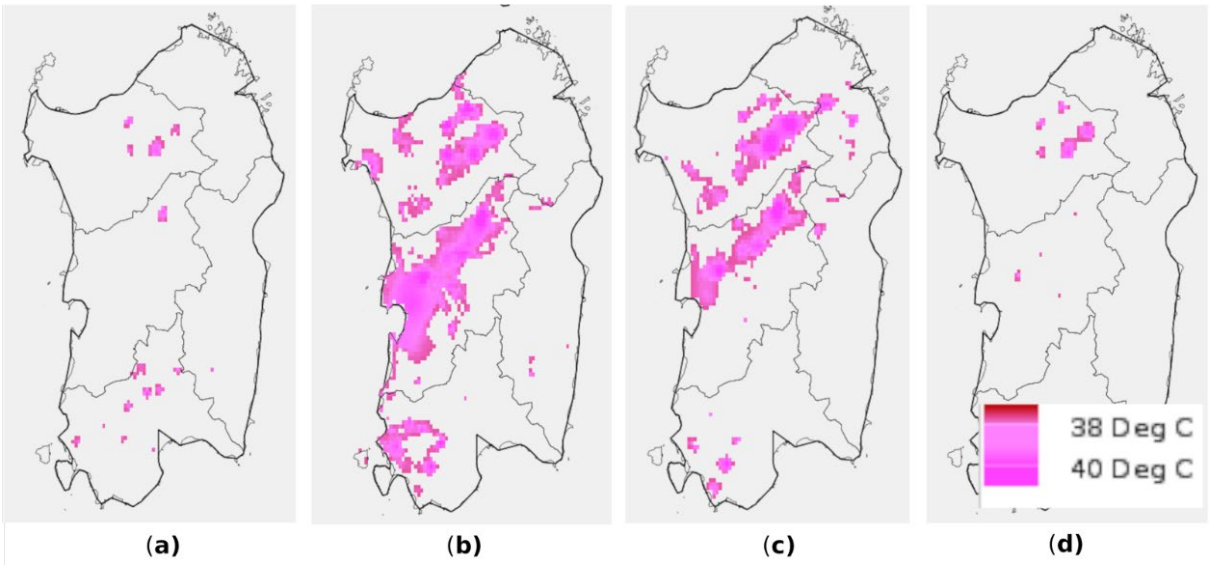


Figure 49 – Maximum temperature values above 37°C, as interpolated by the Dewetra integrated system of the Italian Civil Protection Department, from the data observed in the weather stations from July 23rd to 26th.

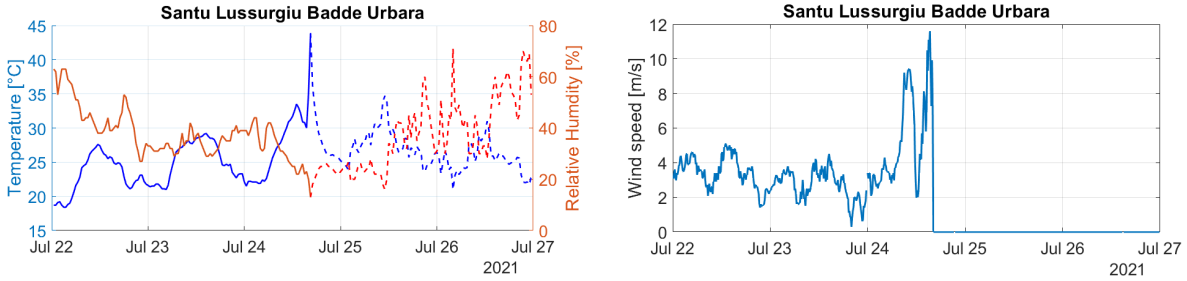




Figure 50 – Temperature and relative humidity, and wind intensity measured in the Badde Urbara (1,033m a.s.l.) weather station. The dotted line highlights when data of temperatures and humidity are not reliable as they refer to the period following the passage of the fire. The third image is evidence of the damage to the weather station caused by the wildfire.

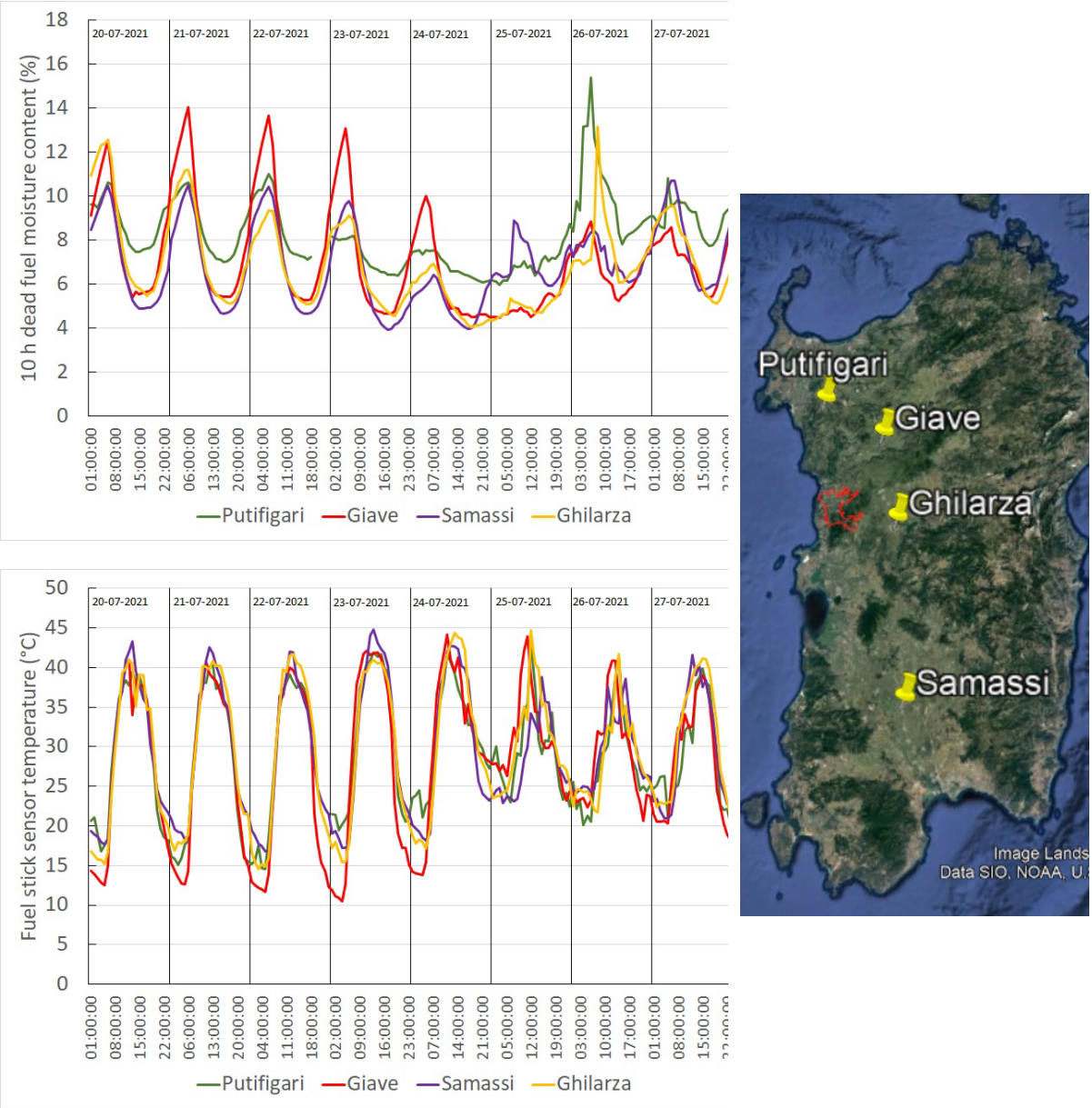
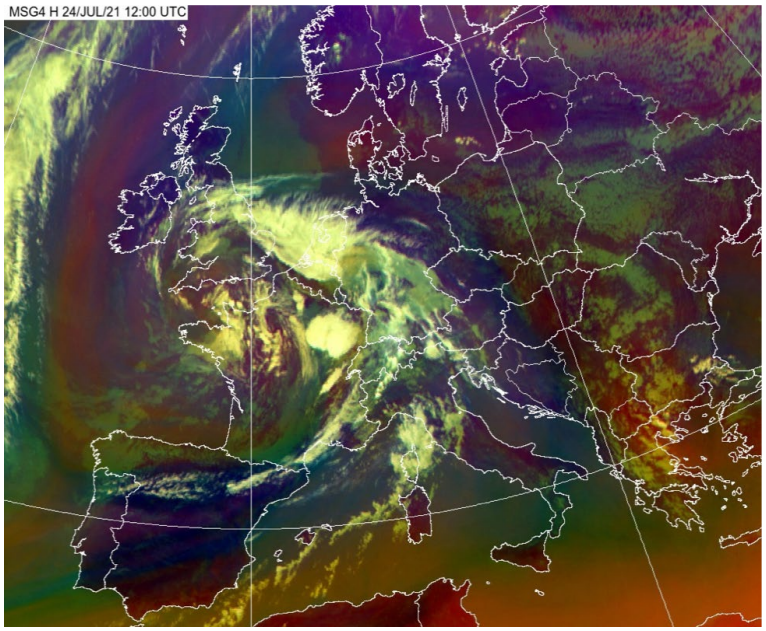


Figure 51 – 10h dead fuel moisture content and fuel stick sensor temperatures observed in four stations of monitoring, located in Putifigari, Giave, Ghilarza, and Samassi, from July 20th to 28th

As mentioned before, an Atlantic perturbation was initially located northwest of Spain in a further movement towards the Bay of Biscay. This weak depression wave caused the advection of moist air in the mid-high troposphere from the Sardinian Sea over the burning landscape, as shown by the MSG (Meteosat Second Generation) Air Mass RGB composition and radar scans from the afternoon of July 24th and the early morning of July 25th (Figure 52).

(a)



(b) *(c)*

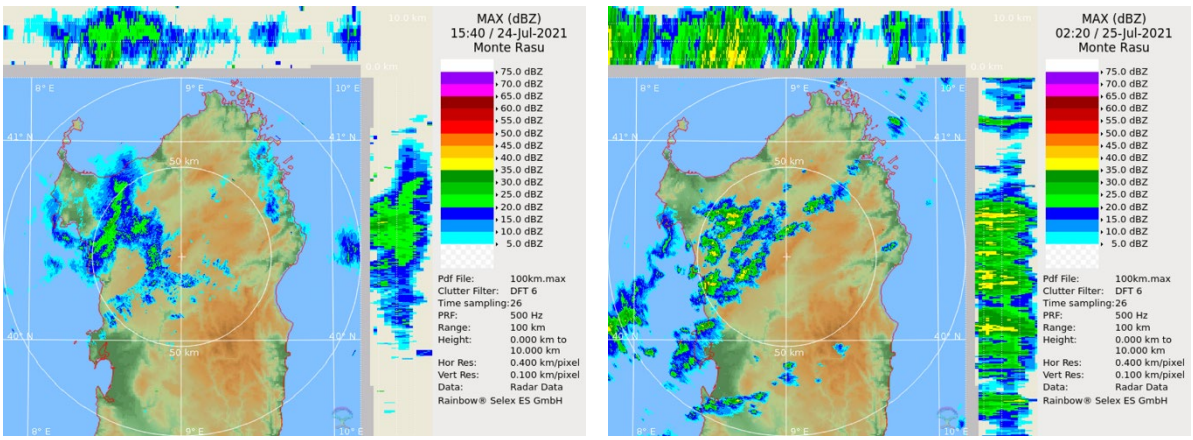


Figure 52 – Meteosat Second Generation (MSG) Air Mass RGB composition at 02.00 p.m. (12.00 UTC) of July 24th. Figures "b" and "c" present the vertical maximum reflectivity (dBZ) observed by the ARPAS weather radar (focus on two timeframes characterized by high wildfire growth rates).

These observations are compliant with the radiosounding of Decimomannu (16546 LIED) (July 25th, 00.00 UTC), at around 150km SE from the Montiferru area (Figure 53). In particular, between about 6 000m and 7 000m (a.s.l.), the actual and dew point temperatures were very close, which means hygrometric conditions close to saturation. This led to mid-high cloud formation in this layer, while the lower atmospheric layers were particularly dry. Figure 53b shows the radiosounding of Decimomannu on July 25th at 12.00 UTC. The atmospheric layer thickness close to saturation increased to 6 000m, from about 5 000m to 11 000m (a.s.l.), a condition that enhanced the possibility of precipitation. About this, some light rains were indeed recorded in the first hours of July 25th in northern Sardinia, mainly due to the synoptic moisture flow from the Sardinian Sea; an additional increase in water vapor at low levels was also due to the fire activity in the Montiferru area. It can be supposed that in the observed remarkably dry-adiabatic boundary layer conditions, the precipitation could not have reached the ground. Also, it is possible that the thermodynamic configuration of the troposphere drove the formation of dry microbursts with consequently anomalous erratic wildfire behavior, with the further possibility of synergistic interaction with the dynamics of the ongoing fire.

(a) (b)

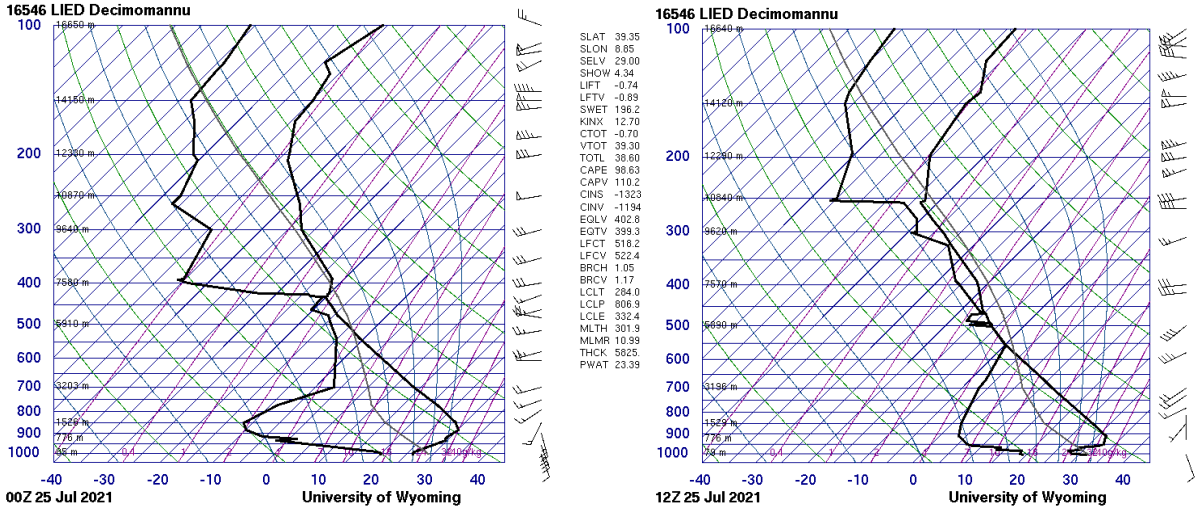


Figure 53 – Atmospheric radiosonde charts of Decimomannu (CA), 150km SE to the Montiferru, of July 25th, 00Z and 12Z.

4.4 Fire development and operational response

The Montiferru wildfire was divided into five main phases (from 0 to 4), according to the factors that mostly influenced wildfire spread and behavior, as well as topography and wind direction, and speed. The images from Figure 54 to Figure 61, reporting the isochrones of advancement of the wildfire were done by the Sardinia Forest Service.

On July 23rd, at 05.53 p.m., a fire was reported in the area named "Crachedu", in the countryside of Bonarcado, on the road that connects Bonarcado and Santu Lussurgiu (Figure 54). It was caused by a vehicle fire. In a few minutes, the Sardinia Forest Service (two operators and a firefighting pickup) arrived at the ignition zone. The fire moved towards SE driven by moderate NW winds, crossed the road, and attacked herbaceous pastures and grasslands moving downslope. A firefighting helicopter (EliFenosu) took off at 05.56 p.m. and began operating on the fire at 06.07 p.m. Other ground teams responded quickly to support aerial teams and, by 06.13 p.m., four more firefighting pickups (Forest Agency, Barracelli, Volunteers), a tanker, and thirteen operators were operational. Elibosa (06.25 p.m.), EliAnela (06.55 p.m.), and Superpuma (07.01 p.m.) helicopters further supported suppression operations. The helicopters returned to their bases at 08.22 p.m. (Elibosa), 08.25 p.m. (EliAnela), 08.42 p.m. (Superpuma), and 08.52 p.m. (Elifenosu), respectively, and by 09.00 p.m., the fire was reported as extinguished (Figure 54). The cleanup operations continued until midnight and a nighttime monitoring service in the area was guaranteed. By 07.00 a.m., on July 24th, the intervention of numerous teams was ordered for continuing the mop-up operations. EliFenosu returned to the fire area to complete the mop-up in support of the ground crews. Figure 54 presents a picture of the fire perimeter at 09.15 a.m.: the fire appeared to be completely extinguished, with no active flames or smoke. At mid-morning, two operators started mapping with GPS systems the entire fire perimeter: the area estimated as burned was about 17ha (Figure 54).

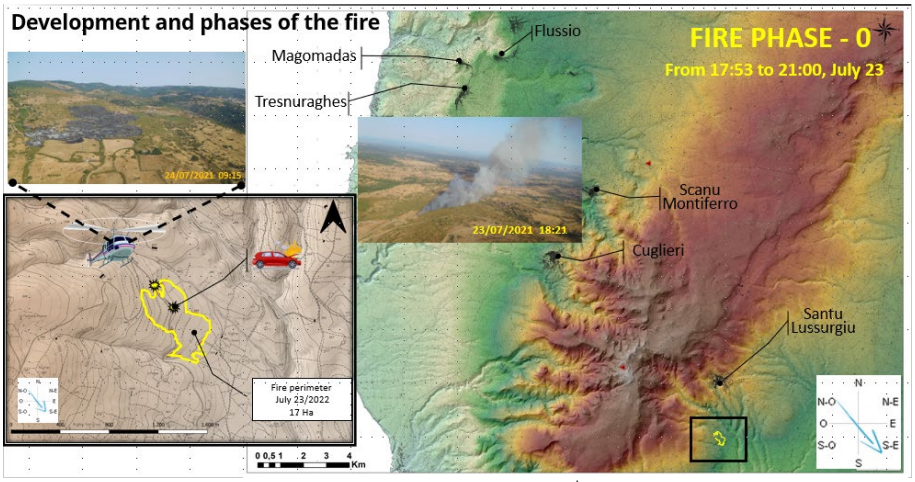


Figure 54 – Phase 0 of the Montiferru wildfire, July 23rd, from 05.53 p.m. to 09.00 p.m.

At 11.56 a.m., a new ignition along the provincial road activated a new fire, which initially affected an area not contiguous with the area burned the previous day. All personnel quickly went to the ignition zone to fight the fire, but the flames immediately became intense, and in a few minutes the smoke created a high column with very strong convective activity (Figure 55). This initial fire behavior was favored by the alignment of slope and winds from SE, the high temperatures, and the dry fuels (mainly herbs and low shrubs, including *Rubus ulmifolius*).

The EliFenosu interventions against the fire started at 12.02 p.m., but after the first drop, the wildfire managers realized that the containment of the fire propagation was very hard, due to weather conditions, topography, and the lack of safe roads or barriers in the area. Additional terrestrial forces, helicopters, and aircrafts were requested, as it was clear that the wildfire was moving towards the first steep Montiferru hills, characterized by higher fuel load and continuity. At 12.15 p.m., 20 minutes after the ignition, as presented in Figure 55, the smoke column looked very strong and sustained by increasingly strong S-SE winds. After 12.20 p.m., the convective motions originated by the smoke column promoted the occurrence of frequent and long spotting phenomena, as documented in Figure 55. Terrestrial force attacks were only possible in the rear and rear-flanks, while the front was out of containment capability for the forces operating at that time. Moreover, as reported by the Elifenosu and EliBosa pilots, the abrupt and recurrent changes in wind direction associated with the strong smoke plume restricted the potential of the helicopters in dropping water in the most effective spots, thus limiting the suppression effectiveness. The wildfire head spread aggressively, in very irregular ways, and presented three principal spread directions that, in a very short time, impacted some buildings and livestock farms in the countryside, for the protection of which the suppression efforts were concentrated. Two Canadairs started operating against the wildfire from about 01.15 p.m. until 04.00 p.m. At 03.00 p.m. and 03.30 p.m., two more helicopters went to support suppression operations in the area. The wildfire area remained uncovered with fixed-wing vehicles (Canadairs) for 30 minutes (from 04.00 p.m. to 04.30 p.m.). At this phase, about 270ha of land was burned (Figure 55).

The wildfire growth rate in these first hours was estimated close to 60ha per hour. The main concern was related to the enlargement of the front, which was progressively heading the south-west fringe of Santu Lussurgiu. Thus, the priority was set to operate with aerial forces on the right flank of the fire. The wildfire was declared a WUI (wildland-urban interface) fire at around 04.20 p.m. by Sardinia Forest Service and Vigili del Fuoco. Indeed, the buildings and houses of Santu Lussurgiu were evidently endangered, and the municipality was heavily covered by the tilted smoke plume that originated from the wildfire.

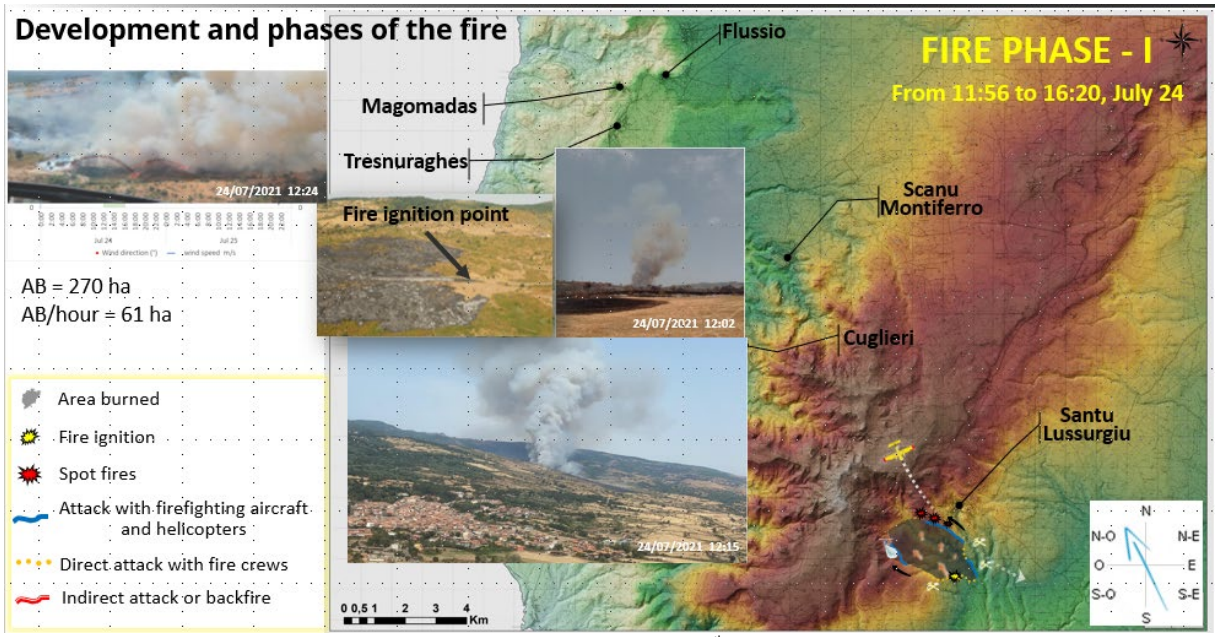


Figure 55 – Phase I of the Montiferru wildfire, July 24th, from 11.56 a.m. to 04.20 p.m.

The second phase of the wildfire covers the timeframe 04.20 p.m. – 06.10 p.m. of July 24th. In this phase, the wildfire moved upslope driven by the SE winds and reached the Montiferru mountain ridge line. About 390ha of land was burned in these two hours, with a growth rate close to 210ha per hour (Figure 56). At 04.30 p.m. a Canadair and then at 05.10 p.m. a second Canadair were again active against the wildfire. In the 04.00-05.00 p.m. time frame the wildfire heavily threatened the village of Santu Lussurgiu, so all terrestrial forces moved to protect the interface areas (Figure 56). The strategic plans of suppression were consequently mostly influenced by the need to defend and guarantee the safety of the community of Santu Lussurgiu. Aircrafts and helicopters were frequently used to drop water for protecting isolated structures in the countryside, such as agro-pastoral farms, animals, and isolated residential houses. Ground forces were concentrating their efforts on the wildfire rear, the only zone where operations were possible due to safety reasons, as well as on the village of Santu Lussurgiu and isolated structures. The other wildfire fronts were spreading almost uncontrolled towards Pabarile and then towards the steep and inaccessible areas of the Montiferru, where even aerial forces had very huge limitations in dropping water for safety reasons (dense smoke, strong atmospheric turbulence, impossibility to drop water efficiently at low height). Aerial means focused their launches on the two flanks of the wildfire only when there were no requests for water drops to protect houses or isolated structures in the countryside. On average, three regional helicopters and three Canadairs were supporting the firefighting operations in this timeframe. Moreover, the amount of aerial and terrestrial forces available for fighting this wildfire was strongly affected by the concomitant propagation of a number of large wildfires in other parts of Sardinia, which as described in the previous section was largely classified in Red Flag fire danger conditions.

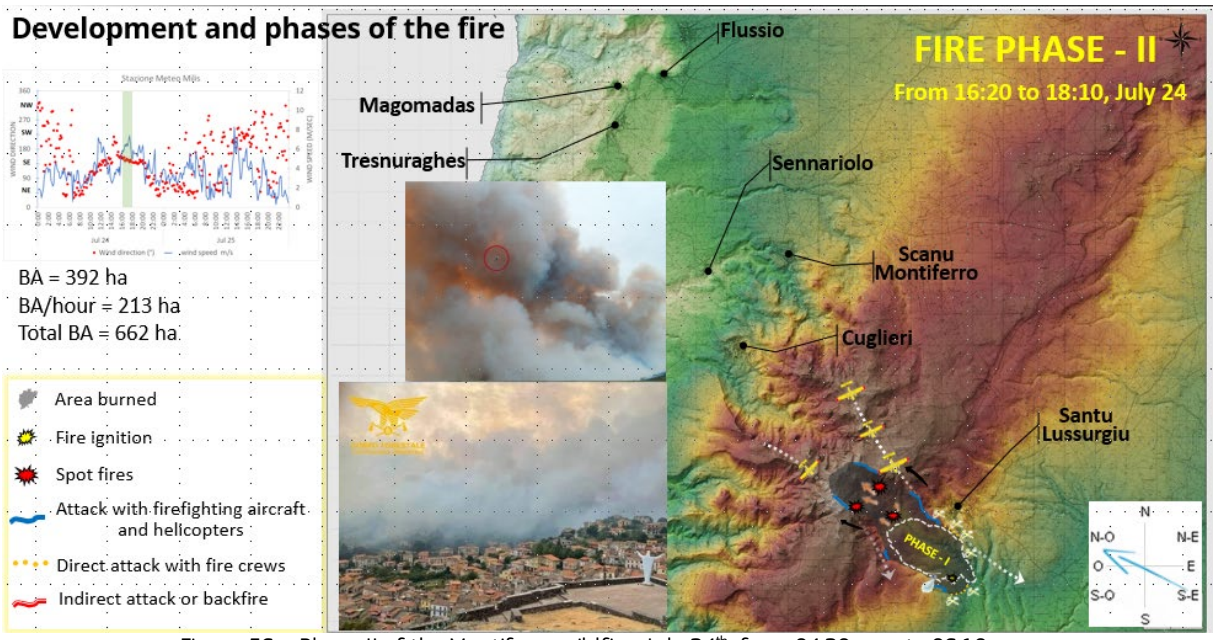


Figure 56 – Phase II of the Montiferru wildfire, July 24th, from 04.20 p.m. to 06.10 p.m.

The third phase of the wildfire is that from 06.10 p.m. to midnight on July 24th (Figure 57). When the different fire fronts of the wildfire arrived at the top of the crest lines of Montiferru, moving at high intensity in the slopes aligned with the SE winds, the wildfire behavior changed abruptly and became even more forceful. In about six hours, the wildfire burned an area of approximately 9 100 hectares, with growth rates of about 1 500 hectares per hour (Figure 57). This is by far the highest growth rate at night-time ever observed in Sardinia in recent years, and one of the most impressive of all time even considering daytime data.

From 08.00 p.m. to 08.40 p.m., due to the impossibility of aerial means to operate against fires at night, all helicopters and Canadairs had to leave the wildfire area and go back to their airbases. The wildfire progressively increased its intensity and spread rate: apart from the wind speed increase observed in several weather stations in the area and forecasted by ARPAS, several interviews and videos support the possible occurrence of strong downburst or downdraft phenomena that promoted the downslope propagation of the wildfire during this phase.

Considering the communication with ground forces and the requests for help from diverse majors, citizens, and agro-pastoral farms, the Regional Operation room requested the availability of more Canadairs for the early morning of July 25th and of supporting terrestrial forces from the neighboring areas of the island.

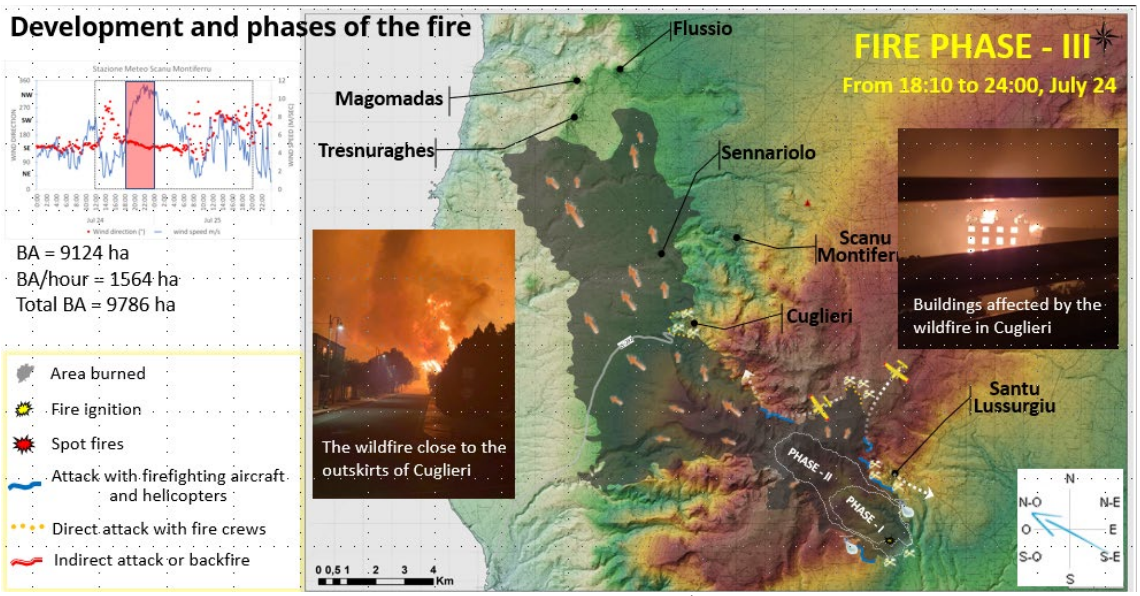


Figure 57 – Phase III of the Montiferru wildfire, July 24th, from 06.10 p.m. to midnight.

The last phase of the Montiferru wildfire was between 00.00 and 09.00 p.m. on July 25th (Figure 58). About 3 880 hectares were burned during this timeframe, with an average growth rate of about 180 hectares per hour. Part of the area burned was observed in the left flank of the wildfire, which spread towards the sea (Porto Alabe) and was associated with winds moving from SE and E; on the other hand, the most relevant area burned on July 25th was related to the right flank, which from mid-morning, due to the change in wind direction, became the new fire front and propagated north-west to Scano Montiferro. On this day, particularly after mid-morning, the weather conditions resulted much less severe than the previous day, with a decrease in temperatures and wind speed, and an increase in relative humidity, due to the SW wind fluxes bringing moister and milder air masses from the sea to the inlands. Moreover, the high presence of aerial forces and ground forces since the first hours of the morning allowed a great increase in the potential of suppression and blocking of the different active fronts distributed all over the wildfire perimeter. Two Canadair from the neighboring island of Corsica (France) and, later on, two from Greece, sent in the framework of the European Civil Protection mechanism, contributed to the firefighting suppression operations from July 25th to the next days. The days after July 25th were mostly devoted to mop-up operations and contrast fire rekindle, particularly frequent in the forest areas and the more remote or topographically complex spots. The Montiferru wildfire was considered fully extinguished about 1 month after the ignition, even if the fire spread and the area burned after the night of July 25th was very limited. The final area burned by the fire was about 13 000 hectares.

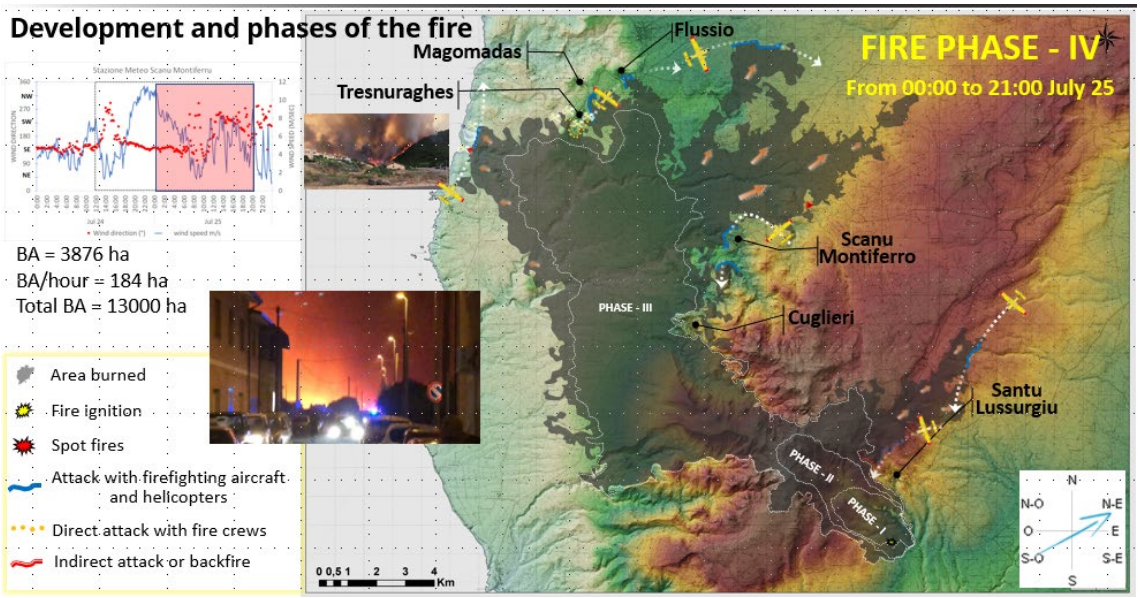


Figure 58 – Phase IV of the Montiferru wildfire, July 25th, from 00.00 to 09.00 p.m.

4.5 Smoke emissions and dispersion

Large wildfires have a series of negative and significant impacts on people, properties, and the environment with disastrous consequences on structures, habitats, and loss of human life. Moreover, fires emit significant quantities of smoke and numerous pollutants such as carbon monoxide, methane, nitrous oxide, nitrogen oxides, volatile organic compounds, and particulate matter (PM) that affect air quality and can threat human health. With the aim to understand this type of impact, CNR analyzed the Montiferru fire and its connection with air quality data levels, with a particular focus on PM_{10}.

To investigate the trajectory of the fire plume, the forward trajectories of air masses were computed with the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model developed by NOAA's Air Resources Laboratory (ARL) (Draxler et al., 2009; Stein et al., 2015). Then, to investigate the impact of Montiferru fire plume, PM_{10} concentration values measured at ARPAS's air quality stations have been used.

According to the HYSPLIT trajectories (Figure 59), fire plumes impacted the northern part of the Island, reaching the urban area of Sassari (NW) and Olbia (NE), which are located 80 and 140km away from the fire occurrence area. On the other hand, the temporal evolution of PM_{10} air concentration showed that a sudden increase in PM_{10} was registered at the closest air quality station in the central part of Sardinia, with a peak of 261µg.m^{-3}. Consistent peaks were also measured in the northwest stations 1-2 days after the fire ignition. The atmospheric conditions seemed to recover to their initial levels between 48 and 72 hours after the event (Figure 60).

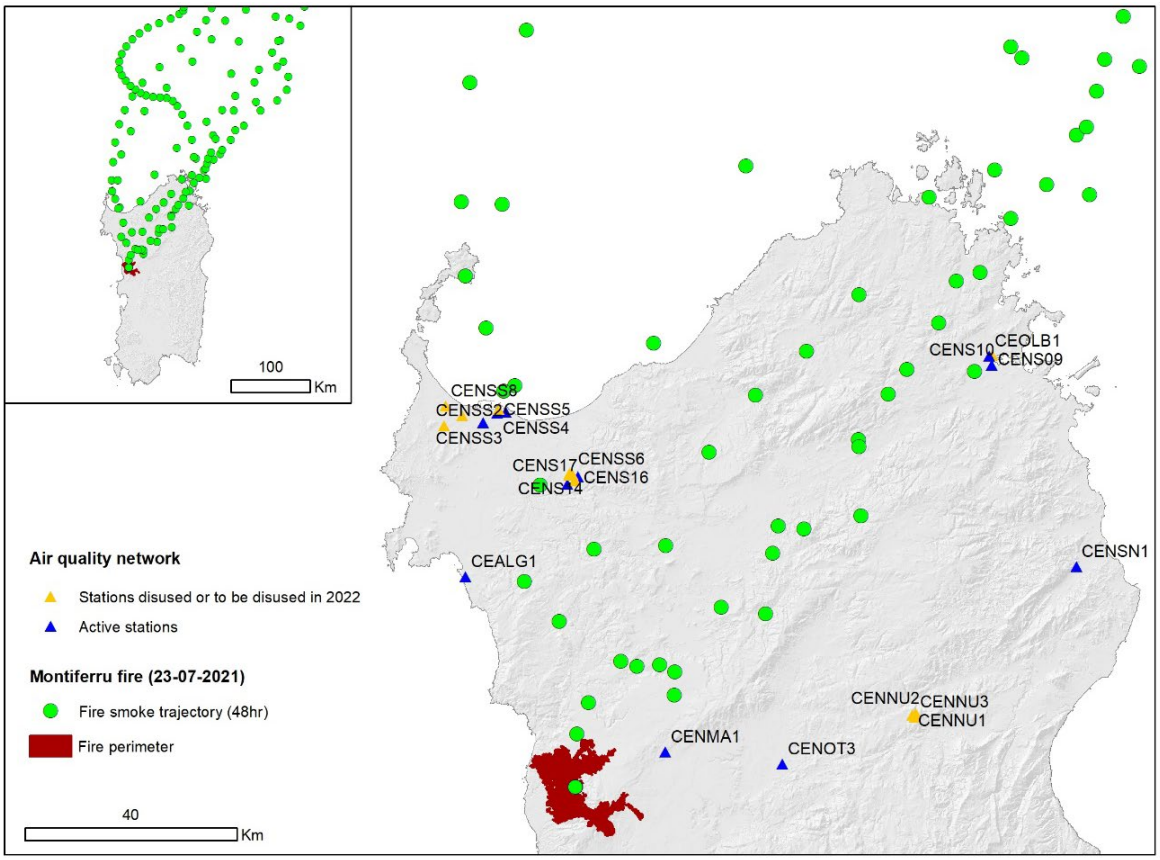


Figure 59 – Montiferru fire smoke plume trajectory at larger (a) and detailed (b) scale.

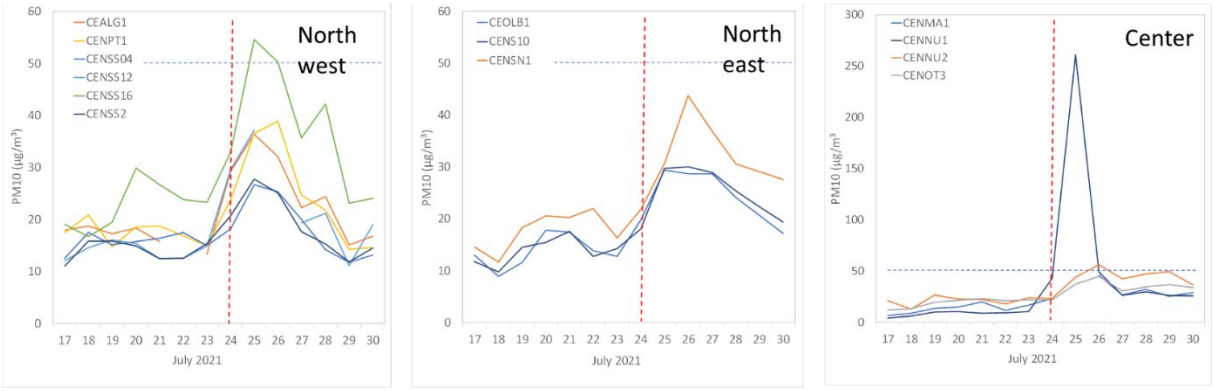


Figure 60 – Daily evolution trends for PM_{10} measured in ARPAS stations (Sassari, NW Sardinia; Olbia, NE Sardinia; and Nuoro, Central Sardinia), from July 17th to 30th.

4.6 Fire impacts

Burn Severity

Burn severity has been assessed from Earth Observation data and, in particular, by using Sentinel-2 multi-spectral satellite data acquired before (July 12th, 2021) and after (July 30th, 2021) the fire event. Remote sensing burn severity is a qualitative way of assessing the damage that occurred to the vegetation strata during a fire event and it is computed based on the values of the difference of the Normalized Burn Ratio index (ΔNBR) between pre-fire and post-fire Sentinel-2 images. The ΔNBR index has been computed within the fire perimeter (Figure 61) and pixel values have been assigned to burn severity classes based on widely accepted literature reference values (Keeley, 2009). The areas characterized by the highest burn severity account for about 5 000 hectares and are mainly located in the southern portion of the wildfire perimeter. Only 10% of the area burned was characterized by low severity values, while unburned conditions were found in about 4% of the area affected by this event.

The map of burn severity depicts the spatial distribution of the damage level that occurred to vegetation; however, it can be related to damage assessment carried out after the fire event over the burned landscape.

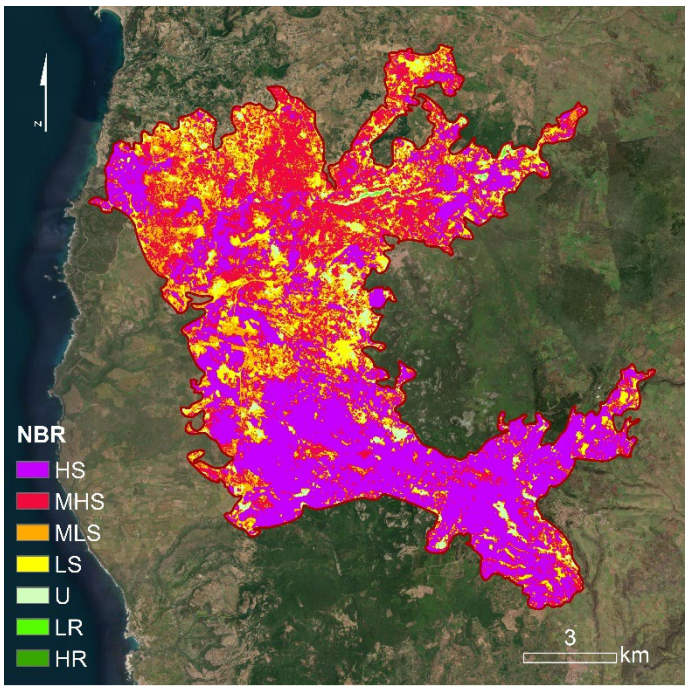


Figure 61 – Burn severity estimated for the Montiferru wildfire. This output was derived by rescaling the Normalized Burn Ratio index (NBR). HR=high regrowth; LR=low regrowth; U=unburned; LS=low severity; MLS=medium-low severity; MHS=medium-high severity; HS=high severity.

Impacts on buildings

According to the survey of Vigili del Fuoco and Civil Protection, the impact of the Montiferru wildfire on buildings was significant and involved not only residential structures, mainly concentrated in small villages but also agricultural structures, characterized by a substantial dispersion degree within the burned area landscape; in addition, although to a lesser extent, tourist and commercial structures were affected. It has been estimated that 1 420 structures required the evacuation of the population due to the high and imminent risk of fire. A large number of structures actually suffered damage (Table 6), particularly agricultural warehouses (457, of which 68 had medium to severe damage) and residential structures along the interface areas (53, of which about 50% suffered medium to severe damage). On average, high amounts of damage were observed in about 11% of the structures hit by the wildfire. In many cases, post-fire damage surveys detected minor damage to buildings, or simply signs of the fire passage, but considerable damage to outdoor equipment or facilities (e.g., verandas), which by their nature are more vulnerable than buildings, which are generally not constructed of wood or flammable materials. 53 residential houses were damaged, with particular relevance in the municipalities of Cuglieri and Sennariolo (Figure 62). Damage to farms mainly concern fences, buildings, and stocks. Damage to 31 public buildings are also reported; other damage not yet quantified includes power lines, telephone lines, and roads (Figure 63 to Figure 65).

Table 6 – Classification of the structures damaged by the Montiferru wildfire, discriminated by damage severity.

Structure type	Low damage	Medium damage	High damage	Total
Residential	28	13	12	53
Agricultural residences	2	3	1	6
Agricultural warehouses	389	31	37	457
Tourist structures	1	0	2	3
Artisan structures	2	0	1	3
Commercial structures	2	2	2	6
Other	5	3	7	15
TOTAL	429	52	62	543

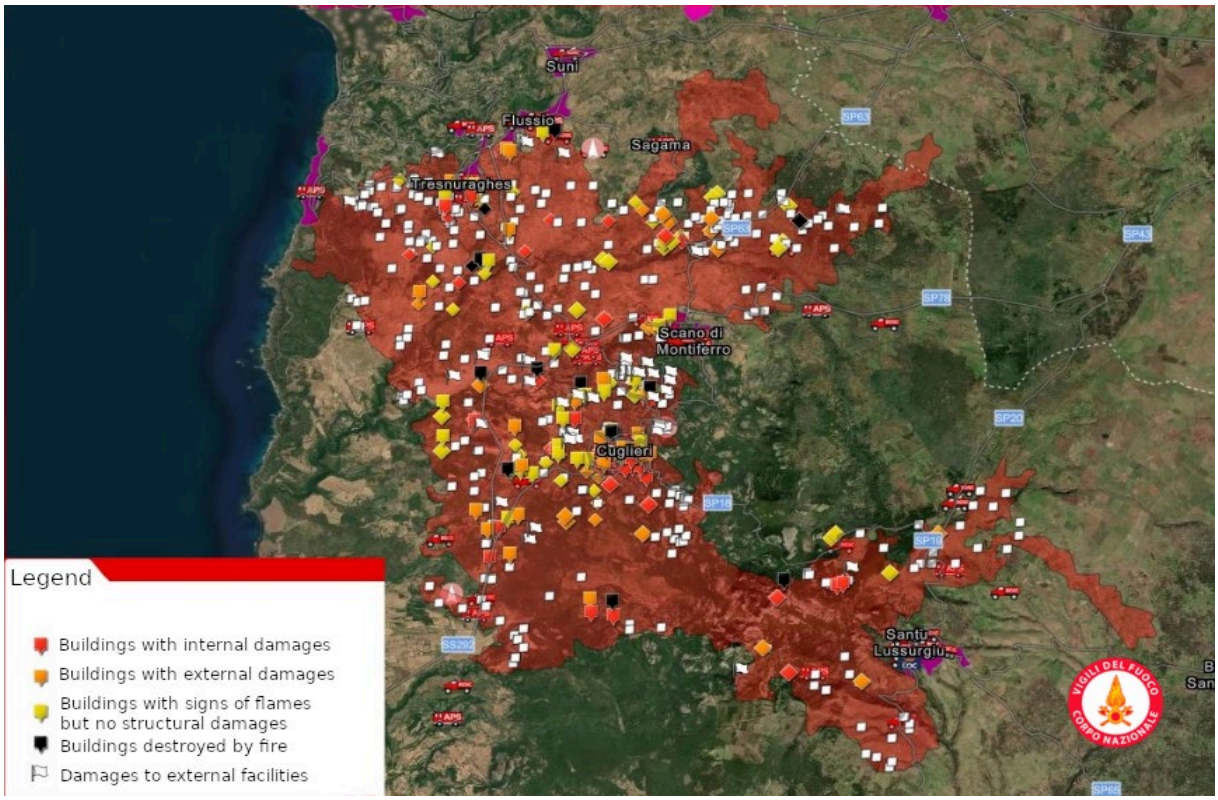


Figure 62 – Location of residential, agricultural, and other buildings partially or heavily damaged by the fire.



Figure 63 – Damage to a telecommunication infrastructure installed within a forest area affected by the fire (Source Protezione Civile).



Figure 64 – Damage to a private company in the industrial area of Cuglieri (Source Vigili del Fuoco).



Figure 65 – a) A house heavily damaged by the fire; b) Agricultural warehouse seriously compromised (b) (Source Vigili del Fuoco).

Impacts on agricultural and livestock farms

The losses for the olive-growing heritage are considerable. The Laore Regional Agency, responsible for managing the register of olive-growing areas, estimated that 680 ha of olive-growing, with about 84 000 olive trees, suffered extensive damages and required major restoration interventions. These losses were mainly concentrated in the municipalities of Cuglieri and Sennariolo.

According to preliminary estimation, about 300 livestock farms, distributed throughout the Montiferru area, were affected by the wildfire (Figure 66), and about 40 livestock farms reported dead, injured, or lost animals (Table 7). Most of the losses occurred to sheep farms. Finally, 8 beekeeping farms suffered damage to over 400 hives, with an estimated loss of 36 million bees (assuming 90 000 bees per hive in the peak of the summer period).

Table 7 – Number of livestock farms that suffered damage, together with the animals that were injured or lost due to the Montiferru wildfire. The data refer to preliminary surveys and might be underestimated.

Comune	Farms (#)	Donkeys	Cattle	Goats	Horses	Sheep	Pigs
Cuglieri	26	27	37	1	5	297	3
Flussio	1	--	--	--	--	185	--
Santu Lussurgiu	3	--	1	--	--	--	4
Scano Montiferro	2	--	--	--	2	10	--
Sennariolo	3	--	1	--	--	34	--
Tresnuraghes	5	--	--	--	--	343	--
Totale	**40**	**27**	**39**	**1**	**7**	**869**	**7**

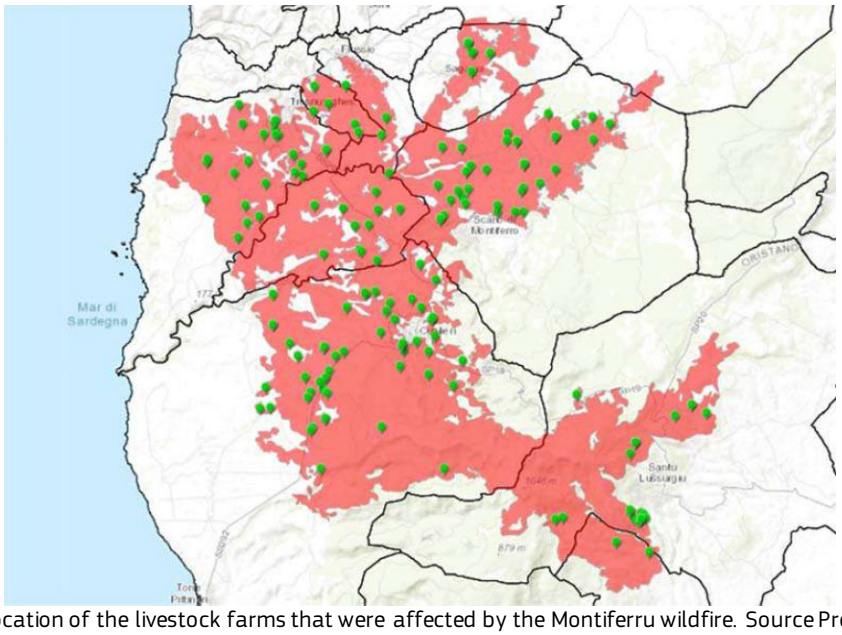


Figure 66 – Location of the livestock farms that were affected by the Montiferru wildfire. Source Protezione Civile.

Post-fire soil erosion

The high wildfire intensity caused the loss of the organic component and the mineral part of the soils, thus contributing decisively to strong damage to the soil structure, particularly in the surface horizons, and to its exposure to winds and surface run-off from meteoric waters. The lack of protection given by vegetation and litter, now completely burned, the slope of the terrain and the soil characteristics favored the run-off of the finest soil material, which some days after the fire event presented accumulations up to 20-40 cm thick. This situation was especially evident along the road that connects Bonarcado and Santu Lussurgiu, as well as in Badde Urbara area and on the tilted areas bordering Santu Lussurgiu (Figure 67). The presence of a superficially stratified ash layer has made the soil impermeable in several areas, mainly in forest zones characterized by high surface and ground fuels, and this has caused several limitations in rain infiltration even for moderate rainfall events. Consequently, an increased potential for the occurrence of phenomena such as debris flows or landslide is expected. Overall, this could be a relevant risk in the two years following the fire, with a period of maximum incidence between 2 and 10 years.

In order to monitor these hydrological processes, CNR-IBE installed in the Montiferru area six silt fences, made of wooden posts and geotextile fabric, to measure post-fire sediment erosion (Figure 68). The sediment fences were installed at the base of six plots of 30m^2 (3x10 m^2) in two areas with a slope of 12% and 20%; the first area was mainly characterized by *Quercus ilex* and *Erica arborea* (Plot A), the second by *Arbutus unedo* and *Quercus ilex* (Plot B). The sediment trapped in the fences was periodically removed, weighted, dried, and analyzed to determine water content, particle size distribution, and dry sediment weight. The total precipitation in the area from October 2021 to March 2022 was 557mm. An uncommon lack of precipitation was observed from January to February with only 58mm of rainfall. The first rainfall events after the Montiferru wildfire were heavy. During the first months of monitoring, high values of post-fire sediment erosion, equal to 4.3ton/ha in Plot A and 4.7tha^{-1} in Plot B respectively, were observed. Previous research carried out by CNR-IBE in Northwestern Sardinia in an area covered by *Quercus suber* and similar slopes highlighted lower values of soil erosion (2.8 tons/ha) in the first year after the fire.

In addition, a significant increase in landslide events was observed in the municipalities affected by the wildfire. As presented in Table 8, the landslide events that occurred in the period August 2021 to April 2022 in the Montiferru area were higher than those observed in the previous five-years period (2016-2020).

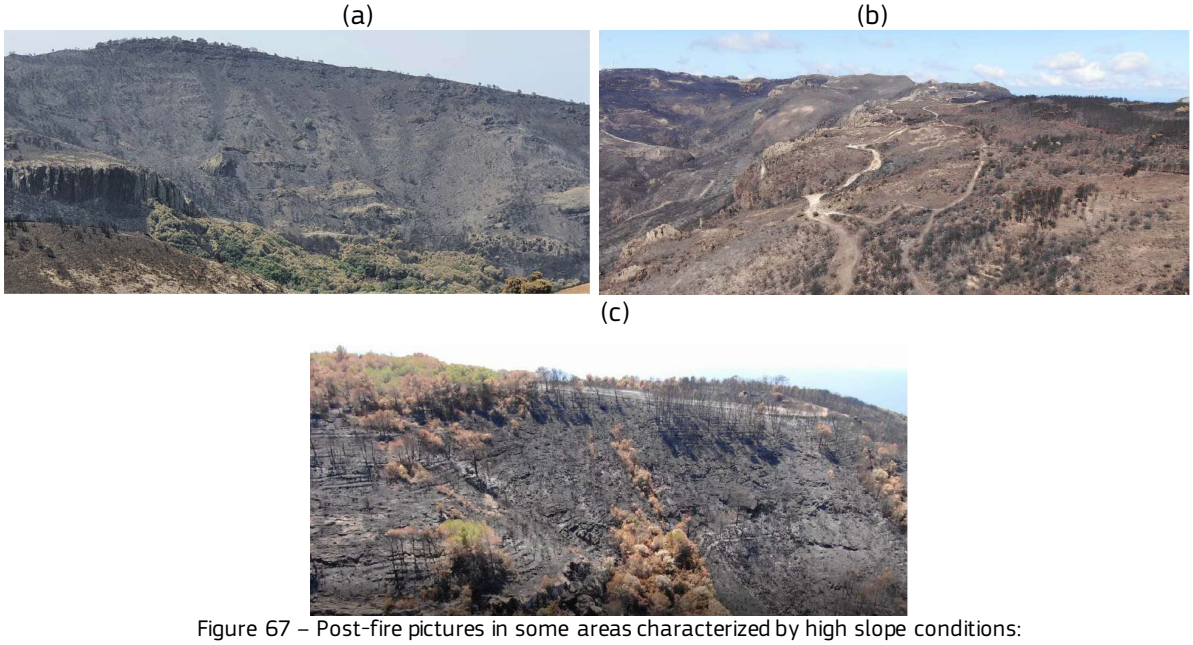


Figure 67 – Post-fire pictures in some areas characterized by high slope conditions: (a) Cuglieri, (b)Santu Lussurgiu, and (c) Tresnuraghes.



Figure 68 – The sediment fences installed in the Montiferru area a few weeks after the fire, prior to rain events.

Table 8 – Number of landslide events that occurred in the Montiferru area during the period 2016 – 2022 (data provided by Vigili del Fuoco).

Reference period	Landslide events (#)
2016	2
2017	2
2018	1
2019	2
2020	1
Aug. 2021 – Apr. 2022	**14**

4.7 Conclusions and lessons learned

The occurrence of large wildfires is progressively increasing in Mediterranean Europe, as well as in other areas. These large wildfires generally spread on days characterized by difficult weather conditions (e.g.: strong winds, low relative humidity, and high temperatures). During these days, even aerial suppression forces could not be enough to limit fire spread. The increasing abandonment of Mediterranean rural and forest areas and the consequent increase in continuity and load of flammable fuels are making suppression operations increasingly complex, even with moderate fire weather and environmental conditions. Agro-silvo-pastoral activities are therefore crucial to manage wildland and rural fuels, maintaining the population in remote areas, and avoiding depopulation and loss of income. Specific agreements between agro-sylvo-pastoral farms and community/national/regional Agencies should be promoted to tie a portion of funding to the performance of adequate prevention activities by the farms while maintaining agro-silvo-pastoral productions. In addition, it is crucial to integrate fire risk into urban planning, as well as to effectively support anthropic area protection through fuel management and prevention activities.

FIRE OF ATTICA

Authors	
George Eftychidis	KEMEA
Vassiliki Varela	KEMEA
Ilias Gkotsis	SATWAYS

5 The Varybobi Fire Event, Attica (Greece)

5.1 General description

The fire started on Tuesday, August 3rd, at 1:20 p.m., 18km north of the center of Athens, near a settlement called Varybobi, which is one of the WUI areas that exist around the city, located in the lower part of the foothill of Mount Parnes (Figure 69). The temperature at that time had reached 42°C, and the relative humidity was dropped nearly 10%, while the wind strength was around 8km/h with gusts exceeding 15km/h. The fire grew, mainly through radiation and profuse short-distance spotting since the wind was not strong. Several instances of damage to houses and infrastructure were caused by the fire, while indirect human losses have also been reported.

(a) *(b)*



Figure 69 – Initial phase and development of the Varybobi 2021 fire.

5.2 Characterization of the affected area

The Varybobi fire, named following the name of the settlement where the fire started, affected a number of wildland-urban interface settlements in North Attica, including Varybobi, Tatoi, Thrakomakedones, Adames, Afidnes, and Ippokrateios Politeia. The fire burned for five days and blackened 8 453.8 ha of forest, agricultural and wildland-urban interface land.

Varybobi is a typical wildland-urban mixture settlement (Figure 70), located 17km northeast of the Athens city center in a *Pinus brutia* forest, 300m above sea level at the foothill of Mount Parnes. The settlement is surrounded by several other WUI areas, including Thrakomakedones 3km westward, Kryoneri 4km eastward, and Acharnes 7km to the southwest. The Olympic Village of the 2004 Summer Olympics is located 3km southwest of Varybobi. Administratively, it belongs to the Municipality of Acharnes – Thrakomakedones in northeastern Attica, and it was a separate settlement until 2001 when it joined Acharnes.

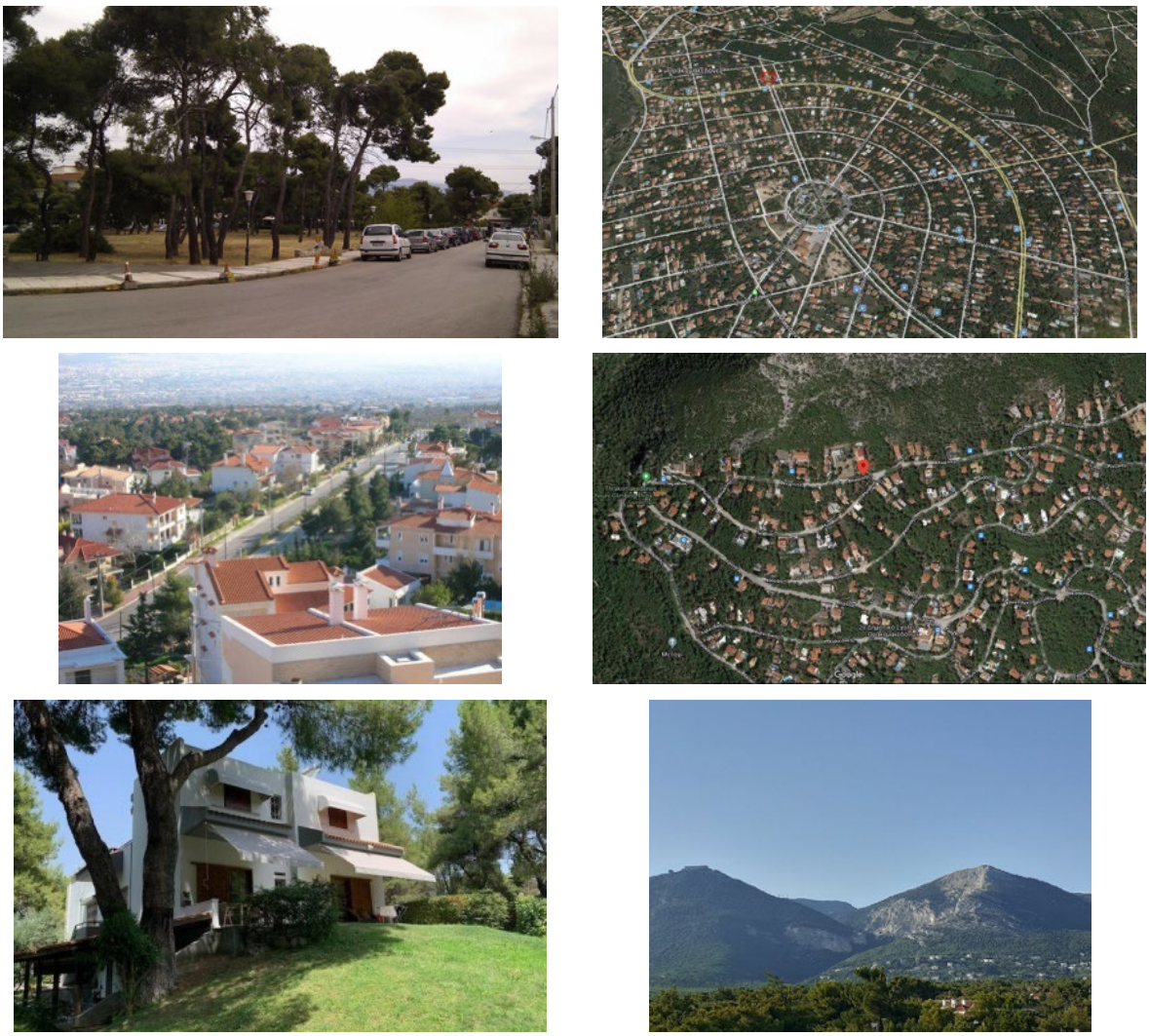


Figure 70 – Wildland urban interface in the wider area of the Varybobi 2021 fire.

Varybobi was a small settlement till 1940 when a building cooperative created a new settlement in the area. With the creation of new housing, the population increased. The reconstruction of the area continued in the remaining decades, resulting in the population reaching lately 1,500 inhabitants. The area is known for its recreation facilities and the large, closed equestrian and societal clubs, the Tatoi Club, Jockey Club, and Ariadne Estate being historical. Important facilities in the area of Varybobi are the Tatoi Airport, located in the south part of the settlement, the Montessori schools of Athens, the facilities of the Varybobi Equestrian Club, and the Northern Suburbs Equestrian Club. The old royal palace of Tatoi is located near the homonymous settlement.

Two main hydrographic systems exist in the wider area. The first is developed by the Oinoi River, which flows in the direction of the Marathon, and the other is based on the Kifissos River, which flows towards the western suburbs of Athens. The landscape is hilly and mountainous, and the topography of the area is characterized by gentle (up to 10%) slopes in 15.4%, moderate (up to 20%) slopes in 28,6%, and steep (up to 45%) slopes in 52,5%. The geology of the burned area is represented by Neogene and sub-pelagonian (limestones) formations.

The more flammable forest vegetation in the area is represented mainly by mature Aleppo pine (*Pinus halepensis*) stands, with a dense and thick understory of shrubs. According to Corine Land Cover 2018 classification, the area is covered by vegetation represented by mixed (22.16%), broadleaved (4.53%), and coniferous (15.36%) forests as well shrubs (2.92%) and scrublands (24.17%). There is also 10.73% coverage with dispersed cultivations, while 10.13% of the area is occupied by natural vegetation that replaced old, abandoned agricultural land. Urbanized areas cover 7.93% of the area (Figure 71).

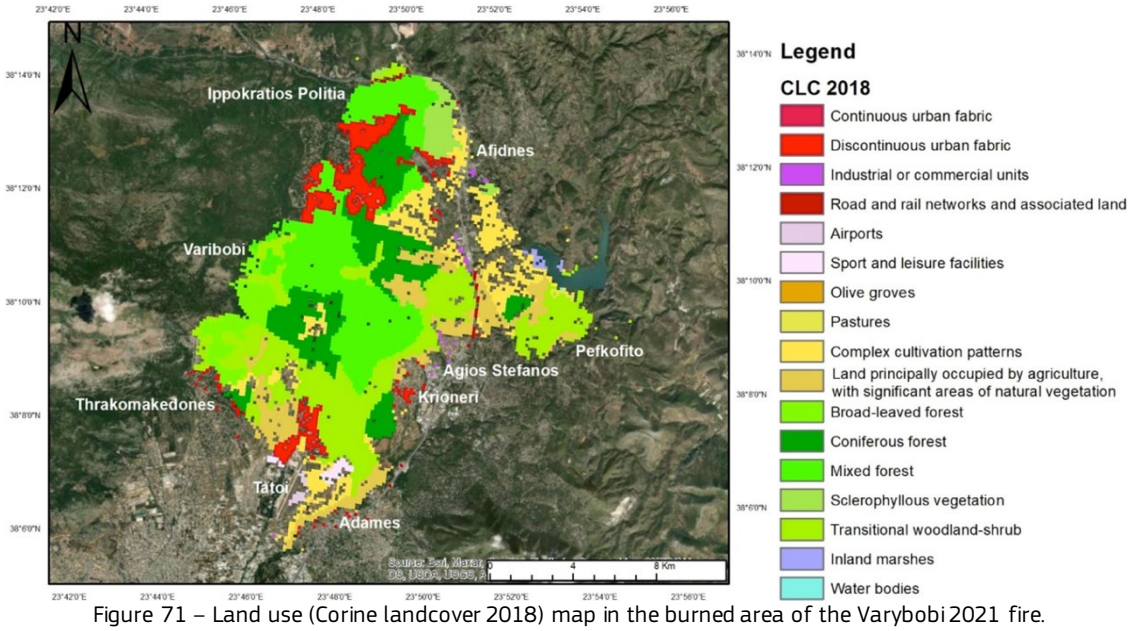


Figure 71 – Land use (Corine landcover 2018) map in the burned area of the Varybobi 2021 fire.

The vegetation structure corresponds to PROMETHEUS [22] fuel models 2,3, 6, and 7. The more severe fire behavior and impact correspond to areas covered by models 6 and 7. A fuel mixture that comprises structures and high vegetation, which is a typical situation in the WUI areas as seen in the photos above (Figure 70), should also be added to the forest fuels.

5.2.1 Fuel conditions

Earlier in 2021 (mid-February), the snowstorm "Medea" had caused significant damage to the forested areas of Attica, with several trees broken and downed. This situation greatly influenced the forest fuel load and, in particular, the quantity and distribution of the downed heavy fuels. An urgent cleaning program was decided on and carried out in 21 areas, Varybobi being one of them (Figure 72). Due to legal constraints and conflicts, the local authorities did not complete the cleaning of broken and fallen trees caused by the Medea storm until the end of April as initially was scheduled/decided, that is before the start of the fire season. An extension till mid-July was given to address delays; however, the fuel load remained excessive during the entire fire season.

(a) (b)





(c) (d)





Figure 72 – Damage in forest vegetation increased the heavy forest fuel load (a and b) and cleaning operations (c and d) following the snowstorm Medea, which occurred in mid-February 2021.

5.2.2 Fire ignition

The area where the fire started is a pine forest in the north-eastern boundary of the Varybobi settlement. The ignition was linked to malfunctioning in a pylon of the high voltage network of ADMIE (the National Independent Power Transmission Operator – IPTO). The pylon was located in a dense pine forest at a distance of about 500m from a well-known restaurant (Leonidas) in Ano-Varybobi. According to the findings of the private fire investigator representing the Cooperative of homeowners "Hippocrateios Politeia", the ignition was caused by a strong electric arc due to pure maintenance of the pylon. From the pieces of evidence found in the area, the course of the fire, and the direction of the wind, the source of the fire was found under a high voltage (150KV) pylon called "XA 44". At the ignition time, the wind was moderate, the temperature exceeded 40°C, and the relative humidity was less than 20%. Besides the above, the prosecutor's investigations have not attributed the fires to the electricity transmission or distribution network.

5.3 Fire conditions

5.3.1 Meteorological conditions

Due to the anticyclonic circulation established at the beginning of August in southwest Greece, hot air masses moved towards Greece from Northern Africa, causing the third and longer lasting heatwave of 2021. July was also a rainless month for the whole Attica Region (Figure 73), intensifying the drought observed in southern Greece in the first half of 2021. No precipitation was observed for several days before and, of course, during the evolution of the heatwave. The weather station of Varybobi recorded 2.4mm on August 12th.

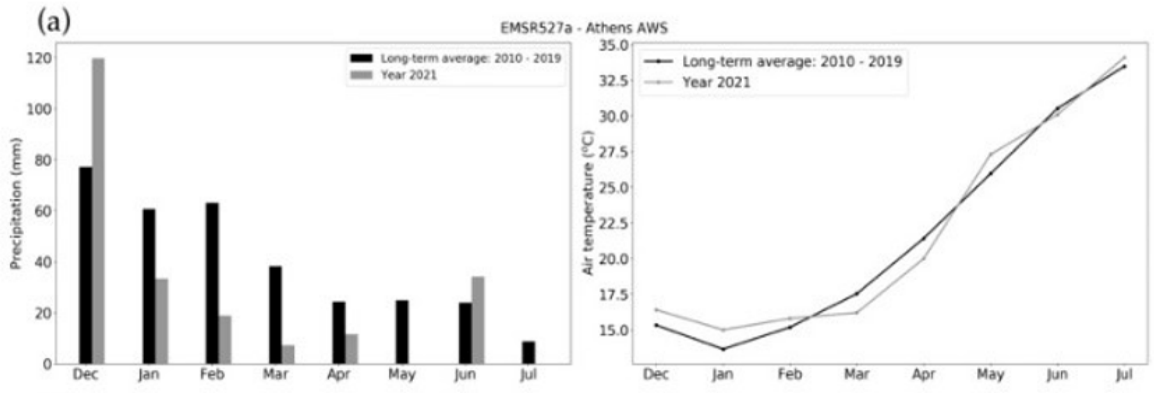


Figure 73 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527a).

According to the data of the weather stations network of the National Observatory of Athens-NOA (www.meteo.gr), on August 3rd, Varybobi experienced a maximum temperature (Tmax) of 41.8°C, while the temperature at the neighboring station of Tatoi reached 42.6°C. On the same day, the meteorological station of Ippokrateios Politeia, which is a mountainous settlement of Eastern Attica with an altitude of approximately 600m, recorded a Tmax of 40.8°C. Agios Stefanos, a semi-mountainous northern suburb of Athens, recorded 41.4°C, again on August 3rd. Anomalies exceeding 0.26°C of the surface air temperature in the wider Attica region were observed on August 4th, 2021, for the 1981-2021 climatology [23].

The average winds in the area on the day of ignition (03/08/2021) were weak to moderate, with strength not exceeding 10km/h, blowing from the N-NNE direction as recorded by the Varybobi weather station with a decrease following the next days. Thus, they were within the normal ranges of the 1981-2021 climatology data. Low wind speed allowed the formation of a pyro-cumulus cloud.

5.3.2 Fire Risk

The long-lasting drought and two prolonged heatwaves with temperatures reaching up to 35–40∘C by the end of June, the first, and the second starting on July 28th and peaking up to 40–45∘C, led to an excess of heat since mid-June. Furthermore, the excess heat was accompanied by extremely dry atmospheric conditions that reduced the relative air humidity levels to below 20% [23]. This situation, combined with the current meteorological conditions, was depicted by changes in the country's fire risk map during the first week of August 2021, as shown in the next figure, based on the General Secretariat of Civil Protection data. The risk level in the Attica region changed to "very high" (orange color) on August 2nd and remained in this category until August 6th, when the risk class changed to "alert" (red color) due to the existence of several active fire fronts in the wider area (Figure 74). It is evident that the increase in the risk level has been assessed on time.

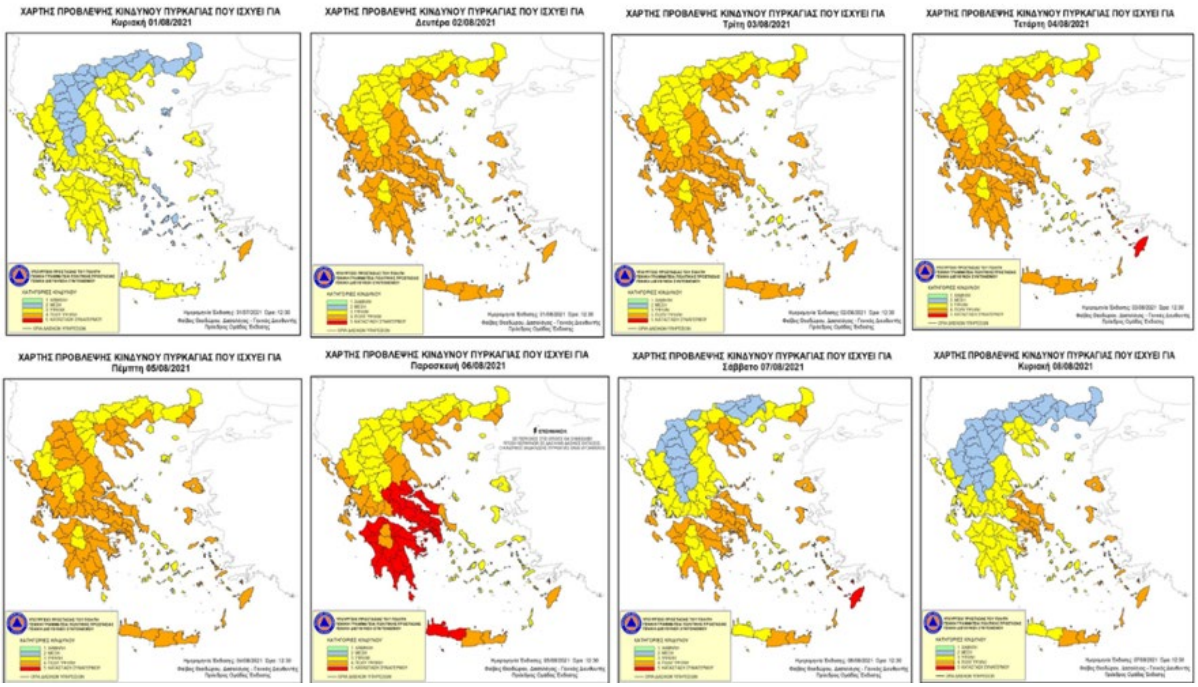


Figure 74 – Daily Fire Risk maps for 1-8 August 2021 issued by the General Secretariat of Civil Protection.

According to the Fire Danger Forecasts of Copernicus EMS for August 3rd, the Fire Weather Index (FWI) and the Drought Code (DC), computed from the MeteoFrance model (10km resolution), were increased to maximum values in the wider area (Figure 75). It is evident that only a valid assessment of the fire risk level is not enough to address the challenges of wildfires. There is a need for preparedness planning and vegetation/fuel management well before the start of the fire season.

(a) *(b)*

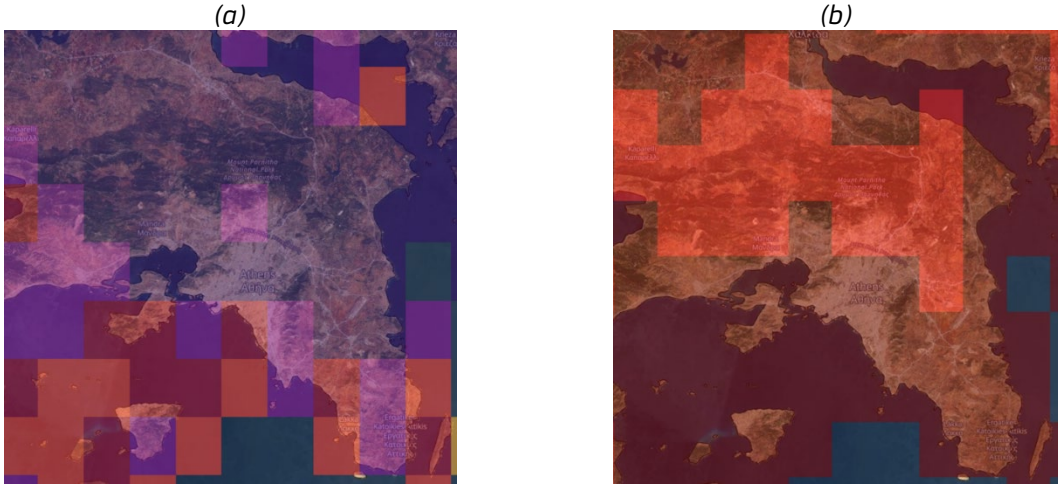


Figure 75 – Snapshot from the European Forest Fire Information System (EFFIS) showing the forecast of Fire Weather Index (a) and Drought Code (b) for the area of Varybobi on August 3rd.

The daily dead fuel moisture content (DFMC) calculations show that DFMC dropped below 10% since the end of June. By the time the fire started, the DFMC was calculated to be 6–7% (Figure 8.10), a value linked to a very large wildfire potential and intense burning [23]).

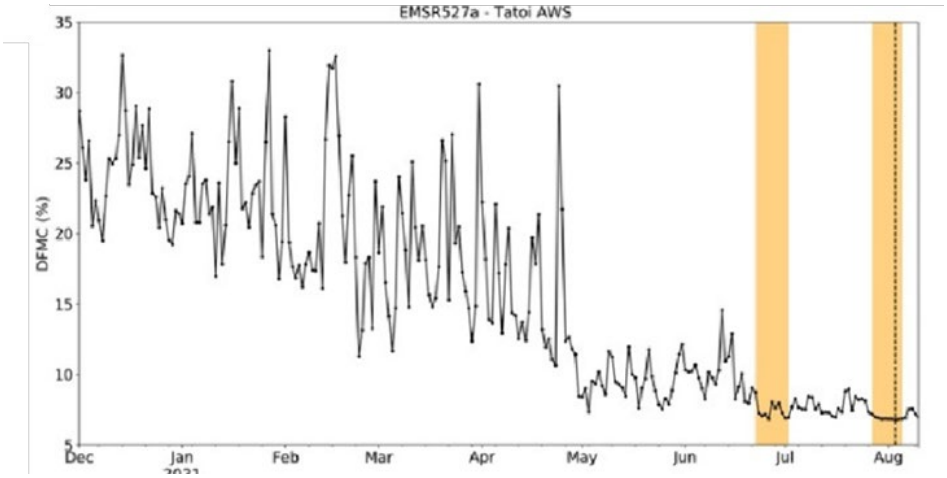


Figure 76 – Time series of the daily dead fuel moisture content (DFMC) for the period December 2020 and August 2021 [23].

5.4 Fire behavior

The fire ignited in Ano Varybobi early in the afternoon of August 3rd and initially was suppressed during the morning of the following day. However, due to inadequate mop-up and rekindling, it re-ignited in the late evening hours of August 4th. During the next two days, the fire burned through more settlements and destroyed Tatoi estate, where the summer palace of the ex-king is located. The re-ignited fire soon crossed the eight-lanes wide National Road E1, connecting Athens to Thessaloniki, at three different points, the most critical being between Drosopigi and Pefkofyto settlements, which allowed the fire to spread east and reach the shore of Lake Marathon, burning mostly agricultural and rural land. The fire front spreading towards the west was finally stopped when it reached the core of the National Park of Mount Parnes. The fire was finally contained, suppressed, and secured on the afternoon of August 7th. Nevertheless, re-ignition and rekindling episodes were observed till August 11th.

As can be seen in Figure 77, where the daily development of the fire is depicted, the fire growth culminated on August 6th, following the rekindling of August 5th, progressing slowly over the next few days. In total, the fire burned an area of 8 454ha in six days.

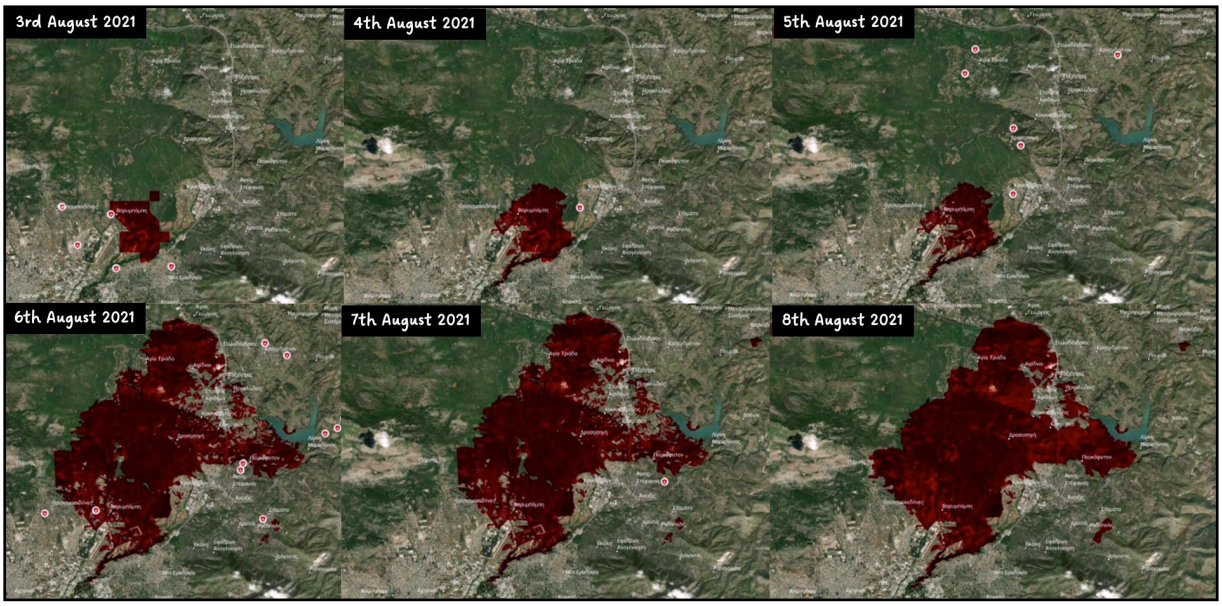


Figure 77 – Daily burned areas (Copernicus EMS) of the Varybobi fire between August 3rd and 8th (NKUA EDCM Newsletter, 2021 [24]).

According to the classification performed by the Geography Department of Harokopeion University of Athens (HUA), the area burned with moderate-low to moderate-high severity in approximately 85% of the area (Figure 78). The reason for the severe burning is associated with the excessive fuel load which was particularly high because of the preceding Medea snowstorm of February 2021.

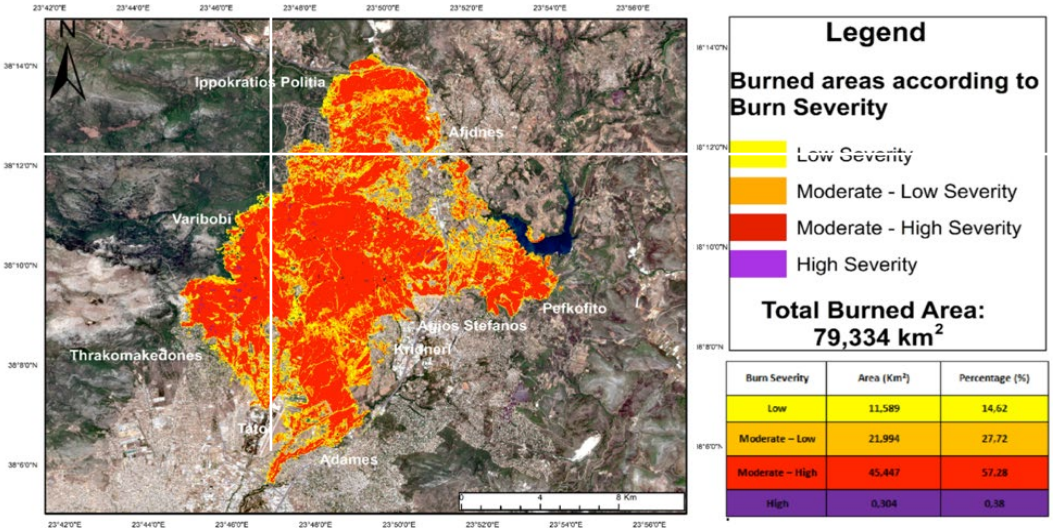


Figure 78 – Burned area mapping and classification according to Burn Severity using Sentinel-2B L2A images of July 29th and August 8th (Harokopeion University of Athens).

Observational evidence indicates that all wildfires showed extreme fire behavior, characterized by erratic fire spread, massive spotting, and the occurrence of pyroconvection [23]. Pyroconvection, forced by the wildfire, created pyrocumulus clouds (pyroCus). The hot gases and ash particles (smoke) that are released by the fire rise in the air, influence the fire behavior significantly by being associated with strong convective updrafts and downdrafts that result in unpredictable changes in surface winds and the rapidity of fire growth due to increase of the fire radiation power (FRP), ember generation and long-range spotting, which soared on August 5th (Figure 79).

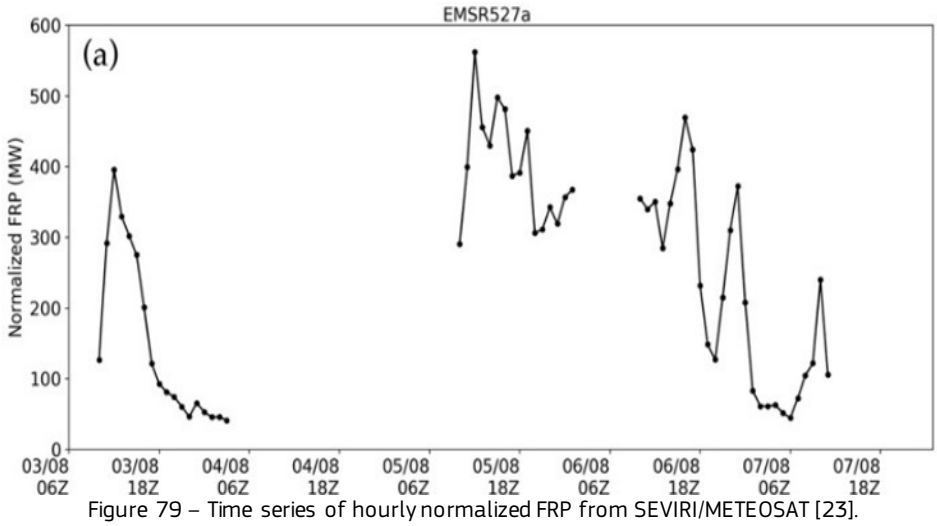


Figure 79 – Time series of hourly normalized FRP from SEVIRI/METEOSAT [23].

The occurrence of pyroconvection strengthened the potential of the fire and significantly increased the rate of perimeter growth. The factors contributing to extreme wildfire behavior, limited control capability, and fast perimeter growth are directly linked to antecedent meteorological phenomena and conditions, which allowed the accumulation and extreme dry-out of forest fuels and the concurrent adverse fire weather that enabled the wildfire to couple with the atmosphere and to evolve into extreme pyroconvective events [23].

The fire threatened settlements that are built in the wildland-urban interface and spread among isolated houses and constructions in the wider area. The firefighting forces focused on saving properties, leaving the fire control to the aerial resources. Due to the low relative air humidity, the fire kept restarting after the aerial drops.

As aerial firefighting was not supported by hand crews and dozers on the ground, and with the suppression efforts dispersed in the various settlements, the overall firefighting was ineffective in containing the fire. For this reason and to avoid human losses, repeated evacuation orders were issued for Varybobi and the neighboring settlements, which were managed by Hellenic Police.

The response to the Varybobi fire included 450 firefighters with 150 firetrucks and 40 firefighters in ground troops, coordinated locally by the "Olympus" mobile Command and Control Centre of the Hellenic Fire Service. The operations were supported by relevant organizations, including the Hellenic Police, the Hellenic Army, the Emergency Service (EKAV), Municipalities' civil protection personnel, representatives of local and regional authorities, and volunteers. Moreover, 40 firefighters from Cyprus assisted in the operations. Regarding aerial resources, seven firefighting airplanes and three helicopters were deployed. The European Union Civil Protection Mechanism (EUCPM) and international aid were also activated with aid from France (42 firefighters), Qatar (65 firefighters and 5 vehicles), Kuwait (40 firefighters and 6 vehicles), and Israel (16 firefighters).

5.5 Fire impacts

In terms of the impact, the situation of the Varybobi fire was very complex due to the involvement of several settlements, houses, and infrastructures challenged by the fire and its extreme local behavior. Despite the early detection of the fire and the low wind speed during the first hours of the fire, it was difficult to organize an efficient firefighting strategy due to the human presence and the dispersion of the assets at risk in the area.

In the Varybobi fire, a total area of 8 453.8 ha was burned with Moderate-High burn severity (57.28 %), which caused damage to buildings and houses where the fire reached the boundaries of the settlements (Figure 80). Based on the Corine Land Cover 2018 classification, the burned areas are predominantly in the category of transitional woodland-shrub (24.17 %) and mixed forest (22.16 %). The fire caused significant losses to agricultural cultivation, wine, and olive yards.



Figure 80 – Map showing the area burnt from the wildfire of Northern Attica (Source: EFFIS/WILDFIRE Database).

The surface runoff erosion risk in the surrounding areas is very low, despite the medium to high slope gradient, which might facilitate the removal of soil and rock material (i.e., accelerates erosion). The burned areas are slightly more vulnerable to erosion and may experience low risk [25].

Despite the moderate-high severity of the burn, the area is expected to regenerate naturally since the burned pine trees were mature, and the environmental conditions are considered adequate for the Mediterranean forest species (trees and shrubs). However, the natural regeneration may be disturbed since, in the aftermath of such fire incidents in the wildland-urban interface, there is always a discussion on replanning and strengthening the protection of the population and their properties by replacing the "flammable" vegetation.

Furthermore, damage was experienced by houses and constructions that were isolated inside the wooded landscape, in the boundaries of the settlements, or across a forest vegetation corridor inside the settlements.

Around 80 buildings, mainly dwelling houses and several businesses (restaurants, crafts, small industrial installations) were severely damaged or completely destroyed. Buildings with reinforced concrete frames and infill walls performed well even with high fire intensity. In most of them, the impact was limited to a change of color (blackening) in external walls. The weak point in most cases of damaged buildings remained the roof, which once caught in flames brings it to collapse. The consequence is the burning of the interior of the building. The fire ignition was due to firebrands (Figure 81a and Figure 81b) in the case of houses with no direct contact with trees (e.g., in building blocks) and radiation in the case of very high trees exceeding the height of the building in isolated houses (Figure 81c and Figure 81d).



Figure 81 – Collapsed roofs and burned house interior in building blocks in a) and b) Adames settlement (NKUA Newsletter); c) and d) Tatoi settlement (NKUA Newsletter)[24].

More damage occurred to old and clumsily made constructions (Figure 82). In such cases, the fire invaded not only from the roof but also from openings such as doors and windows. These constructions were completely damaged and their interior was totally consumed.

(a) (b)



Figure 82 – Damage due to fire entrance by openings in isolated houses in Tatoi settlement (NKUA Newsletter)[24].

The improvisation of the fire, the absence of the owners, and the difficulty of vehicle circulation in an area with active fire resulted in the burning of many vehicles, mainly parked or which owners could not remove in time (Figure 83). Due to the very high temperatures, in most cases of burned cars, aluminum wheel rims were melted and car glasses shattered. It is worth mentioning that more than 20 historical models and collectible cars have been destroyed.

(a) (b) (c)

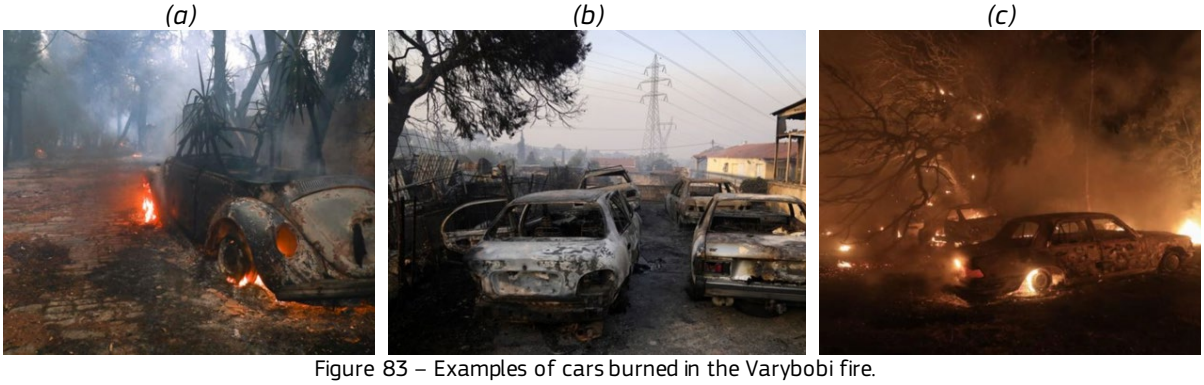


Figure 83 – Examples of cars burned in the Varybobi fire.

The fire also spread through part of the royal estate in Tatoi and burned historical buildings, which currently belong to the Ministry of Culture. Specifically. From the 45 buildings that are located in the core of the estate and have been declared monuments by the Ministry, the fire passed through the following: House of Sturm, Telecommunications Building, House of caretaker, the building of the guard of the royal tombs, Forestry building, Staff building and the Directorate building (Figure 84).



Figure 84 – Overview of the burned core of the royal estate in Tatoi.

In the area operate several equestrian groups and horse-riding clubs. During the fire was a need to remove the horses. From the first hour that the fire broke out, the managers of the clubs moved the horses to the nearest safe club using special trucks. Approximately 253 sport horses and 23 ponies at risk were transferred during the night of August 3rd from the Tatoi and Varybobi area to the Olympic Equestrian Center in Markopoulo (Figure 85).



Figure 85 – Sport horses at risk in the Tatoi club (a) are moved (b) for transfer to Markopoulo.

5.5.1 Air pollution

A sudden increase of "Particle pollution" (also referred to as particles, particulate matter, or PM) and high values of ultra-fine particles (PM1.0, i.e., diameter less than 0.1μm) concentration were measured on August 4th (project Envicare) at the closest air quality station in Heraklion (Figure 86). The PM values of greater size, such as PM25 and PM10 (particle diameter 2.5μm and 10μm, respectively), remained high during all the days the Varybobi fire was active (NKUA EDCM Newsletter, 2021) [24]. PM travels with the smoke long distances and may be responsible for the deposition of viruses in the human lungs. Persistent high values of PM smaller than 10μm have a greater impact on people with cardiovascular or respiratory disease, older adults, children under 18 years of age, pregnant women, and outdoor workers. The Varybobi fire occurred in a wildland-urban interface area and very close to Athens, exposing a very large part of the population of the Athens metropolitan area to smoke pollution consequences.

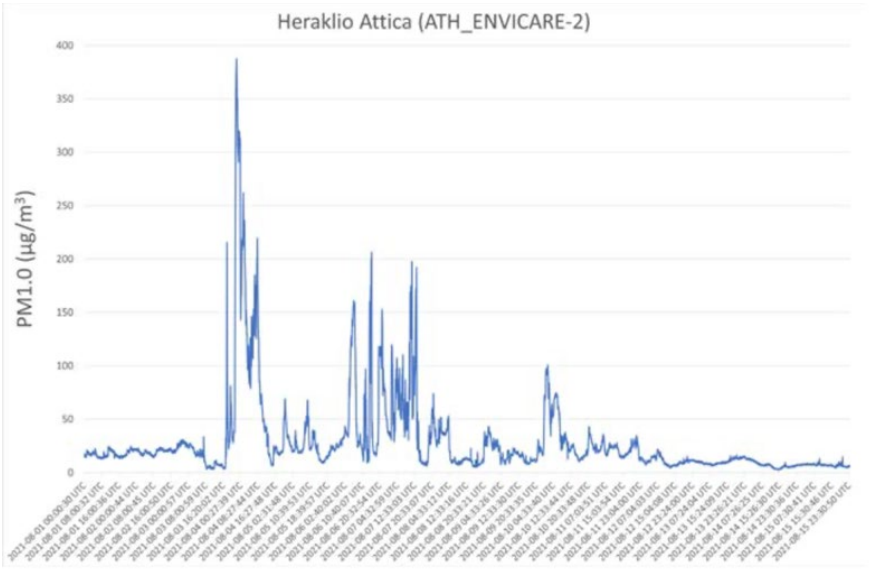


Figure 86 – Ambient particulate (PM1.0) pollution from the smoke of the Varybobi fire (Source: Project Envicare).

5.5.2 Fatalities

Despite the prioritization (in the aftermath of the 103 losses Mati fire in 2018) of avoiding human fatalities, which was practiced with extensive evacuation and removal of the population from the threatened settlements well beyond the fire's reach, some losses occurred from the firefighting side. Thus, the fatalities included two volunteers who died fighting the fire, and a third succumbed to his burns six months later.

5.6 Conclusions and lessons learned

The fire of Varybobi was the first large wildland-urban interface fire following the fatal fire in Neos Voutzas and Mati in 2018. It made evident the weakness of organizing fire prevention and protection in such areas due to persistent and underlying causes for several decades. There are several lessons learned from this event that can be summarized as follows:

- Firefighting in the wildland-urban interface is a complicated issue since it involves citizens/people safety and management, addressing challenges in protecting properties dispersed in forested areas and buildings occluded by flammable vegetation, as well as ensuring evacuation for older people, children, and animals.
- In the current conditions and due to the heavy load of forest fuels, the accumulation of biomass, and inadequate mop-up, rekindles are a significant threat to losing control of a previously contained fire.
- The firefighting mechanism can hardly address simultaneously two large fires in the same region (and maybe in the country), triaging between the fires which may severely increase the impacts.
- The management of forest vegetation is imperative for improving the capabilities of firefighting. Particular attention is needed following large-scale disasters (e.g., snow or windstorms, drying out of the vegetation caused by pest and insect attacks) to control the sudden increase of heavy fuel load that maintains fire and contributes to rekindling.
- Prioritization of human lives during fires is legitimate; however, precautionary use of evacuation must not be used excessively. It needs to ensure that the citizens are informed, trained and that they won't lose their trust in the public civil protection services.
- Cultural assets placed in wooded areas need a particular fire protection plan.
- Social media have great potential to survey and disseminate information in all phases of the wildfire crisis, particularly concerning the post-analysis of the fire incident. However, caution is needed with the source and usage of this information, mainly during the response phase to avoid the spreading of misleading and unreliable information and fake news.

FIRE OF EVIA

Authors	
George Eftychidis	KEMEA
Vassiliki Varela	KEMEA
Ilias Gkotsis	SATWAYS

6 The Limni Fire Event, North Evia (Greece)

6.1 General description

The fire started on Tuesday, August 3rd, at 3.30 p.m., near the settlement of Myrtias, within the boundaries of the Limni/Mantoudi Municipality and close to the uphill side of the provincial road Strofilias-Rovion. It burned in parallel with the Varybobi fire in the suburbs of Athens for several days, as described in the previous chapter, and it was finally contained after nine days of burning, on August 11th, although it took some more days to assure the extinguished fire. The fire initially spread towards the east coast of Evia Island, and when it reached the sea, it continued to extend to the north and then turned and moved to the opposite coast of the island. Thus, the fire moved north and back and forth between the east (Northern Euboean Gulf) and the west coast (Aegean Sea) of the island, till Pefki, a coastal village sited in the northern boundary of the final fire perimeter. Despite the low winds, flames wound their way up and down mountains and around villages. The evolution was influenced by the intensity of the burning and the heavy fuel load, while the propagation in many cases was against the meteorological wind with the active fire developing large convection columns and pyrocumulus. The fire burned high pine and oak forests, rural and urban areas in Limni, Rovies, Mantoudi, Agia Anna, Papades, Milies, Kokkinomilia, Gouves, Vasilika, and Pefki. A total area of 51 244.93 ha, almost one-third of the islands' woods, including the most productive forests of Greece, was burned in the largest wildfire in Modern Greek history in a year during which the country had the strongest firefighting capacity (Xanthopoulos and Athanasiou 2022).

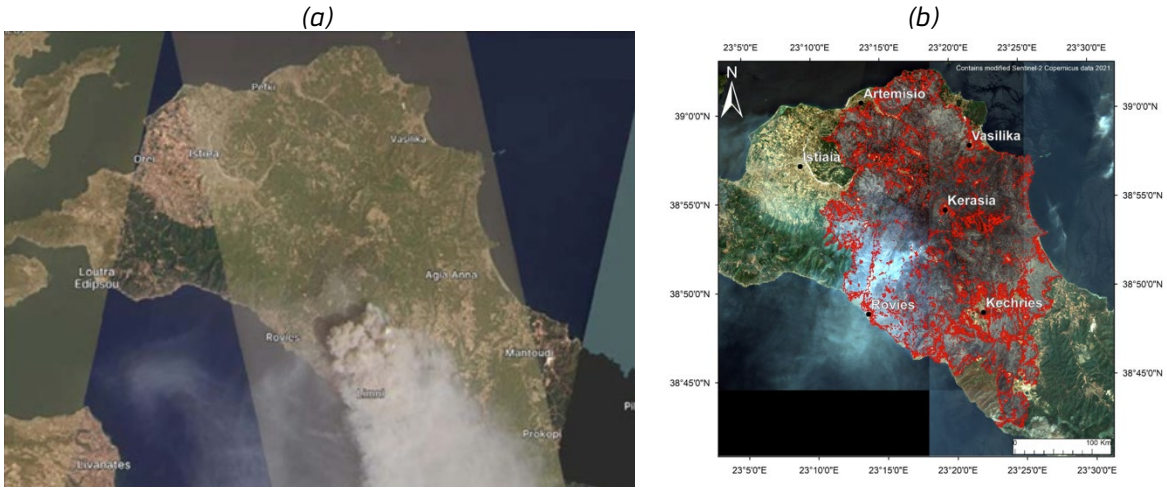


Figure 87 – Burned area and settlements of the North Evia fire (Source: HUA Earth Observation Team, 2021).

6.2 Characterization of the affected area

The fire-affected areas are characterized by steep slopes and several moderate water catchments with a hydrographic network of a limited extent (Figure 88). The processing of the data of the Digital Terrain Model (DTM) of the Hellenic Cadaster shows that the minimum altitude is at sea level (0m a.s.l.), the maximum is 989m and the average altitude is 303m – 27% of the area altitude less than 200m, 35% of the area between 200m and 400m and only 9% above the 600m. The slopes prevailing in the area vary. The average slope is 32,8 %, while 19% of the burned area has a slope of more than 50 % [26].

The most significant water catchments covering a large part of the affected area end at the Gouves, Rovies, Neochori, and Krya Vrysi settlements.

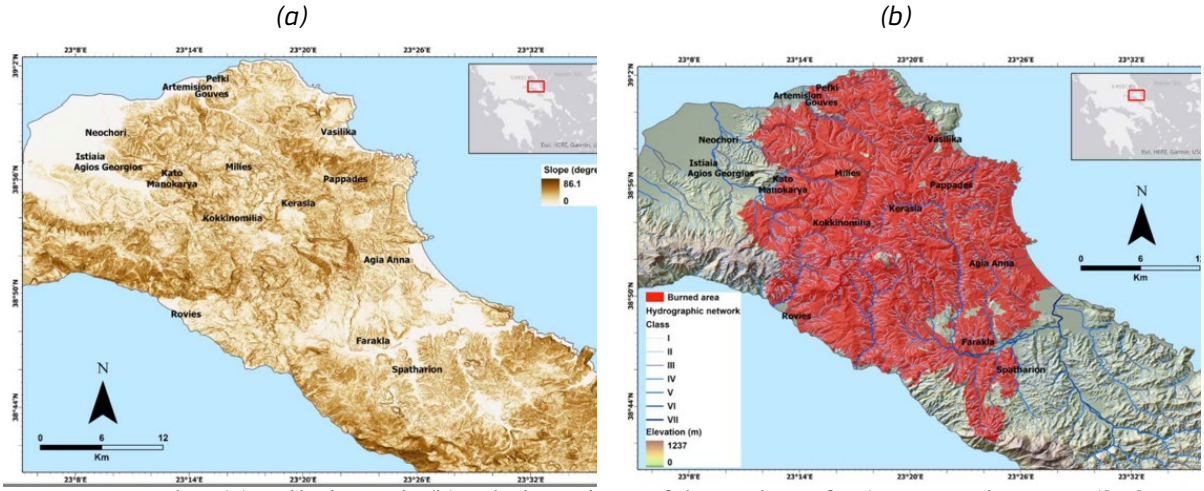


Figure 88 – Slope (a) and hydrography (b) in the burned area of the North Evia fire (NKUA Newsletter 2021)[24].

According to the Corine Land Cover 2018 classification, the area is covered by vegetation represented by mixed (21.31%), broadleaved (5.06%), and coniferous (31.02%) forests as well shrubs (2.92%) and scrublands (24.17%). There is also 4.53% coverage with irrigated and 3.26% with non-irrigated cultivations, and 5,69% covered by olive groves, while 16.14% of the area is occupied by natural vegetation that replaced old, abandoned agricultural land. Urbanized areas cover 0.07% of the area (Figure 89).

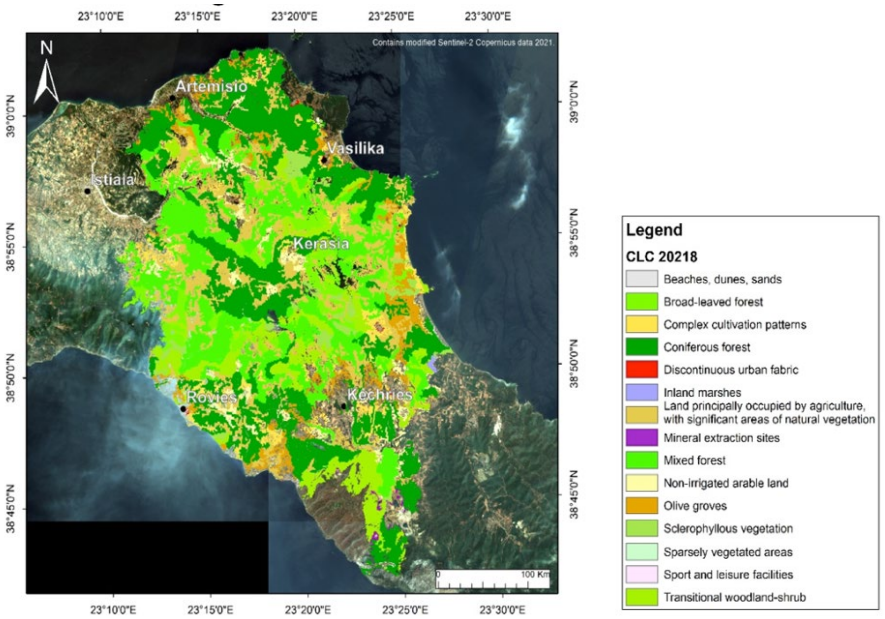


Figure 89 – Land use (CLC 2018) map in the burned area of North Evia 2021 fire (NKUA Newsletter) [24].

The landscape of Northern Evia is characterized by mountainous high forest vegetation represented by pines (*Pinus halepensis*, *Pinus nigra*), fir (*Abies cephalonica*), oaks (*Quercus pubescent*, *Quercus frainetto*, and *Quercus euboica*) and agroforestry lands (Fig. 8.4). The burned area of forests and woodlands is 33 800 ha and being represented (CLC, 2018) by coniferous, broadleaf, mixed forests, transitional forests and shrublands with sparse vegetation. This area corresponds to two-thirds of the total burned area. Of the total area of forests and woodlands, 62.31% is located within the Municipality of Limni-Mantoudi- Agia Anna and 38.61% in the Municipality of Istiaia-Edipsos [26].

(a) *(b)*



Figure 90 – Mosaic and relief of the landscape in North Evia (Google Earth imagery).

Two municipalities have been affected by the fire. In the municipality of Limni-Mantoudiou-Agia Anna, eighteen local communities, representing three-quarters of the municipal area were affected, while in the municipality of Istiaia – Edipsos, a similar number of communities, representing two-thirds of the municipality area, were affected. In some of these communities, the percentage of the burned area reached 80% up to 100%.

6.2.1 Vegetation characteristics

The vegetation structure corresponds to several PROMETHEUS [22] fuel models, including models 1,2,3,4,6, and 7. The worst fire behavior corresponds to areas covered by homogeneous high vegetation modeled as type 7 (Figure 91). A significant part of the burned area is represented by rural land with olive groves, dispersed trees and shrubs, and cultivations. These areas performed better than dense continuous forests to the fire and seem to bounce back more rapidly after the fire (based on observations of the authors' field visits) It is worth mentioning that the cold wave and the snowstorm "MEDEA" (Figure 91) that hit the region early in February 2021 (February 13th to 16th) greatly influenced the forest fuel load and, in particular, the quantity and distribution of the downed heavy fuels.

(a) *(b)*



Figure 91 – Damage due to Medea snowstorm (a) and dense high forest with shrubs understory (b) in North Evia.

There was thus a significant accumulation of heavy forest fuels, which was combined with inadequate forest management, offering abundant fuel to sustain the extreme behavior of the fire even with mild or no winds.

6.2.2 Fire ignition

The fire started in a forested area near Myrtias mountain village sited on the road from Strofilia to Limni. The fire ignited early afternoon (officially at 2.09 p.m.) under high air temperature, very low relative humidity, and low wind speed conditions. The initial spread of the fire was quite slow. There was no initial operational attack; locals and the team of volunteers from Limni town (SEDDE) intervened first (Figure 92). The flames spread and reached dense pine forest stands to the NW, where it became an intense slow spreading fire. The use of social media and communication groups proved to be a very effective coordination tool, among the volunteers, during the fire.

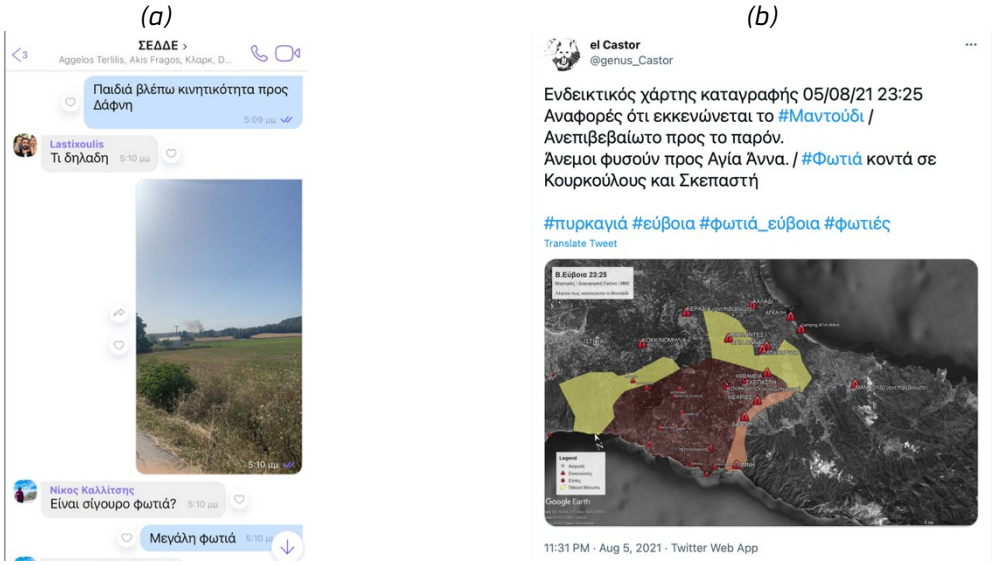


Figure 92 – Chats and information messages by North Evia volunteers using social media and communication platforms.

6.3 Fire conditions

6.3.1 Meteorological conditions

The meteorological conditions at the time of fire ignition were rather normal for the season. However, an extreme heatwave that affected Greece, Turkey, and the southern Balkan peninsula, lasted from the last days of July until the first 10 days of August. The heatwave was the most intense of the past thirty years. From the data of the meteorological station of the National Observatory of Athens (NOA), located in Vateri in northern Euboea (http://meteosearch.meteo.gr/data/vateri/2021-08.txt) during 10 days in June, 22 days in July and 19 days in August the temperature exceeded the 32°C.

The data of the Istiaia (http://meteosearch.meteo.gr/data/istiaia/2021-08.txt) meteorological station of the same network shows similarly that the temperature exceeded the threshold of 32°C during 9 days in June, 42 days in July and 21 days in August 2021. As can be seen in Figure 8.7 rainfall increased till April 2021, compared to the pattern of the last decade, while there was a deficit in precipitation starting from May. However, this situation is not considered a significant deviation from normal (Figure 93).

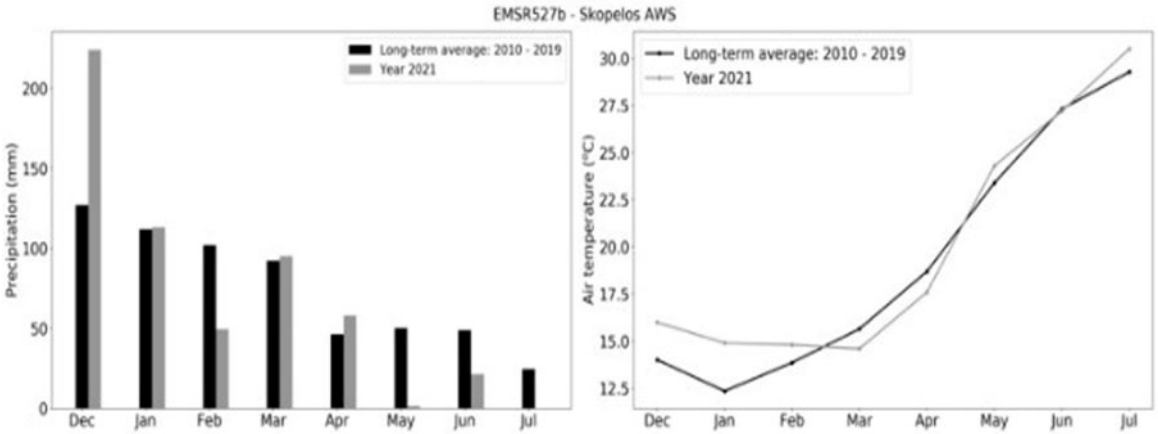


Figure 93 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527b).

According to the data of the Vateri weather station (owned by NOA) the average temperature for August was 28.5°C, the mean maximum temperature (Tmax) value was of 34 °C, and the absolute Tmax for the month 44.2°C, recorded on August 6th. A maximum temperature of 41.8°C was recorded on the day of the fire ignition. The Istiaia meteorological station (owned by NOA) recorded a mean Tmax of 34.3 °C, and an absolute Tmax of 42.1°C on August 25th.

A total of 32.2mm of precipitation was recorded in Vateri during June, of which 14.6mm fell on the 15th. No precipitation was recorded in Vateri from June 15th till August 3rd when the fire started. A similar situation is observed from the data of the Istiaia meteorological station. There were 48 days without rain in the area. Therefore, the result of the rains of June on the soil and fuel moisture content was annihilated by the heatwave of late July and early August.

The lack of precipitation and the warmer-than-average temperatures since May 2021, enabled the dry-out of the fine fuels and created a flammable layer of forest fuels that could efficiently carry the fire. Examination of the daily dead fuel moisture content (DFMC) times series (Figure 94) reveals that fine fuels were already considerably dry (DFMC ~10%) since the beginning of the fire season on May 1st.

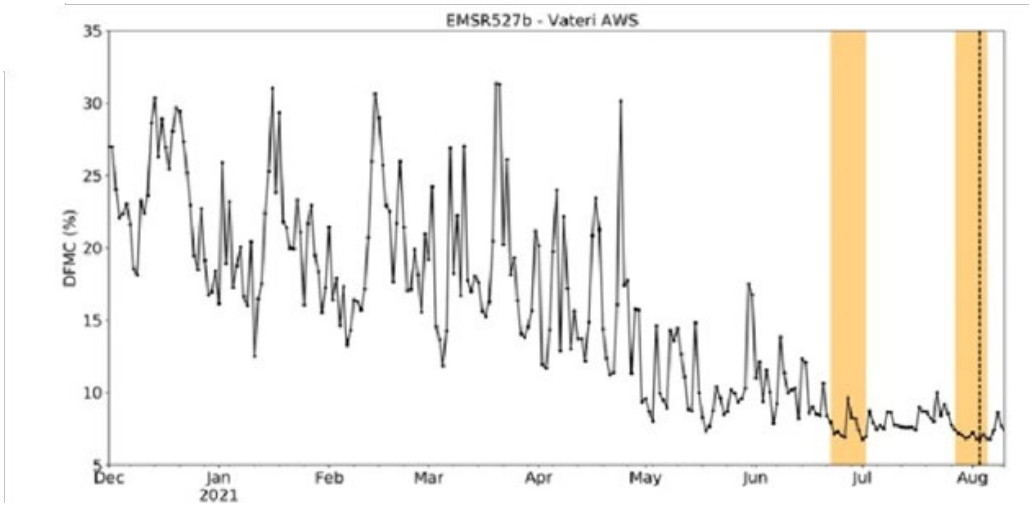


Figure 94 – Time series of the daily DFMC for the period December 2020 and August 2021 using data from the Vateri weather station [23].

The rainfall amount that fell during the first half of June moistened fine fuels and allowed DFMC to recover slightly by the mid of the month. There onwards, the persisting high temperatures and the occurrence of the two prolonged heatwaves (more than 10 days duration each) dried the fuels out rapidly, and since the mid of July, it dropped the DFMC values to 6–7% till the fire ignition on the August 3rd [23]. We can conclude thus that the environmental conditions in North Evia that preceded the fire were quite favorable to developing sustainable conditions for a significant fire event.

The winds were relatively mild to moderate, something unusual for the island of Evia, where Meltemi winds (strong seasonal winds from the Northeast also called "Etisies") prevail during the summer months. At the time the fire started, winds were blowing at a speed of approximately 10km/h.

During the fire, the winds were constantly blowing from NE and did not much exceed 10km/h, although gusts reached speeds up to 64.4km/h, according to the data from Vateri meteorological station. The data of Istiaia station show much lower wind strength (4.4km/h) but from a different direction (NNE) with gusts up to 48.3km/h.

The evolution of the local values of the temperature and wind during the fire event in Northern Evia is shown in Figure 95 [27]. It is evident that temperature decreases while winds present an increase between the fourth and eighth day of the fire.

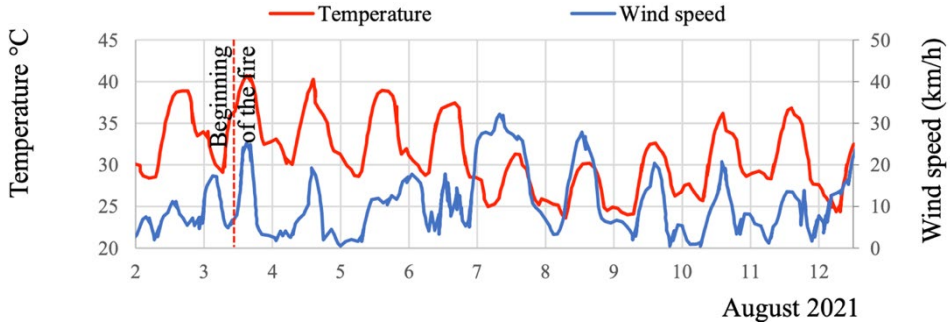


Figure 95 – Time evolution of temperature and wind speed during the North Evia fire ([27]).

Figure 96, which is provided by Sargentis et al [27], shows/outlines that the burned area presented peaks on the 5th and 8th of August with winds blowing from NW and W, respectively. The daily change in the direction of the fire front during the fire is also evident from this graph.

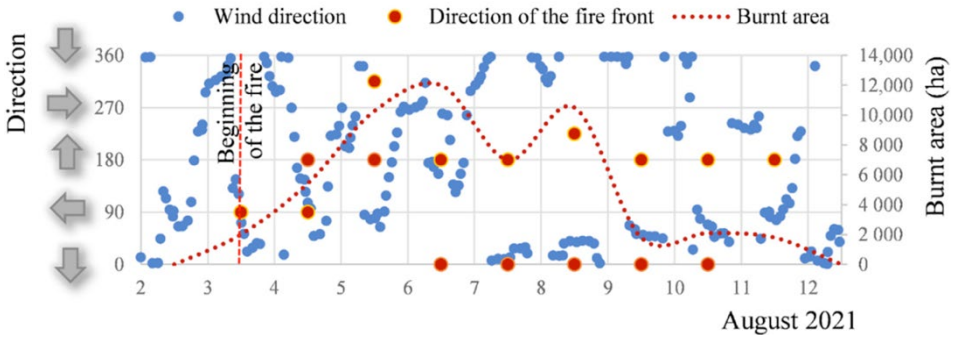


Figure 96 – Time variation of the meteorological wind and fire front direction during the North Evia fire ([27]).

6.3.2 Fire Risk

A series of fire risk maps, which are provided daily by the Greek General Secretariat of Civil Protection, is presented in the following figure for the period August 1st to 8th (Figure 97).

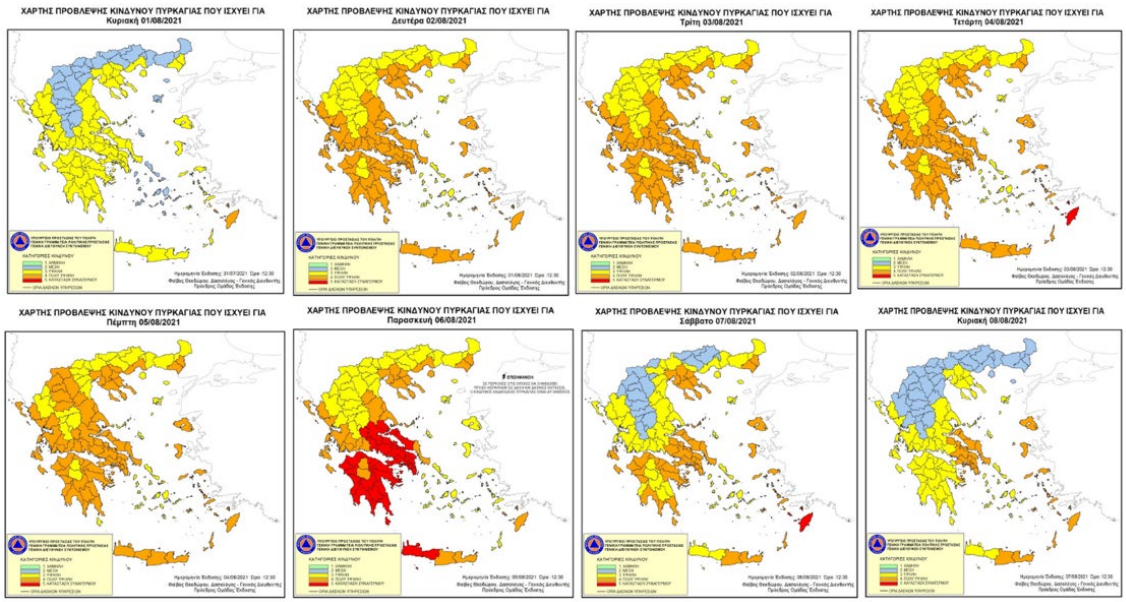


Figure 97 – Daily Fire Risk maps by the General Secretariat of Civil Protection for the period 1-8 August 2021 (Source: Greek General Secretariat of Civil Protection)

The series of maps shown in Figure 97 depicts that Evia Island and, in particular, the North Evia region turned from the "high" class of fire risk (yellow color) to the "very high" (orange color) on the August 2nd, while it escalated to the "extreme" class for one day, the August 6th. It seems thus that the fire danger rating and the risk assessment performed quite well. The response mechanism, although receiving these estimations, addressed several challenges mainly due to the large parallel fire in Varybobi in the region of Attika on the same dates.

According to the Fire Danger Forecasts of Copernicus EMS and the EFFIS records for August 3rd, the Fire Weather Index (FWI) computed from the MeteoFrance model (10km) for the area that was affected by the fire in Northern Evia was classified in the high to extreme class (Figure 98).

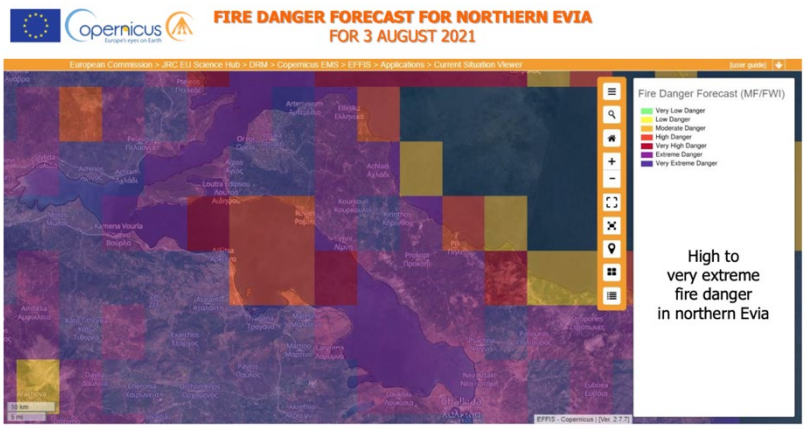


Figure 98 – Fire Danger Forecast based on the Fire Weather Index (FWI) computed from the MeteoFrance model (10km) Snapshot from the European Forest Fire Information System (EFFIS)
https://effis.jrc.ec.europa.eu/apps/effis_current_situation/

6.4 Fire behavior

The fire of North Evia did not receive the necessary attention and aerial support when it started and during its duration. The wildfire response mechanism in Greece heavily depends on the use of aerial means. In the case of the Evia fire, there was a significant delay in responding with aerial means due to another fire in Varibobi (Attika region) that burned in parallel and which had a similarly long duration. This was confirmed by various sources, including the elected head of the prefecture of Evia and the two local mayors. Exhibiting very high intensity due to the accumulation of live and dead forest biomass and the existence of enclaves with heavy downed fuels, the fire, after threatening the town of Limni on the west coastline of Evia, started growing inland, moving towards the east coast. On August 4th, due to doubts as regards the capacity of the Greek firefighting mechanism to handle the situation, the government requested the support of the European Union Civil Protection Mechanism. Over the next 3-4 days, other non-EU countries mobilized and sent resources and firefighters to the fire-front of Evia.

During the first days of the fire, without fierce winds but with intense fire behavior due to heat release and vegetation dryness, the fire kept growing. In northern Evia, the fire, spreading in many cases against the wind, developed towering convection columns (Figure 99) that influenced its propagation and behavior, making it propagate from the west coastline to the east one and vice-versa.

(a) *(b)*



Figure 99 – Convection columns and pyrocumulous cloud created during the North Evia fire (Right photo courtesy J.Tsaloukidis).

The only barrier to the fire propagation proved to be the shoreline, and finally, the fire stopped at the sea. Exceeding 50 000ha of burned area, the Evia fire became the largest fire in modern Greek history, in a year during which the country had the strongest firefighting capacity. According to fire service statements, the coordination center managed up to 102 aerial resources (Xanthopoulos and Athanasiou, 2022).

It has to be noticed that even though the state services gave instructions for evacuating the threatened villages, the local people ignored the orders and decided to stay and defend their homes, as soon as they understood that nobody would take care to protect their property. Around many settlements and productive places (e.g, orchards, farms, warehouses, etc.), damage was avoided due to the fact that the villagers defended these assets effectively on their own, although the surrounding areas were burned with high intensity.

The following observations related to the fire behavior can provide more insight regarding the conditions concerning fire response:

- The relatively narrow roads in the area did not affect at all the fire spread;
- Fuel breaks of less than 50m in width did not stop fire propagation;
- The fire passed back and forth from the same locations several times across the roads;
- Huge smoke emissions covered a very large area for several days, being a risk of suffocating and intoxicating residents and tourists;
- The smoke density ended to low visibility, which fact affected the performance and the efficiency of the aerial firefighting operations;
- Pyrocumulus clouds were formed feeding the fire with upper air masses and strengthening its extreme behavior;

The daily propagation of the fire between August 2nd and 11th over the wooded areas layer is shown in Figure 100 [27].

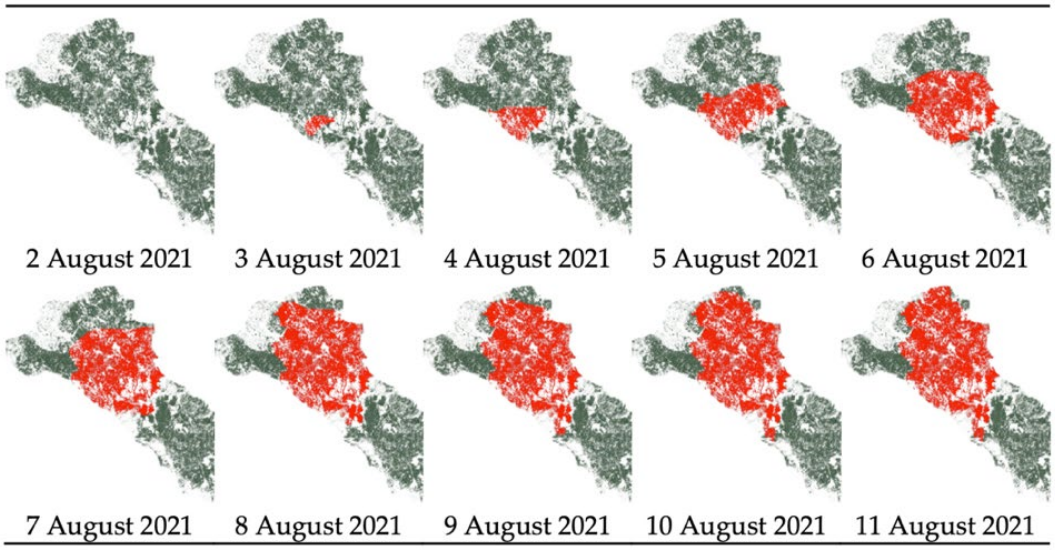
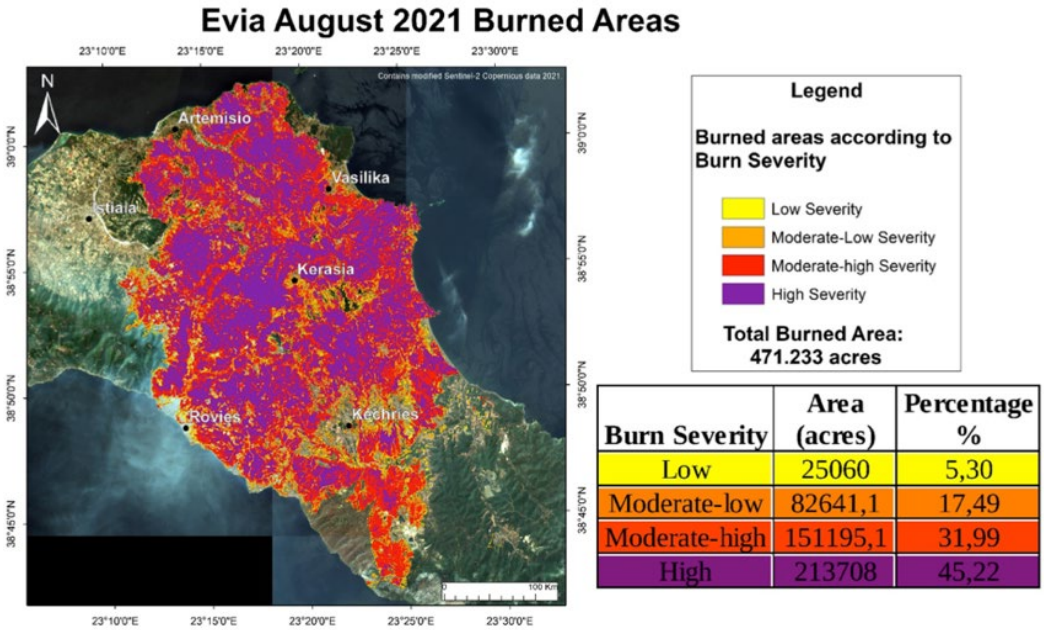


Figure 100 – The evolution of the fire in relation to forest continuity ([27]).

According to the daily fire propagation phases illustrated in Figure 100, the fire started on August 3rd and moved west to Chronia village on the western coast of Evia Island. Then it moved NW towards Rovies village along the west coast on August 4th. On August 5th moved east till it reached the east coast towards Agia Anna. The next day, August 6th, it moved NW and SE towards Kerasia, Kokkinomilia, and Papades settlements. On August 7th, it moved towards the east in the north front to the direction of Vassilika and towards SW in the south front to the direction of Limni town and Moni Galataki area, and in both cases, it stopped at the sea. On August 8th, the boundaries of the fire extended north to Gouves and Agriovotano, while on August 10th and 11th, the perimeter extended further to the north, reaching the northeastern coast of the island at Pefki and Palaiokastro settlements. Such evolution justifies the impression that if there were no sea barrier the burned area would have been much greater.



Burn Severity	Area (acres)	Percentage %
Low	25060	5,30
Moderate-low	82641,1	17,49
Moderate-high	151195,1	31,99
High	213708	45,22

Figure 101 – Burned area mapping and classification according to Burn Severity using Sentinel-2A L2A images of August 1st and August 11th (Harokopion University of Athens).

The burn severity was from moderate-high to high in almost three-quarters of the burned area according to the analysis performed by Harokopion University of Athens (Figure 101). Thus, the greater part of the area was severely burned due to the accumulation of the very heavy fuel load and the lack of winds, which combination allowed the fire to move slowly and to reside for a longer time in the same area.

A closer look at the fire propagation shows that fire was driven by the clustering level of the forest (Sargentis et. al, 2022), and we can thus assume that forest continuity was the most important issue for the evolution of the fire since it influenced the clustering of the fire front, which led to respective massive area burn (Figure 8.16).

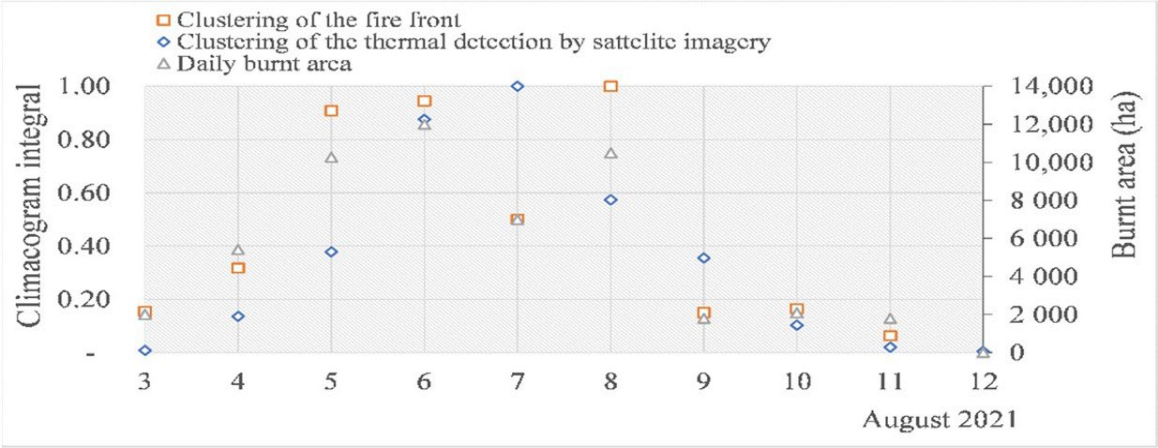


Figure 102 – Climacogram integral of the daily clustering of the fire front related to the respective burned area ([27].

6.4.1 Resources operating on site

According to the testimonies of local people as well as reported by the media, a great part of the response was based on the self-organization of the locals and their active involvement in fire suppression with their means and effort. Unfortunately, the reaction of the response mechanism was very conservative following the fatal incident in Mati (Attica, July 23rd, 2018), and all the focus was on avoiding human losses. The main strategy was to issue evacuation orders for the threatened villages, which were not followed by the locals in most cases. This tactic allowed the fire to advance across the forest areas and attack the villages with almost no organized firefighting intervention from the response mechanism. In the last few days, there was a significant presence of firefighting ground forces from other countries through the European Union Civil Protection Mechanism, which played a key role in dealing with fighting the fire near the villages and controlling rekindles.

The officially reported numbers of firefighting resources are 873 firefighters with 229 vehicles and 35 pedestrian fire units. The "Olympus" Command and Control center of the Hellenic Fire Service was assisting in coordinating operations. Additionally, the Hellenic Airforce contributed with 1 helicopter and 3 aircrafts including 2 Ilyushin I1-76 and the Beriev-200. Moreover, help was provided by the Hellenic Army, the Hellenic Coast Guard, volunteer firefighters, and Municipalities and Prefectures with water trucks and other machines/vehicles.

Through the EUCPM the following resources were mobilized to North Evia from:

- Cyprus, 40 firefighters with 2 vehicles
- Ukraine, 100 firefighters;
- Moldova, 25 firefighters with 4 vehicles;
- Serbia, 39 firefighters with 14 vehicles including an ambulance and 3 helicopters;
- Romania, 108 firefighters with 21 vehicles;
- Slovakia, 75 firefighters with 30 vehicles;
- Poland, 143 firefighters with 46 vehicles;
- Switzerland, 2 helicopters; and
- Egypt (Egyptian Airforce), 3 helicopters, including 1 for coordination.

6.5 Fire impacts

The main impact of the fire is related to the forests, North Evia being among the most wooded regions of Greece. Table 9 shows the areas burned in the two municipalities of North Evia per forest species, vegetation type, or land use.

Table 9 – Damage per forest species, vegetation type, and land use in the municipalities of North Evia [26].

Vegetation type/land cover	Municipality of Limni – Mantoudi – Agia Anna (acres)	Municipality of Istiaia - Aedipsos (acres)	Total (acres)	Percentage of the total burned area (%)
Pinus halepensis	185.979,91	114.287,60	300.266,51	58,64
Pinus nigra	6.017,67	7.911,88	13.929,55	2,72
Abies cephalonica	8.545,39	1.028,14	9.573,53	1,87
Shrublands	3.485,31	979,88	4.465,19	0,87
Grasslands / open shrublands	2.999,43	103,43	3.102,86	0,61
Oaks	792,54	1.524,03	2.316,57	0,45
Riverine vegetation	996,59	515,19	1.511,77	0,30
Chestnuts	37,78	0,00	37,78	0,01
Cultivations	102.124,42	60.701,66	162.826,08	31,80
Abandoned fields	8.422,78	1.737,66	10.160,44	1,98
Houses	1.776,08	736,42	2.512,50	0,49
Bare ground	1.008,03	316,20	1.324,23	0,26
TOTAL	322.184,95	189.842,06	512.027,01	100,00%

It is evident from Table 9 that Aleppo pine (*Pinus halepensis*) and cultivations are the most impacted elements. The main consequence is for the pine forests since they lost production for several years because the fire affected mature stands greatly. It is notable to observe that oaks, mixed with pines or not, performed quite well in the fire, which is the reason that they are now considered positively in future reforestation plans.

The fire of 2021 severely damaged more than 500km^2 of land in the north part of Evia Island, designating it as the largest single forest fire in recent Greek history, being even larger than any single fire, including the fires that occurred in 2007 in the Peloponnese and which were recognized as the most extreme natural disaster in the country's recent history [28].

North Evia is considered a significant region for honey and resin production, cattle breeding, and mild touristic activity associated with the combination of forests and beaches. Thus, the fire had a very negative impact not only on the natural environment and the landscape aesthetics but also on the local economy due to the damage and loss of houses or farm properties, leaving the local population deprived of their main source of income [28], [29].

North Evia has a forest-oriented local economy. It is one of the places in Greece where families work as resin collectors. Some 580 families were active in resin collection from pine trees before the fire. It is estimated that 50% of the Greek production of resin (3 000 tons per year) and 65% (10 000 tons per year) of the Greek production of pine tree honey were lost ([27]). Another 80 families were working before the fire in forest works and tree logging. Others were beekeepers or olive growers. Local reports mentioned that 9 000 beehives were destroyed or severely damaged. Most of this activity relied on the forest, as shown in Figure 103.

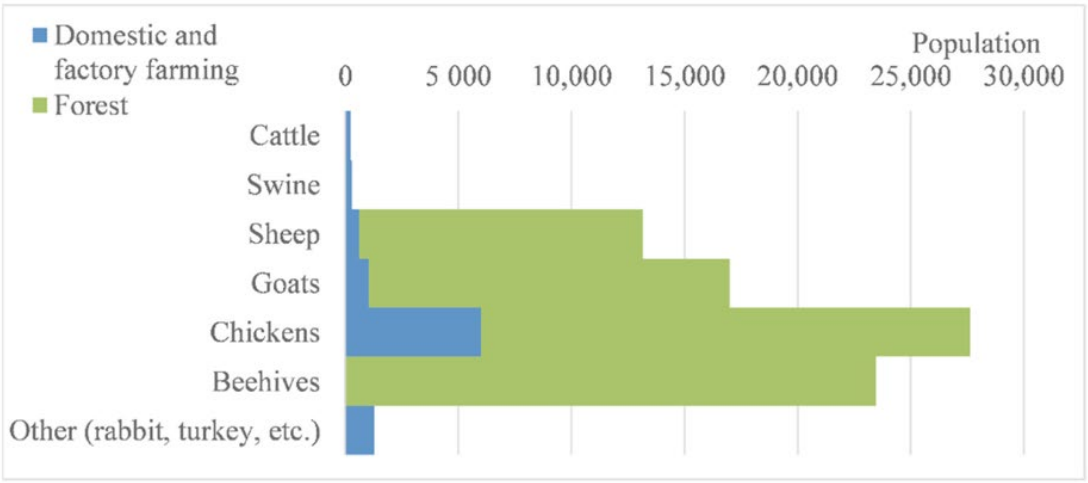


Figure 103 – The livestock and the beehives of the municipalities of Istiaia–Edipsos and Mandoudi–Agia Anna–Limni by the census 2019 ([27].

The livestock activity in the area is quite extensive, with almost 30 000 sheep and goats. There is now a challenge concerning this issue since, according to article 60th of the Greek Law 4264/2014, the state considers livestock as a threat to the burned forests, and grazing is forbidden with an order issued ex officio by the forest service, which prohibits the grazing of any animal in an area that has been declared under reforestation. There is thus a challenge, where these free livestock animals that survived the fire will graze in the coming years and an eventual increase in the cost of animal feeding.

The forest in North Evia works as an open space for family activities for the local economy. Thus, the fire had a tremendous impact on the economy and the local population's activities, even on the people that were not directly affected.

The government reacted rapidly after the fire, issuing Law 4824/201 on "Emergency measures for the effective protection and rapid restoration of the natural environment, the immediate support of those affected by the fires". However, the law can't recover the sustainable wealth that the local population and economy lost for the next several years.

6.5.1 Damage to properties

The impact of the damage to buildings and structures was significant and mainly, although not exclusively, related to old constructions and the use of pure construction materials. The weak point of the houses proved to be, once again, the roof, as is evident in Figure 104 for buildings in the broader area of Limni. The houses were destroyed due to the roof's collapse, without the fire being in contact with the building.



Figure 104 – Fire-induced roof damages identified by UAV flight performed by the University of Athens (Source: NKUA Newsletter., 2021) [24].

The area of North Evia is a traditional destination mainly for internal tourism. There is a large number of secondary residences and summer houses that have been built since the 1960s using pure construction materials, which currently are aged, and their performance and resilience are greatly sublimated. One of the most tourist destinations in the area is the coastal village of Ayia Anna, which was hard hit by the fire not only in the interface with the forest zone but also in houses near the beach. The partial and total collapse of buildings was due not only to roof destruction but also due to severe damage to weak external walls, window frames of wood, and facades with large openings (Figure 105).



Figure 105 – Fire-induced damage due to aged and old building material (Source: NKUA Newsletter., 2021) [24].

Critical infrastructures, mainly powerlines of the low and medium voltage distribution network (Figure 106), were destroyed, challenging for a long time the electrification of the areas the fire passed through.



Figure 106 – Damage to the power distribution network in Ayia Anna (Source: NKUA Newsletter., 2021) [24].

Due to the intensive touristic activity in the North Evia region and the light materials used for construction, associated with its seasonal use, and the need for aesthetic integration in the environment, several relative facilities experienced very severe damage. Especially, the constructions in contact with or under high forest vegetation were destroyed. The relevant economic impact on the area is tremendous. Among the most significant touristic facilities in the area that suffered severe damage are the Camping "Ayia Anna Club" in Ayia Anna, and the Forest Village resort in Papades (Figure 8.22).

(a) *(b)*



Figure 107 – Spot of the Ayia Anna Club (camping) before and after the fire (left) and the restaurant of the Forest Village (resort) in Papades, destroyed by the fire (right).

Apart from the material damage, there were also intangible consequences caused by the burden of the fire potential. Fear, insecurity, and uncertainty about how the residents should behave caused serious negative psychological states and the need for psychological support. The Ministry of Health in consultation with the Region Authority of Central Greece deployed Chalkida and Edipsos, teams of mental health professionals comprising psychologists and social workers for the psychosocial support of those affected by the fires, temporarily accommodated in the closed gyms and hotels of the area.

During the fire, thousands of people evacuated the burning areas near the coast by boats, docked near Limni in the first days, and Pefki later (Figure 108). Coast guard vessels, ships and vessels of the Hellenic Navy, passenger-car ferries, boats, and private boats were used during the fire to support the evacuation effort. It must be noted that this massive evacuation with the boats was implemented while the restrictions on gatherings and movements of the citizens due to the pandemic were still valid.

(a) (b)



Figure 108 – Massive evacuation using boats during the North Evia fire.

6.5.2 Impact on the atmosphere

The Evia fire burning on the same day as the fire in Varybobi (Attica) had a significant impact on the air quality due to the production of polluting agents above the areas where the fire was active. Forest biomass burning emissions affect not only the near-surface pollutant concentrations, which define the air quality but also the amount of aerosol and gaseous species at higher altitudes [30]. Figure 109 shows the modeled aerosol optical depth, which measures column-integrated aerosol optical properties, between August 3rd and 6th for the wider area of South Greece. It is evident that due to the large intensity of the fire and the heavy forest fuel load in North Evia, the values of the aerosol optical depth (AOD) are much higher above this area during the fire evolution (August 3rd and 6th).

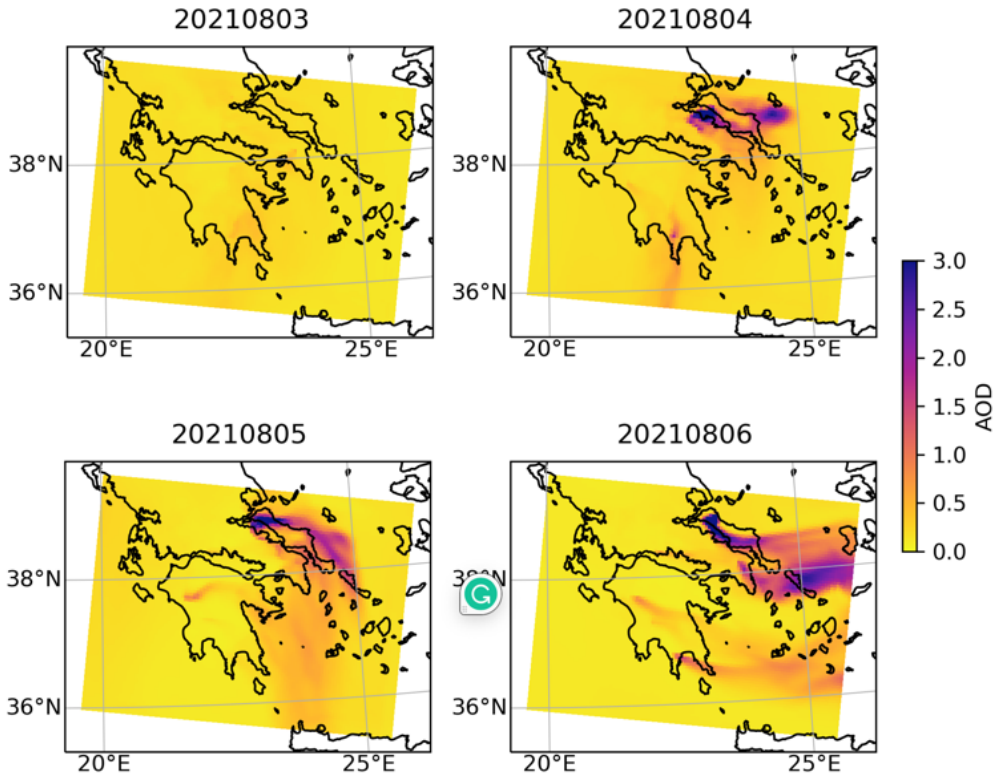


Figure 109 – Spatial distribution of aerosol optical depth (AOD) between August 3rd and 6th at 4.00 p.m., every day.

As regards the air quality parameters, analysis of simulated concentrations of CO, PM_{10}, and O_3 at the surface using a time series of maps with 5km and 1km resolution revealed values exceeding the daily limit values set by the European Directive (2008/50/EC) on Ambient Air Quality (Figure 8.25). Such values were measured by the stations of the Air Quality Network in the Attica region [30].

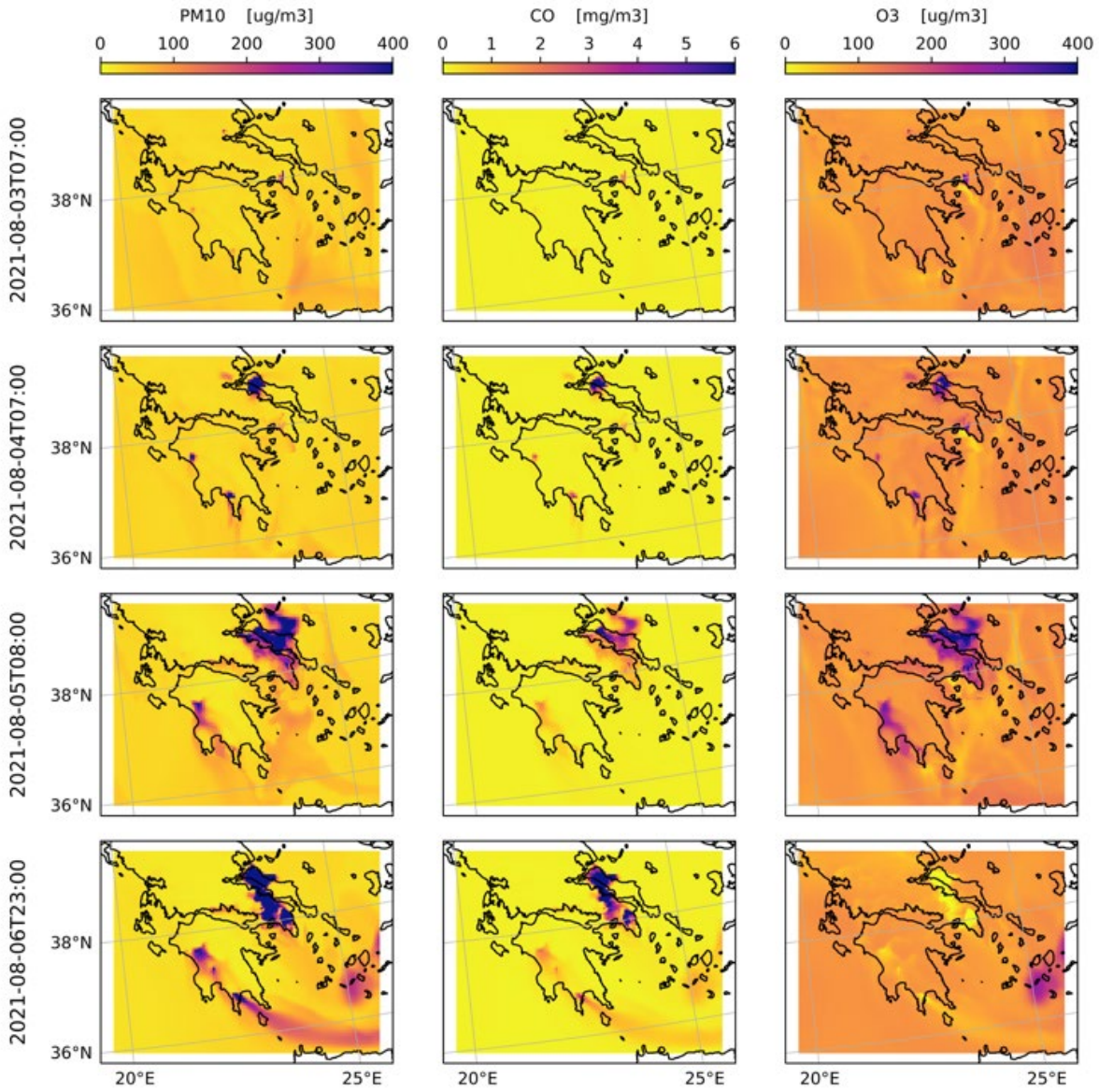


Figure 110 – Spatial distribution of the PM_{10}, CO and O_3 concentrations ($\mu g/m^3$) of simulated values at surface level

6.5.3 Fatalities

A great effort has been made by the state authorities and organizations to avoid human losses. This strategy led to an overuse of the 112 Emergency Service without being able to support its deployment. It should be mentioned that despite the excessive use of evacuation orders, the result was no direct fatalities due to the fire recorded.

However, some collateral damage has been observed. For instance, the head of the Forest Service direction of Evia, having worked for many days on the fire, under high anxiety and being disappointed due to the missed opportunity to control the fire early, suffered a heart attack and died.

6.6 Conclusions and lessons learned

The fire in North Evia was the largest single fire in the modern history of the Greek state. It had all the elements and characteristics to be considered a mega-fire due to its extent and potential, as well as due to the high impact and severe damage it caused, mainly due to inadequate response.

An important conclusion that can be made following the fire is that inadequate forest and landscape management and prevention leads to ineffective and inefficient protection from wildfires. The lack of fuel management over a series of years, coupled with the damage caused by an early spring snowstorm, created a situation that could not be addressed by the fire suppression mechanism. A balanced relationship between fire prevention and suppression, not only in terms of financing but also in terms of perceived interest, and forest management and status monitoring across the entire year are prerequisites for sound protection from landscape fires.

The fire response mechanism has its limits, and it was proved that two significant parallel incidents (the fire in North Evia burned on the same dates as the fire in Varibobi/Attica) overcome its capability to manage both effectively. There was a precedent case with two major parallel fires on the same day (July 23rd, 2018) in Mati and Kinetta (both in Attica), with similarly tragic results. There is a need to reinforce the local response capabilities and elaborate a triage procedure for parallel crucial wildfire events. The close dependence of the forest protection system on aerial means ignoring the significance of the ground forces leaves many areas exposed in case of multiple fires and extreme weather conditions.

The fire of North Evia had a significant political impact, leading the Greek government taking certain initiatives a few weeks after the end of the fire as follows:

- The creation of a brand-new Ministry of Climate Crisis and Civil Protection, which replaced and extended the power of the respective Deputy Ministry, previously belonging to the Ministry of Citizen Protection and was transferred to another Ministry;
- The operational use of counterfire during firefighting has been regulated;
- The centralization of the Forest Service at the national level under the Ministry of Energy and Environment, which previously belonged to the Decentralized Authorities of the Ministry of Interior, was decided;
- A holistic and people-centered reconstruction plan driven by the important tools of integrated territorial investments (ITI), which dominate the NSRF 2021-2027 was decided, and its coordination was entrusted to the organization DIAZOMA (https://diazoma.gr/en/cultural-routes/reconstruction-plan-for-northern-evia/);
- Organization of the preparedness of concrete reforestation and post-fire restoration plan for the burned areas of North Evia.

A significant lesson learned from the fire is related to the overuse of the European Emergency Service (112) by the state authorities, which use proved to be partial and incomplete. However, such use must be associated with the avoidance of human losses. The main reason is that the local population was not informed and familiar with the use of the service prior to the fire. They experienced forced training during the incident, which caused most of them to ignore the relevant instructions. In addition, since they understood that the evacuation orders were not accompanied by a parallel plan for protecting the villages and their properties after the evacuation by the competent forest firefighting services, they reacted by ignoring the instructions given and blaming the authorities because villages that complied with the order suffered destructions while all the villages that didn't obey were salvaged. The relative lesson learned is that the messages and the use of the 112 Emergency Management Service should take into consideration the profile of the recipients of the message, i.e., people in the villages near forests are more resilient and adapted to fire events than people in the wildland-urban interface and they need to be treated accordingly.

The practice of evacuation and rescue of the fire-threatened population in the coastal areas via sea, using boats is critical to be activated early, which was not the case in the Mati fire in 2018, and which led to excessive fatalities. In the case of the North Evia fire, this lesson has been tested successfully.

All the settlements and villages must have a scenario-based fire protection plan that must be activated in an emergency. The plan should consider who will leave the village and who will stay to do what and how. The local people in the villages can react on their own to protect their houses, farms, and properties however, a pre-existing plan would facilitate and optimize their reaction and the use of resources. The volunteers, organized and spontaneous, offered a lot in fighting the fire and protecting properties. They need to be supported by the state by exploiting their local knowledge, professional experience, and willingness to help.

The use of social media may greatly contribute to communication, information sharing, and coordination during wildfire crises. However, it must be used with caution, particularly during the response phase, to prevent the distribution of misleading and unreliable information as well as fake news.

FIRE OF ARAKAPAS

Authors

Klelia Petrou	EUC
George Boustras	EUC
Jason Senekkis	EUC
Judith Kirschner	EUC
Pooja Pandey	EUC

7 The Fire Event of Arakapas (Cyprus)

7.1 General Description

The Arakapas fire broke out in the afternoon of Saturday, July 3rd, in the Limassol district, near the village of Arakapas. During the previous week and the specific day, heatwave conditions with temperatures above 40ºC were observed. The fire danger on that specific day, based on the European Forest Fire Information System (EFFIS) forecast was extreme (Figure 111).

According to the information shared by the Cyprus Police in court on September 6th, during the pre-trial procedures of the suspect who was arrested after the Arakapas fire, the fire was allegedly ignited when the man had been burning stubble earlier on the day.

The fire resulted in 4 445ha of burned area in less than 48 hours and four men died during the incident. The RescEU mechanism was activated later in the afternoon of the same day with a response for Greece with two Canadair aircrafts.

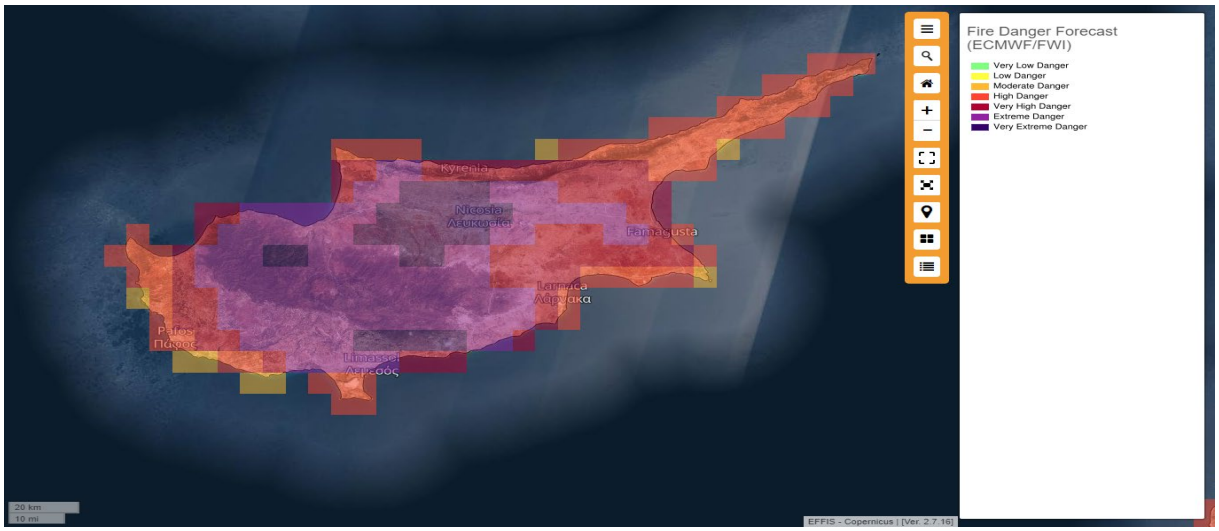


Figure 111 – EFFIS fire danger forecast for July 3rd(https://effis.jrc.ec.europa.eu/apps/effis_current_situation/ Accessed on 18.05.2022).

7.2 Characterization of the affected area

The burned area during the 2021 Arakapas fire event crosses the boundaries of the Limassol and Larnaka districts. The area is a small valley located in the southern hills of the Troodos Mountain range, spanning an elevation of about 250-1250m (a.s.l.), as shown in Figure 112. In the valley can be found several small villages and seven of those have been affected by the fire. Geologically, the area forms part of the Troodos Ophiolite with a predominant occurrence of diabase [31]

The vegetation of the area varies between agriculture fields around the villages; maquis and garrigue shrubland with sclerophyllous vegetation, and on the outskirts of each village there are patches of forest with mixed broadleaf and coniferous trees, dominated by Turkish pine (*Pinus bruit)*, as can be seen, Figure 113 and Figure 114. The cultivated land comprises various crops, fruit plantations, olive trees, and carob trees [32].



Figure 112 – The Valley where the Arakapas Fire occurred in June 2021 (photo courtesy of Judith Kirschner).



Figure 113 – Mixed coniferous and broadleaf vegetation in the Arakapas area one year after the fire (photo courtesy of Judith Kirschner).



Figure 114 – Mixed and broadleaf vegetation burning (photo courtesy of Cyprus Fire Service).

Landscape and wildfires are common during the long summer season, May till October, in Cyprus due to the rare rainfall and prolonged high temperatures throughout the island. In the area of Arakapas and neighboring villages, several fires have been recorded in the past, however, the fire spread was limited and considerably smaller than the fire of July 2021. The recorded fires in the Arakapas area since 2000 with respect to the hectares of burned area are presented in Figure 115.

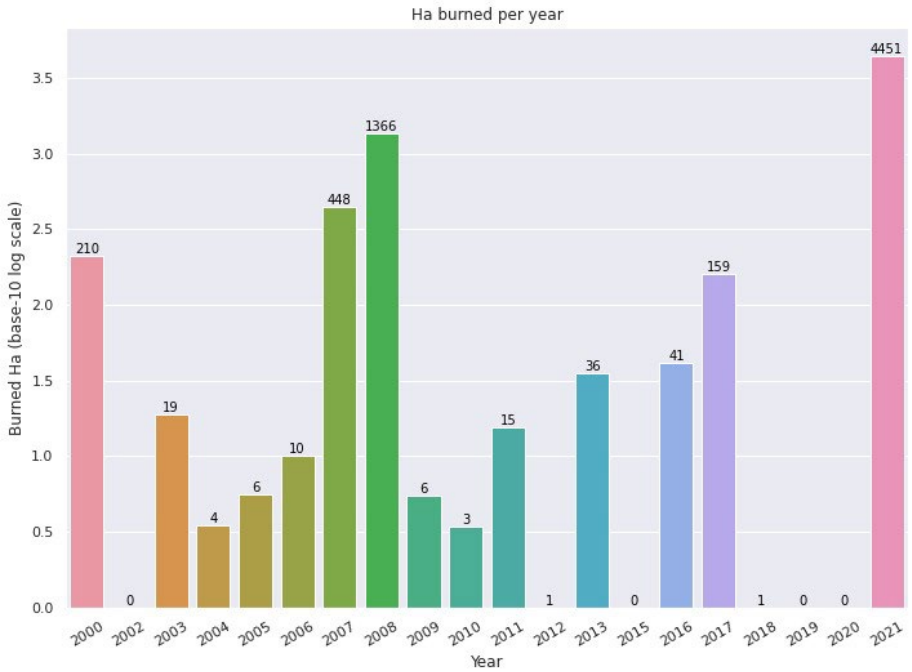


Figure 115 – Burned area in Ha per year in the Arakapas area (data provided by the Cypriot Department of Forests).

7.3 Fire conditions

Weather conditions, according to the nearest meteorological station at Eptagonia at the time the fire broke out, reported a temperature of 35.1°C, a humidity of 13%, wind speed at 6 bf (38.9-49.7km/h – a strong breeze, in the Beaufort Scale) and zero precipitation during the last 30 days. The Cyprus Fire Service received the first call at 01.46 p.m. EET (UTC+2), reporting a fire outside the village of Arakapas.

At the time of the event, in July 2021, there were two fire stations near the area. One was located in the village of Eftagonia, around 5km from the fire ignition point, and was managed by the Cyprus Fire Service. The second fire station was in the village of Parekklissia, about 15km from the fire ignition point and was managed by the Cyprus Department of Forests. At that time, the personnel and the firefighting equipment and vehicles of the two fire stations were responding to a fire near the A1 Nicosia-Limassol highway at a distance of 25km from the Arakapas village, causing a series of delays in ground forces reaching the Arakapas area. Fire stations located in Nicosia (c.a. 60 km away) responded to the Arakapas fire event, but due to the delay in personnel, vehicles and equipment to reach the area, the roads were blocked, thus not allowing the ground forces to approach.

It should be recorded that the Eptagonia fire station was destroyed by the fire that reached the outskirts of the village. Due to the simultaneous response in the two fire events that occurred on the specific day, no personnel or Fire Service vehicles were at the Eptagonia Fire Station at the time the fire reached the village and destroyed the station.

According to the Cyprus Fire Service reports, the first aerial firefighting forces arrived and started operating at the area of the Arakapas fire approximately 10 minutes after the alert. The first ground forces arrived at around 02.15 p.m. EET, 30 minutes after the first call was received. The emergency services that responded to the fire event faced significant difficulties to organize and manage the operations to control the fire.

As mentioned above, due to the fact that personnel and equipment of the two neighboring fire stations were responding to another fire event, authorities and ground forces required approximately ninety minutes (90) after the first call to engage in full power and capacity to the fire in Arakapas. Also, due to the electricity power outage that was caused by the damage to electricity poles and transformers in the area, most fire hydrants, and water pumps were out of order. Water supply for fire trucks of the Cyprus Fire Service, the Cyprus Department of Forests, and for private tankers that participated in the operation, was conducted in the village of Parekklisia, causing delays of 15 to 20 minutes in the ground firefighting efforts.

Cyprus Fire Service protected residential areas and, in cooperation with the Cyprus Civil Defense, the Cyprus Police, and local authorities, evacuated the threatened villages, Arakapas, Melini, Ora, Odou, Sykopetra, Eptagonia, Ayioi Vavatsinias, and Vavatsinia. The Cyprus Department of Forests took over control and fought the fire in the remaining areas.

During the first hours of the fire event, the RescEU mechanism was activated at 03.50 p.m. EET time, with aerial firefighting forces arriving from Greece the following morning. Additional assistance from two air-tractor airplanes was provided the next morning from Israel via a bilateral agreement between the Cyprus and Israel. Thus, a total of 15 firefighting aircrafts were available to operate in the efforts to control of the wildfire:

- 4 airplanes and 5 helicopters from the Republic of Cyprus,
- 2 helicopters from the British Sovereign Bases in Cyprus,
- 2 air-tractors from Israel,
- 2 Canadair airplanes from Greece via the RescEU mechanism.

In total, ground forces included 70 fire engines and trucks, 14 bulldozers and 20 water tanks. In terms of personnel, approximately 600 people were involved in the operations from:

- Cyprus Fire Service officers,
- Department of Forests,
- Cyprus Police,
- National Guard,
- British Sovereign Bases,
- Local Authorities- Community Councils,
- Game and Wildfire Service,
- Volunteers from Civil Protection.

The fire was reported to be fully under control on Monday, July 5th at 8.00 a.m.

Several challenges contributed to the delay in the firefighting response, which in turn led to significant difficulties and time-consuming efforts in controlling the fast spread of the fire, that resulted in the burning a total of 4 445 ha in less than 48 hours. Firstly, the communication between the authorities was not satisfactory due to the simultaneous fire events but also due to the old technology used at the time and the poor management plan. Secondly, the road network was blocked by private cars and volunteer groups that tried to reach the area without cooperation and coordination with the responsible authorities. Finally, the topography and strong winds played a significant role in the development of the fire event, in combination with the convective turbulence caused by the fire.



Figure 116 – Cyprus Fire Service personnel (courtesy of Cyprus Fire Service).

7.4 Fire behavior

As noted in the previous chapter, the extreme weather conditions before and during the wildfire ignition day, contributed dramatically to the fire behavior and spread. As noted earlier the prolonged high temperatures above 40°C and the early dry season in Cyprus with no rainfall registered in the area 30 days before the incident were factors of significant importance for the Arakapas fire. Additionally, the rainfall during the previous winter months, had led to an extraordinary growth of herbaceous which, with the sudden heat wave, dried up, leading to a great amount fuel load available to burn, in combination with the non-appropriate or non-existing cleaning and land management actions by the responsible authorities and land-owners

The fire affected an area of 55 km^2 in less than 24 hours (Figure 117). A running fire was clearly developed in a short period of time with an estimated, by the authorities, a maximum speed of 7km/h (118m/min).

In just 5 hours, the wildfire passed through a total of 8km horizontal extension of land, burning an area of 40km. The total burned area according to the Cyprus Department of Forests was 44.45 km^2. This resulted in the tragic loss of four human lives, a total of 50 houses and premises damaged or destroyed, and the loss of dead livestock animals including a whole chicken farm that was burned and an unrecorded number of wild animals that died.

The winds registered in the area at the time of the incident reached 6 bf (~44km/h) and were increased after the fire development due to the convective effects. The topography of the area - a small valley surrounded by mountains also contributed to the wildfire behavior.

It should be noted that the smoke was visible to other areas of the island such as Nicosia on the North-side, Limassol on the South-side and Ayia Napa on the South-East side of the fire location.

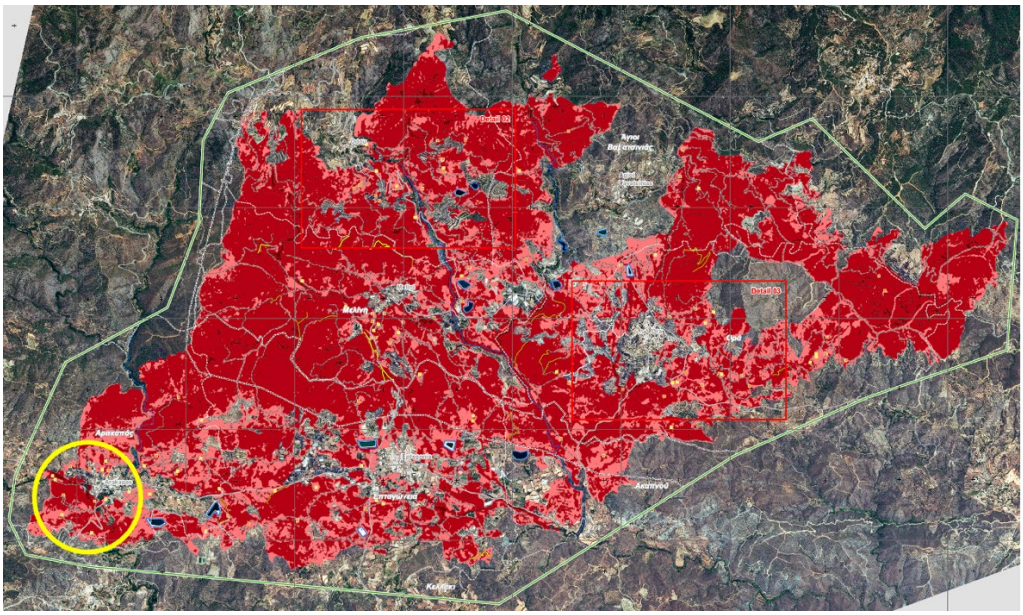


Figure 117 – Copernicus 2021-EMSR515 The map shows the damage grade assessment in Melini/Arakapas.



Figure 118 – Fire Spread over the hills (courtesy of Cyprus Fire Service).

7.5 Fire impacts

The area of the Arakapas fire is a rural area that consists of a small number of villages and communities. The fire affected 12 villages in total, with some being evacuated during the fire (Arakapas, Melini, Ora, Odou, Sykopetra, Eptagonia, Ayioi Vavatsinias, and Vavatsinia). The fire claimed the lives of four Egyptian male workers aged 22-39. The four men were working in tomato crops outside the village of Odou, and according to witnesses and their employer, they got caught up in the burning area while trying to escape in a pick-up truck and then on foot.

Fifty damaged private buildings were officially reported. Also, Copernicus Emergency Management Service records show that the fire affected a total of 1 412ha of agricultural fields, 66ha of those were permanent crops, 1 471ha of forested land, and 996ha of herbaceous vegetation (Copernicus, 2021). A part of the burned area is protected under the Natura 2000 Birds Directive (Cyprus Department of Forests). Moreover, 600 beehives were destroyed in the area.



Figure 119: Damage Properties and Plantation Trees at Arakapas Village (courtesy of Klelia Petrou).

In Ora village, one small olive-oil production unit was destroyed. Additionally, 8 000 chickens died in a poultry farm that suffered extensive damage, with its four production units destroyed by the flames and three more units affected by the fire heat and smoke.

The public roads to and from the villages suffered significant damage and the Eptagonia fire station was completely destroyed by the fire that reached the outskirts of the village (see Figure 119 and Figure 120). According to official statements from the Electricity Authority of Cyprus on July 6th, more than 350 electricity poles and 15 aerial electricity transformers were burned during the fire.



Figure 120: Eptagonia Fire Station (courtesy of Klelia Petrou).

7.6 Conclusions and lessons learned

The aftermaths of this wildfire incident were discussed in the Cyprus Parliament with the participation of the first response authorities and the affected municipalities in order to develop measures and law enforcement on human-caused fires by both arson and negligence. Even though legislation is in place, forbidding the use of fire during the summer months in any private or public area, the majority of wildfires reported in Cyprus in recent years were caused by the specific factor. Thus, the enforcement of higher fines and penalties was deemed critical.

On the governmental level, it was decided to invest in an up-to-date emergency response center and develop better coordination systems among the first responders' services. The Cyprus Fire Service has also suggested an increase in firefighting personnel.

Furthermore, experts and academics participating in the discussion and in public appearances, submitted the following suggestions:

- Upgrade the existing fire management system and develop a holistic approach for dealing with agriculture and forest fires with the use of new technologies;
- Change the traditional way of thinking about and managing of fires;
- Develop better & effective strategies for informing the public aiming at:
    - fuel management of properties before the summer season;
    - Produce press notices informing about the dangers from fires during the summer season, particularly during strong winds days;
- Develop a better land-use planning system to reduce fire risk to homes from wildfires;
- Offer professional and ad-hoc training for the volunteers;

Acknowledgments

The authors of this chapter would like to express their gratitude to the following people who provided data and testimony which were essential to the production of the report. We apologize in advance for any possible omission in the list of acknowledgments. Some people who were interviewed did not wish to be included in this list. To all, our thanks for their contributions to this report.

João Carvalho	Technician of ADAI (Association for the Development of Industrial Aerodynamics)
Pascale Vacca	Researcher of UPC (Polytechnic University of Catalonia)
Miguel Silva	Tavira Municipal Firemen Commander
André Sousa	Senior Technician of the Municipal Civil Protection Service of Tavira
Nuno Pereira	Vila Real de Santo António Voluntary Firemen Commander

This report has been produced as a collaboration between the FirEUrisk project and the European Commission Joint Research Centre. The chapters of the analysis of individual fire events in the report, as well as the work involved in this analysis, was funded by the Project FirEUrisk – Developing a Holistic, Risk-Wise Strategy for European Wildfire Management. This project has been granted funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement nº. 101003890.

8 References

[1] ICNF, "Perigosidade Conjuntural de incêndio 2021." [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj_w66f1MP6AhUR_rsIHe_HAEUQFnoECA8QAQ&url=https%3A%2F%2Fsi.icnf.pt%2Fkml%2Fperigosidade_conjuntural_2021&usg=AOvVaw3VyOGBZ0p40nY-8XW35YbA.

[2] *Censos - Resultados definitivos. Portugal*, vol. 3238, no. C. 2012.

[3] INE (2021), "Plataforma de divulgação dos Censos 2021 – Resultados Provisórios," [Online]. Available: https://censos.ine.pt/xportal/xmain?xlang=pt&xpgid=censos21_dados&xpid=CENSOS21.

[4] DGT, "Especificações Técnicas da Carta de Uso e Ocupação do Solo (COS) de Portugal Continental para 1995, 2007 e 2010," Relatório Técnico. Direção-Geral do Território. Coordenação: Mário Caetano, Cristina Igreja e Filipe Marcelino, Relatório Técnico. Direção-Geral do Território, 2018.

[5] S. E.-A. Henaoui, M. Bouazza, and M. Amara, "The fire risk of the plant groupings with Cistus in the area of Tlemcen (Western Algeria)," *Eur. Sci. J.*, vol. 9, no. 29, 2013.

[6] IPMA, "Índice Meteorológico de Incêndio [FWI] e Probabilidade de extremos – Mapa dinâmico," 2021.

[7] J.-C. Coquet, "Périmètre pilote du massif des Maures," *Rev. For. française*, vol. 27, no. S, pp. 376–384, 1975.

[8] franceinfo avec AFP, "Var : un feu de forêt détruit 'plus de 1 000 hectares' à Gonfaron, 600 pompiers mobilisés." https://www.francetvinfo.fr/faits-divers/incendie/var-un-feu-de-foret-a-deja-detruit-plusieurs-centaines-d-hectares-a-gonfaron_4739567.html.

[9] La Dépêche du Midi, "Trois pompiers périssent brûlés dans le massif des Maures » [archive]," 2003.

[10] S. Lahaye, T. Curt, T. Fréjaville, J. Sharples, L. Paradis, and C. Hély, "What are the drivers of dangerous fires in Mediterranean France?," *Int. J. Wildl. Fire*, vol. 27, no. 3, pp. 155–163, 2018.

[11] F. & R. O. Mortier, "Mission d'appui à la réserve naturelle nationale de la plaine des Maures," 2022.

[12] "Nature reserve, Plaine des Maures – Plan de Gestion 2015-2020 Annexes," *Var Le Département*, 2022.

[13] S. M. Redpath *et al.*, "Understanding and managing conservation conflicts," *Trends Ecol. Evol.*, vol. 28, no. 2, pp. 100–109, 2013.

[14] Direction Régionale de l'Environnement, "Provence-Alpes-Côte d'Azur – Direction Départementale de l'équipement du Var, 2007," 2007.

[15] Syndicat du Massif des Maures, "Elaboration du programme de réhabilitation des espaces naturels et forestiers incendiés suite à l'incendie de Gonfaron.," *Cah. des clauses Tech. Part.*, 2021.

[16] V. R. Vallejo Calzada, N. Faivre, F. M. Cardoso Castro Rego, J. M. Moreno Rodríguez, and G. Xanthopoulos, "Forest fires. Sparking firesmart policies in the EU," 2018.

[17] F. Moreira *et al.*, "Landscape–wildfire interactions in southern Europe: implications for landscape management," *J. Environ. Manage.*, vol. 92, no. 10, pp. 2389–2402, 2011.

[18] K. G. Hirsch and D. L. Martell, "A review of initial attack fire crew productivity and effectiveness," *Int. J. Wildl. Fire*, vol. 6, no. 4, pp. 199–215, 1996.

[19] J. G. Goldammer and V. V Furyaev, "Fire in ecosystems of boreal Eurasia: Ecological impacts and links to the global system," in *Fire in ecosystems of Boreal Eurasia*, Springer, 1996, pp. 1–20.

[20] J. San-Miguel-Ayanz, J. M. Moreno, and A. Camia, "Analysis of large fires in European Mediterranean landscapes: Lessons learned and perspectives," *For. Ecol. Manage.*, vol. 294, pp. 11–22, 2013.

[21] ISTAT, "Istatuto Nazionale di Statistica," 2010.

[22] E. C. Salinero, *Wildland fire danger estimation and mapping: the role of remote sensing data*, vol. 4. World Scientific, 2003.

[23] T. M. Giannaros *et al.*, "Meteorological Analysis of the 2021 Extreme Wildfires in Greece: Lessons Learned and Implications for Early Warning of the Potential for Pyroconvection," *Atmosphere (Basel).*, vol. 13, no. 3, p. 475, 2022.

[24] EDCM NKUA Newsletter, "Environmental, Disaster, and Crises Management Strategies," *Natl. Kapodistrian Univ. Athens .*, no. 25, 2021.

[25] N. Evelpidou *et al.*, "Assessment of fire effects on surface runoff erosion susceptibility: the case of the summer 2021 forest fires in Greece," *Land*, vol. 11, no. 1, p. 21, 2022.

[26] YLI, "Evaluation of the results of the fire in Northern Evia. Report relative to the « Master Plan of the New Forest», part of the post-fire integrated development plan of North Evia," 2022.

[27] G.-F. Sargentis *et al.*, "Wildfires vs. Sustainable Forest Partitioning," *Conservation*, vol. 2, no. 1, pp. 195–218, 2022.

[28] N. Koutsias, M. Arianoutsou, A. S. Kallimanis, G. Mallinis, J. M. Halley, and P. Dimopoulos, "Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather,"

Agric. For. Meteorol., vol. 156, pp. 41–53, 2012.
[29] A. Gemitzi and N. Koutsias, "A Google Earth Engine code to estimate properties of vegetation phenology in fire affected areas–A case study in North Evia wildfire event on August 2021," *Remote Sens. Appl. Soc. Environ.*, vol. 26, p. 100720, 2022.
[30] M. A. Oswald T, Gama C, Fernandes AP, Varela V, "Effects of the wildfires in August 2021 on the air quality of Athens through a numerical simulation," *Int. J. Wildl. Fire*, 2022.
[31] Geological Survey Department, "Geological Survey Department Government of Cyprus," 1979.
[32] R. d'Andrimont *et al.*, "LUCAS Copernicus 2018: Earth-observation-relevant in situ data on land cover and use throughout the European Union," *Earth Syst. Sci. Data*, vol. 13, no. 3, pp. 1119–1133, 2021.

9 List of Figures

Figure 1. Burnt areas mapped during the 2021 fire season. Largest fires are indicated in ha 5

Figure 2. Total number of fires mapped by month and country in 2021 5

Figure 3. Total burnt area of fires mapped by month and country in 2021 5

Figure 4. relative proportions of burnt area mapped in protected areas in 2021, ordered by size 6

Figure 5. Burnt area in Natura2000 sites and other protected areas in 2021 6

Figure 6. Proportions of land cover types affected in 2021 (all countries, ordered by total burnt area) 7

Figure 7. Burnt area in each country in 2021 by CORINE land class. 7

Figure 8. Burnt area weekly evolution in 2021 (European Union countries) 8

Figure 9. Cumulative burnt area in 2021 (European Union countries) 8

Figure 10: Fire events addressed in the study. The circles in red indicate the number of direct fatalities recorded in the respective event. (Background image adapted from REMPEC / Copernicus) 10

Figure 11 – a) Geographical setting of the Castro Marim Fire; b) Conjunctural danger for 2021 (Source: ICNF [1]) 12

Figure 12 – Representation of forest fuels in the fire area: a) land use map; b) image with typical fuels 13

Figure 13 – Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern 13

Figure 14 – Final perimeter of the largest fire events that occurred in the region since 2000 14

Figure 15 – Meteorological conditions registered by the Meteorological Station of Castro Marim between August 15th and 17th, 2021 (source: IPMA [6]): a) temperature and relative humidity variation; b) wind variation 15

Figure 16 – a) Fuel moisture content (mf) for dead Pinus pinaster needles and dead Eucalyptus globulus leaves during 2021 in Faro (Algarve). Data source: MCFIRE/ Univ. Algarve) 15

Figure 17 – a) Fire Weather Index (FWI) determined by the observed meteorological data from the weather station of Faro between 2018 and 2021 and the weather station of Castro Marim between August 15th and 17th (data source: IPMA) 16

Figure 18 – Representation of the estimated fire behavior according to the indications from ANEPC 17

Figure 19 – Damage grading of the burned area (image adapted from Copernicus) 17

Figure 20 – Location of wildland-urban interface elements damaged or threatened by fire, considered to be of greatest interest for the study 19

Figure 21 – a) General view of the building damaged – the yellow arrows indicate the provenience of the fire front; b) photo of the back of the building where it is possible to see the proximity of forest fuels such as trees. 19

Figure 22 – Images before (a) and after (b) the destruction of the building by the fire. The red arrow in image (a) indicates the eucalyptus tree where the witnesses point to have seen the first flames next to the building. 20

Figure 23 – Images of the sheep pen. The red arrow in image (a) indicates the location of the sheep pen. The blue arrow (b) points to the location of the building destroyed by the fire 20

Figure 24 – Overview of the location where the episodes “Faz Fato 1” and “Faz Fato 2” took place. The yellow circle highlights the eucalyptus tree, which was relevant in the ignition of the houses 21

Figure 25 – General view of the building related to the "Faz Fato 1" episode: a) before the fire event (Google Earth image) and b) after the fire event (photo courtesy of Tavira Câmara Municipal) 21

Figure 26 – General view of the building related to the "Faz Fato 2" episode: a) before the fire event (Google Earth image); b and c) after the fire event (photos courtesy of Tavira Câmara Municipal); and d) image of the house during its reconstruction 22

Figure 27 - General view of the integration of the three houses in the landscape. The yellow arrows point to the place where the fire front hit the constructions 23

Figure 28 –Photographs of some of the impacts caused by the fire in the Faz Fato 3 (a) and Faz Fato 4 (b) case studies. The images from (a) were kindly provided by the Municipal Council of Tavira / Volunteer Firefighters of Tavira 23

Figure 29 – Images regarding the case study of Corte António Martins: a) photograph of a reed roof; b) general image of the house where is possible to see the roof area that was damaged by the fire; c) indoor image of the roof that was damaged by the fire, where we can see the reed roof where the fire started 24

Figure 30 – Images of the Intermunicipal Kennel and Cattery of Castro Marim and Vila Real de Santo António. 25

Figure 31 – Images of the private kennel that was destroyed by fire 26

Figure 32 – Map of the history of fires on the impacted territory (source: National Forestry Office). 29

Figure 33 – 3D assembly of the propagation of the fire vis-à-vis the reliefs (source: Departmental Fire and Rescue Service of the Var)- 31

Figure 34 – Cumulative rainfall and ratio to normal in July 2021 (Source: Météo Villes & Météo France) 31

Figure 35 – Dead vegetation: IEP6x planned (purple) (Source: Departmental Fire and Rescue Service of the Var) 32

Figure 36 – Initial phase of the fire – photo taken at 5.59 p.m., 16 minutes after its ignition (Source: Departmental Fire and Rescue Service of the Var) 33

Figure 37 : Photo of the fire taken at 6.30pm, 46 minutes after the original ignition (Source: Departmental Fire and Rescue Service of the Var) 34

Figure 38 – Course of the fire between 05.45 p.m. and 12.00 p.m. of August 16th (Source: Departmental Fire and Rescue Service of the Var) 34

Figure 39 – Fire-covered area, indicating satellite contours, spot fires, and axes of propagation (Source: Departmental Fire and Rescue Service of the Var) 35

Figure 40 – Photos of the Charlemagne campsite destroyed by fire, located in Grimaud 36

Figure 41 – General map of the Montiferru area, including the 2021 wildfire perimeter and the administrative municipal boundaries. ABB=Abbasanta; BAU=Bauladu; BON=Bonarcado; BOR=Borore; BOS=Bosa; CUG=Cuglieri; FLU=Flussio; MAC=Macomer; MAG=Magomadas; MIL=Milis; MOD=Modolo; NAR=Narbolia; PAU=Paulilatino; POZ=Pozzomaggiore; SAG=Sagama; SDM=Scano Montiferro; SEN=Seneghe; SIN=Sindia; SLU=Santu Lussurgiu; SNR=Sennariolo; SUN=Suni; SVM=San Vero Milis; TIN=Tinnura; TRE=Tresnuraghes 39

Figure 42 – Perimeters of the largest wildfire events that occurred in the Montiferru area in recent years 39

Figure 43 – Main fuel types of the area affected by the Montiferru wildfire. AA=anthropic areas; OG=olive groves; HV=herbaceous vegetation; R=rocks; BF=broadleaf forests; CF=conifer forests; LS=low shrubs; WB=water bodies; HS=high shrubs. On the right, some olive groves were affected by the wildfire in the municipality of Cuglieri 40

Figure 44 – Digital elevation model of the Montiferru area. On the right, a picture of the southeastern part of the wildfire area (Sos Molinos), from which the Badde Urbara peak can be seen 41

Figure 45 – MSG (Meteosat Second Generation) Air Mass RGB composition with ECMWF analysis of geopotential height (gpdam) and temperature (°C) respectively at 500 hPa and 850 hPa levels on 02.00 p.m. (12.00 UTC) of July 22nd 41

Figure 46 – Superimposed infrared MSG (Meteosat Second Generation) images and ECMWF analysis of geopotential height and temperature at 850hPa on 02.00 a.m. (00.00 UTC) of July 23rd, 24th, and 25th 42

Figure 47 – Temperature, wind, and relative humidity conditions forecasted by the WRF model for 02.00 p.m. (12:00 UTC) of July 24th 43

Figure 48 – Fire danger bulletins issued by the Sardinia Civil Protection for the period July 23rd to 26th. Sardinia is split into several homogeneous weather sectors (from A to Z). The black star indicates the Montiferru wildfire ignition 44

Figure 49 – Maximum temperature values above 37°C, as interpolated by the Dewetra integrated system of the Italian Civil Protection Department, from the data observed in the weather stations from July 23rd to 26th. 45

Figure 50 – Temperature and relative humidity, and wind intensity measured in the Badde Urbara (1,033m a.s.l.) weather station. The dotted line highlights when data of temperatures and humidity are not reliable as they refer to the period following the passage of the fire. The third image is evidence of the damage to the weather station caused by the wildfire 45

Figure 51 – 10h dead fuel moisture content and fuel stick sensor temperatures observed in four stations of monitoring, located in Putifigari, Giave, Ghilarza, and Samassi, from July 20th to 28th 46

Figure 52 – Meteosat Second Generation (MSG) Air Mass RGB composition at 02.00 p.m. (12.00 UTC) of July 24th. Figures "b" and "c" present the vertical maximum reflectivity (dBZ) observed by the ARPAS weather radar (focus on two timeframes characterized by high wildfire growth rates) 47

Figure 53 – Atmospheric radiosonde charts of Decimomannu (CA), 150km SE to the Montiferru, of July 25th, 00Z and 12Z 48

Figure 54 – Phase 0 of the Montiferru wildfire, July 23rd, from 05.53 p.m. to 09.00 p.m 48

Figure 55 – Phase I of the Montiferru wildfire, July 24th, from 11.56 a.m. to 04.20 p.m 49

Figure 56 – Phase II of the Montiferru wildfire, July 24th, from 04.20 p.m. to 06.10 p.m. 50

Figure 57 – Phase III of the Montiferru wildfire, July 24th, from 06.10 p.m. to midnight 51

Figure 58 – Phase IV of the Montiferru wildfire, July 25th, from 00.00 to 09.00 p.m 51

Figure 59 – Montiferru fire smoke plume trajectory at larger (a) and detailed (b) scale 52

Figure 60 – Daily evolution trends for PM_{10} measured in ARPAS stations (Sassari, NW Sardinia; Olbia, NE Sardinia; and Nuoro, Central Sardinia), from July 17th to 30th 53

Figure 61 – Burn severity estimated for the Montiferru wildfire. This output was derived by rescaling the Normalized Burn Ratio index (NBR). HR=high regrowth; LR=low regrowth; U=unburned; LS=low severity; MLS=medium-low severity; MHS=medium-high severity; HS=high severity. 53

Figure 62 – Location of residential, agricultural, and other buildings partially or heavily damaged by the fire. 54

Figure 63 – Damage to a telecommunication infrastructure installed within a forest area affected by the fire (Source Protezione Civile) 55

Figure 64 – Damage to a private company in the industrial area of Cuglieri (Source Vigili del Fuoco) 55

Figure 65 – a) A house heavily damaged by the fire; b) Agricultural warehouse seriously compromised (b) (Source Vigili del Fuoco) 55

Figure 66 – Location of the livestock farms that were affected by the Montiferru wildfire. Source Protezione Civile 56

Figure 67 – Post-fire pictures in some areas characterized by high slope conditions: 57

Figure 68 – The sediment fences installed in the Montiferru area a few weeks after the fire, prior to rain events 58

Figure 69 – Initial phase and development of the Varybobi 2021 fire. 59

Figure 70 – Wildland urban interface in the wider area of the Varybobi 2021 fire. 60

Figure 71 – Land use (Corine landcover 2018) map in the burned area of the Varybobi 2021 fire 61

Figure 72 – Damage in forest vegetation increased the heavy forest fuel load (a and b) and cleaning operations (c and d) following the snowstorm Medea, which occurred in mid-February 2021. 62

Figure 73 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527a) 63

Figure 74 – Daily Fire Risk maps for 1-8 August 2021 issued by the General Secretariat of Civil Protection ... 64

Figure 75 – Snapshot from the European Forest Fire Information System (EFFIS) showing the forecast of Fire Weather Index (a) and Drought Code (b) for the area of Varybobi on August 3rd 64

Figure 76 – Time series of the daily dead fuel moisture content (DFMC) for the period December 2020 and August 2021 [23] 65

Figure 77 – Daily burned areas (Copernicus EMS) of the Varybobi fire between August 3rd and 8th (NKUA EDCM Newsletter, 2021 [24]) 65

Figure 78 – Burned area mapping and classification according to Burn Severity using Sentinel-2B L2A images of July 29th and August 8th (Harokopeion University of Athens). 66

Figure 79 – Time series of hourly normalized FRP from SEVIRI/METEOSAT [23]. 66

Figure 80 – Map showing the area burnt from the wildfire of Northern Attica (Source: EFFIS/WILDFIRE Database) 67

Figure 81 – Collapsed roofs and burned house interior in building blocks in a) and b) Adames settlement (NKUA Newsletter); c) and d) Tatoi settlement (NKUA Newsletter)[24] 68

Figure 82 – Damage due to fire entrance by openings in isolated houses in Tatoi settlement (NKUA Newsletter)[24]. 69

Figure 83 – Examples of cars burned in the Varybobi fire 69

Figure 84 – Overview of the burned core of the royal estate in Tatoi 69

Figure 85 – Sport horses at risk in the Tatoi club (a) are moved (b) for transfer to Markopoulo 70

Figure 86 – Ambient particulate (PM1.0) pollution from the smoke of the Varybobi fire (Source: Project Envicare) 70

Figure 87 – Burned area and settlements of the North Evia fire (Source: HUA Earth Observation Team, 2021). 72

Figure 88 – Slope (a) and hydrography (b) in the burned area of the North Evia fire (NKUA Newsletter 2021)[24]. 73

Figure 89 – Land use (CLC 2018) map in the burned area of North Evia 2021 fire (NKUA Newsletter) [24] 73

Figure 90 – Mosaic and relief of the landscape in North Evia (Google Earth imagery) 74

Figure 91 – Damage due to Medea snowstorm (a) and dense high forest with shrubs understory (b) in North Evia. 74

Figure 92 – Chats and information messages by North Evia volunteers using social media and communication platforms 75

Figure 93 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527b) 76

Figure 94 – Time series of the daily DFMC for the period December 2020 and August 2021 using data from the Vateri weather station [23] 76

Figure 95 – Time evolution of temperature and wind speed during the North Evia fire ([27]) 77

Figure 96 – Time variation of the meteorological wind and fire front direction during the North Evia fire ([27]). 77

Figure 97 – Daily Fire Risk maps by the General Secretariat of Civil Protection for the period 1-8 August 2021 (Source: Greek General Secretariat of Civil Protection) 78

Figure 98 – Fire Danger Forecast based on the Fire Weather Index (FWI) computed from the MeteoFrance model (10km) Snapshot from the European Forest Fire Information System (EFFIS) https://effis.jrc.ec.europa.eu/apps/effis_current_situation/ 78

Figure 99 – Convection columns and pyrocumulous cloud created during the North Evia fire (Right photo courtesy J.Tsaloukidis) 79

Figure 100 – The evolution of the fire in relation to forest continuity ([27]) 80

Figure 101 – Burned area mapping and classification according to Burn Severity using Sentinel-2A L2A images of August 1st and August 11th (Harokopion University of Athens) 80

Figure 102 – Climacogram integral of the daily clustering of the fire front related to the respective burned area ([27] 81

Figure 103 – The livestock and the beehives of the municipalities of Istiaia–Edipsos and Mandoudi–Agia Anna–Limni by the census 2019 ([27] 83

Figure 104 – Fire-induced roof damages identified by UAV flight performed by the University of Athens (Source: NKUA Newsletter., 2021) [24]. 83

Figure 105 – Fire-induced damage due to aged and old building material (Source: NKUA Newsletter., 2021) [24]. 84

Figure 106 – Damage to the power distribution network in Ayia Anna (Source: NKUA Newsletter., 2021) [24]. 84

Figure 107 – Spot of the Ayia Anna Club (camping) before and after the fire (left) and the restaurant of the Forest Village (resort) in Papades, destroyed by the fire (right). 85

Figure 108 – Massive evacuation using boats during the North Evia fire. 86

Figure 109 – Spatial distribution of aerosol optical depth (AOD) between August 3rd and 6th at 4.00 p.m., every day 86

Figure 110 – Spatial distribution of the PM_{10}, CO and O_3 concentrations ($\mu g/m^3$) of simulated values at surface level 87

Figure 111 – EFFIS fire danger forecast for July 3rd(https://effis.jrc.ec.europa.eu/apps/effis_current_situation/ Accessed on 18.05.2022) 90

Figure 112 – The Valley where the Arakapas Fire occurred in June 2021 (photo courtesy of Judith Kirschner). 91

Figure 113 – Mixed coniferous and broadleaf vegetation in the Arakapas area one year after the fire (photo courtesy of Judith Kirschner) 91

Figure 114 – Mixed and broadleaf vegetation burning (photo courtesy of Cyprus Fire Service) 92

Figure 115 – Burned area in Ha per year in the Arakapas area (data provided by the Cypriot Department of Forests). 92

Figure 116 – Cyprus Fire Service personnel (courtesy of Cyprus Fire Service) 94

Figure 117 – Copernicus 2021-EMSR515 The map shows the damage grade assessment in Melini/Arakapas. 95

Figure 118 – Fire Spread over the hills (courtesy of Cyprus Fire Service) 95

Figure 119: Damage Properties and Plantation Trees at Arakapas Village (courtesy of Klelia Petrou) 96

Figure 120: Eptagonia Fire Station (courtesy of Klelia Petrou) 96

10 List of Tables

Table 1. Areas mapped in 2021 estimated from satellite imagery....4

Table 2. Largest fires mapped by EFFIS in 2021....9

Table 3: Some socio-economic indicators of the parishes most affected by the Castro Marim fire....12

Table 4. a) Fire behavior indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) in Castro Marim weather station between August 15th and 17th; b) Danger scale for ISI, BUI, and FWI....16

Table 5 – Resources pre-positioned by the SDIS of the Var department and the CoZ on August 17, 2021....32

Table 6 – Classification of the structures damaged by the Montiferru wildfire, discriminated by damage severity....54

Table 7 – Number of livestock farms that suffered damage, together with the animals that were injured or lost due to the Montiferru wildfire. The data refer to preliminary surveys and might be underestimated....56

Table 8 – Number of landslide events that occurred in the Montiferru area during the period 2016 – 2022 (data provided by Vigili del Fuoco)....58

Table 9 – Damage per forest species, vegetation type, and land use in the municipalities of North Evia [26].82

Table 10: List of Acronyms....107

11 List of Acronyms

Table 10: List of Acronyms

List of Acronyms	
ADAI	Association for the Development of Industrial Aerodynamics
ANEPC	National [Portuguese] Authority for Emergency and Civil Protection
a.s.l.	Above sea level
BUI	Buildup index
CLC	Corine Land Cover
DFMC	Dead Fuel Moisture Content
DGT	[Portuguese] General Directorate for the Territory
EUCPM	European Union Civil Protection Mechanism
FRP	Fire Radiation Power
FWI	Fire Weather Index
HUA	Harokopeion University of Athens
ICNF	Institute for Nature Conservation and Forests
INE	National [Portuguese] Institute of Statistics
IPMA	Portuguese Institute of Sea and Atmosphere
ISI	Initial Spread Index
PM	Particulate Matter
PM_{10}	Particulate matter with equivalent diameter below 10μm
UTC	Universal Time Coordinated

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

Open data from the EU

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub
EU Science Hub - Joint Research Centre
EU Science, Research and Innovation
EU Science Hub
@eu_science

Publications Office
of the European Union

Appendix A2: 2022 Fires Report

ISSN XXXX-XXXX



JRC Technical Report

Report on the large wildfires of 2022 in Europe

First subtitle line
second subtitle line
third subtitle line

Surname(s), initial(s)

Sensitive/EU RESTRICTED [delete as applicable]

20XX



Joint
Research
Centre

EUR XXXXX XX

This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information [optional element]
Name:
Address:
Email:
Tel.:

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRCXXXXXX

EUR XXXXX XX

Print	ISBN XXX-XX-XX-XXXXX-X	ISSN XXXX-XXXX	doi:XX.XXXX/XXXXXX	XX-XX-XX-XXX-XX-C
PDF	ISBN XXX-XX-XX-XXXXX-X	ISSN XXXX-XXXX	doi:XX.XXXX/XXXXXX	XX-XX-XX-XXX-XX-N

Add the following hyperlink to the doi above: https://doi.org/XXXXXXX

Luxembourg: Publications Office of the European Union, 20XX [if no identifiers, please use Brussels: European Commission, 20XX or Ispra: European Commission, 20XX or Geel: European Commission, 20XX or Karlsruhe: European Commission, 20XX or Petten: European Commission, 20XX or Seville: European Commission, 20XX depending on your unit]

© European Union or European Atomic Energy Community, 20XX [Copyright depends on your directorate, delete as applicable: European Atomic Energy Community for Dir. G, European Union for rest of JRC]



The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of December 12th 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union or European Atomic Energy Community, (delete as applicable) permission must be sought directly from the copyright holders. The European Union or European Atomic Energy Community (delete as applicable) does not own the copyright in relation to the following elements:
- Cover page illustration, © Author name / stock.adobe.com
- [page XX, element concerned], source: [e.g. Fotolia.com]
[When indicating the inclusion of third-party elements, please check if the licensor makes any recommendation on a specific way to attribute.]

How to cite this report: Author(s), *Title*, Editors, Publisher, Publisher City, Year of Publication, doi:XX.XX/XXXXX (where available), JRCXXXXXX. [Always use the PDF/online doi in the citation, even for the print version of the publication.]

Printed by [Xxx] in country] [This will not be present in the ONLINE version.]

Contents <table is generated automatically; simply click on it and press F9 key, then select to update entire table>

Não foi encontrada nenhuma entrada de índice.

Abstract

The year 2022 was marked by large wildfires that caused significant social, environmental, and economic impacts. Describing some of the most impactful occurrences is essential, not only for historical record but also for drawing lessons that can be important for defining policies and improving strategies, tactics, and operations aiming at a more efficient fire management.

This report was developed within the European FirEUrisk Project, in association with the Joint Research Centre of the European Commission. It describes 11 of the largest European fires occurred in 2022, with a special focus on the fire behaviour and the orographic, meteorological, and operational conditions, among others, in which it spread. This analysis revealed the great disparity of policies and functioning capabilities that exist in European countries, many of which result from the importance that fires have in different territories. A reflection of lessons to be learned dedicated to each fire event indicates several aspects that can improve the fire management system, both at the national and European Union levels.

This report also includes a chapter dedicated to fires in Ukraine during 2022, when the country is at war. Naturally, all the constraints raised create additional challenges in the management of wildfires. It was considered that this experience brought learnings that should be shared, so a specific chapter was dedicated to this issue.

Please consult the Interinstitutional Style Guide for drafting your report. It contains uniform stylistic rules and conventions which must be used by all the institutions, bodies, offices and agencies of the European Union. It is available in 24 EU languages, and is obligatory for all those involved in document production.

Acknowledgements

The authors of this chapter would like to express their gratitude to the following people who provided data and testimony that were essential to the production of the report. We apologize in advance for any possible omission in the list of acknowledgements. Several people were interviewed did not wish to be included in this list. To all, our thanks for their contributions to this report.

The production of this report, as well as the work involved, was funded by the Project FirEUrisk – Developing a Holistic, Risk-Wise Strategy for European Wildfire Management. This project has been granted funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement nº. 101003890.

Chapter	Acknowledgement
3. Fire in Europe	Jesus San-Miguel
4. wildfires in Ukraine	We would like to thank early career scientists Iryna Zibtseva and Yevhen Kalchuk from the Regional Eastern Europe Fire Monitoring Center (REEFMC) and National University of Life and Environmental Sciences of Ukraine (NUBiP) for their assistance in mapping landscape fire perimeters of 2022 in Ukraine. The Ukraine Fire perimeters published at: https://zenodo.org/records/8298835 .
5. Fire of Albergaria (Pt)	The authors wish to express their gratitude and appreciation to the Portuguese Ministry of Internal Administration for the request to participate in a Group of Experts that analysed the major fires that occurred in Portugal in the Summer of 2022. Also, the support given to the research actions required and the access to information and data from all involved agencies. We would like to extend our gratitude to all relevant agencies involved, including the civil protection agents and citizens that provided testimonies, data and insights to the elaboration of this report. Our gratitude to all CEIF-ADAI team that contributed during field work, data analysis, etc., to Thiago Barbosa, Catarina Matos, Babak Chehreh, Pegah Mohammadpour and Andreia Rodrigues. We also thank very much all key institutions that provided relevant data and testimonies, including the Portuguese National Authority of Civil Protection (ANEPC), the Institute for Nature Conservation and Forests (ICNF), the Portuguese Institute for the Ocean and Atmosphere (IPMA), the Portuguese Firefighter League (LBP), the Portuguese Air Force (FAP), the Albergaria-a-Velha municipality council CMAV, and Firefighter Associations (Oliveira de Azeméis, Albergaria-Velha, Vale de Cambra, Estarreja). We special thanks the commanders (José Pinto - ANEPC at Aveiro, António Justino - CBOA, Albano Ferreira CBAV, Pedro Oliveira CBAV, Joaquim Rebelo - CBE e Vitor Machado - CBVC) and many other contributors who have played a pivotal role in the creation of this report. Your invaluable insights, feedback, and expertise have significantly enriched our work and ensured its relevance and impact. We are deeply grateful for your time, dedication, and willingness to share your knowledge, which has not only enhanced the quality of our research but also provided valuable perspectives that will guide future decision-making perspectives and valuable lessons that might be improving other regions.
6. Fires of Ourém (Pt)	The authors wish to express gratitude and appreciation to the Portuguese Ministry of Internal Administration for providing the opportunity to conduct a study on the largest fires that occurred in Portugal during the year 2022, which allowed the collection of various information presented here. The support given by the following persons and institutions during this research and the corresponding fieldwork is greatly appreciated: Carlos Guerra and Ricardo Costa from the Leiria Sub-regional Command of the

	National Authority of Emergency and Civil Protection, David Lobato Médio Tejo Sub-regional Command of the National Authority of Emergency and Civil Protection, Carlos Pereira Lisboa e Vale do Tejo Regional Command of the National Authority of Emergency and Civil Protection Firefighter Commander of the Fire Brigade of Leiria and Santarém District.
7. Fire of Garrocho (Pt)	Our gratitude to the Ministry of Internal Affairs of the Portuguese Government for providing the opportunity to conduct a study on the largest fires that occurred in Portugal during the year 2022, which allowed the collection of various information presented here. We would also like to thank the several interviewees who provided their testimony and were essential for the quality of this study. Because there were many dozens of interviews and space is limited in this section, unfortunately we won't be able to mention all the interviewees individually.
8. Fire of Murça (Pt)	The authors wish to express gratitude and appreciation to the Portuguese Ministry of Internal Administration for the request to participate in a Group of Experts to analyse the major fires that occurred in Portugal in the Summer of 2022 and for the support given to the research actions required and the access to information and data from all involved agencies. The support given by the following persons and institutions during this research and the corresponding field work is greatly appreciated: Mário Lopes, Mayor of Murça, Ricardo Inácio Commander of the Fire Brigade of Murça, Hugo Silva Commander of the Fire Brigade of Vila Pouca de Aguiar, Miguel Fonseca and Artur Mota from the Sub-regional Command of the National Authority of Emergency and Civil Protection. We would like to extend our gratitude to all relevant parties involved, including the civil protection agents and citizens that provided testimonies, data and insights to the elaboration of this report. Our gratitude to all CEIF-ADAI team that contributed during field work, data analysis, etc., in particular to Carlos Viegas, Thiago Barbosa, Catarina Matos, Babak Chehreh, Pegah Mohammadpour and Andreia Rodrigues.
9. Fire of Culebra (Sp)	We sincerely thank the information and suggestions provided by Álvaro Picardo Nieto, Ángel Manuel Sánchez Martín, and Manuel Ignacio Moreno López from the area of Natural Heritage and Forest Policy of the region of Castille and Leon (Spain), and the support and revisions of Francisco Javier Ezquerra, from Junta de Castilla y León's Forest Service. We would also like to thank Cristina Escudero Ramirez from the Unit for Risk management and Emergencies in Cultural Heritage of the Junta de Castilla y León for the information provided.
10. Fire of Karst (It)	We would like to thank Salvatore Gambitta (Civil Protection Gorizia) for his support in making the first contact with relevant actors in the field; Antonio Petitto and Ivan Guarino (Firefighters Command Gorizia), Antonio Capovilla (Forestry inspectorate of Trieste and Gorizia), Nazzareno Candotti and Aldo Primiero (Civil Protection Friuli Venezia Giulia Autonomous Region), Tadej Devetak (Voluntary Fire Brigade Šempeter pri Gorici) for participating in the interview process and providing relevant materials; and Simon Vendramin (Fire Department Nova Gorica) for providing relevant materials.
11. Fire of Bohemian (Ge)	We would like to thank Annika Busse and the staff at the Nationalparkverwaltung Saxon Switzerland and Dana Vébrová and the administration from Národní park České Švýcarsko.
12. Fire of Attica (Gr)	We would like to thank all data providers: Data were provided by the European Forest Fire Information System – EFFIS

	(https://effis.jrc.ec.europa.eu) of the European Commission Joint Research Centre. Data were also provided by the Hellenic Fire Service (https://www.fireservice.gr/el)
13. Fire of Dadia (Gr)	We thank the Forest Services of the Greek Ministry of Energy and Environment, the Region of Eastern Macedonia, the Hellenic Fire Service, and the National Observatory of Athens for making available data and information related to the Dadia fire, presented in this report.
15. Fire of Razdel (Bg)	We express our sincere gratitude to the Fire brigades of Yambol and Elhovo for providing us the detailed information about the fire propagation. Special thanks to the chief inspector Yanko Boyanov, who provided us with terrain guidance during our field work data collection. We would like also to thank to the Yambol forestry department team members, who gave their descriptions about the fire behaviour and spread, while participating in the suppression measures.

By fire event following the order of the respective chapter.

Authors

Chapter 1. Introduction – Miguel Almeida (ADAI)

Chapter 2. Extreme drought and heat waves registered in Europe in 2022 – Mikhail Soviev (FMI)

Chapter 3. Fires in Europe in 2022 (Jesus San-Miguel – JRC) – Jesus San-Miguel, ??? (JRC)

Chapter 4. Wildfires in Ukraine in times of war – Sergiy Zibtsev, Johann Georg Goldammer, Victor Myroniuk, Serhii Sydorenko (REEFMC); Oleksandr Soshenskyi (GFMC); Vadim Bogomolov (REEFMC/ URIFFM); Oleksandr Borsuk (ChREBR)

Chapter 5. Fire of Albergaria (Portugal) – Tiago Rodrigues, Domingos Viegas, Daniela Alves, Luís Mário Ribeiro, Miguel Almeida, Carlos Ribeiro (ADAI)

Chapter 6. Fires of Ourém (Portugal) – Carlos Ribeiro, Domingos Viegas, Tiago Rodrigues, Luís Mário Ribeiro, Daniela Alves (ADAI)

Chapter 7. Fire of Garrocho / Serra da Estrela (Portugal) – Miguel Almeida; Daniela Alves, Catarina Matos, Luís Mário Ribeiro and Domingos Viegas (ADAI)

Chapter 8. Fire of Murça (Portugal) – Domingos Viegas, Carlos Ribeiro, Tiago Rodrigues, Luís Mário Ribeiro, Daniela Alves (ADAI)

Chapter 9. The Fires of Sierra de la Culebra (Zamora, Spain) – Emilio Chuvieco, Patricia Oliva, Mariano García (UAH)

Chapter 10. Fire of Karst (Italy/Slovenia) - Ramona Velea, Riccardo Laterza, Marco De Lucia, Paola Lorenzoni (ISIG); Bachisio Arca, Michele Salis, Valentina Bacciu, Liliana Del Giudice, Grazia Pellizzaro, Pierpaolo Duce (CNR-IBE)

Chapter 11. Fire of Bohemian and Saxon Switzerland (Germany / Czech Republic) – Christopher Marrs, Matthias Forkel, Kristina Beetz, Eric Kosczor (TUD); Markéta Poděbradská (CzechGlobe)

Chapter 12. Penteli Attica Fire (Greece) – Nadia Politi, Athanasios Sfetsos, Diamando Vlachogiannis (NCSRD)

Chapter 13. Dadia National Park-Evros Region Fire (Greece) – George Eftychidis, Dimitris Stavrakoudis, Giannis Gitas, and Vassiliki Varela (AUTH)

Chapter 14. Fires in Romania – Johan Sjöström (RISE); Marius Petrila, Adrian Lorenţ (INCDS)

Chapter 15. Fire of Razdel (Bulgaria) – Nina Dobrinkova, Vassil Vasilev, Nadya Tsvetkova (IICT); Yanko Boyanov (FSPP – Yambol); Ilian Gospodinov (NIMH).

Chapter 16. Conclusions – Miguel Almeida (ADAI)

1 Introduction

In recent decades, the pattern of wildfires has undergone significant changes, marked by a notable increase in intensity, expanding burned areas, and heightened social, economic, and environmental impacts. This shift is especially evident in regions historically less affected by wildfires that nowadays register events with great magnitude and difficult controlment. Understanding the historical record of wildfires, both statistically and descriptively, is crucial for comprehending their evolution over the years. This knowledge allows for reflection on trends and the assessment of policy effects. Additionally, studying wildfires provides valuable insights to enhance fire management efficiency and mitigate associated impacts.

In 2022, Europe experienced weather conditions conducive to a severe fire season, particularly during extremely dry and heatwave-prone summer months. These conditions led to numerous large fires with significant social, cultural, and economic consequences. The Joint Research Centre highlights that 2022 marked the second-worst fire season in terms of impacts since 2000 (San-Miguel-Ayanz, et al., 2023), when data registers from Copernicus had started, surpassed only by the dramatic year 2017. Mediterranean countries, above all Spain and Portugal, reported the highest burned areas. Nevertheless, all 28 European Union countries, except Luxembourg, recorded noteworthy wildfires (JRC, 2023).

Some areas with a nearly non-existent history of wildfires experienced concerning fire events in 2022. For instance, the typically wet region of SW Slovenia and NE Italy witnessed the worst fire in decades (LSA SAF, 2022). The increasing size of wildfires has led to more events crossing borders, becoming international in scope, and imposing coordinated operations involving forces from different countries with diverse firefighting methodologies. Consequently, beyond the growing size, intensity, and impacts of wildfires, additional challenges demand innovative perspectives, policies, and strategies. This report aims to contribute to this new paradigm by compiling and analysing relevant wildfires in Europe in 2022. It seeks to extract lessons that can be instrumental in averting future disasters or mitigating impacts associated with similar events.

The outbreak of the war in Ukraine in 2022 has introduced a distinct reality to Europe. Among the various impacts stemming from a conflict, this report highlights the emergence of a new ignition source related to explosions of military origin. Additionally, the enforced confinement reduced citizen activities, and the exodus observed in areas with intense combats have altered ignition patterns and the self-protection capacity of communities. Moreover, the reduction in financial resources, challenges in mobility, and the allocation of civil protection resources to other emergencies, particularly rescue of people from collapsed buildings and medical care, have significantly diminished firefighting capabilities. An analysis of the fire situation during wartime and the operational response, navigating through the difficulties and opportunities posed by these constraints, is of paramount importance for the learning of all nations.

This report includes a dedicated chapter addressing the fire situation in Ukraine during times of war. Moreover, it reports and analyses 11 major wildfires or groups of wildfires occurred in Europe during 2022, spanning Portugal, Spain, France, Italy/Slovenia, Germany/Czech Republic, Greece, Romania, and Bulgaria (Figure 1). The selection criteria considered their fire event size, associated impacts, the transnational nature of the burned area, and the historically low susceptibility of the regions where these fires occurred. Each wildfire is discussed in a dedicated chapter, beginning with framing of the event and a characterization of the affected region, the orographic, meteorological, and land-use conditions of the burned area, the fire front spread, and the primary economic, social, or environmental impacts and cascading effects, culminating in a section dedicated to lessons learned. The sequence of the chapters describing the fire events followed an order from West to East, so not evidencing any other sequence related to the burned area dimension, impacts or other.

Figure 1. Fire events addressed in the study.



Data Source: background image adapted from European union Website (https://european-union.europa.eu/).

NOTES:

1) This report results from collaborative efforts between the Steering Committee of the European Horizon 2020 FirEUrisk project (www.fireurisk.eu) and the European Union Joint Research Centre. It follows a previous report (Almeida et al., 2021) by the same groups focusing on selected major wildfires in Europe in 2021.

2) To simplify the text exposition, all dates refer to the year 2022, except when another year is explicitly mentioned. The times mentioned are local times in the countries concerned – Portugal: UTC+01h; Spain, Germany, Check Republic, Italy and Croatia: UTC+01h; Greece and Romania: UTC+03h.

References

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Liberta`, G., Oom, D., Branco, A., De Rigo, D., Ferrari, D., Roglia, E. and Scionti, N., Advance Report on Forest Fires in Europe, Middle East and North Africa 2022, EUR 31479 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-68-02143-9, doi:10.2760/091540, JRC133215

JRC: Joint Research Centre (2023). The EU 2022 wildfire season was the second worst on record. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-2022-wildfire-season-was-second-worst-record-2023-05-02_en

EUMETSAT (2023). The Largest Wildfire in Slovenia in Recent Decades – Analysing Fires with LSA SAF Fire Radiative Power Pixel. https://landsaf.ipma.pt/en/news/news/the-largest-wildfire-in-slovenia-in-recent-decades/

2 Extreme drought and heat waves registered in Europe in 2022

2.1 Assessment of weather conditions and fire strength in Europe in 2022.

The current section shortly outlines the specificity of the fire season 2022 in Europe and compares it with previous years. We have concentrated on basic meteorological variables during the fire season and on the total fire originated $PM_{2.5}$ in 2022. Other variables, such as Fire Weather Index, are considered in other sections of the report.

2.1.1 Weather anomalies in 2022

Two key variables were taken as the most-representative for the fire season: mean temperature during the summer season (May-September), and total amount of precipitations during the same period. The variables were compared with previous years (Figure 2, Figure 3).

Figure 2. Percentile of the mean-summer near-surface temperature (at 2m above ground) in 2022. The rank 20 (dark red) means that 2022 was the hottest year since 2003 in this grid cell. Conversely, rank 1 (dark blue) denotes the grid cells where 2022 had the coldest summer since 2003.

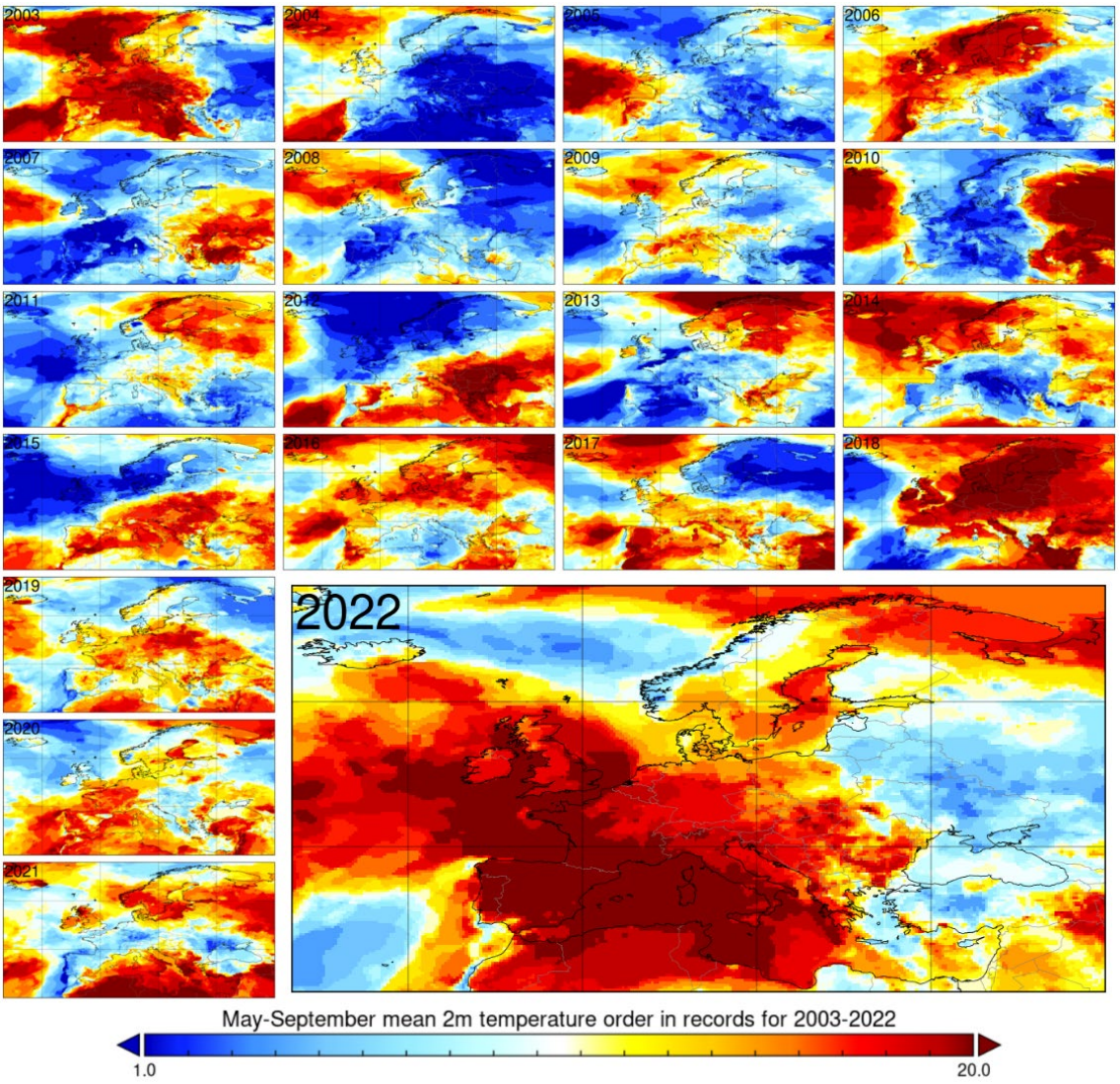
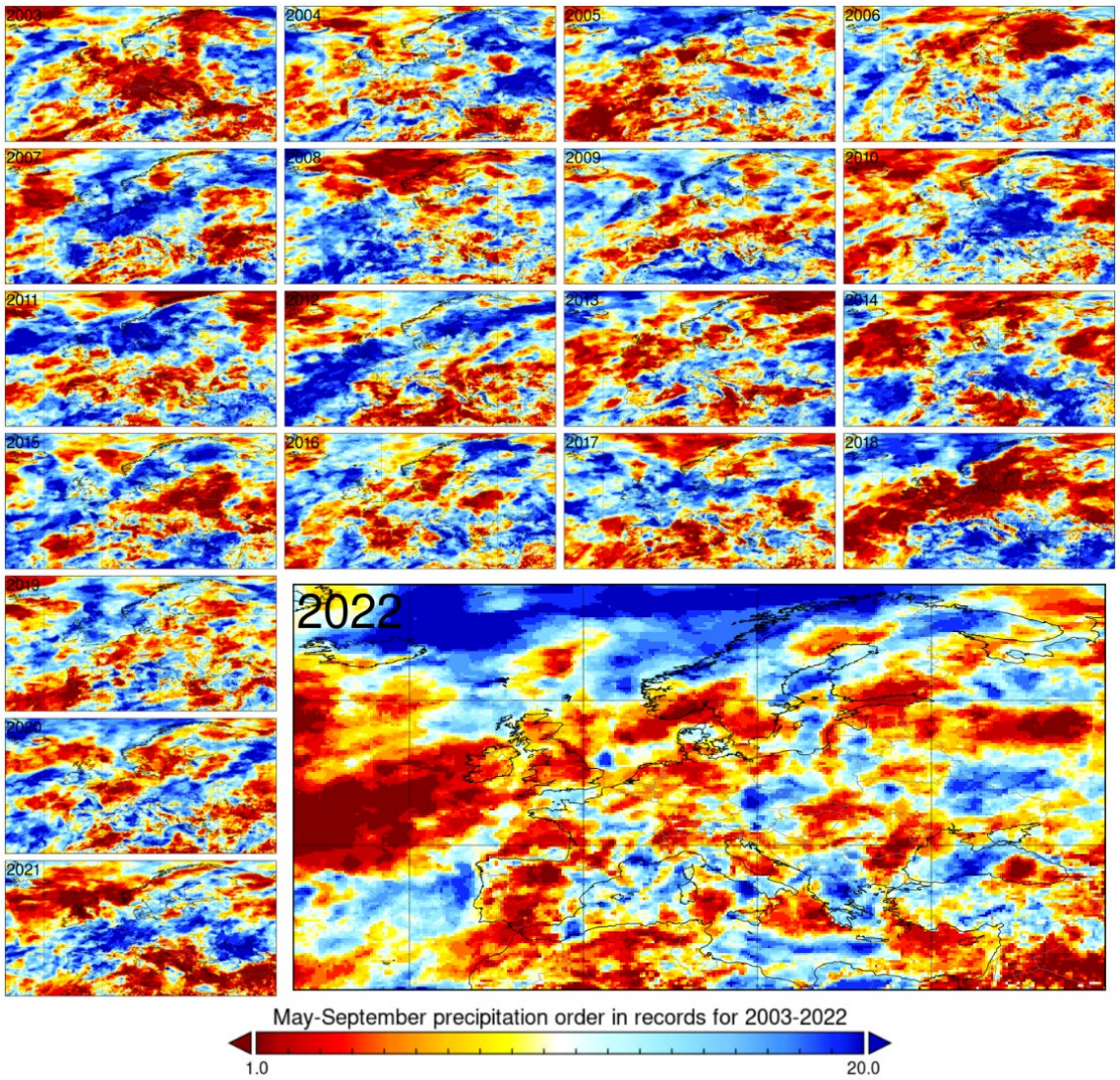


Figure 3. Percentile of the total precipitation amount during summer season 2022. The rank 1 (dark red) means that 2022 was the driest year in the corresponding grid cell. Conversely, dark blue (rank 20) denotes the grid cells where 2022 was wettest year out of 2003-2022 period.



Comparing the Figure 2 and Figure 3, one can notice that summer of 2022 was both the driest and the hottest since 2003 in large areas of Spain, Portugal, and Southern France. In general, south-westerns Europe experienced one of the hottest summers. Precipitation-wise, the pattern is patchier, e.g., Katalonia, despite the record-hot summer, had about-median total precipitation amount, some areas even received more rain than the 20-years median.

In contrast with the South-Western Europe, east of the continent was noticeably colder than the median – the rank 5-7 over, e.g., Central Russia and Turkey, corresponds to 25% of mean summer temperature. The precipitation pattern was also very patchy, with near-record-dry and near-record-wet regions sometime adjacent to each other.

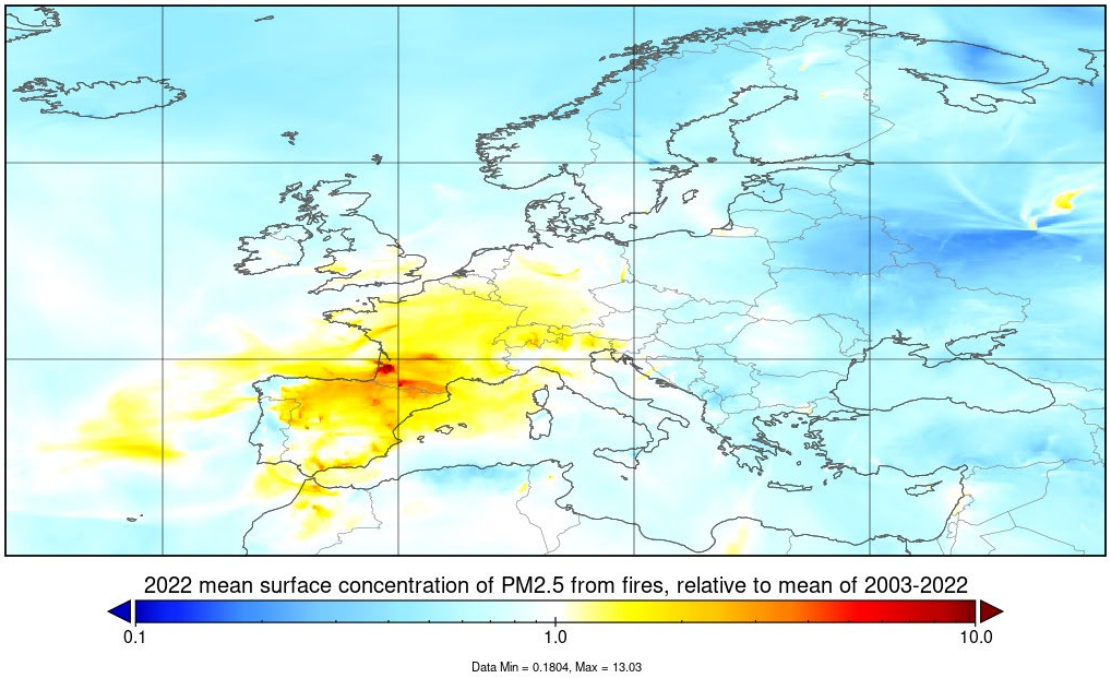
Comparing the anomalies in different years, one can see that year-to-year variations of the mean-summer temperature are huge: the record-hot year can follow the record-cold one. About-same observation can be made for total precipitation.

This outline, being evidently limited in many dimensions, highlights the main features of 2022: hot summer with often low precipitation in the south-west and cold one with or without sufficient rain in the east.

2.2 Fire intensity and smoke concentrations in 2022

The above meteorological anomalies expectedly brought about the corresponding anomalies in the fire intensity and corresponding impact on air quality (Figure 4). The mean concentration of fire-induced $PM_{2.5}$ exhibits very similar patterns as were noticed in the meteorological variables: higher-than usual. Noteworthy, the smoke concentration (and corresponding population exposure) is high in the areas, where the weather was both hot and dry. If any of these factors is absent (e.g., near-normal precipitations or moderately hot summer), the fire smoke concentrations are low. An exception is Moscow region, where cold summer was still not enough to avoid fires, which are almost completely man-made in that region.

Figure 4. Mean surface concentration of fire-induced fine particles ($PM_{2.5}$) in 2022, normalized with the mean 2003-2022 level [relative unit]. Dark red denotes 10-fold higher annual concentration, whereas dark blue shows the 10-fold lower level.



2.2.1 Methodology

The outline was based on: ERA5 reanalysis for the years 2003-2022, from where the temperature and precipitation fields were extracted and averaged.

The dataset generated by the fire prediction model of Integrated System for wild-land fires, IS4FIRES (Soares et al., 2015; Sofiev et al., 2012, 2009). The fire information was obtained from MODIS active-fires retrievals, the Fire Radiative Power (FRP) product. IS4FIRES data were previously used in a short-term evaluation of the fire-related mortality in Europe and the globe (Daalen et al., 2022; Kollanus et al., 2017; Romanello et al., 2022).

The fire plumes were calculated with a System for Integrated modeLling of Atmospheric composition, SILAM, http://silam.fmi.fi (Kouznetsov and Sofiev, 2012; Sofiev, 2002; Sofiev et al., 2015, 2010), by converting the FRP to PM2.5 emissions. The model has been designed for atmospheric composition and air quality simulations at horizontal scales ranging from sub-kilometre scale up to the whole globe. For the current study, SILAM was run at 0.1°×0.1° horizontal resolution with 19 vertical layers up to 106 hPa over continental Europe and surrounding islands. The model was run from 2002 to 2022, from where the period when two MODIS instruments onboard Aqua and Terra satellites were available, 2003-2022, was used for the analysis. Boundary conditions were obtained from global SILAM simulations at horizontal resolution of 0.5°×0.5° and a temporal resolution of 1 hour. [Hänninen, R., Sofiev, M., Uppstu, A., and Kouznetsov, R. (2023). Daily surface concentration of fire related PM2.5 for 2003-2022, modelled by SILAM CTM when using the MODIS satellite data for the fire radiative power [Data set]. Finnish Meteorological Institute. https://doi.org/10.23728/FMI-B2SHARE.722BB9D1937548908D2B6C1CFD9F8E5D] The simulations

were governed by meteorological variables obtained from the European reanalysis ERA5 (same meteodata as the ones used for the temperature and precipitation anomalies).

References

Daalen, K.R. van, Romanello, M., Rocklöv, J., Semenza, J.C., Tonne, C., Markandya, A., Dasandi, N., Jankin, S., Achebak, H., Ballester, J., Bechara, H., Callaghan, M.W., Chambers, J., Dasgupta, S., Drummond, P., Farooq, Z., Gasparyan, O., Gonzalez-Reviriego, N., Hamilton, I., Hänninen, R., Kazmierczak, A., Kendrovski, V., Kennard, H., Kiesewetter, G., Lloyd, S.J., Batista, M.L., Martinez-Urtaza, J., Milà, C., Minx, J.C., Nieuwenhuijsen, M., Palamarchuk, J., Quijal-Zamorano, M., Robinson, E.J.Z., Scamman, D., Schmoll, O., Sewe, M.O., Sjödin, H., Sofiev, M., Solaraju-Murali, B., Springmann, M., Triñanes, J., Anto, J.M., Nilsson, M., Lowe, R., 2022. The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. The Lancet Public Health. https://doi.org/10.1016/S2468-2667(22)00197-9

Kollanus, V., Prank, M., Gens, A., Soares, J., Vira, J., Kukkonen, J., Sofiev, M., Salonen, R.O., Lanki, T., 2017. Mortality due to Vegetation Fire–Originated PM 2.5 Exposure in Europe—Assessment for the Years 2005 and 2008. Environmental Health Perspectives 125, 30–37. https://doi.org/10.1289/EHP194

Kouznetsov, R., Sofiev, M., 2012. A methodology for evaluation of vertical dispersion and dry deposition of atmospheric aerosols. Journal of Geophysical Research 117. https://doi.org/doi:10.1029/2011JD016366

Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L.B., Belesova, K., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., van Daalen, K.R., Dalin, C., Dasandi, N., Dasgupta, S., Davies, M., Dominguez-Salas, P., Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Escobar, L.E., Georgeson, L., Graham, H., Gunther, S.H., Hamilton, I., Hang, Y., Hänninen, R., Hartinger, S., He, K., Hess, J.J., Hsu, S.-C., Jankin, S., Jamart, L., Jay, O., Kelman, I., Kiesewetter, G., Kinney, P., Kjellstrom, T., Kniveton, D., Lee, J.K.W., Lemke, B., Liu, Y., Liu, Z., Lott, M., Batista, M.L., Lowe, R., MacGuire, F., Sewe, M.O., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., McMichael, C., Mi, Z., Milner, J., Minor, K., Minx, J.C., Mohajeri, N., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K.A., Neville, T., Nilsson, M., Obradovich, N., O'Hare, M.B., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Rabbaniha, M., Robinson, E.J.Z., Rocklöv, J., Salas, R.N., Semenza, J.C., Sherman, J.D., Shi, L., Shumake-Guillemot, J., Silbert, G., Sofiev, M., Springmann, M., Stowell, J., Tabatabaei, M., Taylor, J., Triñanes, J., Wagner, F., Wilkinson, P., Winning, M., Yglesias-González, M., Zhang, S., Gong, P., Montgomery, H., Costello, A., 2022. The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. The Lancet S0140673622015409. https://doi.org/10.1016/S0140-6736(22)01540-9

Soares, J., Sofiev, M., Hakkarainen, J., 2015. Uncertainties of wildland fires emission in AQMEII phase 2 case study. Atmospheric Environment. https://doi.org/10.1016/j.atmosenv.2015.01.068

Sofiev, M., 2002. Extended resistance analogy for construction of the vertical diffusion scheme for dispersion models. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 107, ACH 10-1-ACH 10-8. https://doi.org/10.1029/2001JD001233

Sofiev, M., Ermakova, T., Vankevich, R., 2012. Evaluation of the smoke-injection height from wild-land fires using remote-sensing data. Atmospheric Chemistry and Physics 12, 1995–2006. https://doi.org/10.5194/acp-12-1995-2012

Sofiev, M., Genikhovich, E., Keronen, P., Vesala, T., 2010. Diagnosing the Surface Layer Parameters for Dispersion Models within the Meteorological-to-Dispersion Modeling Interface. Journal of Applied Meteorology and Climatology 49, 221–233. https://doi.org/10.1175/2009JAMC2210.1

Sofiev, M., Vankevich, R., Lotjonen, M., Prank, M., Petukhov, V., Ermakova, T., Koskinen, J., Kukkonen, J., 2009. An operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling and forecasting. Atmospheric Chemistry and Physics 9, 6833–6847. https://doi.org/10.5194/acp-9-6833-2009

Sofiev, M., Vira, J., Kouznetsov, R., Prank, M., Soares, J., Genikhovich, E., 2015. Construction of the SILAM Eulerian atmospheric dispersion model based on the advection algorithm of Michael Galperin. Geoscientific Model Development 8, 3497–3522. https://doi.org/10.5194/gmd-8-3497-2015

3 Fires in Europe in 2022 (Jesus San-Miguel – JRC)

General panorama and tendences

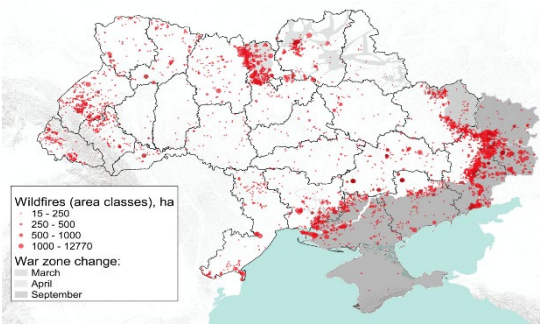
…

To be written after the file is sent to JRC

4 Wildfires in Ukraine in times of war

Authors

Sergiy Zibtsev	*REEFMC*
Johann Georg Goldammer	*REEFMC*
Oleksandr Soshenskyi	*GFMC*
Victor Myroniuk	*REEFMC*
Dmytro Holiaka	*UIAR/REEFMC*
Serhii Sydorenko	*REEFMC*
Vadim Bogomolov	*REEFMC/ URIFFM*
Oleksandr Borsuk	*ChREBR*



4.1 Introduction

From 1990 to 2020, farmers and rural populations in Ukraine extensively employed controlled burns as a tool for pre-harvest or post-harvest clearance of vegetation residues on croplands, vegetable gardens, pastures, and other land categories. This practice stemmed from the privatization of agricultural lands coupled with a lack of technical, technological, and financial support for farmers and small landowners from the government. Periodically, during severe dry spells, which commonly occur in spring (April) and summer (July-August), uncontrolled agricultural burnings spread beyond croplands into forests, desiccated wetlands and protected areas, resulting in large wildfires that cause severe damages to the natural and cultural landscapes including society living therein. Before 2020, wildfires were generally well-managed, and the average annual area of forest fires did not exceed 5,000 to 7,000 ha.

Over the past decade, climate change has heightened the risk of large fires by creating conditions for increasing recurrence of heatwaves, droughts, and windy weather. On the one hand, the high amount of combustible materials in the landscapes resulted in a high wildfire potential. On the other hand, weakness of performance and coordination of responsibilities between public agencies, notably the State Agency of Forest Resources of Ukraine and the State Emergency Service of Ukraine (SESU), which are responsible for prevention and suppression of wildfires, as well as a lack of experience in controlling large fires, have contributed to the catastrophic fires of 2020. Between April and October 2020, three major fires in the Chornobyl Exclusion Zone (CEZ), Zhytomyr oblast (i.e., region) and Luhansk oblast destroyed at least 170,000 ha of mainly pure pine forest land and the surrounding areas. For the first time in Ukraine's history, 22 villages were directly affected by forest fires, leading to fatalities and significant damages of residential areas and critical infrastructure.

On February 24th, 2022, the Russian Federation's military forces invaded Ukraine. The war of aggression spanned vast territories from Belarus to the Azov/Black Sea. Russian military operations involving the movement of hundreds of thousands of soldiers, armoured equipment, tanks, rockets and artillery shelling, aerial bombing, including phosphorous bombs, resulted in extensive collateral damages including wildfires in ecosystems that civilian fire brigades found impossible to tackle. The most intense shelling and burning damage was observed in shelterbelts and pine forests, as these areas were used by military forces to evade detection by drones and satellites. After more than 500 days of rigorous military operations along the Belarusian and Russian border with Ukraine, the contamination of over 1.6 million hectares of land by unexploded ordnance (UXO) and landmines became the most pressing challenge in fire management.

4.2 Fire management on territories contaminated by UXO and landmines

Specialist of mine action teams of the State Emergency Service of Ukraine (SESU) identified at least 70 types of UXO, including anti-tank mines, various types of ground force-targeting mines, and remnants from shelling. These were found across occupied territories, in places like villages, shelterbelts, agricultural fields, vegetable gardens, pastures, forests, and roadsides. Periodic fires in these areas often led to UXO detonations, which frequently resulted in injuries and deaths. Land mines have impacted the lives and health of hundreds of Ukrainian citizens. Over 700 agricultural and forestry tractors, used for regular land and forest management practices, were severely damaged by mines. Foresters and firefighters are among the most vulnerable groups residing in liberated areas that remain affected by UXO contamination.

The contamination of forests by UXO has placed significant constraints on routine fire management, necessitating special measures to safeguard the lives and security of personnel. The implementation of Martial Law by the Ukrainian Parliament in February makes it almost impossible to prevent and control large fires. Restrictions now prohibit activities like the use of fire aviation, fire detection cameras, publishing maps, patrolling territories off hard roads, radio station usage, the establishment of firebreaks, and many other standard fire management procedures. SESU, which actively participated in combating large forest fires before the war, had to shift its focus towards protecting citizens from rocket and drone attacks and supporting their daily needs like supply of water, electricity, and other essentials. Many forest firefighters have enlisted in the Ukrainian Armed Forces, and key elements of fire management infrastructure like fire lookout towers, fire detection cameras, fire engines, and other special equipment were removed or destroyed during the occupation of Zhytomyr, Kyiv, Chernihiv, Sumy, Kharkiv, Luhansk, Donetsk, Kherson, and other oblasts.

Contamination of forests by UXO and landmines is a widespread aftermath of wars, seen more recently in regions like the Balkans, Afghanistan, Iraq, and various countries across Africa, South America, and Asia (Goldammer, 2013). This was highlighted recently in Germany's Brandenburg region where fires in former Soviet military test areas detonated hidden WWII-era UXO. Specialized international NGOs such as Fondation suisse de déminage (FSD), Hazardous Area Life-support Organization **(**HALO Trust), the Geneva International Centre for Humanitarian Demining, Danish Demining Group, the Croatian Centre for Anti-Mine Activities, and others, have over the years developed various methodologies to clear forests of UXO and landmines. However, these mine clearance operations are often costly. The Global Fire Monitoring Centre (GFMC) has innovated a specialized technology designed to safely conduct prescribed burnings in military testing sites, safeguarding personnel. This technology incorporates a suppression tank, ignition tank, and drones for monitoring fire progress. This approach was recently put to the test during fires that triggered UXO explosions in Brandenburg (Goldammer et al., 2014; 2016; see also GFMC 2023).

At present, the Ukrainian Government is focusing on clearing settlements, agricultural lands, and roads in territories yet to be liberated from unexploded ordnance and landmines. A Special State Mine Action Centre has been established to coordinate the efforts of various agencies, NGOs, and international donors. Forest clearance is projected to commence in 2030, once all other areas have been deemed safe. The demining process in forests is very slow, season-dependent, and involves several stages: personnel training, planning, public risk awareness campaigns, and the work of technical and non-technical survey teams. It requires significant financial and technical support, amounting to millions of dollars.

4.3 Number and area of landscape fires during 2022 in Ukraine

Over the past decade, climate change and land use modifications have led to an increased frequency of large fires, reaching an unprecedented level. The fire season in 2020 was the most severe in modern Ukrainian history, with an extraordinary extent of forest fires. In the Luhansk oblast, forest fires spread to villages, destroying over 730 homes, resulting in 17 fatalities and injuring 861 people (SESU, 2021; Soshenskyi et al., 2022). In 2020, forest fires affected seven villages and damaged 82 homes in the Zhytomyr oblast, destroyed 22 private residences in the Kharkiv oblast, and caused an estimated 8.5 billion UAH in damages to natural landscapes within the CEZ (Soshenskyi et al., 2021).

The large fires of 2020 exposed various shortcomings in the operations of the agencies responsible for landscape fire management and civil protection. These included a lack of interagency coordination during fire prevention and suppression efforts, poor preparedness levels, and insufficient use of scientific data for risk assessment and fire weather forecasting. Presently, official data on the area affected by fires, which is based on reports from various agencies, does not accurately reflect the reality. For instance, the State

Statistics Committee of Ukraine reported 28,056 ha of forest dieback from fires in 2020 and only 6,310 ha in 2022. However, the total area of landscape fires, encompassing fires in forests, cropland fires, degraded land fires, and others across different landscape types is not officially accounted for in Ukraine.

Following the outbreak of war on February 24th, the Regional Eastern Europe Fire Monitoring Centre (REEFMC), in collaboration with the GFMC and with the support of ZOÏ Environment Network, began tracking every landscape fire using remote sensing techniques. To detect fires and map burned areas, they relied on two different data sources. Fires were pinpointed using OroraTech's forest fire monitoring technology, which merges the fire detection capabilities of over 20 satellites to identify fire locations daily. Fire perimeters were then mapped using time series of surface reflectance from Sentinel-2 images (level 2A), based on the locations and dates of the fires. These fire perimeters were manually delineated from the images. According to SESU, around 30% of Ukraine's territory – equating to 17.4 million hectares of land – is mined. This significantly increases the risk of large and catastrophic fires in the future due to limitations in access.

Within the delineated fire perimeters, the area of each fire was classified by land cover type using the latest published Copernicus land cover map with a 100 m resolution for 2019 (Buchhorn et al., 2020). Daily frontline coordinates, provided by ZOÏ, were also utilized to categorize each detected fire into one of three zones: government-controlled, battle zone (extending 30 km on both sides of the frontline), and occupied zone (cf. Table 1, Figure 6).

In 2022, fires affected a total of 754,941 ha in Ukraine. Most of the affected areas were agricultural lands, accounting for 419,112 ha, and abandoned non-forested lands, amounting to 273,674 ha. Forest fires consumed 56,595 ha. Altogether, around 19,930 fires were detected in 2022. A significant proportion of these fires occurred within a 60 km buffer zone along the frontline, comprising 69% of the total fire-affected area, and 43% of all fires took place in occupied territories.

Table 1. Monthly distribution of fires by landscape type in Ukraine in 2022.

Month Category	Number of fires	Area of fires (ha)	Distribution of fire area by types of landscapes (ha)				
			Forests	Thereof coniferous	Agricultural lands	Other natural landscapes	Settlements
January	17	1,881	1	0	206	1,269	405
February	241	11,350	194	33	6,257	4,621	278
March	7,513	301,727	19,318	6,361	136,254	144,116	2,039
April	1,111	26,461	2,790	573	8,722	14,716	233
May	1,854	46,985	18,187	14,105	6,311	21,974	513
June	1,116	20,852	1,605	984	9,918	9,118	211
July	5,418	213,189	6,424	4,097	163,616	42,335	814
August	2,398	114,313	4,180	2,008	84,035	25,496	602
September	161	10,781	3,206	2,328	2,913	4,621	41
October	53	4,663	385	346	230	3,953	95
November	41	2,363	303	275	420	1311	329
December	7	376	2	0	230	144	0
Total	19,930	754,941	56,595	31,110	419,112	273,674	5,560

Military Combat Zone[1]	12,734	520,376	46,522	30,055	300,627	169,319	3,908
Occupied Territories	7,095	321,056	22,787	13,918	186,259	109,732	2,278
Conservation Areas (Emerald Network)	803	88,427	25,358	17,426	10,767	52,243	59

The territories most affected by fires are those where active military operations were ongoing in the eastern, southern, and northern parts of Ukraine. Specifically, the most significantly impacted oblasts were Donetsk (146,300 ha), Kherson (84,100 ha), Kyiv (70,900 ha), Zaporizhia (65,600 ha), Luhansk (65,600 ha), Mykolaiv (47,700 ha), and Kharkiv (42,600 ha).

In 2022, landscape fires across Ukraine resulted in the prompt release of over 1.4 million tons of carbon, averaging about 4 ton/ha. The greatest contributors to these carbon emissions were fires on croplands (62.8%), abandoned lands (25.5%), and forests (11.7%). Almost half of the carbon emissions, 48%, were caused by fires in the occupied territories of Ukraine (Zibtsev et al., 2023). The net release and thus the long-term impacts of the carbon emissions on the composition of the atmosphere and thus climate change will be determined by the recovery of fire-damages ecosystems and the subsequent sequestration of atmospheric carbon.

4.4 Impact of war on fires within ecosystems

While most fires affect vegetation across all types of land cover, the most extensive and rapidly spreading fires predominantly occur on croplands. These fires often damage agricultural crops like wheat, rye, corn, and sunflowers at varying growth stages. Several fields that were not seeded in spring of 2022 and which had been subjected to ecological succession, were affected by wildfires. Uncontrolled fires on croplands often spread to other types of land cover, igniting pine forests, sparse vegetation, wetlands, reeds, pastures etc.

Fires adversely affect large areas, primarily through the intense heat (300-500°C) they generate, which devastates black soil by destroying organic humus and available nutrients, particularly nitrogen, which results in diminished crop yields post-war. Small animals and soil microbiota, unable to escape the fires, are also significantly impacted. Furthermore, fires on agricultural lands are responsible for most carbon emissions, particularly emission of black carbon, which is transported airborne over long distances and deposited, among other, on highly vulnerable ecosystems including the Artic.

The most diverse and enduring negative effects are observed in the shelterbelts and extensive pine forests in the East and South of Ukraine. Situated at the edge of their natural water and nutrient zones, these pine forests are highly vulnerable to even moderate disturbances. The traditional approach of dense planting, about 5,000 to 6,000 seedlings per hectare, coupled with infrequent or absent thinning, leaves individual trees nearly incapable of survival. At the same time, such dense pine forests create ideal conditions for crown fires, as exemplified by the Luhansk fires in 2020. When these fires reach high intensities, they become difficult and sometimes impossible to control. Wind can carry burning particles over 500 m ahead of the fire's frontline, igniting various land covers, villages, and infrastructure. The presence of UXO and landmines in these forests complicates fire control efforts, making them almost unmanageable unless trained and specially protected professional firefighters are setting backfires (counter firing / suppression firing).

Severe fires can inflict high-temperature damage to tree bark up to 8-10 m in height, leading to their immediate or gradual decline and dieback. Even fire-adapted species, such as Scotch pine over 50 years old with thick bark, can be weakened and deteriorate (Sydorenko et al., 2021). When these trees fall due to snow, wind, or other natural disturbances, they add to the fuel loads that will create a higher wildfire hazard

[1] *Military Combat Zone: This term refers to a permanent corridor extending 30 km on either side of the Line of Contact (LoC). This corridor is established at the onset of active military combat and continues to be a part of the monitoring areas, even after active military combat operations cease. The reason behind this is the presence of unexploded ordnance in the area, which continue to pose a significant ignition threat.*

and make suppression of future fires more difficult. In war and UXO contaminated zones, forest fires typically go unaddressed due to the risk they pose to human safety. As a result, these fires often persist for weeks or even months until they are stopped by fire breaks (roads, rivers, hardwoods etc.), weather events, or until all ground litter is consumed.

Depending on the drought level and wind speed, fires in these UXO zones can be either fast – burning only the surface litter, or slow – consuming all surface fuels, damaging the topsoil layer and tree roots within the upper 5-10 cm of soil. Regardless of the fire type (slow/fast, surface/deep, ground/crown), all other elements of forest ecosystems, such as grass layers, brushes, and undergrowth, are usually destroyed.

A war-specific type of forest fire is one ignited by phosphorus bombs and shelling under any weather condition, typically short-lived unless the Fire Weather Index (FWI) is high. Most forest animals, birds, and other organisms try to escape the fires or perish if unable to do so, leading to fatal consequences for forest ecosystems.

4.5 Fire conditions

4.5.1 Meteorological conditions in 2022

In the 2022 fire season, cold and rainy weather in regions most vulnerable due to active combat mitigated fire risks. These regions include Chernihiv, Sumy, Kharkiv, Poltava, Dnipro, and Luhansk.

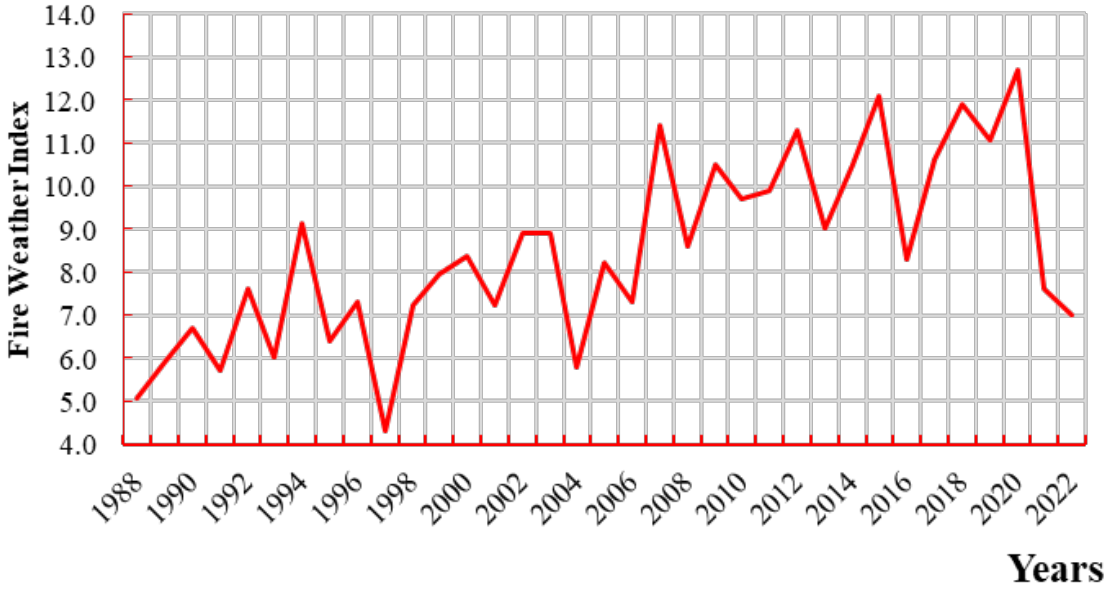
Government-controlled weather stations in war-affected regions (Zhytomyr, Kyiv, Sumy, Kharkiv, Luhansk, Donetsk, Zaporizhia, Kherson, Mykolaiv) recorded significant precipitation, particularly in the spring and autumn. April and May saw 21.2 and 16.3 mm more rainfall than the long-term average. In contrast, June and July experienced a precipitation deficit (10.9 and 0.2 mm respectively) and relatively high temperatures (25°C), creating hazardous fire conditions, especially in pine forests. Despite this, wildfire spread was limited in open landscapes due to high moisture content in grasslands and some agricultural landscapes. From August to the end of the fire season, significant rainfall occurred, with levels 100 mm higher than the regions' average long-term rate.

Another critical element of fire weather that significantly influenced fire behaviour during the 2022 fire season was high wind speed, especially at the start of the fire season in early spring. In April, maximum wind speeds reached up to 37.2 km/h. This, combined with the availability of fuel in open landscapes (dry grass) and the collapse of the fire management system in regions with active combat, led to large wildfires. Midway through the fire season, maximum wind speeds rarely exceeded 21.2 km/h, only picking up again towards the end of the season, with wind speeds reaching a maximum of 26.7 km/h in October.

4.5.2 Fire danger

Given the difference in fire weather conditions in 2022 compared to other years, we conducted an analysis comparing the average Fire Weather Index (FWI) during the Russian invasion in 2022 and the period from 1988 to 2021. The FWI, a commonly used index that indicates fire danger based on weather conditions, was chosen for this analysis. The choice of FWI was also informed by the fact that a new fire danger methodology was only implemented in Ukraine in 2018, and there is no official historical fire danger archive for years prior to 2018. FWI index calculations for the territory of Ukraine were performed on the Climate Data Store platform provided by Copernicus (https://cds.climate.copernicus.eu/) using custom Python scripts. The "cells-fire-historical" database, containing daily FWI values, was used as input data. After preprocessing the data, we calculated the combined average FWI values for each year from 1988 to 2022 (Figure 5). In 2022, a relatively low level of fire danger was observed – one of the lowest in the past 18 years.

Figure 5. Annual average Fire Weather Index dynamic in Ukraine 1988-2022.

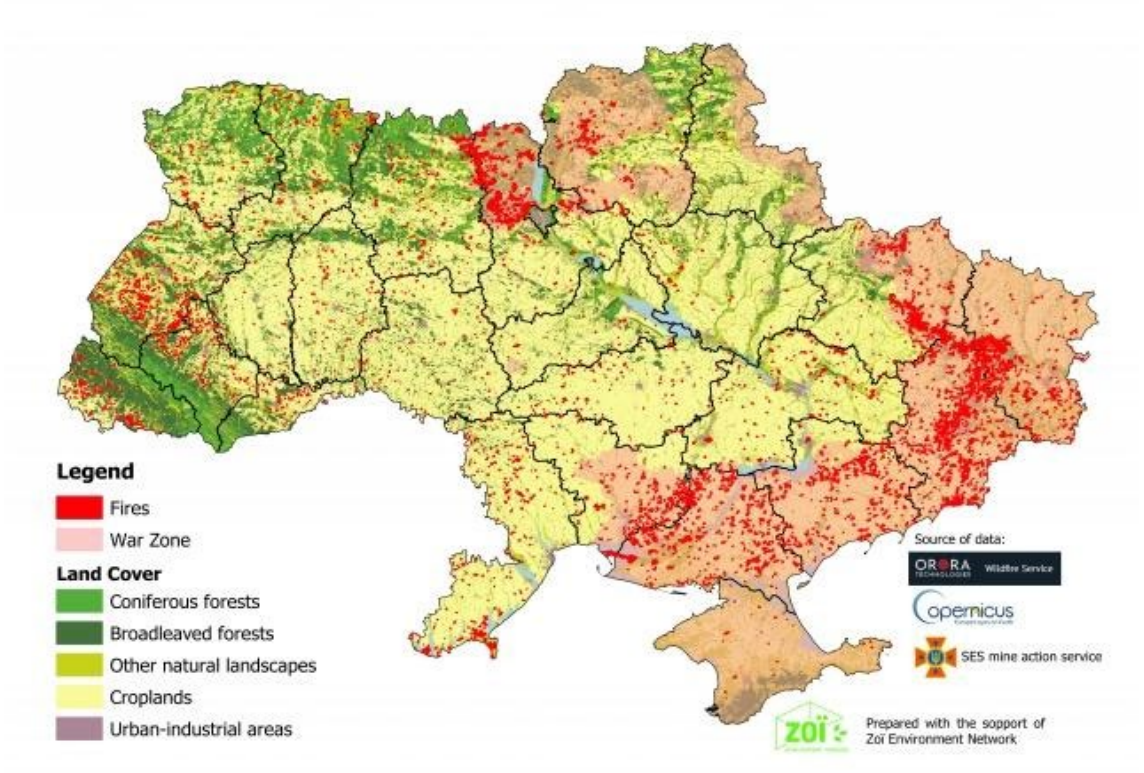


Thus, it becomes apparent that the severity of Ukraine's 2022 fire season was mainly due to war impacts, not extreme weather conditions.

4.5.3 Typical fire behaviour during war

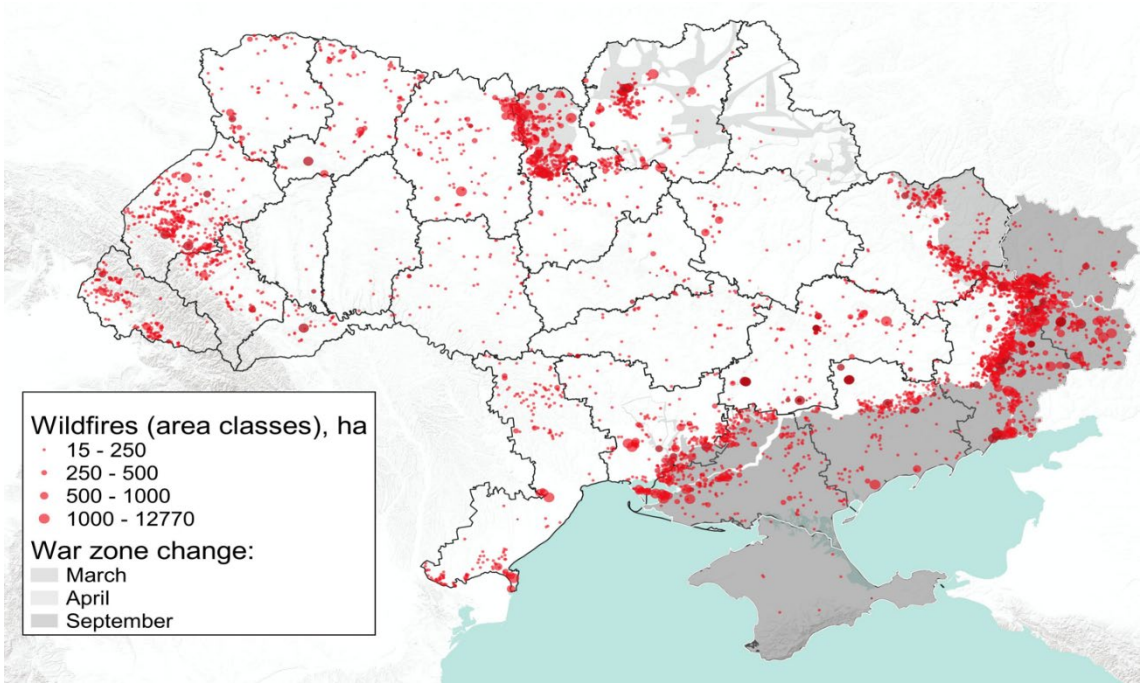
Though the weather conditions in 2022 were relatively unfavourable for fire propagation, a substantial number of wildfires and burnt areas were still recorded. Most instances of wildfires occurred in areas directly or indirectly affected by active combat, particularly in the occupied territories (Figure 6 and Figure 7).

Figure 6. Spatial distribution of wildfires during the 2022 fire season and relation to land cover.



Data Source: Fires mapped by the REEFMC and the GFMC on a land cover background (REEFMC, 2022).

Figure 7. Spatial distribution of wildfires during the 2022 fire season and relation to the war zone.



Data Source: Based on European Forest Fire Information System (EFFIS) data. The frontline zone data provided by ZOÏ.

Largest forest fires predominantly took place in the Eastern, Southern regions, and the Chornobyl Exclusion Zone, largely due to the unfeasibility of implementing fire suppression actions near frontlines or within occupied territories. Consequently, minor surface fires rapidly evolved into unmanageable crown fires within these areas. Fires in such territories were often allowed to run their natural course, occasionally self-

extinguishing. However, fire prevention and suppression activities within the liberated territories were greatly hindered by the presence of UXO, with vast expanses of forested landscapes mined by Russian forces.

A notable aspect of the 2022 fire season was the imposition of Martial Law across the entirety of Ukraine, as declared by the Presidential Decree No. 64/2022 (February 24th) "On the introduction of martial law in Ukraine". This led to the restriction of public access to forests and other natural landscapes, subsequently lowering the fire risks in territories not involved in active combat. Consequently, within regions controlled by Ukraine, the spatial density ranged between 0.007-0.009 ha of burnt area per 1000 ha of landscapes, while the fire density hovered around 0.098-0.116 fires per 1000 ha of landscapes. Spatial density, defined as the burnt area per 1000 ha of landscape, was observed to be 2.29-3.85 times higher in the war zone compared to the rest of Ukraine's territory. This difference in average combustibility within the war zone is statistically significant. Concurrently, fire density was found to be 1.75-4.3 times greater in the war zone. Both combustibility and fire density show an increase as the width of the buffer zone reduces, reaching a maximum at a buffer width of 5 km, which accounted for 0.45 wildfires per 1000 ha.

4.6 Characterization of the affected area

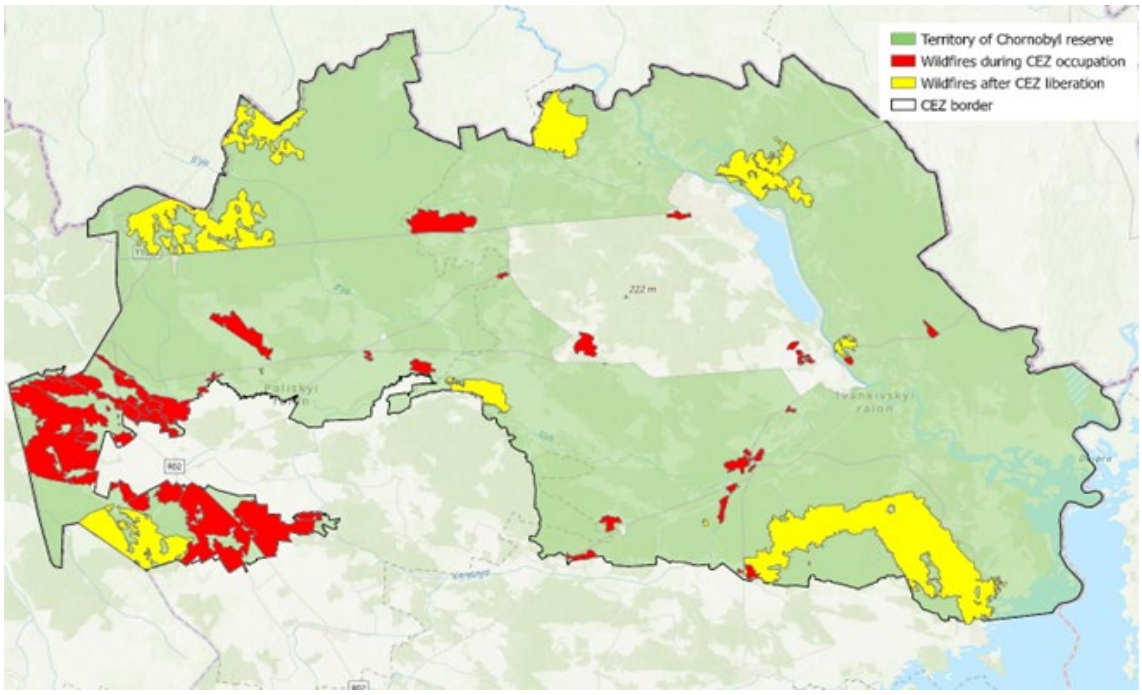
4.6.1 Large fires in Chornobyl Exclusion Zone (CEZ)

Despite the restricted access, wildfires occur annually in the CEZ. While their frequency varies, these fires typically cover a small area. However, due to climate change, the incidence of large fires has increased over the last decade. Particularly severe fire situations were observed in 2015 and 2020. Due to the Russian military aggression, 2022 has now joined the ranks of these challenging years.

The Russian military invasion had a significant impact on the incidence and proliferation of fires within the CEZ in 2022. Generally, the timing of fires in this territory can be divided into two stages: those that broke out while the area was under Russian occupation, and those that occurred following the liberation of the CEZ.

In total, fires affected approximately 31,758 ha within the CEZ, with 13,380 ha of that area burned during the occupation of the territory (Figure 8). Contamination of the territory by unexploded ordnance and reduction of capacity of fire service in the CEZ were the reasons of large areas burned after deliberation.

Figure 8. Representation of fires in the CEZ during 2022. Fires that occurred during the occupation are highlighted in red, while those following the territory's liberation are highlighted in yellow.



Determining the precise causes of these fires is extremely difficult, yet it is plausible to attribute them primarily to military activities and the territory's contamination with unexploded ordnance and landmines. Despite the inherent risks fires pose in radioactively contaminated regions, that occurred after the disaster at the Unit 4 of the Chornobyl Nuclear Power Plant in 1986, their potential repercussions, and the consensus that any fire in these territories is unacceptable, we feel that it is worth detailing the most considerable incidents. Table 2 provides a summary of the largest fires (those exceeding 1000 ha) in Ukraine.

Table 2. Characteristics of large fires within the Chornobyl Exclusion Zone

№	Location	Wildfire duration	Affected area by land cover (%)						Total area, ha
			Pine forests	Deciduous forests	Dead forest	Grasslands	Swamp	Abandoned villages	
1	Southwestern CEZ	March 08th – 11th	1.4	11.6		79.6		7.4	2,210
2	Southwestern CEZ	March 18th – 24th	24	14.7		56.6		4.7	3,224
3	Southwestern CEZ	March 23d – 24th	3.2	15.6		79.6		1.6	1,552
4	Dytiatky village	May 04th – 24th	74.2	16.9	0.4	4	4.5		7,836
5	Yasen and Shevchenkove	March 08th – May 30th	84,4	11,2	2	0,5	1,6		2,110
6	Vilcha village	July 01st – September 10th	79.8	16.4	1.3	0.5	2		3,052
7	Denysovychi village	August 10th – September 10th	84.9	14.1		0.2	0.8		1,316
8	Zymovyshce village	August 23d – September 10th	32.7	21.5	1.2	16.5	24.7		1,715
9	Benivka village	September 02nd – 10th	75.6	20.8	1.8	0.5	1.3		1,466

Beginning with the onset of a full-scale war, the CEZ fell under occupation by Russian military until its liberation on April 1st. Throughout this period, only essential personnel involved in the safe operation of the nuclear plant, radioactive waste storage facilities, and other CEZ enterprises remained within the territory. Additionally, a unit from the state emergency service was present. In the early days of occupation, this unit could battle fires around Chornobyl, but their actions were increasingly restricted, and eventually firefighting efforts ceased. Consequently, fires in the exclusion zone could neither be extinguished, nor was their spread controlled. Fire monitoring during this period was only possible via satellite data (Figure 8).

The defining characteristic of fires during the occupation was their initiation and propagation under weather conditions typically non-conducive to fires in the CEZ. Fires during this time expanded uncontrollably, their spread governed primarily by fuel dryness and meteorological conditions. Given the high litter humidity, fires ceased their advance upon reaching forests, as substantiated by the traits of the scorched areas. Even the slightest rainfall played a role in extinguishing these fires.

Figure 9. Sentinel-2 satellite images illustrating the situation during the largest wildfire in the CEZ, near Dytiatky village, on May 19th.



Data Source: Borsuk, 2022

After the liberation of the CEZ territory, it was discovered that the occupying forces had stolen or destroyed much of the fire management equipment, including fire trucks. The issue of UXO and landmines contaminating the territory remains unresolved. As the Russian troops retreated, they mined not only the premises of institutions and organizations but also the roads and ecosystems within the CEZ. All these factors significantly complicated the detection and suppression of fires.

In 2022, approximately 18,720 ha of forests, 8,945 ha of grasslands, 1,610 ha of swamps, other habitats, and deserted villages were burnt. The contamination of the territory with unexploded ordnance and landmines poses a high risk to firefighters, thereby necessitating access restrictions to many areas in the future. Given these conditions, the occurrence of large fires in the upcoming years can be anticipated.

4.7 Wildfires in the war impact zone (60 km around front line)

According to the results of spatiotemporal analysis of fires, a significant increase in landscape fires within the combat zone, specifically within a daily 60 km range along the front line, was observed.

To identify the fires that occurred in the area of direct impact of military operations (Military Combat Zone – MCZ) we used the dynamic coordinates of the front line provided by ZOÏ. In this report, the MCZ means permanent corridor spanning 30 km on each side of the Line of Contact (LoC). The corridor is determined at the beginning of active military combat and continues to be included in the monitoring areas even after the ending of active military combat operations. Reason: UXO remains in this area and continues to pose a threat of ignition.

Out of the total area of 754,900 ha affected by landscape fires in Ukraine in 2022, 69% (520,400 ha) occurred in the war-impacted zone. Furthermore, the occupied territories accounted for 321,100 ha, which corresponds to 43% of all fires (cf. Figure 6 and Table 3). The primary reasons for these fires were the absence of fire department response, military-related ignition sources, hazardous weather conditions for fires, and low fuel humidity. The peak months for fires within the war-impacted zone were July (with 4,600 fires), March (2,900), May (1,400), and August (1,400). This is a distinct deviation from typical years, when the maximum number of fires usually occur in April and August.

Table 3. Breakdown of landscape fires in 2022 within the military engagement zone (30 km each side of front line), by land cover type and month, measured in hectares.

Month	Area of fires (ha)	Distribution of fire area by types of landscapes (ha)				
		Forests	Thereof coniferous	Agricultural lands	Other natural landscapes	Settlements
February	8,497	173	33	4470	3,623	231
March	156,869	10,737	5,838	72,481	72,189	1,462
April	18,433	2483	553	4,331	11,441	178
May	39,838	17,660	13,879	3,772	17,917	489
June	19,738	1,519	915	9,649	8,427	143
July	171,770	6,184	4,045	134,555	30,259	772
August	94,276	4,092	2,008	68,322	21,288	574
September	9,496	3,157	2,301	2,420	3,878	41
October	443	333	327	8	84	18
November	640	182	156	389	69	0
December	376	2	0	230	144	0
Total	520,376	46,522	30,055	300,627	169,319	3,908

In terms of distribution of areas burned within the MCZ by administrative regions, the worst impact of the war was observed in Donetsk (128,915 ha), Kherson (78,605 ha), Kyiv (69,549 ha), Kharkiv (40,266 ha), Zaporizhia (64,130 ha), Luhansk (51,432 ha), and Mykolaiv (44,343 ha). Since the MCZ is a relatively narrow 60 km strip, such extents suggest that nearly all territories within the MCZ (70-80%) were burned once, and in some cases, twice during the war period, heavily impacting soils, vegetation, and wildlife.

Monoculture pine forests, characterized by high fire risk and susceptibility to rapid fire spread, are prevalent in the southern and eastern regions of Ukraine. These regions ended up within the military operations zone. In these areas, the fire response system is practically non-existent, so forests are subjected to the maximum possible damage that can be caused by fires and explosions (Figure 10).

Figure 10. Direct military operations causing extensive damage to forests (Luhansk oblast).



Data Source: tribun.com.ua

Between the beginning of the war in February 2022 and July 1st, 2023, many large fires occurred in Ukraine even there were not drought periods like in 2020 (Table 4).

Table 4. List of largest landscape fires that occurred in Ukraine (whole country) during war period of February 24th and July 1st (note: LC = Land-use Classes).

Date	Oblast	Area							
		Total (ha)	Forest (ha)			Other natural vegetation (ha)	Cropland (ha)	Urban (ha)	Other land covers (ha)
			Total forest	Incl. coniferous	Other types				
Mar 11th	Kyiv-Chornobyl	4,983	1,109	756	353	2,651	1,221	1	1
Mar 11th	Kyiv-Chornobyl	4,564	270	24	246	1,265	3,029	0	0
Mar 12th	Zhytomyr	4,513	147	14	133	3,106	1,258	0	2
Mar 12th	Lviv	3,241	200	0	200	2,231	785	25	0
Mar 14th	Rivne	4,866	711	63	648	3,885	270	0	0
Mar 14th	Rivne	3,749	638	33	605	2,595	487	0	29
Mar 14th	Rivne	2,850	359	0	359	2,396	88	0	7
Mar 19th	Zhytomyr	5,554	3,072	2,556	516	2,285	191	2	4
Mar 20th	Donetsk	3,064	31	0	31	333	2,698	0	2

Date	Oblast	Area							
		Total (ha)	Forest (ha)			Other natural vegetation (ha)	Cropland (ha)	Urban (ha)	Other land covers (ha)
			Total forest	Incl. coniferous	Other types				
Mar 21st	Donetsk	4,686	0	0	0	451	4,174	59	2
Mar 21st	Luhansk	3,115	98	0	98	1,262	1,738	17	0
Mar 22nd	Donetsk	3,515	18	0	18	1,810	1,685	2	0
Mar 23rd	Donetsk	4,115	10	0	10	590	3,505	10	0
May 4th	Kharkiv	5,628	4,018	3,432	586	1,583	0	27	0
May 11th	Kyiv	7,552	5,302	4,392	910	2,241	0	0	9
Jul 27th	Kherson	3,569	970	184	786	2,527	21	0	51
Aug 1st	Kherson	4,152	397	22	375	3,753	2	0	0
Sep 1st	Kyiv	4,694	2,163	1,563	600	2,372	56	0	103
Oct 4th	Odesa	3,559	0	0	0	3,523	0	0	36

Collateral impacts of the war were directly or indirectly responsible for fires in Kyiv, Zhytomyr, Chernihiv, Sumy, Kharkiv, Luhansk, Kherson, Donetsk oblasts near frontline, while fires in Western Ukraine related with reduced capacity of fire management due to limitations for fire management during the war (prohibition of deployment of fire aviation), transfer of part of fire personnel and fire engines to the Ukrainian army.

4.8 Fires in conservation areas

Utilizing the Emerald Network, a system of significant European nature conservation areas established under the Council of Europe's Bern Convention for the Protection of European Wild Flora and Fauna and their Natural Habitats (http://emerald.net.ua/), it was determined that valuable natural landscapes were also devastated by the fires. The conflict directly affected approximately 25% of Ukraine's nature conservation areas in the form of extensive, uncontrolled fires, the destruction of biological and landscape diversity, soil chemical contamination, and territory contamination with UXO and land mines. Fires within the Emerald Network covered an area of 88,400 ha, comprising 25,400 ha of forests, 10,800 ha of agricultural lands, and 52,200 ha of other natural landscapes. Some protected areas reported forest fires exceeding 1,000 ha – for example, the Chornobyl Radiation-Ecological Biosphere Reserve experienced nine major forest fires, with areas ranging from 1,200 to 7,800 ha.

4.9 Constraints on fire management due to wartime conditions

A crucial factor impacting both forests and biodiversity, with immediate and far-reaching implications for forestry, is the contamination of terrain with UXO and landmines. Their detonation can initiate fires and inflict direct harm to trees, in addition to causing fatalities among wildlife and humans. Conventional forestry practices become perilous and challenging, and frequently, the harvested timber is littered with projectile fragments rendering it unusable.

In addition, extinguishing forest fires becomes significantly more challenging in contaminated areas where it is impossible to use conventional equipment and carrying out forest management activities becomes virtually impossible due to the inherent risk to personnel. Forest wildfires ignited by mine detonations have

often led to casualties, creating reluctance among staff to confront these fires, or leading to directives instructing firefighters to avoid such hazardous zones.

Territories that were occupied and later liberated and controlled by the Government of Ukraine, are also substantially impacted by the war. This includes the loss of fire management capacity and threats from UXO, as demonstrated by the large areas burned.

Over 690,000 ha of land are contaminated with UXO. Consequently, the forests in these areas, with their valuable timber and non-timber resources, are excluded from forest management. This not only escalates the risk of fires but also has a negative impact on the economic condition of local communities and the state as a whole.

Another significant issue is the destruction and damage of forestry infrastructure. In cases where enterprises in de-occupied zones are not completely destroyed, Russian forces often seize all equipment and vehicles. This leads to a significant decrease in the capacity for fire suppression.

4.10 Conclusions and lessons identified

The full-scale military invasion of Ukraine by the Russian Federation in 2022, along with over 500 days of military conflict across vast territories in eastern and southern Ukraine, have presented an unprecedented challenge for fire management in the country. This necessitates the development of a new national strategy for the post-war recovery period. To mitigate the impacts of climate change, the adoption of new technologies and methods is required. This includes utilizing modern remote sensing tools for daily fire monitoring, establishing firefighter training programs, and creating awareness programs for the forest-fire-threatened rural populace. Moreover, effective fire management strategies with limited resources in safe zones and protected networks must be devised, with special attention given to fire control in UXO-contaminated areas, safeguarding personnel. The national strategy should be based on advanced interagency cooperation and scientific tools for fire risk assessment. This national strategy should be founded on advanced interagency cooperation methods and scientific tools for fire risk assessment.

Wildfires are inevitable consequences of military activity, and, during war, their prevention or control is hampered due to destroyed fire management infrastructures, risks to the life and health of firefighters. Following the liberation of territories, novel approaches must be developed that factor in the risks posed by UXO contamination, as well as the necessity to safeguard rural populations, their assets, as well as fire brigades. The escalating fire risks associated with climate change and the necessity of integrating research models and tools for predicting these risks must be considered as a mandatory component of this strategy.

The absence of an implemented national strategy for integrated landscape fire management in Ukraine, combined with the shortage of well-trained, organized, and equipped firefighters, diminishes the effectiveness of landscape fire control efforts in the western region of Ukraine, which is under government control. Despite the war, rural populations and farmers continue to utilize fire for agricultural purposes in safe conditions, largely due to the cost-effectiveness of this measure. As such, any new national strategy must consider the interests and needs of all stakeholders, including SESU, rural and volunteer fire brigades, local authorities, and the population. This strategy should encompass legislative initiatives, a new financing system for fire management, and training programs.

The primary objectives of post-war national fire management efforts should be the development of fire resilient landscapes and communities, and the management and reduction of fuel and ignition sources. A thorough evaluation of the war's influence on fire regimes and the environment, grounded in advanced and proven scientific methodologies, will not only elucidate the scale and nature of immediate impacts, but also shed light on long-term, regional, and global impacts including the loss of ecosystems related to the war.

References

Buchhorn M., Smets B., Bertels L., De Roo B., Lesiv M., Tsendbazar N.-E., Herold M., Fritz S. (2020). Copernicus Global Land Service: Land Cover 100 m: collection 3: epoch 2019: Globe 2020. DOI 10.5281/zenodo.3939050

Global Fire Monitoring Center (GFMC) (2023). Fire Management on Terrain Contaminated by Radioactivity, Unexploded Ordnance and Land Mines in Temperate-Boreal Eurasia: https://gfmc.online/globalnetworks/SEEurope/SEEurope_1_radio.html

Goldammer J.G. (2013). Beyond climate change: Wildland fires and human security in cultural landscapes in transition – Examples from temperate-boreal Eurasia. Chapter 22 in: Vegetation Fires and Global Change: Challenges for Concerted International Action. A White Paper directed to the United Nations and International Organizations (J.G. Goldammer, ed.), 285-311. A publication of the Global Fire Monitoring Center (GFMC). Kessel Publishing House, Remagen-Oberwinter, 398 p. (ISBN 978-3-941300-78-1).

Goldammer J.G., Kashparov V., Zibtsev S., Robinson S. (2014). Best practices and recommendations for wildfire suppression in contaminated areas, with focus on radioactive terrain. Report of the Global Fire Monitoring Center (GFMC), Ukrainian Institute of Agriculture Radiology (UIAR), National University of Life and Environmental Sciences of Ukraine (NUBiP of Ukraine), Regional Eastern European Fire Monitoring Center (REEFMC) and Green Cross Switzerland, commissioned by the Organization for Security and Cooperation in Europe (OSCE). Freiburg – Basel – Kyiv, 53. p. Published online: English version: http://gfmc.online/GlobalNetworks/SEEurope/OSCE-GFMC-Report-Fire-Management-Contaminated-Terrain-2014-ENG.pdf

Goldammer J.G., Brunn E., Hartig S., Schulz J., Meyer F. (2016). Development of technologies and methods for the application of prescribed fire for the management of Calluna vulgaris heathlands contaminated by unexploded ordnance (UXO): Problems and first experiences gained in a research and development project in Germany. Naturschutz und Biologische Vielfalt 152, 87-122. DOI 10.19213/973152; ISBN 978-3-7843-4052-4.

Hall J.V., S.V. Zibtsev L. Giglio S. Skakun V. Myroniuk O. Zhuravel J.G. Goldammer, Kussul N. (2021). Environmental and political implications of underestimated cropland burning in Ukraine. Environ. Res. Lett. 16, 064019.

Regional Eastern Europe Fire Monitoring Center (REEFMC) (2022). REEFMC website: https://nubip.edu.ua/node/9087/2)

Soshenskyi O., Myroniuk V., Zibtsev S., Gumeniuk V., Lashchenko A. (2022). Evaluation of field-based burn indices for assessing forest fire severity in Luhansk Region, Ukraine. Ukrainian J. Forest and Wood Sci. Vol. 13, No 1. Vol. 3, 21-34. https://doi.org/10.31548/forest.13(1).2022.48-57.

Soshenskyi, O.M., Zibtsev, S.V., Terentiev, A.Yu., Vorotynskyi, O.G. (2021). Social and environmental consequences of catastrophic forest fires in Ukraine. Ukrainian J. Forest and Wood Sci. Vol. 12(3), 21-34. https://doi.org/10.31548/forest2021.03.002

Sydorenko S., Voron V., Koval I., Sydorenko S., Rumiantsev M., Hurzhii R. (2021). Postfire tree mortality and fire resistance patterns in pine forests of Ukraine. Cent. Eur. For. J. 67, 21-29. DOI: 10.2478/forj-2020-0029

SSSU (2007-2021). State Statistics Service of Ukraine. Publication. Statistical Yearbook of Ukraine. Issues 2007-2021. URL: https://ukrstat.gov.ua/druk/publicat/Arhiv_u/01/Arch_zor_zb.htm

SSSU (2021). State Statistics Service of Ukraine. Publication. Statistical Yearbook of Ukraine. Issues 2021. URL: https://ukrstat.gov.ua/druk/publicat/kat_u/2022/zb/11/Yearbook_2021.pdf

Zibtsev S.V., Soshenskyi O.M., Goldammer J.G., Myroniuk V.V., Borsuk O.A., Humeniuk V.V., Meshkova V.L., Vasyluk O.V., Buksha I.F. Forest Management on Territories Contaminated with Unexploded Ordnance. Short report of the project WWF-Ukraine “Supporting responsible forestry for sustainable development in Central and Eastern Europe”. WWF-Ukraine, 2023. 24 p. URL: http://dx.doi.org/10.13140/RG.2.2.22495.12966

Zibtsev S.V., Soshenskyi O.M., Goldammer J.G., Myroniuk V.V., Borsuk O.A., Humeniuk V.V., Meshkova V.L., Vasyluk O.V., Buksha I.F. Forest Management on Territories Contaminated with Unexploded Ordnance. Short report of the project WWF-Ukraine “Supporting responsible forestry for sustainable

development in Central and Eastern Europe". WWF-Ukraine, 2023. 24 p. URL: http://dx.doi.org/10.13140/RG.2.2.22495.12966 .

SES of Ukraine. (2021). Analytical information on the emergencies in Ukraine in 2020. State Emergency Service of Ukraine.

5 Fire of Albergaria (Portugal)

Authors

Tiago Rodrigues	ADAI
Domingos Viegas	ADAI
Daniela Alves	ADAI
Luís Mário Ribeiro	ADAI
Miguel Almeida	ADAI
Carlos Ribeiro	ADAI



5.1 General Description

The forest fire of Albergaria-a-Velha, in Central Portugal, started on the July 13th and the alert was given at 12:54. Although the ignition was placed in Pinheiro da Bemposta, Oliveira de Azeméis municipality, as the major impacts were observed in the Albergaria-a-Velha municipality, the fire was named accordingly. The ignition was intentionally placed in an area (Lat: 40°46'16.10"N, Long: 8°30'23.30"W) of great accumulation of fuels (vertical continuity of shrubs and eucalyptus trees) at the base of a slope and nearby canyons with limited road access.

Eucalyptus trees were the dominant species in the area, with some of the plots without fuel management, having horizontal and vertical continuity as well as areas of very large amounts of fuel. After the initial phase of the fire where the propagation was mostly dominated by orography, the fire propagation was wind-driven and in some periods the propagation was very intense. During the more intense hours of fire propagation, extreme fire behaviour was observed, including crown fires and many spot fires due to the propensity of eucalyptus trees to produce medium to long distance spotting, which were potentiated by the very low fuel moisture content. Around 12 hours of intense burning were sufficient for this fire to burn around 2761 ha (ICNF, 2022). It must be noted that in 2010 a fire that occurred in this region had a very similar trajectory and pattern, but it took three days to burn a much smaller area (Figure 12a).

In some periods of the fire, there was no suppression capacity due to fire intensity and smoke, being most of the operations focused on mitigating people and buildings damages. No major effects were reported in citizens or on their houses. However, some small agricultural facilities were destroyed. The fire became dangerous in some very relevant structures including, very high voltage power lines (VHVPL), highways (A1, A25, A29 and IC2) as well as the industrial areas of Albergaria-a-Nova and Albergaria-a-Velha. The powerful approach towards these structures produced the potential to cause a significant threat to many citizens and assets. In the end, only one enterprise was significantly affected, given the fact that a spot fire was developed in a very large accumulation (several tons) of wood sawdust.

In sum, the Albergaria-a-Velha fire represented a more prevalent type of fire nowadays. Due to the climatic change, very intense fires are having very intense and more frequent phases above suppression capacity. In this case, the area was also dominated by fire-prone species (mostly eucalyptus trees), which actively contributed to intense fire propagation and spotting. These fires may not very large in terms of burned area, but they normally develop the intensity and potential to in few hours deeply threaten many citizens, relevant infrastructures, and other assets. Their intensity and velocity impose many challenges considering suppression capacity and the ability to effectively protect all stakeholders involved.

5.2 Characterization of the affected area

5.2.1 Socioeconomic characterization of the region affected.

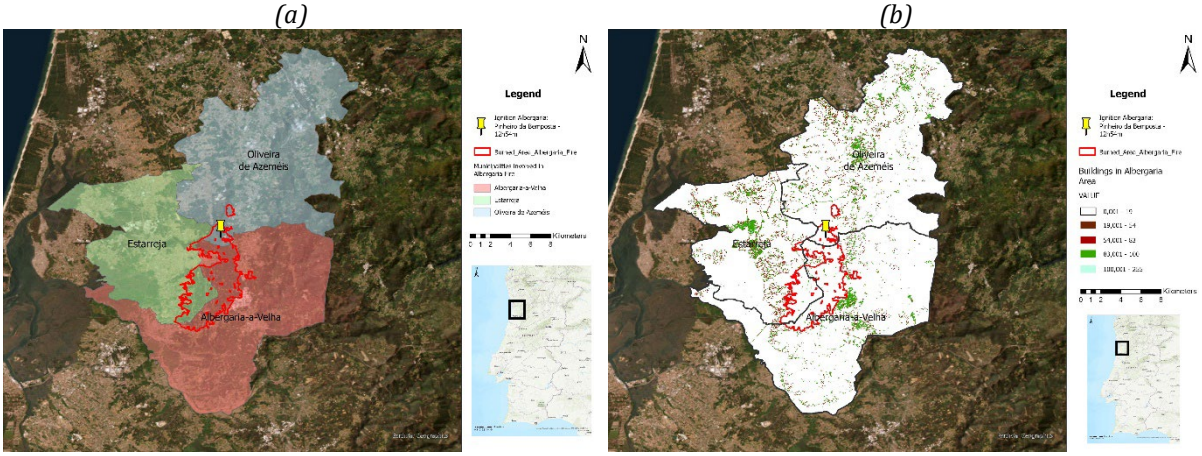
As mentioned before, the fire started in Oliveira de Azeméis municipality, but the main effects occurred on Albergaria-a-Velha municipality (Mendonça et al., 2023). The municipality of Estarreja was also partially affected, as shown in Figure 11a.

Oliveira de Azeméis is a municipality located in the district of Aveiro. According to the 2021 census, the municipality has a population of approximately 66,175 inhabitants with an average density of 410 inhabitants per km^2. The municipality has a slightly higher percentage of females than males, with women making up around 51.6% of the population. Most of the population is of working age, with a significant proportion employed in the manufacturing and services sectors. In terms of education, the municipality has a good level of schooling, with a high proportion of the population holding secondary and higher education qualifications. However, there are still some areas of the municipality where educational levels are lower. Socially, the municipality is characterized by a mixed urban and rural landscape. While there are some densely populated urban areas, there are also many rural communities with traditional ways of life.

Albergaria-a-Velha is a municipality also in the district of Aveiro, in the northern region of Portugal. According to the most recent available census data from 2021, it has an area of 158.83 km^2, with approximately 24840 inhabitants. The population density was 156.4 inhabitants per km^2. There is a higher percentage of females (51.4%) than males (48.6%). The elderly population is increasing while the number of young people is decreasing, with this trend becoming more significant in the last 20 years. The municipality is crossed by four relevant roadways in the country (A1, A25, A29 and IC2), allowing for quick access to the metropolitan areas of Lisbon and Porto and the port of Aveiro. In terms of employment, most of the population was employed in the services sector (over 63%), while approximately 28% of the population was employed in industry and construction. Agriculture, forestry, and fishing accounted for a smaller proportion of employment (8.9%).

In Figure 11b, the population density for the three affected municipalities is shown.

Figure 11. a) Map of the burned area in the municipalities affected; b) Map of the population density in the municipalities affected.



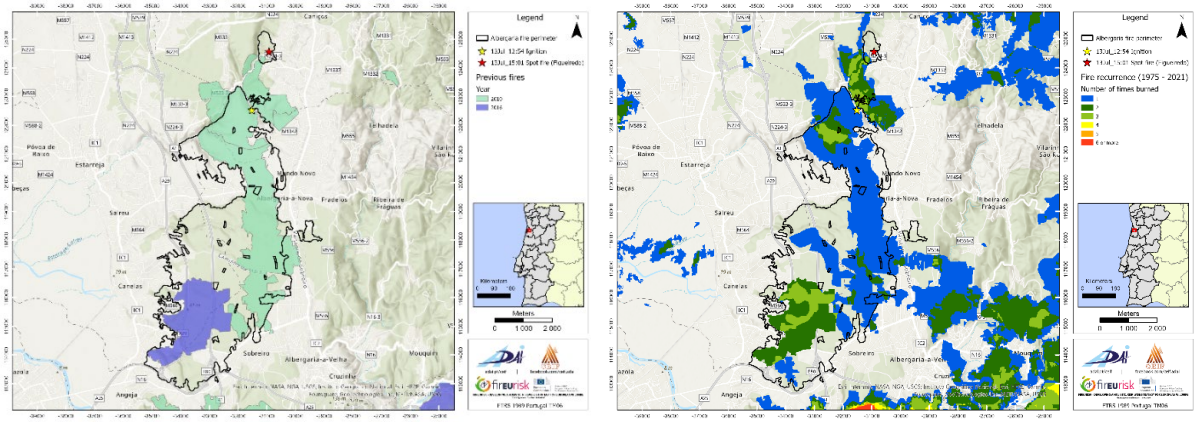
In economic terms, the municipality of Albergaria-a-Velha has agriculture and livestock farming, but it is mainly characterized by industry, especially in the manufacturing industry sector, which represents more than 58% of the total gross value added in the municipality. However, this industrialization is not homogeneous, with the parishes of Albergaria-a-Velha and Branca concentrating most industrial activity. Data from 2017 shows that about 700 companies in this area have a turnover of more than 1 billion euros, with 7,000 jobs; 155 of the exporting companies generate 400 million euros in exports.

5.2.2 Fire recurrence, topography and fuels on the region affected.

The region affected by the Albergaria-a-Velha fire was not significantly affected by fires since 2010 and 2016. There were two fires (Covais, July 26th, 2010 at 15:27 and Salreu, Aug 7th, 2016 at 9:26) that damaged almost 1,000 ha and 500 ha, respectively, in the same area. These two previous fires are shown in Figure 12a. In terms of fire recurrence, some smaller areas within the fire perimeter were also burned partially before and in some areas three times between 1975-2021, as shown in the Figure 12b. For the last 20 years, Pinheiro da Bemposta parish had 290 ignitions in total. In line with the increasing rate of success for the initial attack in Portugal, only 27 of them (less than 10%) originated fires larger than 1 ha. The relevant fire events in the area are shown in Figure 12b.

Figure 12. a) Map of relevant previous fires (2010 and 2016); b) Map of fire recurrence between 1975-2021.

(a) *(b)*

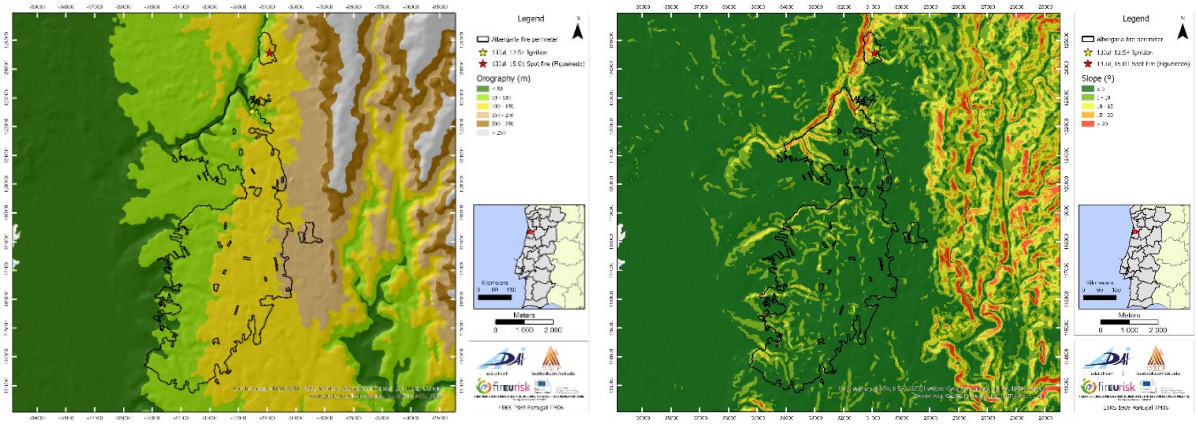


Prior to the event, the parish of Pinheiro da Bemposta had suffered multiple ignitions during several weeks. In fact, around 1 hour before the fire of Albergaria-a-Velha (12:54) there was another ignition at 11:48 on the July 13th. Although the region was under significant vigilance by several authorities as well as firefighters' teams by car, t also using drones trying to dissuade the author or authors of these fires. Unfortunately, these actions failed in preventing the event. This extra vigilance was implemented considering the large number of ignitions that were caused by a particular *modus operandi* using forest fuels in a certain configuration to promote delayed ignitions which was used in this fire as well.

The event occurred in an area relatively close to the sea, that is less than 20 km apart from the ignition point. In the map of Figure 13a, we can see that the area has quite low altitude, namely the area affected by the fire footprint, being between 14 and 185 m of altitude. Regarding the topography and orography at the ignition point area, it was relatively complex having several canyons embedded in steep slopes, but most of the area burnt afterwards was relatively flat. The average slope was around 4,99 degrees and the area with slopes higher than 15 degrees was 1,22 km^2 out of 28,2 km^2. The topography map is shown in the Figure 13b. Most of the area was significantly exposed to solar radiation, which also contributed to dry the vegetation and promote increased propagation.

Figure 13. a) Map of the orography in the region of Alberaria-a-Velha fire; b) The topography map in the region of Alberaria-a-Velha fire.

(a) *(b)*

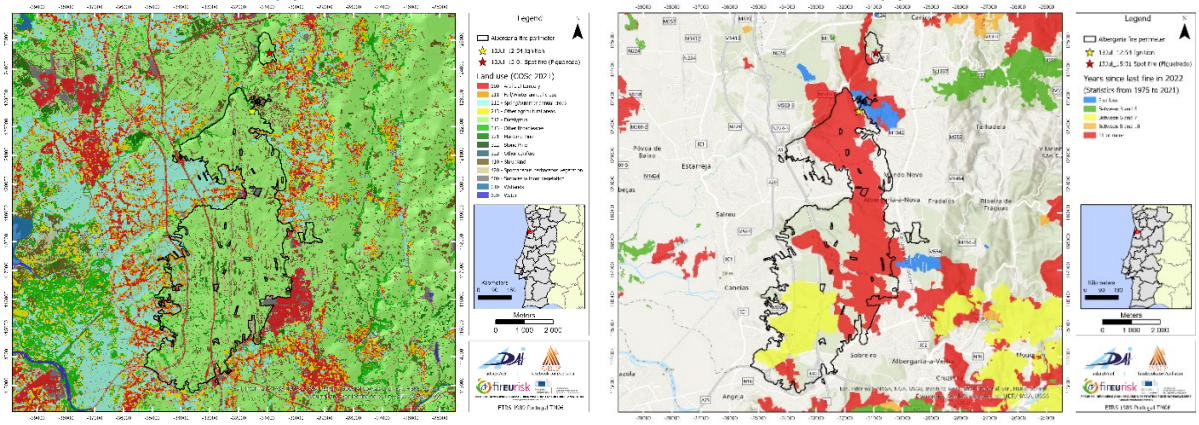


The land use and land cover map of the area (Figure 14a) shows the significant presence of eucalyptus trees in the region. It was also reported the presence of large areas without proper fuel management and high density of trees, and therefore the presence of vertical continuity and great accumulation of fuel, being the cover vegetation mostly composed by shrubs (Figure 14d). In terms of previous fires, most of the areas that burned in the past already had large amounts of fuel. The last fires relevant within the area of the event occurred between 6 and 11 or more years before, as shown in Figure 14b.

In the area, the fuel management breaks were mostly maintained previously to the event. In addition, the fuel management breaks that were created due to the presence of VHPTLs were maintained by RNT (*Redes Energéticas Nacionais*, REN – National Electricity Transmission Grid, RNT) in 2021, being still in relatively good maintenance condition. Also, where eucalyptus trees were previously cut, there was a great accumulation of dead fuels either in the field (and Figure 14c and d) or collected in big piles of wood. One fire chief reported that one of these big piles of wood (Figure 14e) when burning might have triggered the two spot fires near Branca and the industrial area of Albergaria-a-Nova.

Figure 14. Maps of the region of Albergaria-a-Velha fire characterizing the fuels available: a) Land use; b) Previous fires and respective periods; c) and d) pictures taken during the fire; e) Representative image of big piles of dead hood in the fire scene.

(a) *(b)*



(c) *(d)*




Source: Photo c provided by 2nd Commander of Albergaria-a-Velha Firefighters as a courtesy.

It is important to highlight the presence of very relevant infrastructures, in the area where the event occurred, including the very high voltage power lines (Figure 25), the two industrial areas having large facilities, a main railway and the busy motorways (Figure 15). These critical infrastructures posed high risks and concerns during the suppression phase.

5.2.3 Fuel management in the area affected by the fire

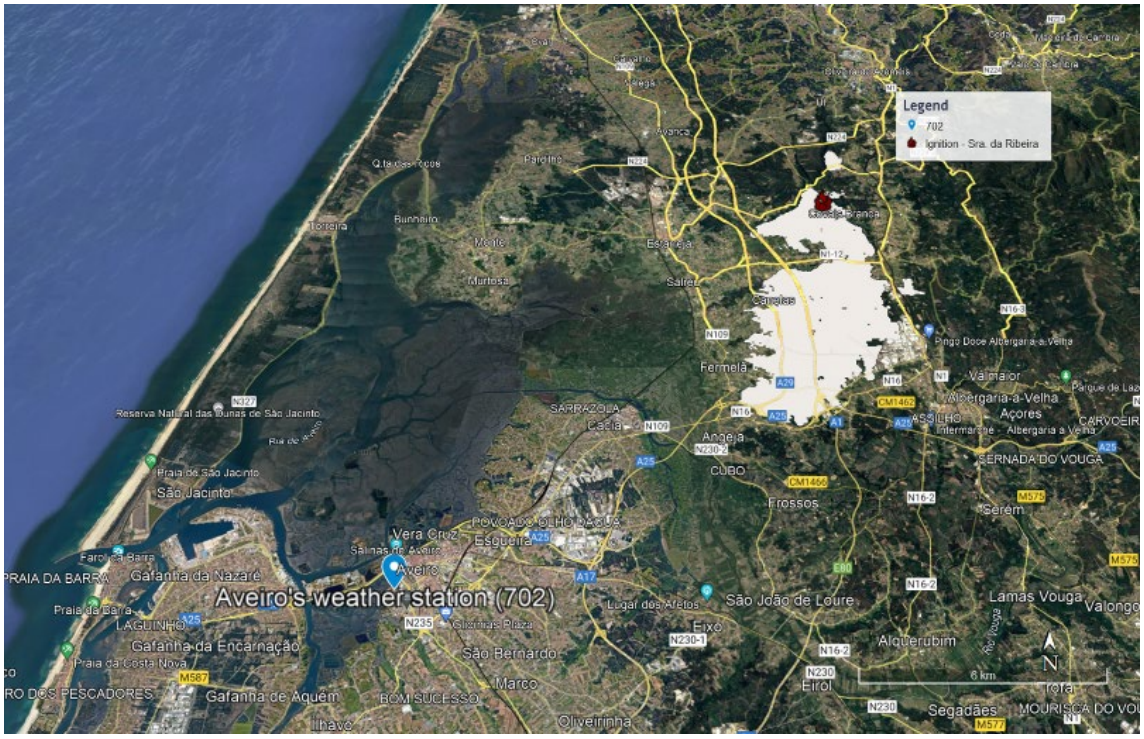
In general terms, the fuel management breaks (FGC) in the region affected were mostly done. Those under the responsibility of the municipality were carried out prior to the event. Regarding the FGCs under the responsibility of REN and E-Redes they were mostly carried out in 2021 and were still in relatively good conditions. In the case of REN's FGCs associated to the very high voltage power lines, there were areas where land was mobilized when planting strawberry trees (*Arbutus unedo*), which proved to be partially beneficial, even contributing to the survival of a significant number of trees in the FGCs and in some areas that resisted to the fire progression. However, in several areas where trees had been collected previously, there was a lot of dead and dry forest fuel accumulated (Figure 14d and Figure 14e). Even without trees these areas had enough fuel to keep fire propagation. In addition, there were also very large piles of forest material collected near forest settlements waiting for transportation/conversion. These piles are composed by dead and dehydrated forest fuels that when ignited burn with high intensity and could be associated as a possible trigger for spot fires nearby, including those that occurred in Branca and the Albergaria-a-Velha industrial facility.

5.3 Fire conditions

In the period of this fire, Portugal was experiencing a significant drought period, having low humidity for long time. The maximum temperatures were above the average, with very hot nights with low humidity recovery. On the July 13th the level of forest fire danger in the region was Very High and Maximum. The day before, Oliveira de Azeméis and Albergaria-a-Velha had three forest fires in each municipality, out of the 20 registered for Aveiro's district. At the time, Leiria region was significantly affected by many ignitions and relatively large forest fires, which required the help of a group of firefighters from the Aveiro district.

To better understand the conditions of Albergaria-a-Velha fire, we have used the records of the closest weather station (ID: 702) of the Portuguese Institute of Sea and Atmosphere (IPMA) network located in Aveiro, which is shown in Figure 15. This weather station is around 18 km from the ignition point, being significantly closer to the sea and therefore, exposed to sea influence. This may significantly affect temperature, relative humidity and wind intensity and direction registered at this station, being the conditions underestimated when compared to local fire conditions. Several firefighters' chiefs reported moderate and intense wind during the fire.

Figure 15. *Loca*tion of Aveiro's weather station when compared to fire burnt area *(ID: 702).*

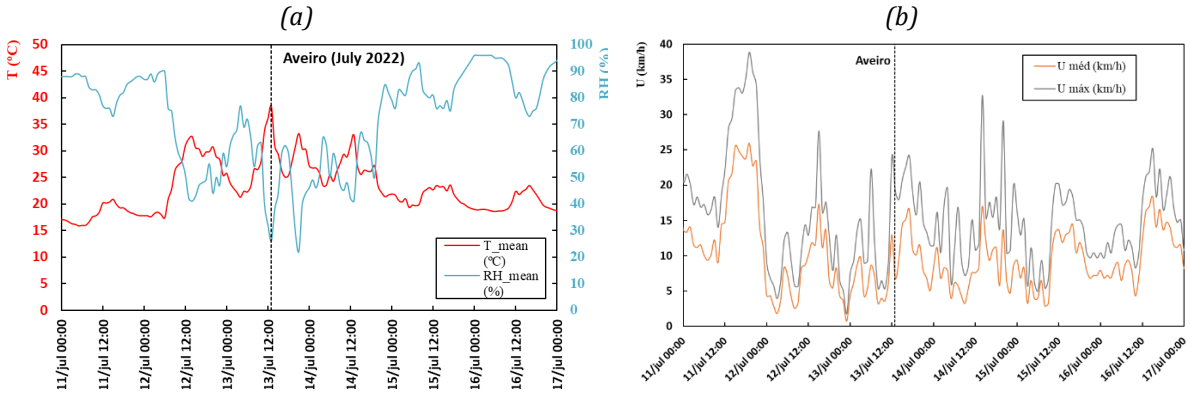


Source: adapted from Google Earth.

5.3.1 Meteorological data

The fire of Albergaria-a-Velha on July 13th occurred during a heat wave period that lasted from July 2nd to July 18th in Western Europe and was one of the most extensive, intense and long-lasting registered in the region. This weather condition was characterized by the persistence of high temperatures in mainland Portugal. Figure 16a shows the variation of the average temperature (T_mean) and the relative humidity (RH_mean) from July 11th to July 17th. The Figure 16b shows the average and maximum wind intensity (U_mean and U_max, respectively) during the same period.

Figure 16: Meteorological conditions between July 11th and July 17th, registered at Aveiro's weather station (ID. 702.): a) Temperature average (T_mean) and relative air humidity average (HR_mean); b) Windspeed average and gust maximum windspeed.

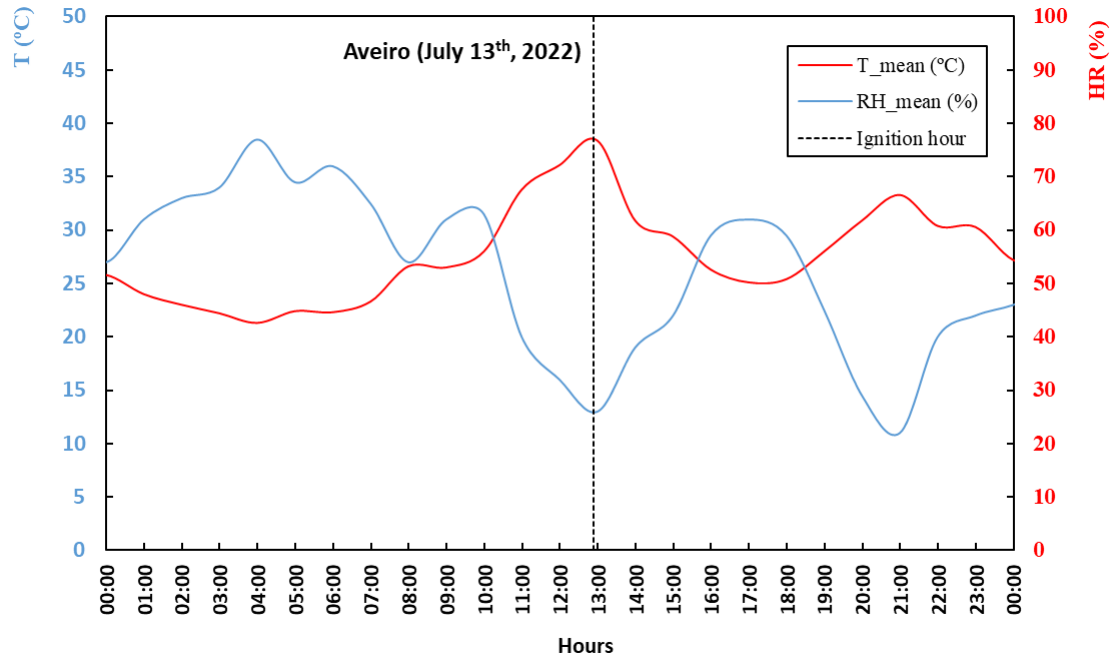


Data source: IPMA.

On the day before the fire, there was a significant increase in the air temperature and a decrease in relative air humidity. From 12:00 on July 12th, the highest temperature values and the lowest relative humidity values were recorded, remaining with low variations until 20:00 on July 14th. Only on the night of July 14th there was a recovery of relative humidity, which was observed during the night period. The temperature also gradually decreased on July 14th. The wind intensity showed a turbulent behaviour during the period under analysis, with the highest gust value being reached on July 12th with values close to 40 km/h at 7:00 pm, while the average wind intensity reached values of 25 km/h.

On July 13th (Figure 17), the temperature remained most of the time above 25°C, even since the early hours of the day, rising from 10:00 onwards. At the time of the alert (12:54), the temperature reached its maximum value at 38.4°C and the minimum value of relative air humidity was 26%. The temperature decreased until 5:00 pm, although with values above 25ºC. It increased again from 17:00 to 21:00, reaching a peak of 33.3°C. This diurnal oscillation may have been due to the occurrence of thermal inversion during this time interval as well as the direction of the wind possibly exposing this weather station to warmer air and smoke from the fire.

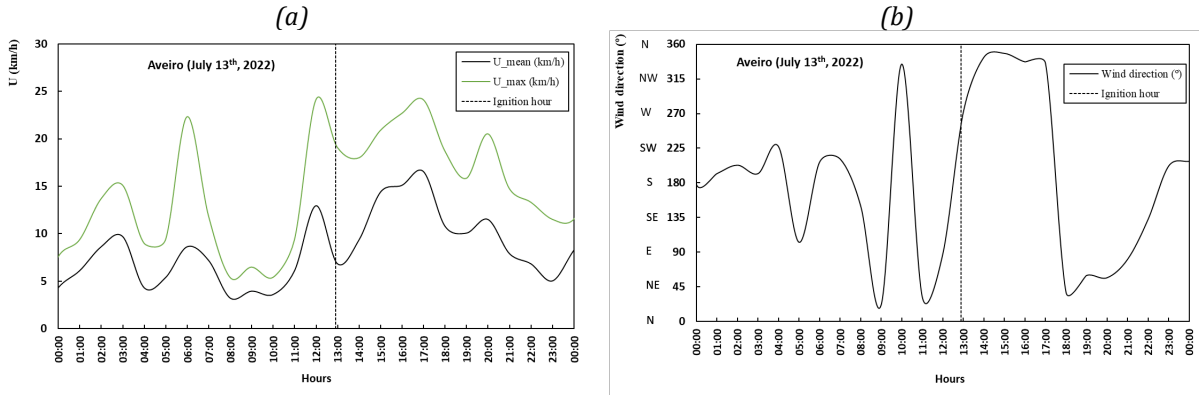
Figure 17. Average hourly values temperature (T_mean) and relative air humidity (RH_mean) on July 13th, recorded at Aveiro's weather station (ID: 702). Being the dashed line indicative of the alert hour.



Data source: IPMA.

On July 13th, changes were observed on wind intensity (Figure 18a) and direction (Figure 18b). The maximum windspeed value registered was 25 km/h and occurred at 12:00. High values were also observed around 17:00 and 20:00. The wind direction at the beginning of the day was mainly from S/SW. At 5:00 the wind direction was E, but from this hour on it presented erratic behaviour, whose direction varied from S at 7:00 and from N at 9:00. Between 9:00 and 11:00 its direction was N/NW. At 12:00 the dominant wind was from NE and at 13:00 (close to the alert time) the wind was coming from W. During the afternoon (13:00–18:00) the predominant wind was again N/NW, having varied from NE (19:00-21:00), to E (10:00) and finally to S (11:00-12:00). After the initial phase where the fire propagation was partially affected by topography and by the transition period of changing in wind direction, when wind and propagation direction were aligned, the event became wind driven. The wind as the predominant factor induced periods of fast and intense propagation having several directional spreads during the main propagation phases. Locally, wind was much more intense than the registered in Aveiro's weather station (ID: 702), this being particularly evident from the pictures that show impressive wind-driven smoke plumes (Figure 18)

Figure 18. a) Average and maximum wind velocity (U_mean e U_max); b) Wind direction on July 13th, registered at Aveiro's weather station (ID: 702). The dashed line indicates the alert hour.



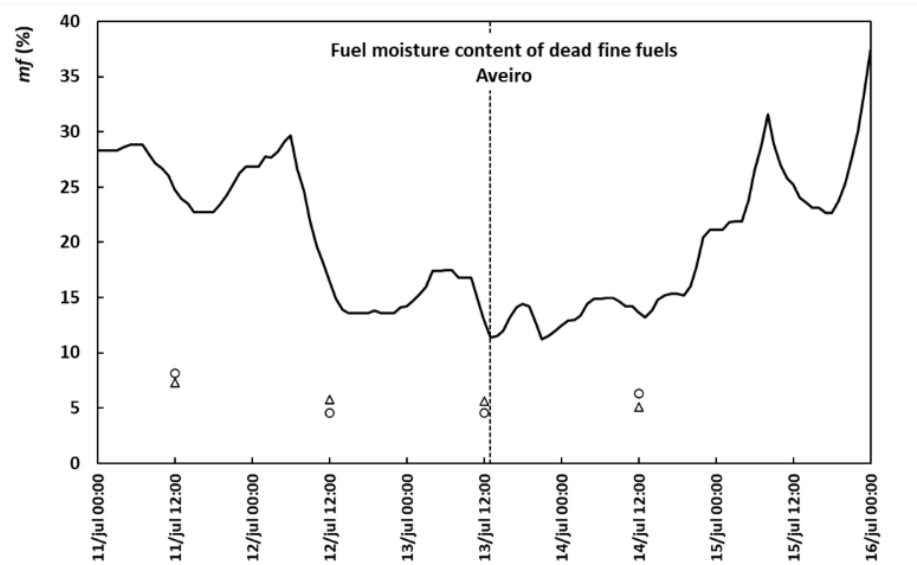
Source: IPMA.

5.3.2 Fuel moisture of dead fine fuels

Dead fine fuels moisture content (mf) was estimated using hourly meteorological data (air temperature and relative humidity) registered by the meteorological station of Aveiro (ID:702), according to the methodology described in Lopes (2013). In Figure 2, this estimated hourly evolution of mf (mf modelled) is presented for the period from July 11th to July 16th, and the moisture content of dead needles of Maritime Pine (*Pinus pinaster*) and dead leaves of *Eucalyptus globulus* both measured in Lousã (mf *Pinus pinaster* and mf *Eucalyptus globulus*, respectively)) are presented as a reference.

From July 11th to July 16th in Aveiro, the estimated average fine fuel moisture content was 21.7%. During the period from 12:00 on July 12th to 12:00 on July 14th, the variation of the estimated mf values was very low, with the lowest values being recorded on July 13th. The minimum value of mf was 11.2% on July 13th at 21:00. Dead fine fuels respond quickly to present weather conditions, so at this late hour high temperature values (33.3ºC) and low relative humidity values (22%) were still being recorded, which may have caused the low value of mf.

Figure 19. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Aveiro (ID:702) according to Lopes (2013); and mf of *Pinus pinaster* and mf *Eucalyptus globulus* measured in Lousã. Data from July 11th to July 16th. The dashed vertical line indicates the hour of the alert for Albergaria-a-Velha.



Source: IPMA.

On July 12th, the Lousã station recorded the highest temperature value in the country at 46.3ºC. This condition was confirmed as well by the *mf* measured in Lousã, which was 4.55% and 4.56% on July 13th. These were minimum record values reached in the long series of years that we have registered, since 1987 until now. This is a significant indication of the effects of climatic change as well as the extreme conditions experienced, for instance in central Portugal. The observed *mf* parameter is measured in the Central Region of Portugal and for this reason it is considerably lower than the *mf* estimated for Aveiro, a region near the coast, so highly exposed to sea environment, namely having more benign conditions of air temperature and relative humidity.

5.3.3 Fire danger

On the day of the fire, in the district of Aveiro, the forecast indicated a Very High and Maximum fire danger and a Haines index up to 13/14 in the interior.

In Portugal, in accordance with current legislation (DL nº 82, of October 13th, 2021), the RCM (Conjunctural and Meteorological Risk) is used to define the fire danger level of a region. The RCM is usually called the "Rural fire danger index" and is mainly addressed to the population.

The RCM is calculated every day and results from the combination of two components (IPMA 2020):

- Conjunctural and structural component given by cartography of the land use, slopes and burned areas of the last 10 years (from 2020, the burned areas of the last 3 years are also considered) – updated every year by ICNF.
- Meteorological component given by the Fire Weather Index (FWI) from the Canadian system (Van Wagner, 1987) that represents the intensity of the fire front, defined as energy per unit of time and of length of the flame front – updated every day by IPMA;

The integration of the two components is performed by applying a weighting matrix. RCM is rated on a 5-level fire danger scale (Low, Moderate, High, Very High and Maximum) and it is available at municipality and district level. The single interpretation of the FWI value, widely used in European countries, is also made using a danger scale where the increase in FWI corresponds to an increase in fire danger.

Table 5 presents the FWI danger level according to two classifications: *IPMA 2023* and *Viegas et al. (2004)*. The first considers a single scale (limit values of FWI for each level) to define the level of danger for the entire territory of Portugal (IPMA, 2023). The second classification considers a danger scale for each district of the country since the authors consider each of these classes has a relative interpretation, which changes from one district to another (Viegas et al., 2004). Despite this comparison, we highlight that the classification made by IPMA (2023) is the official one used in Portugal.

Table 5. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Aveiro, and FWI description according with IPMA (2023).

Level	Limit values of FWI		Description according to IPMA (2023)
	IPMA (2023) for Portugal (a)	Viegas et al. (2004) for Aveiro (b)	
1	<8.2	<10	Surface fires.
2	17.2	17	
3	24.6	23	High fire intensity with crown fires
4	38.2	40	

5	50.1	>40	Exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control.
6	64.0	-	Exceptional fire intensity with extreme difficulty of control
7	>64.0	-	

The level of fire danger on July 13th based on Aveiro's weather station (ID: 702) is shown in Table 6 considering: a) FWI and, b) the RCM. This table presents the observed values for July 13th and the predicted values at 24h, 48h, and 72h for July 13th in Aveiro's weather station (ID: 702).

Table 6. RCM and FWI observed and predicted on July 13th as well as the classification-related colours considering the level of danger for RCM.

Day	RCM observed and predicted				FWI observed and predicted			
	Obs.	Predicted			Obs.	Predicted		
		24h	48h	72h		24h	48h	72h
July 13th 2022	32.0	26.1	37.9	29.1	4	5	4	4

On July 13th, using data from Aveiro's station (ID. 702), the observed FWI and RCM were classified as "Very High," the fourth most severe level on a scale of five levels. Both FWI classifications (IPMA, 2023 and Viegas et al., 2004) attributed the fourth fire danger level. For FWI values between 24.6 and 38.2, which were observed at this station, the fire is characterized by "High fire intensity with crown fires" (IPMA, 2023).

In this case, the RCM and FWI coincided in the danger level classification, but we emphasize that both indices used data from a station close to the coast, which may not reflect the real conditions experienced in the area of the fire.

5.3.4 Resources allocation: pre-positioning and overall deployment of operational teams

The day before the fire event (July 12th), there had been two events in the municipality of Oliveira de Azeméis, namely in Nespereira de Baixo fought by 153 personnel, which resulted in a slight injury to a firefighter and an agricultural fire in which a woman was found dead in the burned area. These indicators were mentioned during the daily operational briefing at the Aveiro District Civil Protection Headquarters. They were also considered together with the danger in at local level within the district. The district pre-positioning aimed to have increased capacity of firefighter teams on these identified locations. These high-risk locations are normally identified from several aspects, namely considering fire history and meteorology. The locations having increased risk should benefit from a better coverage of the area and decreased time of response from supporting teams, in addition to those reacting at first place. The district's firefighter pre-positioning was established on July 13th, and among other pre-positioning locations to cover the district, one dedicated fire brigade was placed very near the ignition point:

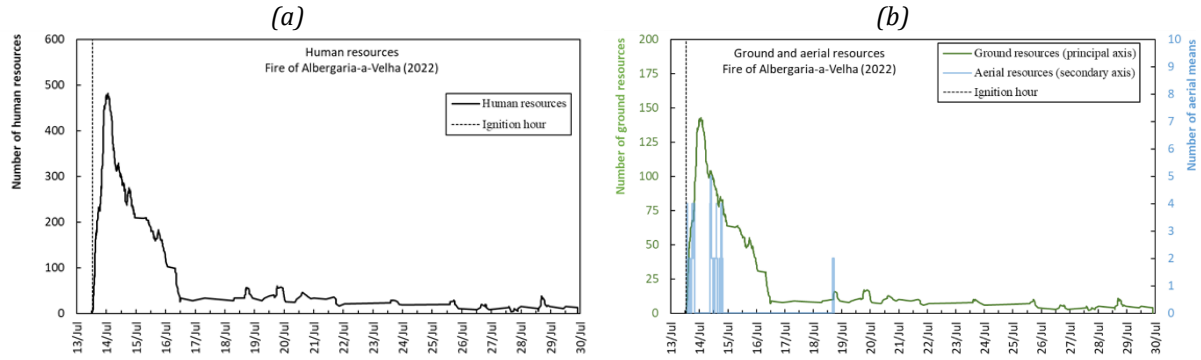
- ALBERGARIA-A-VELHA – Logistic support base (around 10 km from event location)
    - VFCI CBV 0101 – Aveiro Velhos
    - VFCI CBV 0102 – Aveiro Novos
    - VTTU CBV 0115 - Vagos

In sum, this fire involved a total of 373 vehicles and 1178 operatives from several entities that belong to the Portuguese Special Resources for Combating Rural Fires (DECIR), who were organized in six operational sectors defined to better tackle local fire dynamics. In Figure 20b, we can see a great deployment during the

first two days of fire duration, being the means progressively decreased afterwards. The fire was considered active for many days because there were many reactivations in the fire perimeter, which were caused by substantial difficulties in effectively consolidating some areas with limited access.

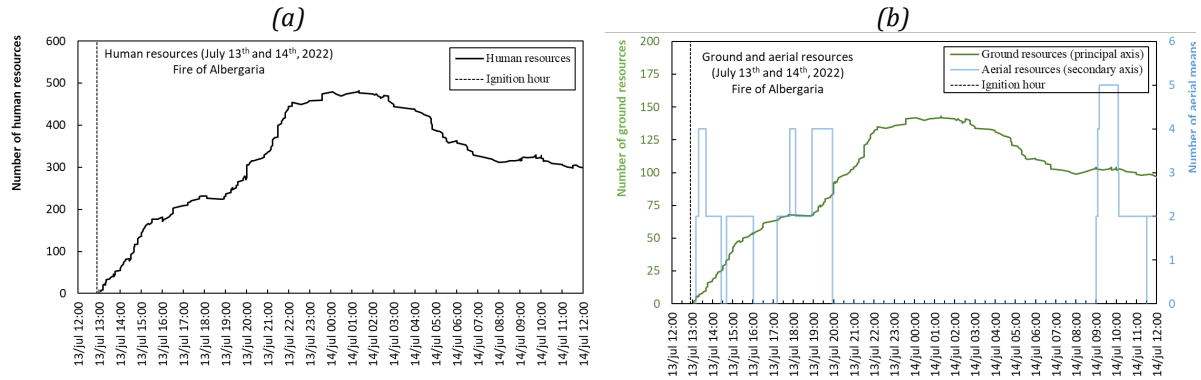
Considering the aerial means, the first day was considerably limited in aerial resources deployed. In fact, they were limited in number and time of availability, but also operationally due to decreased visibility caused by the smoke plume in some periods of intense wind-driven fire propagation. During the second day, these aerial means were reinforced in number and time of allocation, being their actions important to consolidate hot spots and preventing powerful reactivations. The second day had similar temperatures and relative air humidity values, but higher wind average and gust velocities. These efforts were fruitful in preventing fire continuation even when the operatives were challenged by a worst weather situation on the July 14th.

Figure 20. Operational means deployed in Albergaria-a-Velha fire: a) Human resources; b) Ground and aerial means.



Looking at the initial phase of the event (Figure 21), there was an important deployment of resources. Two hours after the alert, 136 operatives and 40 vehicles and four hours later, 209 and 63, respectively. These numbers were even limited due to the involvement of some relevant means in the fires occurring in Ourém and Leiria regions during the previous days but still under consolidation. A combat group from Aveiro district was afterwards demobilized and returned to be engaged in this fire. The maximum number of operatives and ground resources was observed at 01:20 on Jul 14th, when 482 operatives and 143 vehicles were deployed.

Figure 21. Operational means deployed in Albergaria-a-Velha fire during the first 24 hours: a) Human resources; b) Ground and aerial means.



5.4 Fire Behaviour

5.4.1 Ignition cause on July 13th

The Judicial Police, through its Northern Directorate, with the collaboration of the Working Group for the Reduction of Ignitions in Rural Areas - North Zone, identified and arrested on July 19th, caught in *flagrante*

delicto, the alleged perpetrator of the rural fire, initiated in some areas of the parish of Pinheiro da Bemposta - Municipality of Oliveira de Azeméis, Aveiro. The fire was initiated by the alleged authors through the organized accumulation of forest fuels in areas of easy access, but large fuel accumulation and complex orography. Through the identification of the *modus operandi* to start the ignitions, other fires under investigation were also registered. Those cases are also suspected to have been caused by the accused at nearby dates and locations. The detainee, a 39-year-old unemployed man with a criminal record for the crime of rural fire, was presented to the competent judicial authority for the initial judicial inquiry and was subjected to the measure of preventive detention.

The area where the ignition was placed on July 13th, was being thoroughly monitored, which contributed to the success of the detaining operation afterwards. Even the local fire department promoted drone flights on site and active and visible surveillance actions in the area to try to dissuade these deliberate behaviours, but without success in preventing ignitions, namely the one on Jul 13th. It should be noted that the success of this operation was due to the close collaboration between the Judiciary Police and the Volunteer Firefighters of Oliveira de Azeméis, establishing an example of successful cooperation that should be replicated in other locations where there is a significant number of ignitions occurring in a given region.

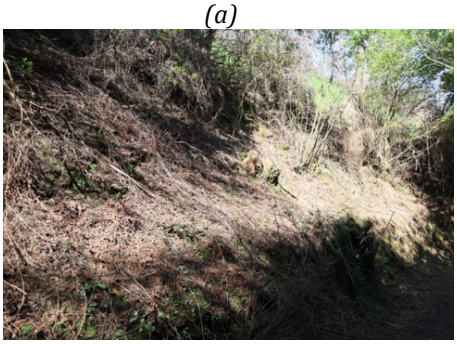
5.4.2 Fire propagation – initial phase

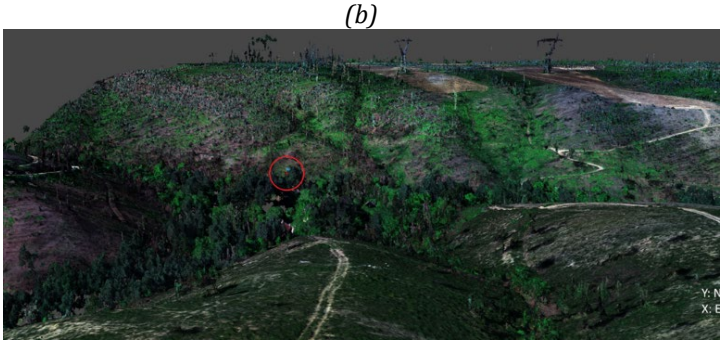
At 12:54, there were very favourable meteorological conditions for the spread of rural fires ("Red alert" level for civil protection operations and "Very high" or "Maximum" fire danger in the region), including very hot weather (temperature above 35ºC) and dry weather (relative air humidity below 15%). At the time of the fire, there was weak recovery of fuel moisture overnight, but also moderate wind blowing with some intensity throughout this period, especially during the phase of greatest spread of the fire. Therefore, there were conditions for the occurrence of extreme behaviour in its various aspects, but above all, there were phases of propagation with great intensity in active crown fire with high rate of spread and generating various spot fires.

The ignition was placed near the Curval small river stream, near the chapel of Nossa Senhora da Ribeira, through a small path along the water line. At the time, the area contained great accumulation of fuel, including large shrubs potentiating vertical continuity, also associated with a steep slope and nearby canyons, which were preeminent for the increased intensity in an initial phase of the fire. The local of ignition is shown in the Figure 22a-d, as well as the pictures taken by the first aerial brigade (Figure 22c) and incident commander (Figure 22d). In Figure 22e, it is possible to see spot fires originated near the very high voltage power lines, even in an initial phase of the fire.

Figure 22. Images of the ignition area: a) local of ignition; b) Drone images collected after the fire focusing the area of the ignition; c) Image of the first aerial mean arriving to the fire; d) Image taken from the COS of the fire when arriving to the fire; e) Image taken from the helicopter showing spot fires near the electric grid.

(a) *(b)*





(c) *(d)* *(e)*



Source (images c-e): ANEPC and incident commander during the first hours (A. Justino, CB Oliveira de Azeméis).

As expected, given the meteorological context and the characteristics of the ignition site, described earlier, the alert was given by a fire lookout tower nearby at 12:54. The first description was already referring an intense fire. Upon the arrival of the aerial brigade on site, the first POSIT (team leader of H10 at 13:07) indicated a fire with great intensity in an eucalyptus plantation, with firefighting initiating on the right flank. At 13:10, the incident commander (COS) requested a combat group and a pair of firefighting airplanes (alphas) and informed good access to the head of the fire, but flanks without access. In an initial phase, there was an attempt to prevent the fire from entering the canyon on the right, but the difficulty in accessing and fighting through the flank made this objective ineffective. The fire continued to progress, and a new operational status (POSIT) at 14:35 indicated high intensity of propagation with strong winds on site. The available aerial means were also limited in what concerns the time of their operation. The COS requested 2 additional combat groups and two pairs of alphas.

At this stage, there was an increase in windspeed and gusts following a rotation (mostly coming from the south towards N/NE), which contributed to an increase in intensity at the rear of the fire. This change also caused many spot fires that landed near the area of the first ignition. These spotting was limited by the burned area of the previous fire (Figure 12b) but were promptly attacked with two brigades and aerial means as support. However, one relevant spot fire was reported at 15:01 by a local resident near Figueiredo and Pinheiro, Oliveira de Azeméis. This reported secondary focus near the Cerciaz farm had landed more than two kilometres away from the area of active propagation. After some time, a secondary ignition near Figueiredo, threatening houses and citizens, rapidly concentrated increasing attention. The growing propagation within the WUI caused a relevant dispersion of the operatives. At this stage, visibility was greatly reduced, with smoke accumulating near the ground in a northward direction (towards the back of the fire), making it difficult to perceive its behaviour as well as the various projections in the adjacent northern areas. There was a window of opportunity to conclude the primary fire, which was propagating against wind direction. The head of the fire was under consolidation, but the flanks without proper accesses were still active at the time.

5.4.3 Fire propagation – development phase

Although the fire was progressively yielding, around 15:30, the wind shifted again and aligned with the initial propagation direction towards south and increased slope, allowing for a new surge of the fire. At first, the fire head was under consolidation, but the flanks that were still active and increased their intensity. The flanks rapidly engulfed the small village of Covais (PCO location) around 16:00, becoming a wind-driven propagation. Without effective suppression capacity, the village of Covais was protected by firefighters and no losses were registered. Cristelo was the next village to be protected and at this stage, the operatives concentrated their actions in protecting people and assets. All resources were being repositioned from the back of the fire to these populated areas, which required great agility. Without suppression capacity, the fire continued to increase its size and energy release until 18:00, also through spotting ahead of the fire. The Aveiro's district firefighter group previously mobilized from the wildfires under consolidation in Leiria region, received a mission to act near Cristelo, but it was no longer possible due to rapid fire propagation. This is indicative of the incapacity to plan in advance due to very rapid-fire propagation during this period.

After the first intense hours of fire propagation, the incident commander from ANEPC took over as established in the National Operational Directive - *Diretiva Operacional* Nacional – DECIR (Comando Nacional de Emergência e Proteção Civil, 2022). However, the previous incident commander, which was experienced and knowledgeable of the area integrated a team with another firefighter commander, acting as fire analyst providing information and mapping/identifying risks and opportunities. At this period, it is important to highlight the rapid transition of means from the areas near the ignition area (back of the fire) towards the fire front, which was progressing fast. This moment showed a good coordination of the means as well as a quick response to protect the assets endangered by the fire front and multiple spot fires.

After 18:00, with the increased wind intensity on site, mostly coming from north/northwest, all energy was directed towards the fire front, with preheating of fuels and resulting in a very fast and intense longitudinal propagation. In addition, crown fire but also spotting was always very relevant during fire propagation, given the fact that each new ignition developed very fast, potentiating the rapid progression of the fire front. This wind-driven (also observed in fire plume, Figure 23b) behaviour potentiated high intensity, namely when reaching the industrial zone of Albergaria-a-Nova and Albergaria-a-Velha (Figure 23a). In Figure 23a, it is possible to see several spot fires upon the arrival at the industrial zone of Albergaria-a-Velha (infrared image seen from west to east from the industrial zone at 19:35). There was great concern about the industrial zone (namely the briquettes production company) considering the great intensity of the fire and the exposure of large facilities, as visible in the image on the right (heading 229º - SW) taken at 20:17.

Figure 23. Images taken when the fire was reaching the industrial zone: a) Infrared image taken at 19:35 showing several spot fires; b) Image taken at 20:17 showing great fire intensity and windy conditions.

(a) *(b)*



Source: ANEPC.

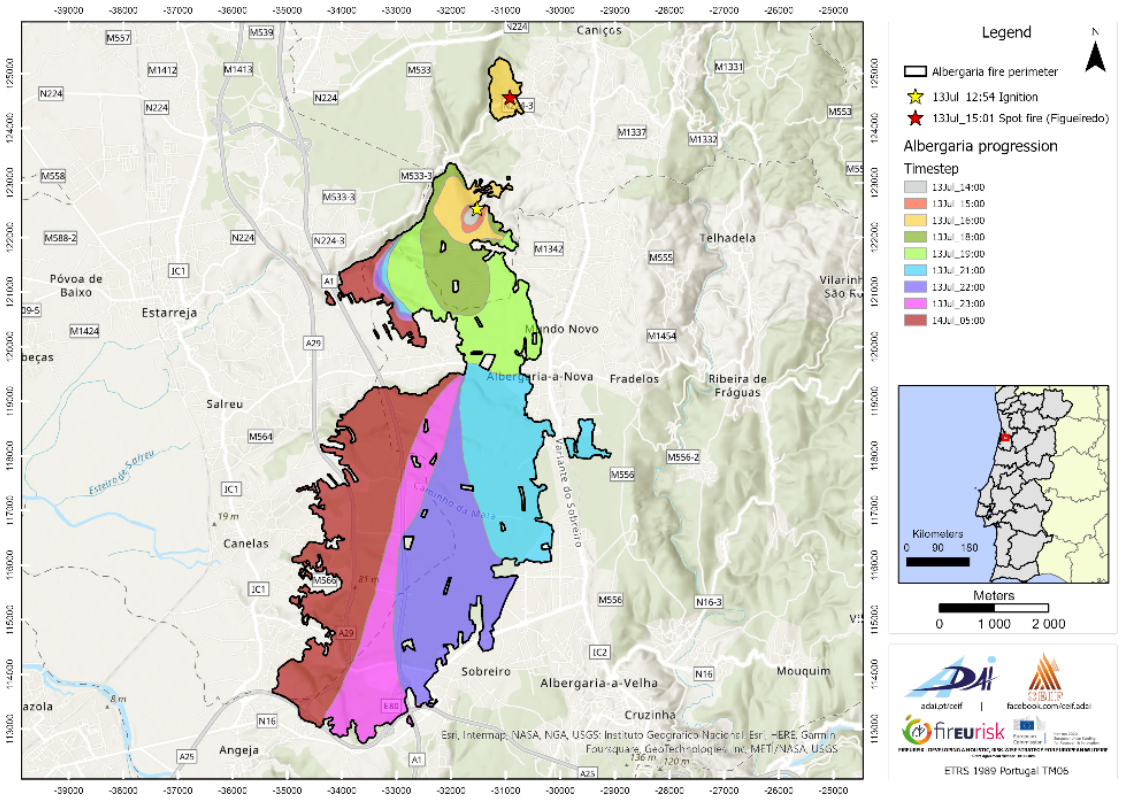
During this period of high fire intensity, there were also many projections at the fire front. Still at a distance, and even with the industrial zone already under protection (urban fire brigades were deployed) one spotting hit the biomass park (where large tons of sawdust were stored in the open air) of a briquette manufacturing industry. This ignition involved many operatives in a very difficult suppression operation, which progressed causing partial damages to the main facility. The left flank and the fire front stopped at the industrial facilities boundary as well as in areas with reduced amount of fuel. The right flank was still very active. During this phase, local winds were moderate and high, as shown in Figure 23b, but they were not previously foreseen in operational support data. Between 18:00 and 21:00, the fire progressed 7731 m on an average of 0,42 m/s (1,52 km/h) and producing around 18651 kW/m, which is significantly above suppression capacity. The aerial means were also limited in their actions due to the smoke plume.

After approximately 21:00, possibly due to the entry of land breezes, the wind shifted predominantly to the east quadrant, pushing the fire progressively towards SW/W. The right flank expanded during this phase towards relevant motorways and several villages, including Fermelã and Canelas in the municipality of Estarreja. The right flank became the major concern, progressing until reaching the agricultural land, and dangerously threatening many buildings considering the large fire front entering the WUI. In these areas, citizens are used to have fire. They are organized in groups and using agriculture machines they were able to help supressing the large fire front entering their lands. The resilience of these citizens together with the operational system prevented major losses, since only small agricultural facilities and some buildings suffered minor damages.

In the last very active phase of the fire, the propagation occurred towards northwest, which were caused by winds coming from S/SE, especially after 23:00. Some uncertainty in the direction of the wind was also present during this extended phase. This was also relevant in other phases of the fire. As dawn approached, the lower temperature, decreased wind, especially gusts, and increased humidity created the conditions for the operational forces to significantly control the fire.

Lastly, a difficult consolidation process began, with a significant perimeter, which took place with many reactivations that required multiplied efforts from the operational forces in the following days. The main phases of the fire are approximately detailed based on data from ANEPC and ICNF since Copernicus services were not activated for this event. We also complement existing data by collecting reports from local operational forces. The most important propagation phases, some of them strongly wind-driven ones are approximately identified in Figure 24.

Figure 24. Map of the key propagation phases during Albergaria-a-Velha fire.



5.5 Fire management at the WUI – residential and industrial interface

As reported before the fire developed the potential to have massive effects on many citizens and their assets, including relevant highways, industrial areas as well as very high voltage power lines and many buildings in the WUI.

5.5.1 Analysis of the Portuguese program on “Safe Village, Safe People”

The region where the fire occurred does not have any settlements that were part of the "Safe Village, Safe People" Portuguese program to increase citizen resilience through better preparedness and capacitation. The nearby villages belonging to the program (Vilarinho de São Roque, Vila Nova de Fusos, Carvalhal) were not affected or threatened by this occurrence. This situation can be locally improved in the future, as it has been unanimous among the operational forces that in the villages involved in this program, citizens have better performance following their advice and taking safety actions during rural fires, namely in confinement or evacuation processes. In this event, there was no need to evacuate the populations, and some of the affected settlements demonstrated resilience, an example of which was the effective use of

agricultural machinery by citizens organized in suppression actions near buildings and other agricultural structures.

5.5.2 Analysis of the presence of the very high voltage power lines

In the area of Albergaria-a-Velha, the company REN - "Redes Energéticas Nacionais" is the responsible for the network used for the transmission of very-high voltage electricity. In Albergaria-a-Velha municipality, REN operates four lines (Recarei - Paraimo, Carrapatelo – Mourisca, Estarreja – Mourisca and Feira de Lavos) that cross forest areas as shown in Figure 25a-c. As can be seen in the figure below, there is one line (Feira de Lavos on the left) alone and 3 lines (Recarei - Paraimo, Carrapatelo – Mourisca and Estarreja – Mourisca) that are placed side-by-side crossing the municipality and the burned area of this event.

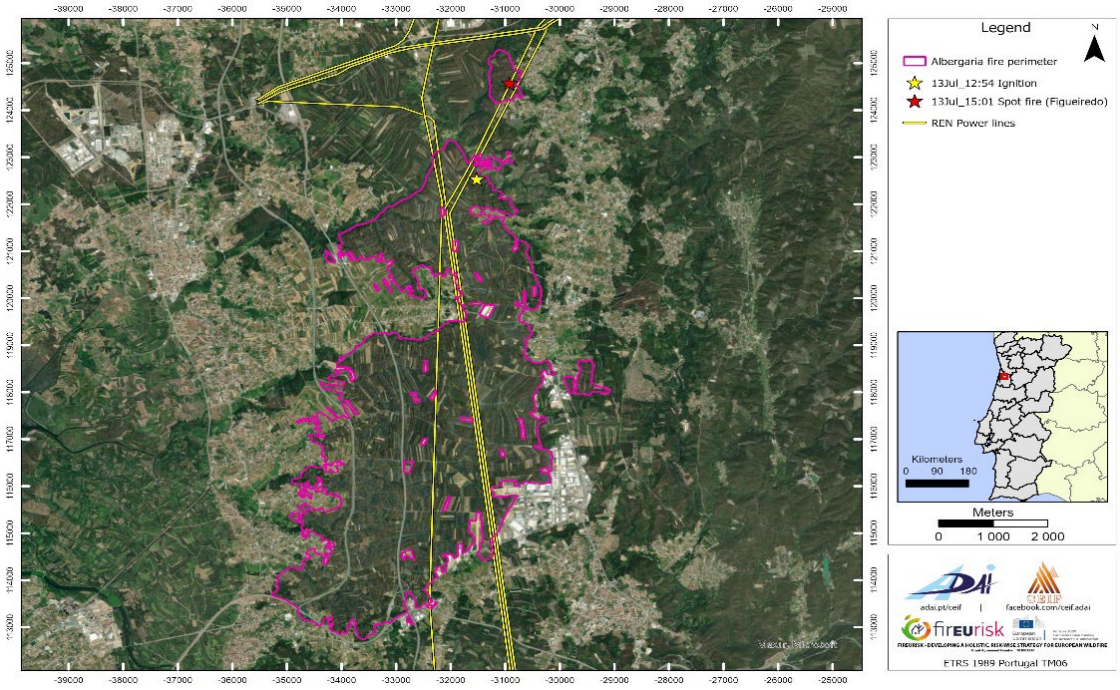
In 2021, REN implemented a plan to defend the forest against fires in the region of the municipality of Albergaria-a-Velha, managing more than 87 ha of land. For 2022, REN planned to clean up 97 ha in the municipality's region. The cleaning work is carried out in agreement with the landowners, as the areas do not belong to REN. In this sense, REN has collaborated with the Municipality of Albergaria-a-Velha and other entities to potentiate the defence of this relevant and critical structure against forest fires. A large amount (more than 57 ha and 66 k trees) of these areas were also planted with autochthonous species i.e., *Arbutus unedo* shrubs, which resulted in areas with terrain mobilization and without fuels other than a tiny layer of herbaceous or shrubs, as shown in Figure 25c. The *Arbutus unedo* shrub produces a fruit that can be used to extract alcohol and provide an income to the landowners in few years after plantation.

In the initial phases of the fire, these structures were used as anchoring points, but following the most intense phases of fire propagation, these structures were engulfed by the fire, namely due to spotting. However, there were areas where fire did not burn continuously, and most of the fruit shrubs were able to survive even facing considerable radiation from the fire.

Although the very high voltage power lines were considerable exposed, the well-maintained fuel break allowed them to operate at full capacity and without the need for a power cut. This is very relevant for a critical infrastructure, which prevent energy loss for many citizens and industries. The economic investment in effective and good management and maintenance of fuels in these structures has mitigated the economic losses, being an example of what should be done in relation to other assets. Additionally, LMATs are relevant structures for fire suppression activities, namely considering their dimension and maintenance. They can be relevant safe zones or anchorage points, but they are also important as they can provide a window of opportunity to stop the fire. If these structures are associated with complementary measures of land management and planning, like the performance of prescribed fires, the results could be even greater towards improved fire suppression capacity.

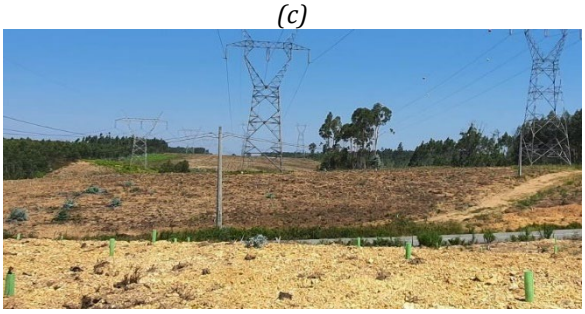
Figure 25. Network of transmission of very-high voltage electricity in the area: a) Map of the lines in the affected area; b) Drone images showing the dimension and fuel management of the grid; c) Image showing the strawberry trees planted under the grid.

(a)



(b) *(c)*





5.5.3 Overall civil and operational safety

The suppression operations and capabilities were carried out effectively, at certain moments of the fire propagation even without the possibility of direct combat and with most of the means engaged in the protection of people and assets. The operatives worked following the safety rules preventing major losses and the existence of casualties or fatalities in this event. Nevertheless, it is regrettable that two professionals and two civilians were slightly injured as well as the five firefighters that had to be assisted on site. Unfortunately, a firefighter chief of one of the urban-dedicated teams placed to protect the industrial facilities, was also assaulted by a civilian during the operations, but there was no need of any medical care. There were also some minor incidents involving citizens interfering with civil protections agents and bulldozer actions.

The losses in the interface were significantly mitigated considering the potential damage generated by the fire, namely considering the industrial areas and the busy motorways. The industrial area of Albergaria-a-Velha was already under protection. However, fire intensity caused some damages, which were reported by the companies and sum up to 1 M euros. A spot fire that landed in a large amount of wood sawdust triggered its ignition that caused partial damages to a big facility dedicated to briquettes production. This company had full coverage insurance of 11 M euros, reporting 3 M euros of damages and 1 M euros of additional labour losses. Also, the annex of one house was destroyed due to an ember which ignited the structure. Among other several losses, also agricultural assets were destroyed in a total amount identified around 40 K euros.

Citizens in the area are also used to be exposed to forest fires, so they have already developed additional resilience, namely organizing themselves using agricultural equipment to protect their assets. This

organization is being potentiated by the parish coordination, namely through the organization of dedicated exercises and scenarios involving the citizens. In this case, the local availability of interested citizens having agricultural tractors equipped with water containers and pumps contributed to the fire suppression activities, especially near the buildings and agricultural assets from Canelas until Fermelã, Estarreja.

It is also important to emphasize that it was reported that two civilians traveling by motorcycle, near the Antuã service area, were seen setting fire. Without additional information, we can state that this situation may be related to arson or the use of fire to safeguard people and property. The latter is a practice that is rooted in the population, intensified in some regions, which can lead to even more complex and dangerous situations. These behaviours should be the targeted by on site surveillance by all those involved in the operation. These events may completely change fire behaviour, being relevant for the safety of operatives and citizens as well as their assets.

As highlighted before, this event had the potential, in terms of fire propagation intensity and smoke plume, to cause a high number of casualties, especially in the motorways. However, it was also challenging the management of citizens using the large number of roads affected or threatened by the fire was also challenging, as. However, relevant motorways were also affected (A1, A29, A25, and IC2). These motorways had partial blockages for extended periods, resulting in significant practical losses and constraints for both operators and users. However, preventing large-scale accidents, particularly car accidents caused by smoke or even the fire front should be a major priority. Their containment should be timely enforced to avoid having citizens exposed, as shown in Figure 26. In this sense, the time required for the closure of relevant roadways was: IC2 - 17 minutes, A1 - 13 minutes, and A25 and A29 - approximately 18 minutes. With proper planning, and if the request for closure is timely, these motorways can be interrupted in total safety for the users. However, in situations where the fire spread can be very rapid or having spot fires, these longer times can lead to increased risk. Therefore, it is advisable to have good coordination and timely planning for high-traffic routes, allowing for the pre-positioning of resources, resulting in a significant reduction in the time required for the closure of these motorways. In relation to the main motorways, the amount of fuel that is near these infrastructures should be subject of a closer surveillance by the authorities, as greater accumulation of fuels poses an increased risk. These motorways are normally surrounded by large areas of unmanaged land, i.e., in this event having high density of eucalyptus and pine trees, which was also the case during this event.

Figure 26. Picture taken by a TSF journalist traveling through A1 motorway.



Source: TSF – tsf.pt

5.6 Conclusions and Lessons learned.

Some lessons and improvements that can be drawn from this event are partially described throughout the document. However, we will highlight some positive and negative aspects that can be useful in other events and locations:

- Overall management of this fire, protecting citizen and their assets that mitigated larger damages and losses:
    - Protection of citizens and their assets was prioritized as well as the safety of all agents involved.
    - Operatives worked following safety rules and no major effects were suffered by operatives and their resources.
    - Coordination teams and involved civil protection agents from multiple entities were experienced and used to work together, which was very positive to better establish and connect operations.
    - The industrial areas were heavily protected by deploying additional urban fire suppression means.
    - Experienced team of local fire commanders to map and identify risks and opportunities ahead of the fire front.
- The increased resilience and proactive actions of organized groups of citizens, namely using agricultural equipment to protect houses and other assets.
- The effective fuel management under the networks of very-high voltage electricity transmission prevented major effects on these critical infrastructures, namely a large-scale blackout.

On the other hand, it was possible to identify less favourable key aspects that can be improved. Thus, we identify and recall some of those considered relevant below:

- The large accumulation of forest fuels was critical in key aspects:
    - The large areas of eucalyptus trees without fuel management and horizontal continuity, but also vertical continuity contributed to a high-risk forest fire that developed phases of relevant intensity and exposing many citizens and relevant assets at risk.
    - Several tons of wood sawdust, special within rural areas and without any protection against embers should be avoided, because once ignited these fires are difficult to supress and highly-resource demanding, as observed in this event that caused partial damages in the infrastructure.
    - In the areas where eucalyptus trees have been cut, there were considerable amounts of dead wood either spread in the terrain or on the side in very large piles that were waiting to be transported. One of these piles was indicated as the cause of two spot fires.
    - The critical infrastructures as high-density motorways, industrial areas or the networks of transmission of very-high voltage electricity were mainly surrounded by large amounts of forest fuels, as described before. These critical infrastructures should be associated to buffer zones, having increased protection and resilience, to significantly reduce fire intensity and the associated risk.
- At an early stage, the lack of proper access to the fire flanks reduced fire suppression capacity during a period of opportunity with decreased fire propagation. In this case, an early deployment of heavy equipment could have made the difference. Also, aerial means are normally limited, but in this initial phase their reduced capacity as well as lack of redundance may have impaired overall suppression capacity.
- The interaction between forest fires and motorways is difficult to tackle because an early shutdown may force citizens through smaller routes that could be also exposed to the fire. However, the planning should accommodate the pre-positioning of the operatives to partially close these road elements faster and safer in due time. In fact, this is critical during extreme fire events, to prevent people to be trapped and exposed to risk when traveling at high speed.

References

Diretiva Operacional Nacional n.o 2-DECIR. (n.d.). Retrieved August 1, 2023, from www.prociv.pt

Instituto Português do Mar e da Atmosfera. (2020). Nota Metodológica - Cálculo do Índice de Risco de Incêndio Rural (RCM). 1–8.

IPMA. (2023). mf2 - Perigosidade Meteorológica de Fogos Rurais. http://mf2.ipma.pt/about

Lopes, S. (2013). Modelos de previsão do teor de humidade de combustíveis florestais. University of Coimbra.

Mendonça, J. M., Máguas, C., Pereira, J. M. C., Fernandes, P., Xavier Viegas, D., Tedim, F., Keizer, J., Silva, J. S., & Al., E. (2023). Relatório Final do Grupo de Peritos dos Incêndios Rurais.

Van Wagner, C. E. (1987). Development and structure of the Canadian forest fire weather index system. In Forestry.

Viegas, D. X., Reis, R. M., Cruz, M. G., & Viegas, M. T. (2004). Calibração do Sistema Canadiano de Perigo de Incêndio para Aplicação em Portugal. Silva Lusitana, 12(1), 77–93. http://www.scielo.oces.mctes.pt/pdf/slu/v12n1/12n1a07.pdf

Viegas, Domingos Xavier, Almeida, M. F., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Jorge, H., Rodrigues, A., Lucas, D., Lopes, S., & Silva, L. F. (2017). O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017. Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA).

6 Fires of Ourém (Portugal)

Authors

Carlos Ribeiro	ADAI
Domingos Viegas	ADAI
Tiago Rodrigues	ADAI
Luís Mário Ribeiro	ADAI
Daniela Alves	ADAI



6.1 General Description

This was a complex of fires with multiple occurrences in the same territory in the period of two months, indicating possible criminal activity, Figure 27. The territory is not far from the Atlantic Ocean, it is characterized by the existence of an extensive Wildland Urban Interface (WIU), with a lot of population and intense economic activity, different from what is common in regions further away from the coast. There was a great involvement and intervention of the population, either in the defence of the villages or in the evacuation of places. The usually very high speed of initial propagation of the fires generated great difficulty in fighting during the first intervention and, on the other hand, the numerous secondary outbreaks that were registered made it difficult to define a combat strategy, remaining, for the most part, only the defence and safety of people and their property. The fact that the territory affected by the studied fires involves several municipalities, more than one sub-region and two Regions of the ANEPC Command structure, raised some issues of articulation of means that seemed interesting for us to be analysed.

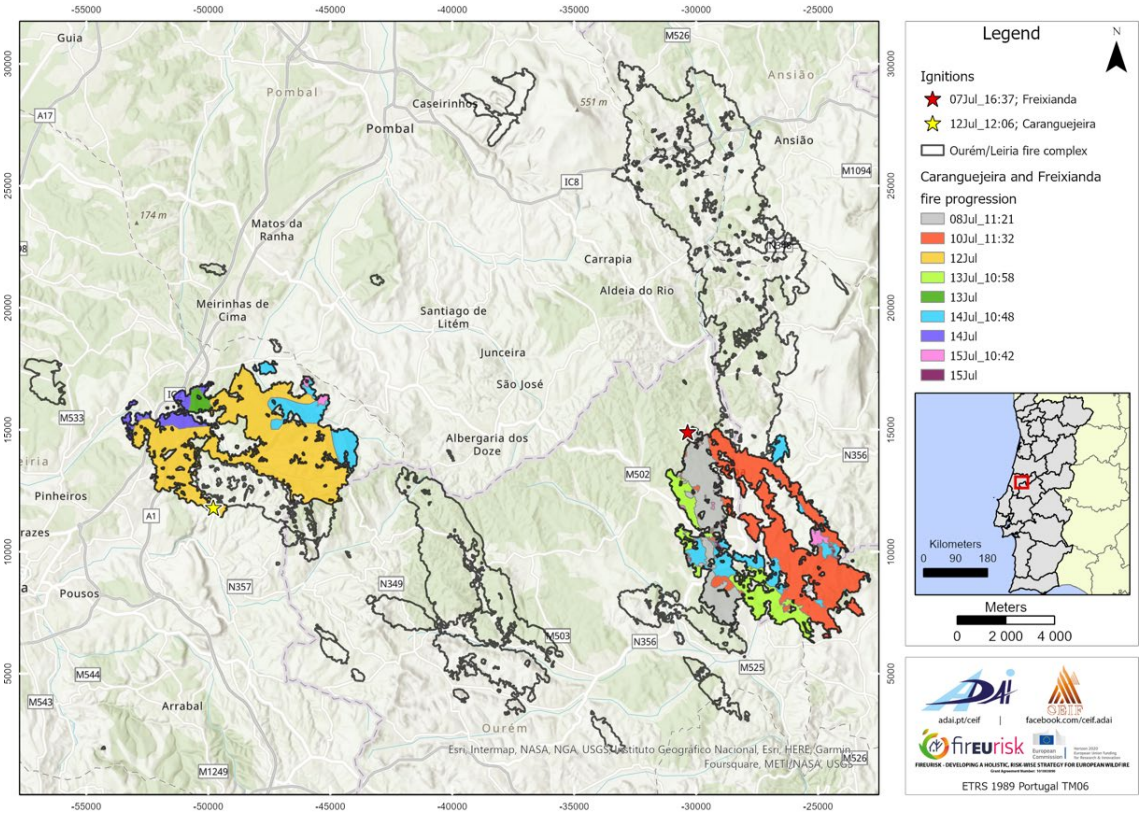
As is shown in Figure 27, the map of in the area of Ourém, that includes the territory of three districts (Leiria, Coimbra and Santarem) there was a large number of fires most of which were suppressed in their early stage and remained small but that was not the case of several others that due to their simultaneity and the particular condition of spread lasted for several days and threatened several villages, industries and communication infrastructures.

The events presented in Table 7 were selected to be analysed in this study.

Table 7. Selected fires of Complex Fires of Ourém.

Case	Designation	Date of ignition	Date of extinction	Burned Area [Ha]
1	Freixianda	July 7th	July 9th	2936
2	Caranguejeira	July 12th	July 16th	2787

Figure 27. Map of burned areas in the Ourém and Leiria fire complex.



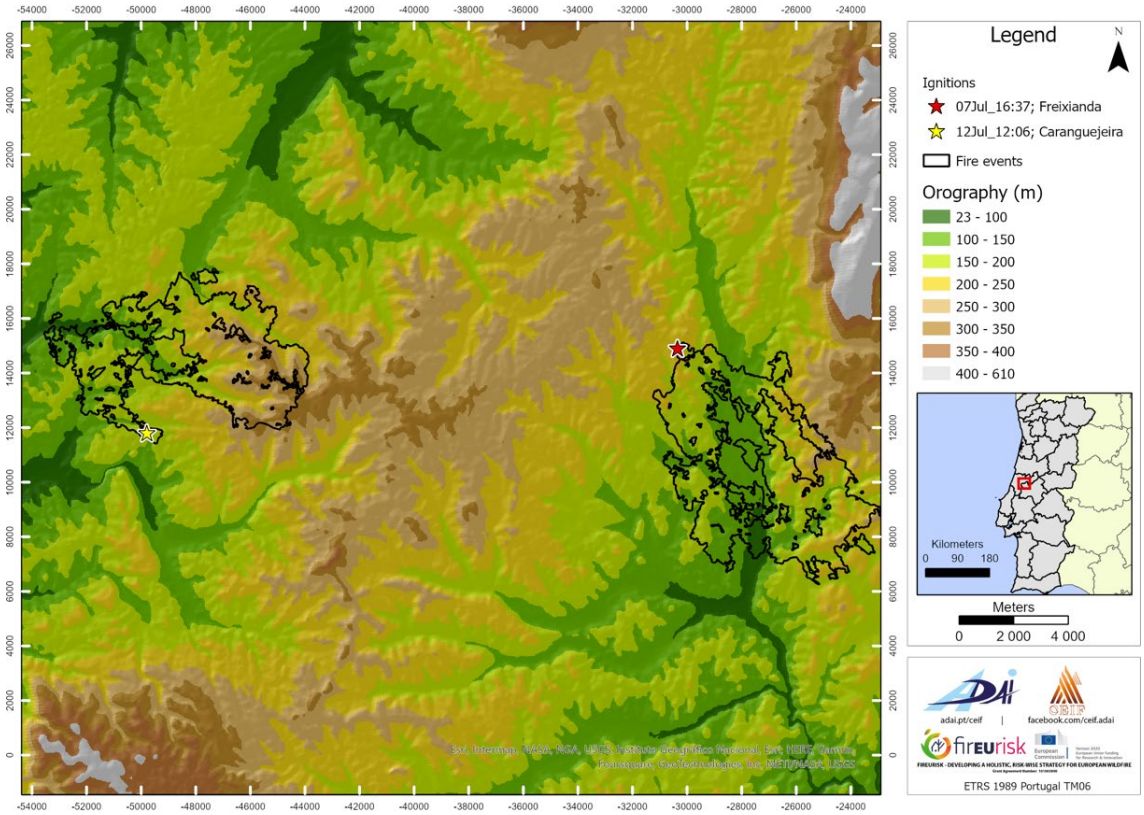
.

6.2 Characterization of the affected area

The Freixianda fire essentially spread at altitudes between 104 m and 261 m (92.0%) in the Nabão river basin (Figure 28). This watercourse runs approximately north to south when crossing the burned perimeter, where the following water lines can be highlighted: Ribeira Murta, Ribeira Barroca, Ribeira Almoster, Ribeira Mogadouro, Ribeira Gaiteiro e Ribeira Ancião Carvalhal.

The Caranguejeira fire covered an area between 74 and 353 m, although most of the perimeter (72.1%) is between 169 and 329 m (Figure 28). The valleys of Ribeira dos Milagres, Ribeira Mortorios, Ribeira Venda Nova and Ribeira Vale do Leão were affected by the fire.

Figure 28. Hypsometric fire map of Freixianda and Caranguejeira.



The Freixianda fire essentially travelled through areas with lower slopes than 12.61° (22.37%). The highest slope class represents only 0.86% of the affected area. The maximum value is 28.90° (Figure 29). In the Caranguejeira fire 53.0% of the area covered by fire has slopes between 7.13° and 16.68°. Some of the valleys have higher slopes (Figure 29).

The Ourém/Leiria area was very much affected by large fires over the years, but most of the areas affected by these fires, had not been affected in the past or had not been affected for over 11 years. Thus, with the increase in rural exodus and the decrease in agricultural activities, there was an increase in areas that became areas with a predominance of scrub areas. Thus, as can be seen in Figure 30, the surface covered by fire is mostly found in areas that do not record a fire history or in areas where there have been no fires for more than 11 years.

Figure 29. Slope terrain fire map of Freixianda and Caranguejeira.

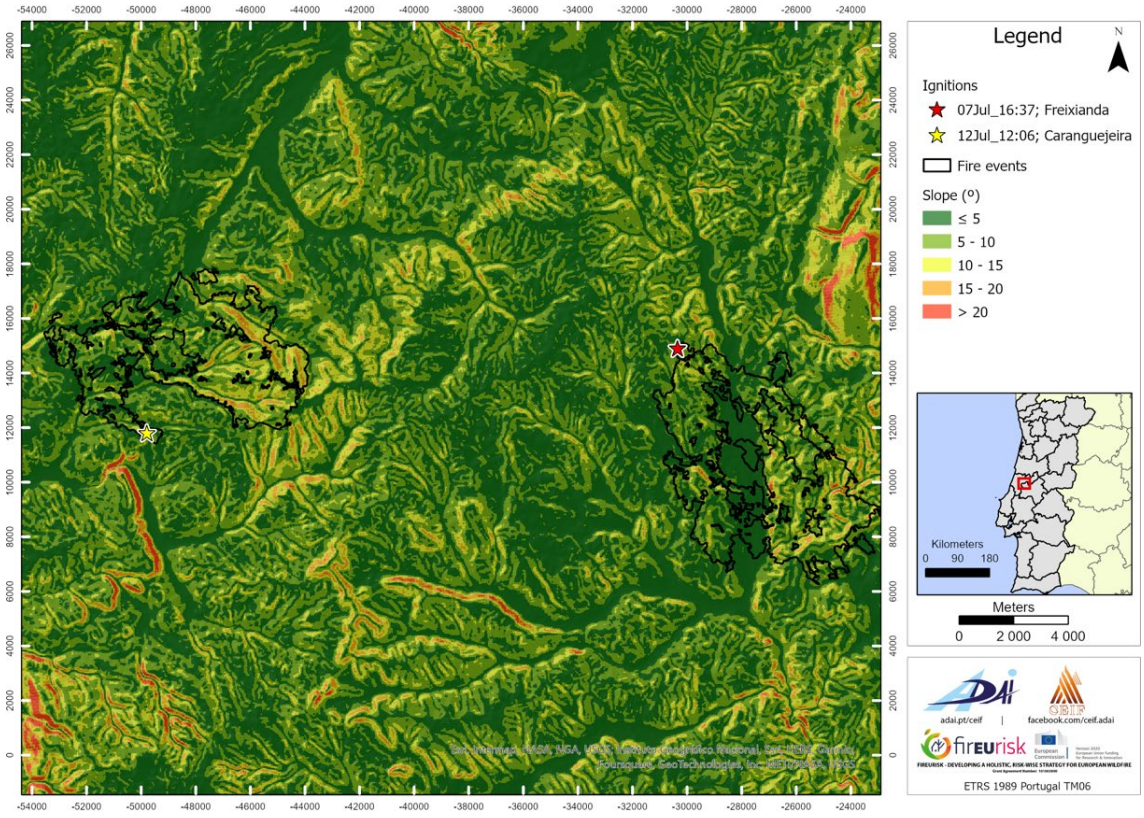
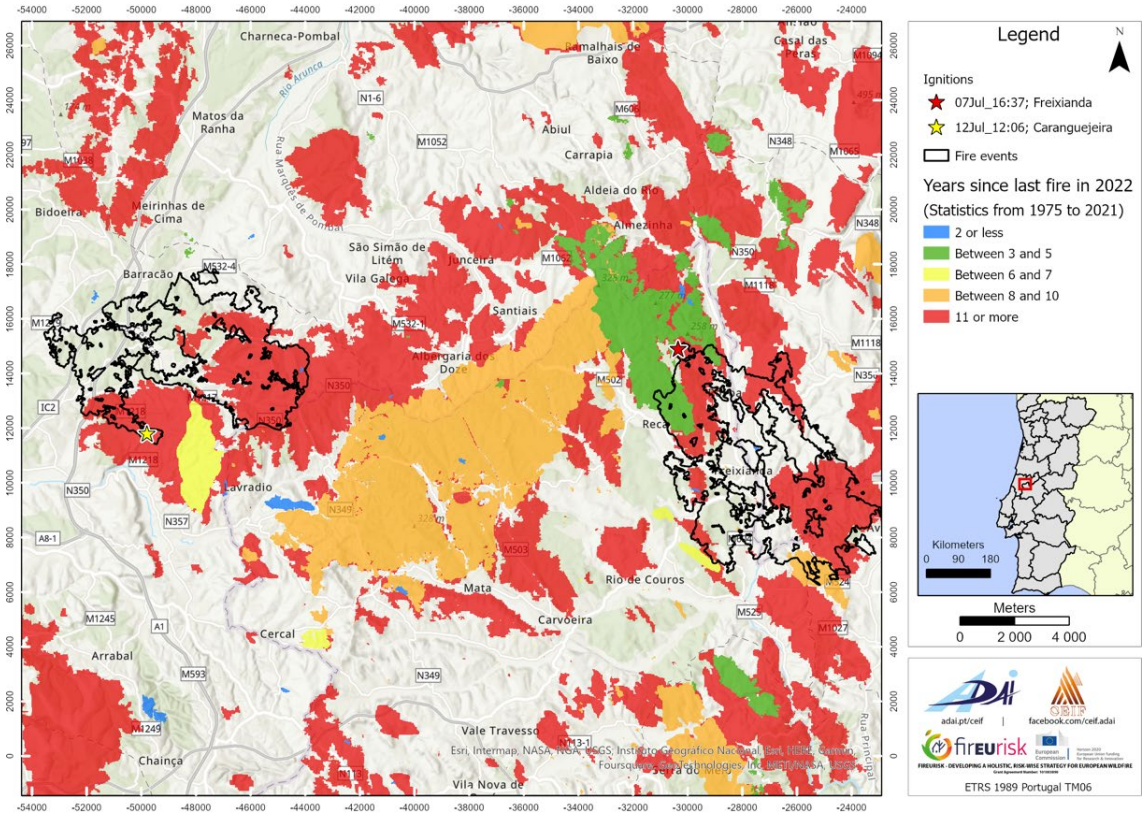


Figure 30. Years since last fire map of Freixianda and Caranguejeira with statistics from 1975 to 2021.



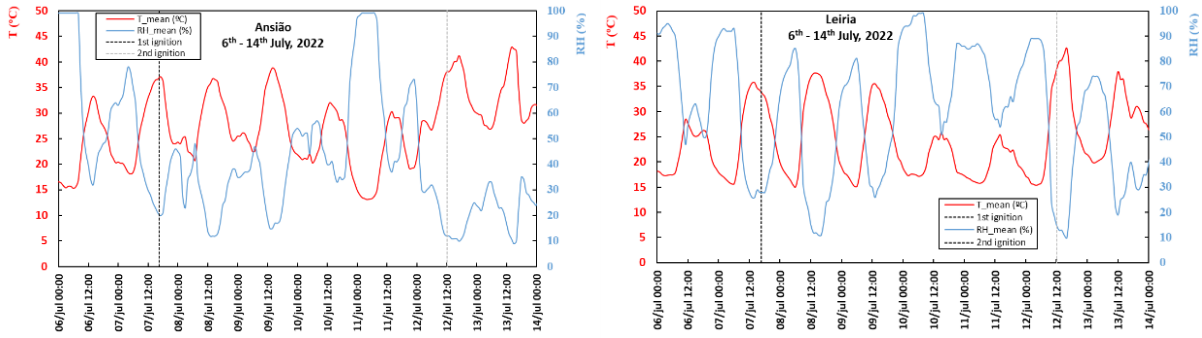
6.3 Fire conditions

6.3.1 Meteorological data

Regarding the meteorological conditions verified during the two fires, and based on the mentioned meteorological stations, the temperature presented, on average, values above 30ºC and the relative humidity below 10%, see Figure 31 and Figure 32. The wind direction in the Freixianda fire on July 7th initially was from the North, however, later tended to rotate towards the East. On the July 9th, it returns to the preferential North course. In turn on the July 12th, in the fire of Caranguejeira, the wind direction was initially from the East, but later, on the first day, the wind turned to the West. On the July 13th, the wind direction becomes erratic, alternating between Southwest, Northeast, Northwest, and North (see *Figure 33*).

Figure 31. Average hourly temperature values recorded at IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718).

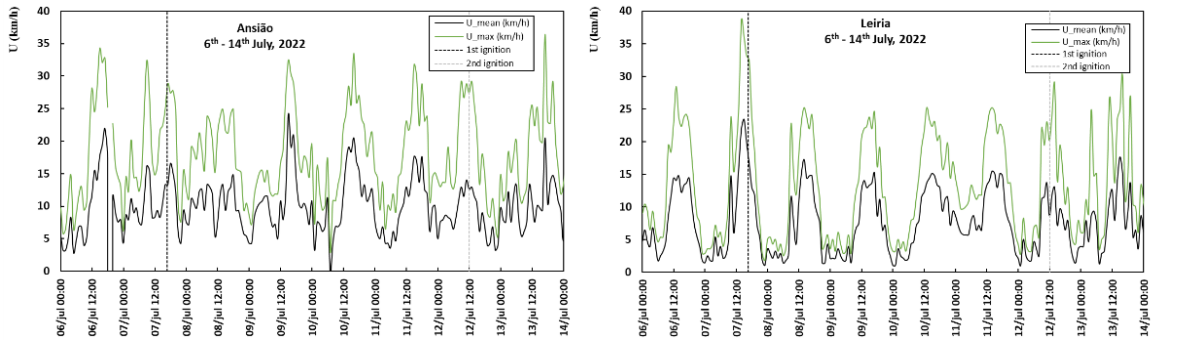
(a) *(b)*



Data source: IPMA

Figure 32. Hourly values of average speed and daily wind gusts recorded in the IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th: a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718).

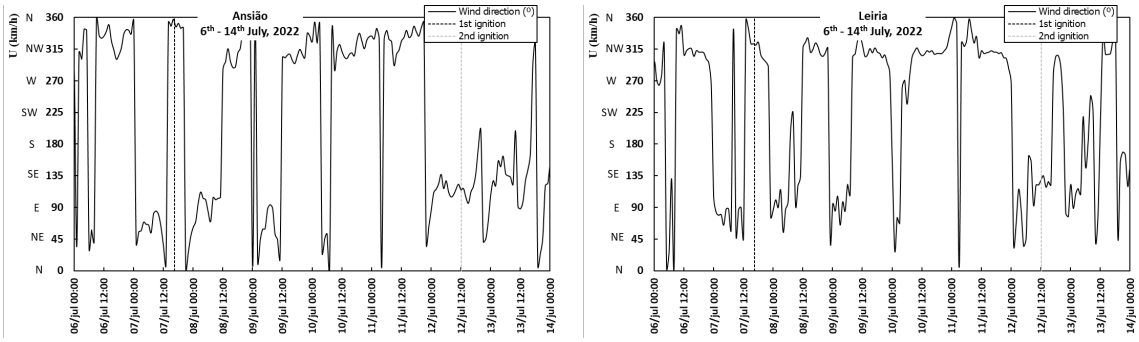
(a) *(b)*



Data source: IPMA

Figure 33. Hourly values of wind direction recorded at weather stations of the IPMA in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID:716). b) Leiria weather station (ID: 718).

(a) *(b)*



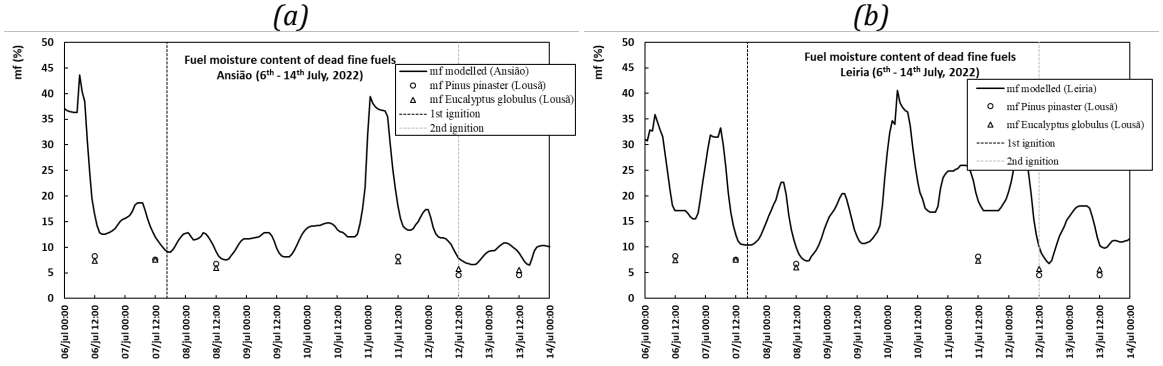
Data source: IPMA

6.3.2 Fuel moisture content of dead fine fuels

The dead fine fuels moisture content was modelled for the Ourém region using hourly meteorological data (air temperature and relative humidity) according to the methodology described in Lopes (2013). Figure 34 presents these results for the period from July 6th to July 14th. Additionally, in the same figure, the fuel moisture content variation for dead needles of *Pinus Pinaster* dead leaves of *Eucalyptus globulus* measured daily (12:00) in Lousã is presented.

Considering the meteorological data collected at the Ansião and Leiria stations, the estimated dead fine fuel moisture values ranged between 10 and 15%. These data were, on average, like those observed in Lousã (cf. Figure 34).

Figure 34. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from 6th July to 14th July. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718).



Data source: IPMA and ADAI/MCFIRE (PCIF/MPG/0108/2017).

6.3.3 Fire danger

As presented in the fire danger analysis of the previous Albergaria fire, in Portugal the RCM (Conjunctural and Meteorological Risk) is used to define the fire danger level of a region. The RCM results from the combination of two components: conjunctural and structural component and a meteorological component given by the Fire Weather Index (FWI) of the Canadian Fire Weather Index System.

The classification of the FWI value is made using a danger scale where the increase in FWI corresponds to an increase in fire danger. Table 8 presents the FWI level according with classification of IPMA, 2023b and Viegas et al. (2004) only for the district of Leiria, since the classification of Viegas et al. (2004) was made at a district level.

Table 8. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Leiria. FWI description according with IPMA (2023).

Level	Limit values of FWI	Description according to

	IPMA (2023) for Portugal (a)	Viegas et al. (2004) for Leiria (b)	IPMA (2023)
1	<8.2	<15	Surface fires.
2	17.2	25	
3	24.6	30	High fire intensity with crown fires
4	38.2	50	
5	50.1	>50	Exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control.
6	64.0	-	Exceptional fire intensity with extreme difficulty of control
7	>64.0	-	

In Table 9, we compare the level of fire danger given by the FWI and the RCM. This table presents the observed values for July 7th and for July 12th for Leiria and Ansião as well the predicted values at 24h, 48h, and 72h for these days.

Table 9. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for July 7th and July 12th. The colours indicate the fire danger level (cf. Table 8).

Day	Region	RCM observed and predicted				FWI observed and predicted			
		Obs.	Predicted			Obs.	Predicted		
			24h	48h	72h		24h	48h	72h
July 7th	Ansião	36.3	37.2	33.4	34.1	4	4	4	3
	Leiria	43.2	33.3	38.2	35.2	3	3	3	3
July 12th	Ansião	65.5	67.7	71.6	73.6	5	5	5	5
	Leiria	56.7	62.3	53.9	80.7	4	4	4	4

Data source. IPMA.

On July 7th, the predicted FWI value at 72h, 48h and 24h for Leiria and Ansião were classified as Very high danger (level 4) by IPMA definition (24.6<FWI≤38.2) and by Viegas et al. (2004) definition (30<FWI≤50). The RCM observed and predicted (48h and 24h) in Ansião was classified as level 4 (Very high), and it was classified as level 3 (Moderate) in Leiria. For both regions, the predicted FWI (almost higher than 38.2) were very close to change to the level 5 (Maximum) according with IPMA definition. In Leiria this Maximum level was observed since FWI was 43.2. The RCM has a daily changing component (weather/FWI) and an annually changing component (structural) and on July 7th, RCM seems to have underestimated the weather conditions predicted and observed by the FWI.

On July 12th the FWI values (observed and predicted) were extreme in both regions with values mostly higher than 64 which means that any eventual wildfire would be expected to have an exceptional intensity with extreme difficulty of control. In Ansião, this fire danger condition was accompanied by the RCM (observed and predicted) since RCM also classified the day with Maximum level. In Leiria the extreme weather conditions given by FWI was not verified in RCM that classified the day as level 4 on the fire danger scale.

6.3.4 Fire Behaviour

The main objective of this work was to analyse two fires that occurred on the July 7th in the locality of Cumeada / Freixianda, in the Municipality of Ourém and on the July 12th in the locality of Caranguejeira, in

the Municipality of Leiria, within the fire complex that occurred in this area. Although these fires do not show a very large burnt area, 2936 ha burned in Freixianda and 2787 ha in Caranguejeira, they were characterized by a rapid initial spread, and the occurrence of several spot fires, since the first stages of the fire. These spot fires made the first intervention very difficult and forced to redefine suppression strategies several times. On the other hand, these fires occurred in extensive WUI areas and for this reason, the main strategy was, very often, the defense of people and their property, to the detriment of firefighting.

Through the national platform of the Forest Fire Information Management System, the essential data were analysed for the Districts of Santarém and Leiria with the information on the rural fires that are ignited in each municipality of the respective District. Table 10 presented the data for the districts of Santarém and Leiria. The Municipality of Ourém in the district of Santarém is the municipality with the largest area burned, presenting a total of 87 occurrences, 11% more on average than in the period 2012-2021. Except for Sardoal, all other municipalities in the district of Santarém showed a reduction in the number of ignitions, compared to the average for the period 2012-2021.

Table 10. Information on rural fires to the municipality for the districts of Santarém and Leiria.

District	Municipality	Nº of Fires (2012-2021)	Nº of Fires (2022)	Inc. [%]	Burn area (2012-2021) [Ha]	Burn area (2022)
Santarém	Abrantes	71	47	-33	799	124
	Alcanena	33	16	-51	29	1
	Almeirim	31	18	-41	11	3
	Alpiarça	20	10	-50	5	0
	Benavente	53	32	-39	119	20
	Cartaxo	32	23	-28	16	15
	Chamusca	24	16	-33	17	6
	Constância	11	8	-27	24	22
	Coruche	47	32	-31	99	24
	Entroncamento	9	7	-22	2	1
	Ferreira do Zêzere	15	11	-26	35	1
	Golegã	5	2	-60	2	0
	Mação	16	11	-31	116	8
	Ourém	78	87	+11	857	7446
	Rio Maior	38	28	-26	44	96
	Salvaterra de Magos	40	26	-35	121	32
	Santarém	105	70	-33	113	16
	Sardoal	14	17	+21	33	60
	Tomar	91	49	-46	748	400
	Torres Novas	45	37	-17	18	5
	Vila Nova da Barquinha	11	2	-81	11	0
Leiria	Alcobaça	61	15	-75	2025	2
	Alvaiázere	21	6	-71	2372	0
	Ansião	21	7	-66	28	5136
	Batalha	12	10	-16	4	1

District	Municipality	Nº of Fires (2012-2021)	Nº of Fires (2022)	Inc. [%]	Burn area (2012-2021) [Ha]	Burn area (2022)
	Bombarral	23	6	-73	15	1
	Caldas da Rainha	61	21	-65	62	616
	Castanheira de Pêra	8	7	-12	59	3
	Figueiró dos Vinhos	16	6	-62	80	24
	Leiria	96	72	-25	63	2912
	Marinha Grande	24	26	+8	5	2
	Nazaré	12	0	-100	4	0
	Óbidos	55	6	-89	121	3
	Pedrógão Grande	21	3	-85	3100	0
	Peniche	36	1	-97	10	0
	Pombal	90	82	-8	379	331

Source SGIF

In the municipality of Ourém, 87 occurrences, according to the SGIF were recorded. The cause of each occurrence was registered. In 47 occurrences the cause was intentional, 15 occurrences where the cause was negligence, 15 occurrences where the cause was rekindling, and 10 occurrences where the type of cause is unknown.

In the municipality of Leiria 72 occurrences, according to the SGIF were recorded. From these in 33 occurrences the determination of the cause was intentional, 31 occurrences where the cause was negligent, five occurrences where the cause was rekindling, and three occurrences where the type of cause is unknown. The Municipality of Ansião in the district of Leiria is the municipality with the largest burned area in this district, presenting a total of 7 occurrences, 66% less than in the period 2012-2021 and the municipality of Leiria is the second with the largest burned area, registering a total of 72 occurrences, but 25% less than in the period 2012-2021. Except for Marinha Grande, all other municipalities in the district of Leiria showed a reduction in the number of ignitions, compared with the average of the period 2012-2021.

6.3.5 Freixianda Fire

In the Freixianda fire, the first response took place on the July 7th at 16:37, for the locality of Cumeada / Freixianda (Lat: 39.800093, Long: -8.49274). The synoptic situation at the time was under the influence of an anticyclone located northwest of the Iberian Peninsula which led to a thermal depression and low relative humidity in the afternoon with weak recovery at night. The predominant wind was from the North and Northwest quadrant with a speed of around 20 km/h and at altitude it was approximately 40 km/h from the same quadrant. As the hours advanced, the wind at altitude tended to shift to the east quadrant. Thus, there were meteorological conditions conducive to the spread of rural fires, with meteorological conditions of high temperatures and low relative humidity, poor night humidity recovery, and wind blowing with some intensity. In this way, the initial propagation speed of the fire was expected to be high, with very difficult extinguishing operations and difficulty in the mop up operations due to the dryness of the forest fuels.

According to ANEPC data, in the first response, 13 VCI's, 3 VTT's, and 2 initial air attacks (H24 and H32) were activated and one more fire truck (GCIF) was mobilized. The responders informed that at 16:50: "Active fire in shrub land and eucalyptus tree with some intensity, highest slope, the fire comes descending and we will protect the houses". After 6 minutes of arrival at the fire, the first commander reported: "Intensity increases, VFCI 02 from Ourém carrying out protection at the school and awaiting the arrival of more resources". The first commander requested heavy air resources at 16:58, justifying that the fire was

burning very intensely, and informed that there was a projection already with some intensity, requesting again the reinforcement of resources from another Brigade. After this information from the first commander, the national commander of the emergency and civil protection (CNEPC) activated the air resources under national command, two Canadair (Alfas A17, A18), and one Kamov (KILO2).

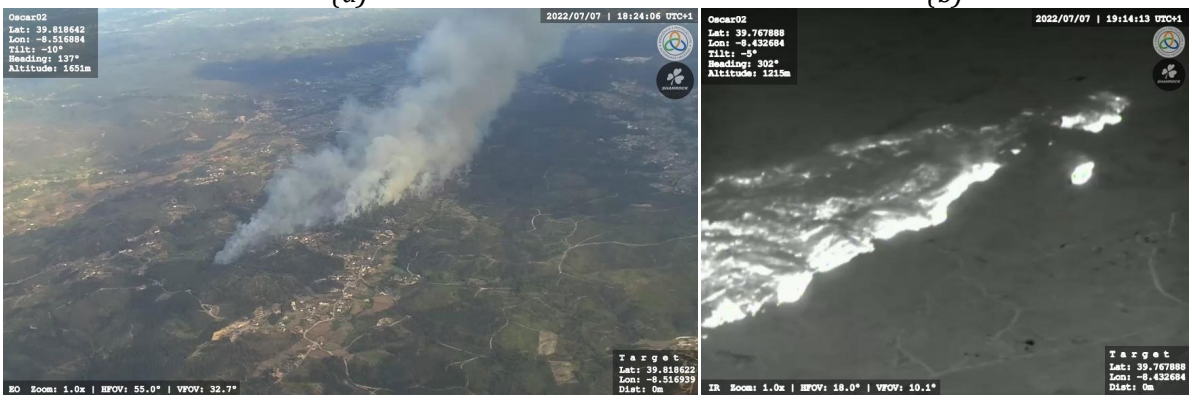
The first commander informed the district commander of ANEPC in Santarém that there was a shed burning next to the school, in the Cumeada / Freixianda, and that the fire appeared to be a crown fire, in shrubland and eucalyptus trees, with higher intensity towards the location of Abades. So, the local commander requested reinforcement with two more combat groups (GCIF).

Due to the influence of the wind on the behaviour and the consequent difficulty in fighting the head fire front, the commander requested several times more terrestrial and aerial teams to fight this fire. The fire progressed as crown fire in areas with eucalyptus and undergrowth undercover, and the existence of many spot fires at medium/long distances (500 and 600 m) made it difficult to define the strategy. Therefore, to combat and consolidate the flanks in areas with a high slope, the commander requests Bulldozers to support these tasks.

The air way to support the analysis of the fire (OSCAR02) was triggered for the fire and at 18:48 aerial images were uploaded in FEB system. Figure 35 shows two images with a visible camera (Figure 35 a) and an IR camera (Figure 35 b). In the image Figure 35 a), it was possible to see the difficulty of suppressing the fire due to the high rate of spread of the head fire, during the first hours. The wind was the main dominant factor and influenced the fire spread, as can be seen in the column of smoke and the elongated elliptical shape of the perimeter of the fire. On the other hand, in Figure 35 b), through the IR images, it was possible to observe the existence of spot fires on the left flank of the fire, already of some size.

Figure 35. The aerial images presented here were provided by ANEPC and taken on July 7th during the fire through air way to support the analysis of the fire OSCAR02. a) Image of fire by 18:24 where can be seen a fire with an elongated elliptical configuration, configuration typical of a wind driven fire. b) Image of the fire at 19:14 that can be seen a spot fire on the left flank of the fire.

(a) *(b)*



Data source: ANEPC.

Until sunset (~20:30) there was a constant reinforcement of aerial support that remained until the maximum time allowed, for example, the stay of the Alfas A17 and A18 of the Aircraft Base (CMA) of Ponte de Sor until 20:08 and A10 and A21 from CMA of Proença until 20:30 and H24 from CMA de Figueiró until 20:19.

Later, the command organization was changed according to what is defined by the Incident Command System (ICS). By 20:41 the fire was divided into three sectors (Alfa, Bravo and Charlie), with an active fire and multiple spot fires making combat operations and strategies difficult to define. In the Bravo sector, which corresponded to the head fire, there were several houses at risk and some sheds ended up being hit by the flames.

The Bulldozer became a solution to consolidate the perimeter of the fire, mainly on the right flank. Thus, at this time the communication of the commander to ANEPC was: "The fire is ongoing and divided into 3 sectors. The firefighters working and moving to spot fires in all sectors. The helicopter continued to work; however, all remaining aerial support was removed from the forest fire. Bravo sector with a threat to housing and some small houses was affected. One bulldozer working and awaiting the arrival of other three

bulldozers". In the period between 20:30 and 21:00, there were several spot fires, initially near a plastics company, in Freixianda and then another, which was communicated by 112, in Casal da Sobreira. At 22:00 a National Guard informs that there is a house on fire in Ramalheira. At 22:03 in the Abades, a cylinder of gas bursts in a house, but no one was injured.

On the July 8th at 02:00 the work was supported by one bulldozer and the various sectors began remaining in resolution except for the Delta sector. At this time this sector was already created, which remained with active fronts and many spot fires. At 09:57 the fire remained on course but was beginning to show signs of yielding to combat operations in the several sectors. However, at 10:58, in the Bravo sector, there are records of a reactivation that quickly gained some intensity in Abades.

In the period between 13:31 and 17:43, the various sectors showed several reactivations with intensity, which again made it difficult to fight the fire. During this period there are at least 7 people injured, 5 operational and 2 civilians, several houses were threatened by the flames and two houses were burnt. It was also recorded, on several occasions, that the fire came close to the Gas Stations becoming a threat to people and their goods, but above all to the operatives involved in the combat. There was also the need to carry out the evacuation of some civilians during this period, e.g., in Charneca, Casal do Rei, Abades, and Lumiar. By 15:45 there is information that the fire passes to the Leiria District, entering the municipality of Alvaiázere through the Alfa sector. At this stage, there are many spot fires in this sector and the fire had 4 active fire fronts, see Figure 36.

Figure 36. The aerial images presented here were provided by ANEPC and obtained on July 8th during the fire through OSCAR02 at a) 15:41 and b) 15:50. The figures show the beginning of the various reactivations during the period described above.

(a) *(b)*



Data source: ANEPC.

After the various reactivations recorded and the suppression difficulties in the various sectors, at 17:43 the fire has 5 active fire fronts without control and two houses started burning. At this time, the evacuation of the Lumiares is registered and it is verified that the teams were insufficient.

The part of the fire that corresponded to the Alfa sector had entered the Leiria district through the municipality of Alvaiázere. The ICS attributed the ECHO sector to this part of the fire. During the first hours, the commander of this sector felt some difficulty in carrying out firefighting, due to the great intensity of the fire, the various spot fires, and the lack of operations in this sector. Later, at 19:48 there are records of two houses that burned and resulted in one person being dislodged, and two agricultural sheds destroyed. At 18:10 there was a record of the need to carry out an assessment of the Integrated System for Portugal's Security and Emergency Networks (SIRESP) communications network and to have an aerial vehicle for prevention.

On July 9th at 07:45 new information to the ANEPC was made that demonstrated the success of the works of suppression overnight as, despite the fire still raging, most of the sectors were in conclusion.

Despite the weather conditions and the difficulty of carrying out the aftermath in areas of difficult accesses, in the period from July 09th to 10th the fire tends to decrease in intensity facilitating the combat in the reactivations that were taking place. The great difficulties still consisted, on the one hand, in the occurrence of reactivations in the various sectors of the fire, but also in the occurrence of spot fires during reactivations. By 08:00 on the July 11th, the fire is under control throughout its perimeter. However, on the July 12th at 11:55 it went to the Active state due to three intense reactivations in the Municipality of Alvaiázere and a

reactivation in Quebrada de Baixo, Municipality of Ferreira do Zêzere. At 03:03 on the July 13th, the fire returned to the state of "Resolution" and the state of "Surveillance" at 10:00 on the July 17th.

6.3.6 Caranguejeira Fire

In the Caranguejeira fire, the dispatch of the first responders was on the July 12th at 12:06, Caranguejeira (Lat: 39.773105, Long: -8.714255). The synoptic situation was under the influence of an anticyclonic region with a nucleus located over the British Isles and another nucleus to the west of the Azores archipelago, which led to a weak nocturnal recovery from the July 10th to 11th. The wind speed was around 30 km/h with the possibility of gusts greater than 40 km/h and the main direction remained west/northwest, with a tendency to rotate towards east/northeast. There was a tendency for the wind gust increases to speeds up to 60 km/h. In turn, the atmosphere showed some instability and there was a probability of occurrence of dry thunderstorms in the interior North and Centre. Thus, it was predicted that the fires would be dominated by the wind during the morning, becoming topographic in the afternoon on the July 12th. On the other hand, the Strategic Operational Analysis of NAD-AIR predicted that the intensity of the fire would be very high at maximum for the district of Leiria and in the north and west zone of the Mondego River, and extreme in the rest of the Central Regional. Thus, meteorological conditions were conducive to the spread of rural fires, with high temperatures and low relative humidity, poor nocturnal recovery, and wind blowing with some intensity. Thus, the initial speed of propagation was expected to be fast (>300 m/h and <600 m/h) to very fast (over 600 m/h), evolving seriously from West to East, reinforcing that the mop-up should be carried out to the mineral soil around the perimeter of the fires. Due to the dryness of forest fuels, extinguishing and mop up would be arduous.

According to ANEPC data, in the first responders, 6 VCI's, 2 VTT's, 1 VTGC and 2 helicopters of air initial attack (H53 and H55) were activated, and one more combat group was requested. The first information occurred at 12:23 and informing that: "Fire in Eucalyptus, with medium intensity, several spot fires, requests combat group and air force reinforcement, informs transit point in Caranguejeira next to Santa". On the way to the T.O. at 12:25, the H55 reported that it could see a column of intense smoke with a dark colour and requested more combat teams. As the initial attack progressed, at 12:28, the first commander reported that the fire was aligned with the wind towards the Palmeiria with houses in main direction of the head fire and then at 12:36, it reported that there were several spot fires in front of the head fire. By 12:36, the fire was active with 13 vehicles and 54 operational and more air attack units were activated. The commander reported at 12:56 that: "Fire with part of the head burning freely and only aircraft combat the head and the suppression teams are still insufficient".

During that time and due to the special influence that the wind had on the fire behaviour, considering the various spot fires at medium / long distances (500 and 600 m), which made it difficult to define the strategy, the commander requested several times the need more teams for fighting the fire due to the difficulty in fighting the main head fire. The fire was progressing with great intensity in areas with eucalyptus with shrubs under cover.

The Leiria Commander of the ANEPC, at 13:24, requested the conditioning of circulation on the roads IC2 and A1 due to the occurrence of several spot fires and the proximity of the fire to these roads. The IC2 was banned from circulation in both directions, at the Barracão and Boa Vista, and at 13:24, Brisa reported that the A1 was cut off in both directions. These routes, A1 and IC2, would be open again in both directions only on the July 13th, at 01:26 and 08:06 respectively.

The commander at 13:45 makes a new information through the ANEPC: "Commander informed that requests 5 more combat groups, to make perimeter defence to the houses, head fire passed A1 Road and with several spot fires towards the location of Machados". Thus, the strategy to be adopted was the protection of housing and industries, as the fire was taking place in an area where the WUI was extensive. The fire continued to progress with great intensity and the resources were still insufficient. At 15:25, the Commander makes a new information: "Fire burning with great intensity, insufficient resources on site to protect housing and industrial facilities, requests the dispatch of four combat groups and reinforcement of heavy air assets".

In the period from 14:30 to 20:10, the teams in the terrain were still insufficient in view of the prevailing fire behaviour and there were, on several occasions, houses in danger. The population complicated the definition of strategy because for a long period it was either surrounded or with its assets in danger. Thus, at 20:10, the commander reported a new information indicating that part of the fire was burning freely without fighting and the wind shift towards Portela da Memória.

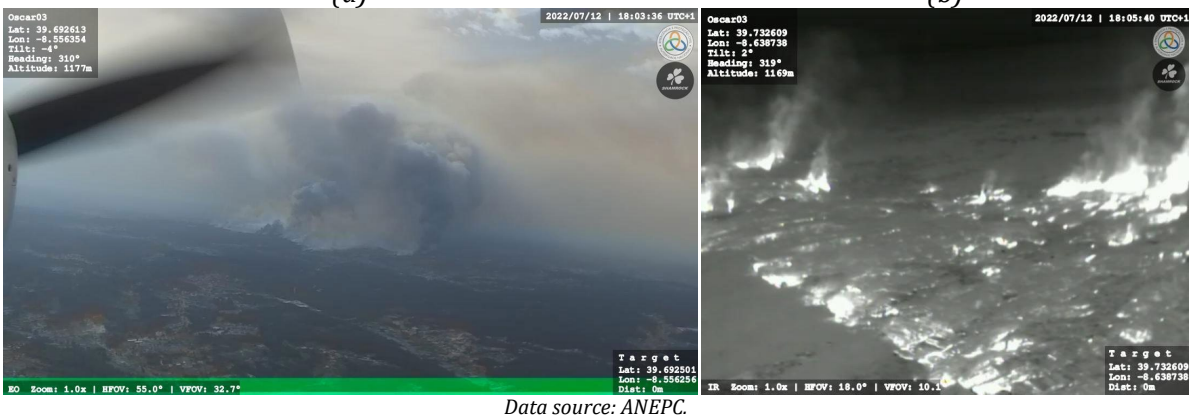
The aircraft OSCAR03 was dispatched for this fire and at 13:43 aerial images were uploaded. Figure 37 shows two images with a visible camera (Figure 37 a)) and an IR camera (Figure 37 b)). In the image Figure 37 a), it was possible to perceive the difficulty of suppressing the fire due to the rapid spread of the main head fire and, in parallel, the verticality of the columns due to the convective power of the fire. Wind was the main dominant factor influencing the spread of fire. On the other hand, in Figure 37 b), through the IR images, it was possible to perceive the existence of flames with a great depth, thus making combat operations difficult.

During the period from 20:10 on the July 12th until 01:30 on the July 13th, the suppression operations, mainly in the Alpha and Bravo Sectors, began to take effect and the fire began to give way to the teams in the terrain and entering the mop up and surveillance phases. The Charlie Sector presented a small active front that the teams worked on, and the Delta Sector was the Sector with the most difficulties in combat.

However, the combat became more effective, and Delta Sector began to enter the mop up phase at 02:36. At 03:54, the commander reported that the fire was almost completely under control. At dawn, new reactivations began to appear in several Sectors, but by 07:32 the results became more favourable with the mop up work and the action of the bulldozer. Until 14:06 there were several rekindles that were quickly fought by the operators on the ground and by air resources. Delta Sector was still concerned about the high number of reactivations. However, with the work carried out in the different Sectors by the operators, air resources and with the support of the bulldozers, at 19:56 the fire was under surveillance throughout the perimeter, even though the reactivations persisted. At 00:12 on the July 14th, the fire changed its status to "In resolution".

Figure 37. The aerial images presented here were provided by ANEPC and taken on the July 12th during the fire by OSCAR03. a) Image of the fire at 18:03 where one can see a fire with an elongated elliptical configuration, typical configuration of fire dominated by the wind and, in parallel, the columns also with a connecting power. b) IR image of the fire at 18:05 where the great depth of flames can be seen, making suppression operations difficult.

(a) *(b)*



Data source: ANEPC.

On the July 14th between 00:30 and 10:00 the fire remained in resolution with small reactivations that were quickly fought. However, at 10:08 there was a reactivation with great intensity in Crasto and this caused a new change in the status of the fire to "In Progress". This state remained in progress until 17:43, after which it changed to "In Resolution" and on the July 16th to "Conclusion".

From the start of the fire until the July 14th, there were several constraints and failures with the SIRESP communications. After the on-site assessment, the responsible elements concluded that it was not a failure of the system, as it was the fibre cable that burned by the fire.

6.4 Fire management at the WUI

Despite the large area burnt and the sporadic spread of the fire with high velocity and intensity, the damage to infrastructure was relatively minor. However, several houses were burnt down, and various other pieces of equipment were destroyed.

The worst effects of a forest fire usually involve the loss of human or animal lives or buildings. Fortunately, there were no human deaths or serious injuries directly related to the fire, and losses of livestock and buildings were relatively low in spite of the large area burned in Ourém complex fires and the conditions under which the fire spread. This was largely due to the firefighting strategy that prioritised the protection of homes and communities, especially during the day when winds were stronger, and the suppression fire was more difficult. On the other hand, compared to previous years, people were confined to villages rather than subject to a mass evacuation.

The Freixianda fire affected 10 parishes belonging to the municipalities of Alvaiázere (Almoster, Pelmá and Pussos São Pedro), Ansião (Ansião, Pousaflores and Santiago da Guarda), Ferreira do Zêzere (Chãos, União das parishes of Areias and Pias), Ourém (União das parishes of Freixianda, Ribeira do Fárrio and Formigais) and Pombal (Abiul).

The parishes most affected by the fire are Almoster (69.7% of the parish area burned), Pelmá (44.7%), Santiago da Guarda (27.9%), Pousaflores (26.2%) and União das Freguesias de Freixianda, Ribeira do Fárrio and Formigais (25.5%) (Table 11).

Table 11. The burnt areas of the Freixianda / Cumeada Fire by Municipality.

Municipality	Parishes	Burnt area	
		ha	%
Alvaiázere	Almoster	1800.5	69.7
	Pelmá	1349.5	44.7
	Pussos São Pedro	1.4	0.03
	Total burned area in the municipality	3151.4	19.6
Ansião	Ansião	165.9	4.3
	Pousaflores	662.0	26.2
	Santiago da Guarda	1148.5	27.9
	Total burned area in the municipality	1976.4	11.2
Ferreira do Zêzere	Chãos	222.3	9.5
	União Freguesia de Areias e Pias	184.4	4.0
	Total burned area in the municipality	406.7	2.1
Ourém	União de Freguesia de Freixianda, Ribeira do Fárrio e Formigais	1634.8	25.5
	Total burned area in the municipality	1634.8	3.9
Pombal	Abiul	1127.1	17.6
	Total burned area in the municipality	1127.1	1.8

Source: SGIG.

The Caranguejeira fire affected six parishes belonging to the municipalities of Leiria (Caranguejeira, Milagres, União de Freguesias de Colmeias e Memória and União de Freguesias de Santa Eufémia e Boa Vista) and Ourém (Espite and União de Freguesias de Matas e Cercal).

The União de Freguesias de Colmeias e Memória was the most affected as around 55.2% of its surface was covered by fire. In each of the remaining parishes, fire affected less than 11% of the area (Table 12).

Table 12: The burnt areas of the Caranguejeira Fire by Municipality.

Municipality	Parishes	Área Ardida	
		ha	%
Leiria	Caranguejeira	311.4	10.0
	Milagres	102.8	6.0
	União das Freguesias de Colmeias e Memória	2570.9	55.2
	União de Freguesias de Santa Eufémia e Boa Vista	197.6	10.1
	Total burned area in the municipality	3182.6	5.6
Ourém	Espite	187.2	9.5
	União das Freguesias de Matas e Cercal	129.7	6.3
	Total burned area in the municipality	316.8	0.7

Source: SGIF.

In the Freixianda fire there were several spot fires, initially near the plastics company and then another, which was communicated by the EU emergency telephone number (112), in Casal da Sobreira. At 22:00 of the first day of the fire a National Guard informed that there was a house on fire in Ramalheira. At 22:03 in Abades, a cylinder of gas bursts in a house, but no one was injured. Later, at 19:48 there are records of two houses that burned and resulted in one person being dislodged, and two agricultural sheds destroyed.

6.5 Conclusions and Lessons learned

6.5.1 Freixianda Fire

This fire showed characteristics typical of a wind-driven fire with several episodes of spot fires and with difficulty in suppression operations during the active phase. It presented itself with several predominant winds from the North / Northwest quadrant, but most of the time, the fire was outside the suppression capacity. Although the suppression teams mobilized were many, due to the difficulty of suppression over time, they remained insufficient for so many occurrences influenced by the spot fires. On the other hand, most reactivations took place in areas with very difficult access and areas where the mop up was non-existent or was very insufficient due to the dryness of the fuels in the soil.

It should be noted that the fire occurred in an area with a large WUI and in populated areas with a high predominance of Eucalyptus, with under cover shrubs. On the other hand, areas that were formerly agricultural crops are now abandoned and shrubs are the dominant fuel cover. Even with this extensive WUI area, there was a low number of houses consumed by the flames. This fact is also due to the implemented strategy that involved the defence of people and their goods, most of the time.

About injuries, a total of approximately 50 incidents were recorded, which included operational and civilians, but the vast majority were slightly injured. It should be noted that during the most active phases of the fire, mainly in the first days, the number of victims that involved operatives increased rapidly, that is, from the July 7th to the 9th, 31 occurrences had already been registered, of which 17 were firefighters and three were of National Guard.

About communications, there are records of difficulties in communications using the SIRESP network. The antenna vehicle was activated to fill this need and ended up being used. It was concluded that this difficulty of communications was supposed to exist in the T.O. shadow areas of the SIRESP network, but also due to poor use of radio equipment by the teams.

There was difficulty in articulating means when the fire entered the district of Leiria. There are records that resources were needed in the ECHO sector, belonging to the area of Leiria in Alvaiázere, but they were not allocated, as described in the records of ANEPC.

6.5.2 Caranguejeira Fire

The Caranguejeira fire also showed characteristics of a fire dominated by the wind, with several fires, which united into one. The speed of propagation of the fire was very fast (above 600 m/h), with a very high to extreme intensity. Thus, the fire suppression operations were very difficult. Atmospheric instability existed for a long period, indicating the possibility of generating a pyro cumulus, followed by a strong thermal inversion. Thus, there was a need to assess all the convective dynamics of the fire so that combat operations could be carried out safely. Although the teams mobilized in this fire were in a large number, due to the difficulty of suppression, they remained insufficient for so many occurrences. On the other hand, most reactivations took place in areas where the mop up was non-existent or very insufficient due to the dryness of the fuel in the soil and near the access roads. Thus, the main strategies adopted consisted of protecting population and industrial zones, prioritizing the right flank with the use of bulldozers and, whenever possible, consolidating the entire perimeter using bulldozers and placing land resources close to hot spots that could reactivate over time.

It should be noted that the fire occurred in a region with a large WUI and in populated areas with a predominance of Eucalyptus, and undercover shrubland. On the other hand, the approach to two main roads with a large flow of traffic, A1 and IC2, meant that there was a constraint on the flow of traffic and that, during the initial phase, the interdiction of these roads had to be considered so that there was no damage for its users.

During the fire, there was a need to evacuate several locations due to the proximity of the fire and the housing areas being surrounded. Thus, there was a need to withdraw 104 evacuees to the Concentration Zone to Population Support (ZCAP) Leiria/Pousos and 15 evacuees to the ZCAP Leiria/Souto da Carpalhosa. According to information from the INEM, a total of approximately nine people were assisted, including operational and civilians, but the majority were slightly injured. Thus, of these nine assisted, of which six were transported to the hospital unit, five citizens and one fire agent.

Regarding communications, there are records of difficulties in using the SIRESP network in the fire scene for which the antenna vehicle was activated. It was concluded that this communication difficulty was verified because there were a high number of talk groups on the SIRESP network, but also due to poor use of radio equipment. There was an antenna that was left with a burned fibre cable that also caused some difficulties in communications.

References

Diretiva Operacional Nacional n.o 2-DECIR. (n.d.). Retrieved August 1, 2023, from www.prociv.pt

Instituto Português do Mar e da Atmosfera. (2020). Nota Metodológica - Cálculo do Índice de Risco de Incêndio Rural (RCM). 1–8.

ICNF. (2022). 8.o Relatório provisório de incêndios rurais - 2022. 8.o RPIR/D, 14. https://www.icnf.pt/api/file/doc/4e8a66514175d0f7

Instituto Português do Mar e da Atmosfera. (2020). Nota Metodológica - Cálculo do Índice de Risco de Incêndio Rural (RCM). 1–8.

IPMA. (2023). mf2 - Perigosidade Meteorológica de Fogos Rurais. http://mf2.ipma.pt/about

Lopes, S. (2013). Modelos de previsão do teor de humidade de combustíveis florestais. University of Coimbra.

Mendonça, J. M., Máguas, C., Pereira, J. M. C., Fernandes, P., Xavier Viegas, D., Tedim, F., Keizer, J., Silva, J. S., & Al., E. (2023). Relatório Final do Grupo de Peritos dos Incêndios Rurais.

Van Wagner, C. E. (1987). Development and structure of the Canadian forest fire weather index system. In Forestry.

Viegas, D. X., Reis, R. M., Cruz, M. G., & Viegas, M. T. (2004). Calibração do Sistema Canadiano de Perigo de Incêndio para Aplicação em Portugal. Silva Lusitana, 12(1), 77–93. http://www.scielo.oces.mctes.pt/pdf/slu/v12n1/12n1a07.pdf

7 Fire of Garrocho / Serra da Estrela (Portugal)

Authors

Miguel Almeida	ADAI
Daniela Alves	ADAI
Catarina Matos	ADAI
Luís Mário Ribeiro	ADAI
Domingos Viegas	ADAI



7.1 General Description

The Garrocho Fire Event, also known as the "Serra da Estrela Fire," was the largest wildfire in Portugal in the year 2022, with a total burned area of 24,333 ha (ICNF, 2022). It ranks as the sixth largest fire event ever recorded in Portugal. The cause of this fire is not publicly known, and the alert was given at 3:18 on August 6th, to near a river beach in Vila do Carvalho, in the municipality of Covilhã, in the central inland region of Portugal.

The fire primarily spread within the Natura Network Serra da Estrela Natural Park, affecting parts of the UNESCO World Geopark – Estrela Geopark - which holds a special place in the hearts of all Portuguese people. This fire also threatened and affected the area of the Zêzere Glacier Valley which, with its 13 kms of extension, is one of the largest in Europe. The national shock caused by the extensive burning in an ecologically and sentimentally valuable area was significant. Furthermore, it took a considerable amount of time, until the 13th day (August 18th), to dominate the fire, which caused great distress among citizens. The fire was officially declared extinguished on September 3rd.

Several favourable conditions contributed to the rapid and intense fire spread. The mountainous terrain with its typical irregular topography, characterized by steep slopes and canyons, created challenges that were increased by poor accesses in certain areas. Additionally, the period of drought and heatwave (July 29th – August 14th) at the time resulted in extremely low fuel moisture content. Moreover, strong winds, particularly between 09:30 and 21:00, further complicated firefighting operations.

The fire event had two main phases in its progression. In the first phase, it spread predominantly in NNE direction until it was declared dominated on August 15th, after burning approximately 15,000 ha. On the same day, there was a strong rekindling that progressed towards the SEE, reaching a final perimeter of approximately 150 km.

The damages at the wildland-urban interface were not extensive considering the vast burned area and the scattered buildings across the territory. However, being one of the Portuguese regions with the highest activity in the primary sector, the social impacts were significant. The economic losses extended beyond agricultural and forestry activities, affecting various sectors. The tourism industry suffered significant impacts since Serra da Estrela, renowned for its natural beauty, attracts many tourists throughout the year. The effects on the tourism sector persisted beyond the duration of the fire due to cascading impacts, which will be described further ahead.

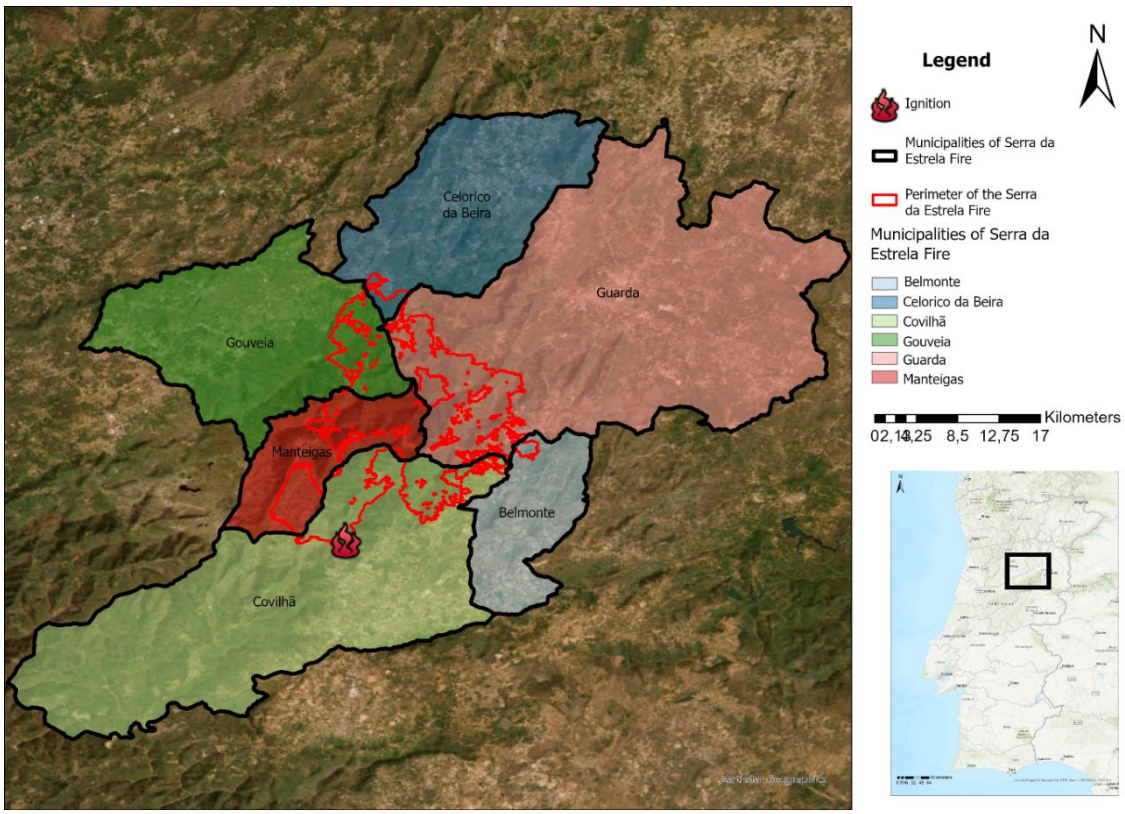
7.2 Characterization of the affected area

The Serra da Estrela Mountain includes the Serra da Estrela Natural Park (SENP), which covers a mountainous area located in the central-eastern part of Portugal, spread over the municipalities of Celorico da Beira, Covilhã, Gouveia, Guarda, Manteigas, and Belmonte, and is the most extensive Portuguese

protected natural area. The SENP comprises a succession of plateaus stretching from Guarda in the northeast to the Serra do Açor's foothills in the southwest. It occupies an area of medium and high mountains, which includes the highest point of continental territory, at 1993 m of altitude. The uniqueness of the highest parts of the mountain and its geographical situation determines a reproductive isolation of populations of fauna and flora that leads to the differentiation into exclusive species, subspecies and varieties (CISE, 2023).

Starting in the Municipality of Covilhã, the Garrocho Fire spread to 22 parishes of the municipalities of Covilhã, Guarda, Manteigas, Gouveia, Celorico da Beira, and Belmonte (Mendonça et al., 2023), covering an extensive area of the protected landscape (Figure 38).

Figure 38. General view of the fire perimeter of the Garrocho wildfire (in black) and the representation of the six municipalities of Serra da Estrela affected by the fire (Celorico da Beira, Covilhã, Gouveia, Guarda, Manteigas, and Belmonte).



Data Source: (EPIC WebGIS Portugal)

The socio-economic markers of the affected municipalities indicate a decrease in the resident population in the 2011 to 2021 period (Table 13). Additionally, a large fraction of the population is more than 65 years old, and the rate of young people (less than 15 years old) is low. A comparative analysis of these data with the average statistics for Portugal shows that this is a region has demographic difficulties, which has an impact on fire management.

Table 13. Some socio-economic indicators of the most affected municipalities of the Garrocho Fire.

Municipality	Residents (Var. 2011-2021)	Residents/km2*	Age > 65yrs	University education
Covilhã	46 521 (-10,3%)	83,8	29,8%	16,9%
Guarda	40 173 (-5,7%)	56,5	25,2%	7,5%
Manteigas	2 909 (-15,2%)	24,3	37,4%	--
Gouveia	12 222 (-13,0%)	40,8	38,2%	--

Celorico da Beira	6 583 (-14,4%)	26,7	34,9%	--
Belmonte	6 205 (-9,5%)	52,1	31,8%	--
Portugal	10 343 066 (-2,1%)	112,2	23,4%	19,8%

Source: (Pordata, 2023).

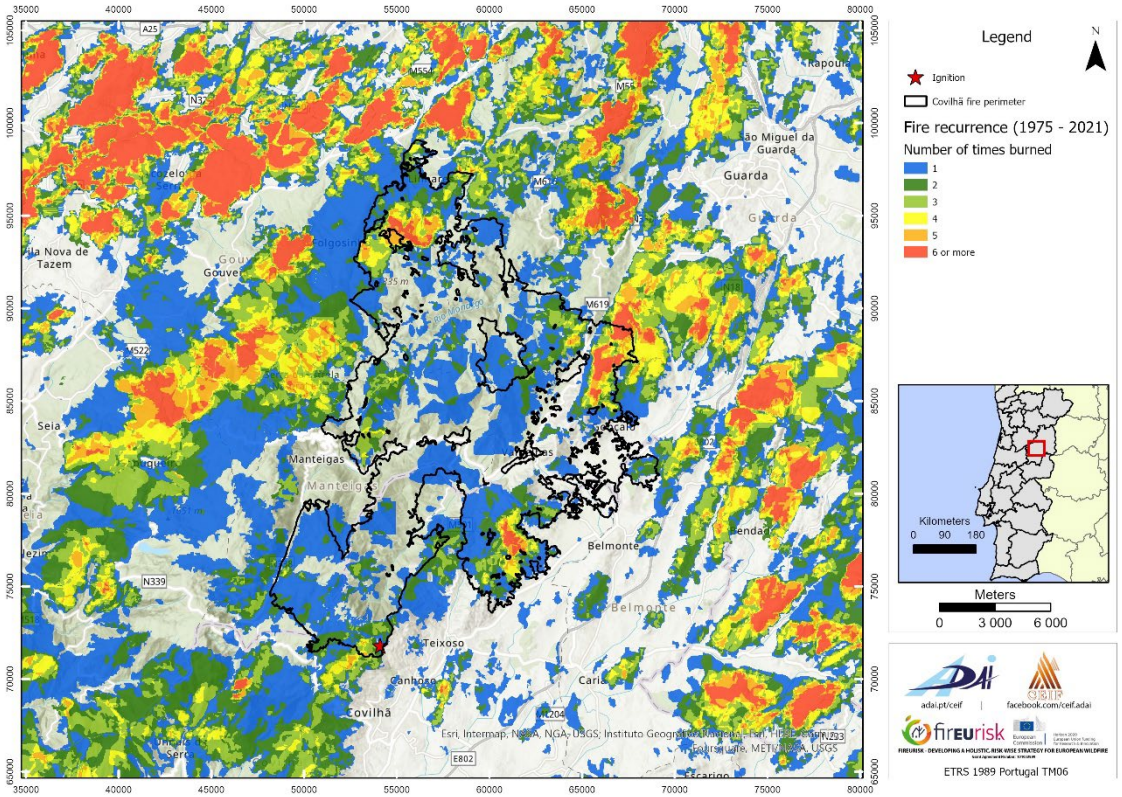
The Garrocho Fire was influenced by the three main factors of the fire triangle: a) fuels, b) weather/wind, and c) topography. Due to drought period and heatwave in Portugal, the vegetation was under water stress, and the natural fuel moisture content was very low.

The vegetation affected was composed predominantly of maritime pine forest (*Pinus pinaster*, 8,021 ha burned), shrub formations (7,158 ha burned), other coniferous (939 ha burned), such as *Pinus nigra*, *Pinus sylvestris*, *Pseudotsuga menziezii*, and broadleaves (2,322 ha burned), as black oak, holm oak, chestnut, beech, birch (Mendonça et al., 2023). The primary fuel management network had a good implementation rate, and the area previously subjected to prescribed burning (679 ha) was reasonable. This figure also shows that in certain parts of the burnt area accesses were scarce. As it will be seen, this aspect greatly complicated the initial firefighting operations when the fire still had a small area.

The history of Portugal's burned areas in the last twenty-two years shows a predominancy of burned areas and fires in the central region of the country, where despite having fewer ignitions in number, has a bigger extension of burned areas.

Serra da Estrela region has been cyclically affected by large forest fires as shown in Figure 39, which represents the number of times burned since 1975.

Figure 39. Fire recurrence of the region between 1975 and 2022.



The topography of Serra da Estrela Figure 40 and Figure 41) was influenced by the geomorphology of granitic mountains and the erosion caused by watercourses and shaped by glacier valleys, and this was also an influencing factor for the fire behaviour. The landscape is dominated by extensive plateaus bordered by steep slopes, where the watercourses are installed, especially at the northern end of the mountain and surrounding areas. In the mountain's southern and southwestern sectors, the landscape is characterized by a succession of individualized undulating forms and a dense and very sinuous drainage network (CISE,

2023). This mountainous topography, characterized by steep slopes, canyons, and ravines, increased the number of hot spots in a fire area that reached an outer perimeter of approximately 150 km in length. The Serra da Estrela fire affected altitudes between 444 m and 1686 m, but 63.6% of the burned area was between 731 m and 1275 m (Figure 40). The main affected basins were the Mondego River and the Zêzere River.

About 54% of the burned area has slopes between 11° and 25°. Slopes greater than 25° occupy 12.3%, which clearly hindered the direct firefighting (Figure 41). The slopes affected by the fire present a great diversity of exposure, but 43.3% are oriented to the east quadrant.

Figure 40. Orography map of Garrocho / Serra da Estrela.

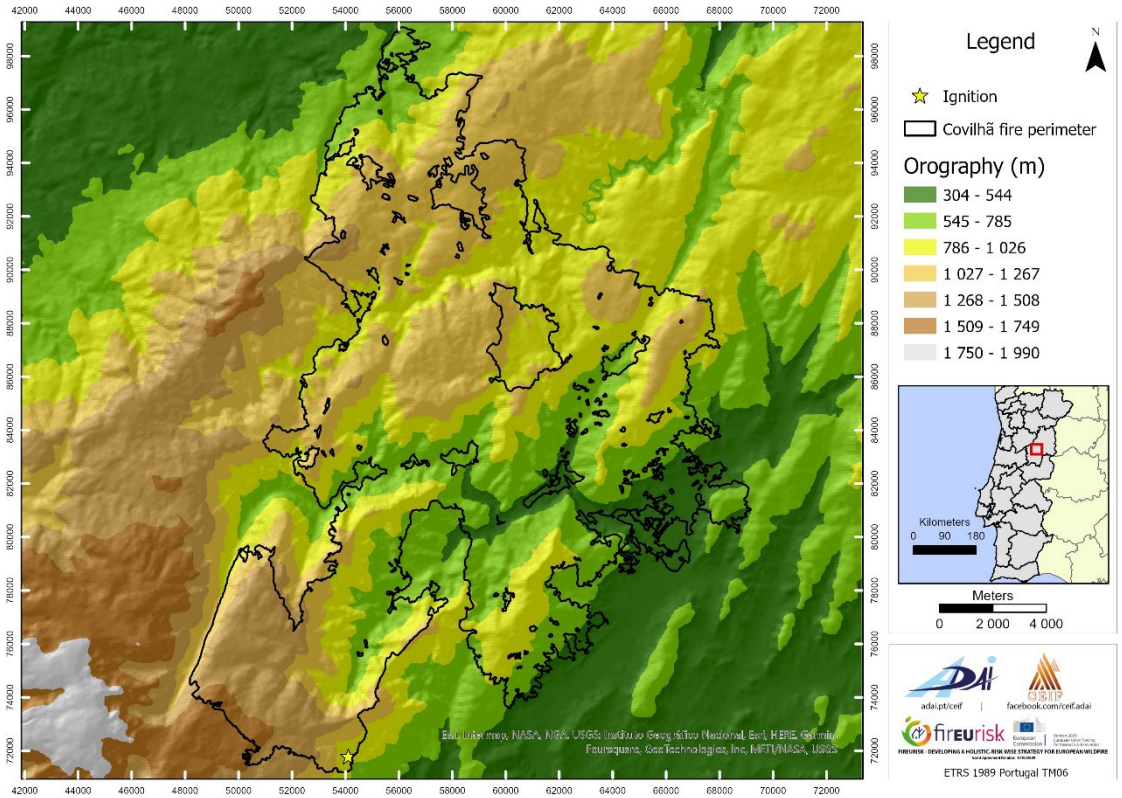
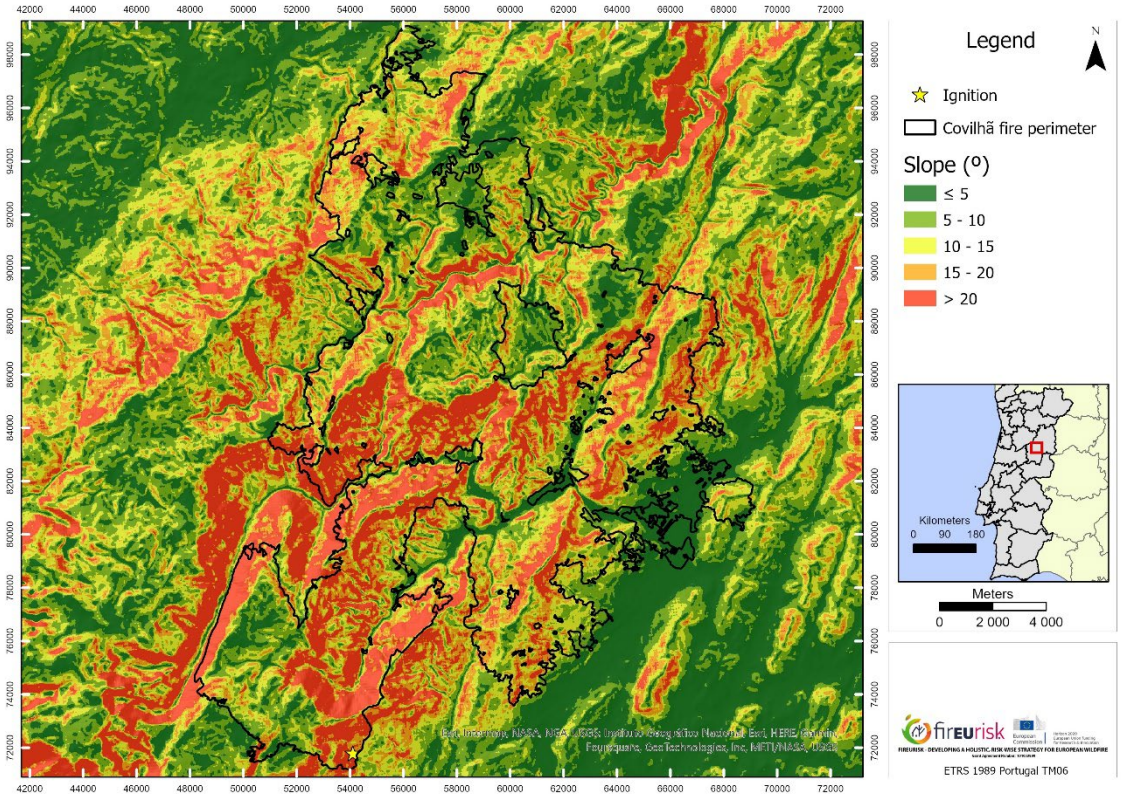


Figure 41. Slope map of Garrocho / Serra da Estrela



Data Source: (EPIC WebGIS Portugal)

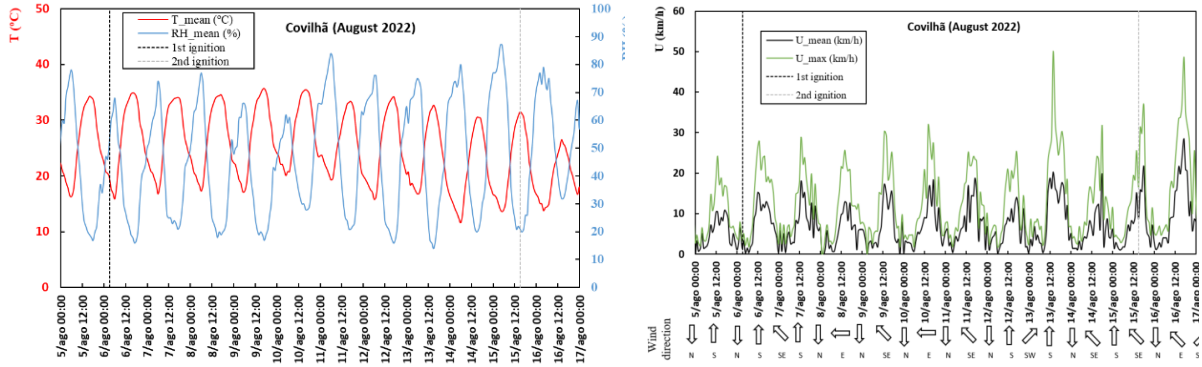
The territory affected by the fire has a low demographic density. The wildland-urban interface boundary is scattered through the Serra da Estrela landscape in small, dispersed villages and farms. The dispersion of buildings can difficult fire management operations due to the insufficient firefighting resources to respond to all the isolated and dispersed requests for help. Due the higher vulnerability and low capacity of self-defence, the average elderly population scattered through the territory also increases the need of assistance so complicating the fire management operations.

7.3 Fire conditions

7.3.1 Meteorological data

The weather station of the of the Portuguese Institute of Sea and Atmosphere (IPMA) located in Covilhã (ID: 687), approximately 5 km from the ignition point, was used to analyse the conditions during the wildfire period (Figure 42).

Figure 42. Meteorological parameters registered by the meteorological station of Covilhã (ID:687) during between August 5th and 17th: a) temperature (T) and relative humidity (RH) variation; b) windspeed (U) and wind direction.



Data source: IPMA.

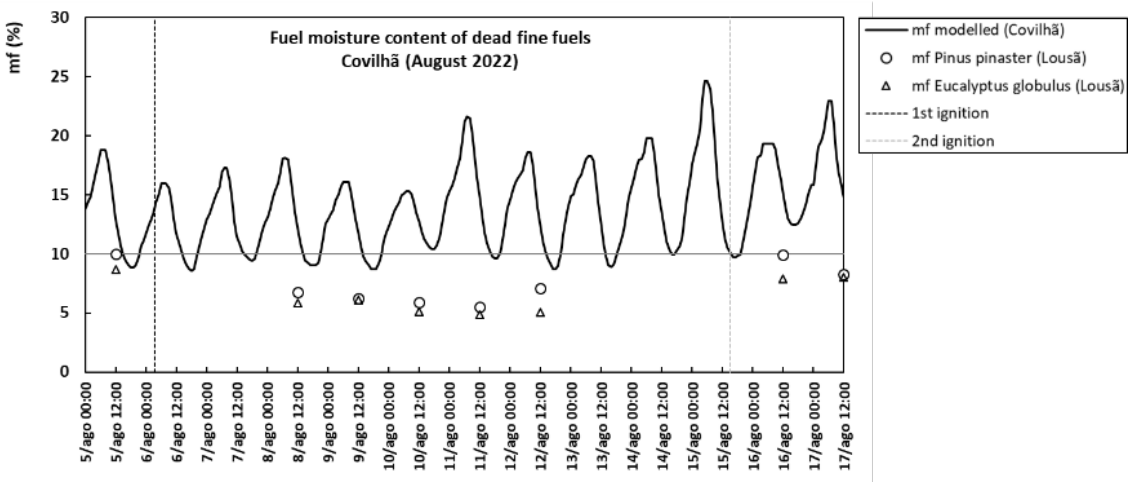
The most critical wildfire period from August 5th to August 17th was marked by the persistence of high temperature (Figure 42a) driven by the heatwave that the country was facing and low relative humidity. However, on August 12th there was in general a slight decrease in temperature (T) and an increase in relative humidity (RH).

Windspeed in the wildfire period had a similar pattern, it increased in the early hours of the morning achieving their maximum at around 12:00 and 14:00 (Figure 42b). On 12th, 14th, 15th August their maximum values were observed latter around 17:00 and 18:00. The predominant wind in the early hours of the day was from N.

7.3.2 Fuel moisture content of dead fine fuels

Dead fine fuels moisture content were modelled for the Covilhã region using hourly meteorological data (air temperature and relative humidity) according to the methodology described in Lopes (2013). Figure 43 presents these results for the period from August 5th to August 17th. Additionally, in the same figure, the fuel moisture content variation for dead needles of *Pinus Pinaster* and dead leaves of *Eucalyptus globulus* measured daily (12:00) in Lousã, about 60 km SW from Serra da Estrela, is presented.

Figure 43. Fine dead fuel moisture (mf): modelled variation using the meteorological data from the weather station of Covilhã according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã.



Data source: IPMA and ADAI/MCFIRE (PCIF/MPG/0108/2017)

From August 5th to August 17th, the *mf* modelled presents a well-defined daily cycle with lower values from 7:00 until 19:00), although with reduced ranges (8% and 20%). In this period, the *mf* modelled was lower

than 10% between 12:00 and 19:00 for nine days, including the August 15th when an outstanding rekindling dramatically complicated the control of the fire. The *mf values* observed for Lousã are very low with an extreme day of 5.5% for *Pinus pinaster* and 4.8% for *Eucalyptus globulus on August 11th*. This was one of the lowest values ever seen in the monitoring that is carried out in Lousã since 1986.

7.3.3 Fire danger

As presented in the fire danger analysis of the previous fires, in Portugal the RCM (Conjunctural and Meteorological Risk) is used to define the fire danger level of a region. The RCM results from the combination of two components: conjunctural and structural component and a meteorological component given by the Fire Weather Index (FWI) of the Canadian Fire Weather Index System.

Table 14 presents the FWI level according with classification of IPMA, 2023b and *Viegas et al. (2004)*. The classification of *Viegas et al. (2004)* was made at a district level, since the closest district to the ignition point is Guarda this analysis is presented for Guarda.

Table 14. Classes of the Fire Weather Index (FWI) values according with: a) IPMA for the Portuguese territory and, b) Viegas et al. (2004) for the district of Guarda, and FWI description according with (IPMA, 2023b).

Level	Limit values of FWI		Description according to IPMA (2023)
	IPMA (2023) for Portugal (a)	Viegas et al. (2004) for Guarda (b)	
1	<8.2	<8	Surface fires.
2	17.2	15	
3	24.6	25	High fire intensity with crown fires
4	38.2	50	
5	50.1	>50	Exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control.
6	64.0	-	Exceptional fire intensity with extreme difficulty of control
7	>64.0	-	

In Table 15 we compare the level of fire danger given by the FWI values and the RCM. This table presents the observed values for August 6th and the predicted values at 24h, 48h, and 72h in Guarda weather station (ID: 683).

Table 15. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for August 6th in Guarda weather station (ID: 683). The yellow colour in RCM indicates the Moderate (level 2) danger classification.

Day	FWI observed and predicted				RCM observed and predicted			
	Obs.	Predicted			Obs.	Predicted		
		24h	48h	72h		24h	48h	72h
Aug 6th	57.7	60.9	68.3	64.7	2	-	2	2

Data source. IPMA.

The predicted FWI at 72h and 48h of August 6th in Guarda had indicated an outstanding fire dangerous condition since FWI was high than 64 which means that any eventual wildfire would be expected to have an exceptional intensity with extreme difficulty of control (IPMA, 2023b). On the August 6th in Guarda, the observed danger slightly decreased but still representing a *Maximum* fire danger (level 5) for both classifications. This danger level is characterized by "Exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control" (IPMA, 2023b). This danger condition was not accompanied by the RCM that predicted a *Moderate* condition (level 2). Also, the observed RCM was classified with *Moderate* level underestimating the real fire danger conditions of the day. The RCM has a daily changing component (weather/FWI) and an annually changing component (structural), on August 6th RCM seems to have underestimated the extreme weather predicted and observed by the FWI.

The wildfire danger conditions for the period August 5th to 7th was analysed using the fire behaviour indices of the Canadian Fire Weather Index System (ISI – Initial Spread Index, Buildup Index – BUI, FWI) as presented in Table 16a for the weather station of Guarda. These indices are interpreted on a danger scale based on IPMA classification (IPMA, 2023a) and they are presented in Table 16b where an increase in the index corresponds to an increase in fire danger.

Table 16. a) Fire behaviour indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) in Guarda weather station (ID: 683) between August 5th and 7th; b) Danger scale for ISI, BUI and FWI.

(a) Indices values

Day	Aug. 5th	Aug. 6th	Aug. 7th
ISI	16.2	18.2	13.8
BUI	240.2	243.9	247.7
FWI	53.7	57.7	48.7

(b) Fire danger scale of the indices (IPMA, 2023a)

Level	1	2	3	4	5	6	7
ISI	2.0	6.0	12.0	17.0	23.0	30.0	>30
BUI	50.0	100.0	150.0	200.0	250.0	325.0	>325
FWI	8.5	17.2	24.6	38.3	50.1	64.0	>64

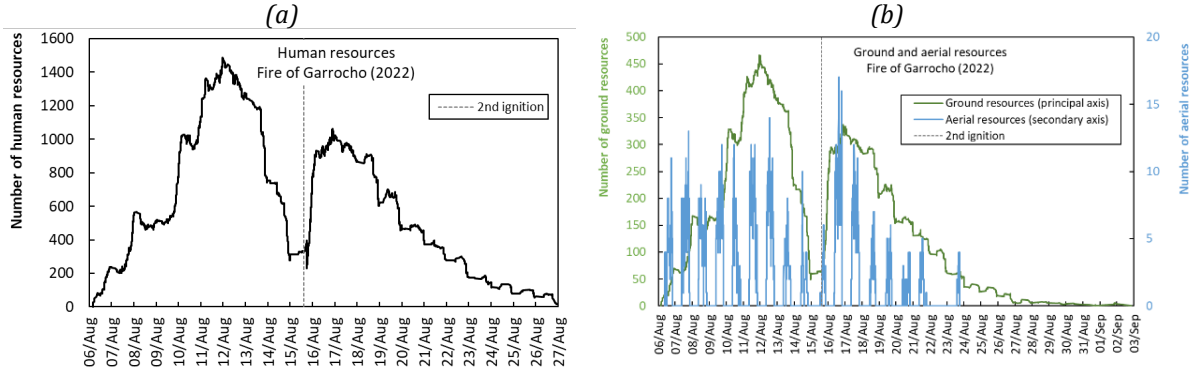
Data source: IPMA

On those days, the fire behaviour indices assumed extremely high values, especially the FWI on August 6th as presented before.

7.3.4 Resources allocation

Based on data provided by the Portuguese Civil Protection Authority (ANEPC) the Figure 44 presents the variation of the firefighting resources allocated to the fireground: a) human resources (firefighters and other civil protection agents), and b) ground and aerial resources. The allocation in the fireground started on August 6th at the time of the first ignition until the closure of the occurrence report (September 3rd), the vertical line presents the time of the rekindling. Resources with incomplete information in the report were excluded (e.g., resources without date and hours of TO departure).

Figure 44. Evolution of the resources in the fireground of Garrocho: a) human resources, b) ground and aerial resources.



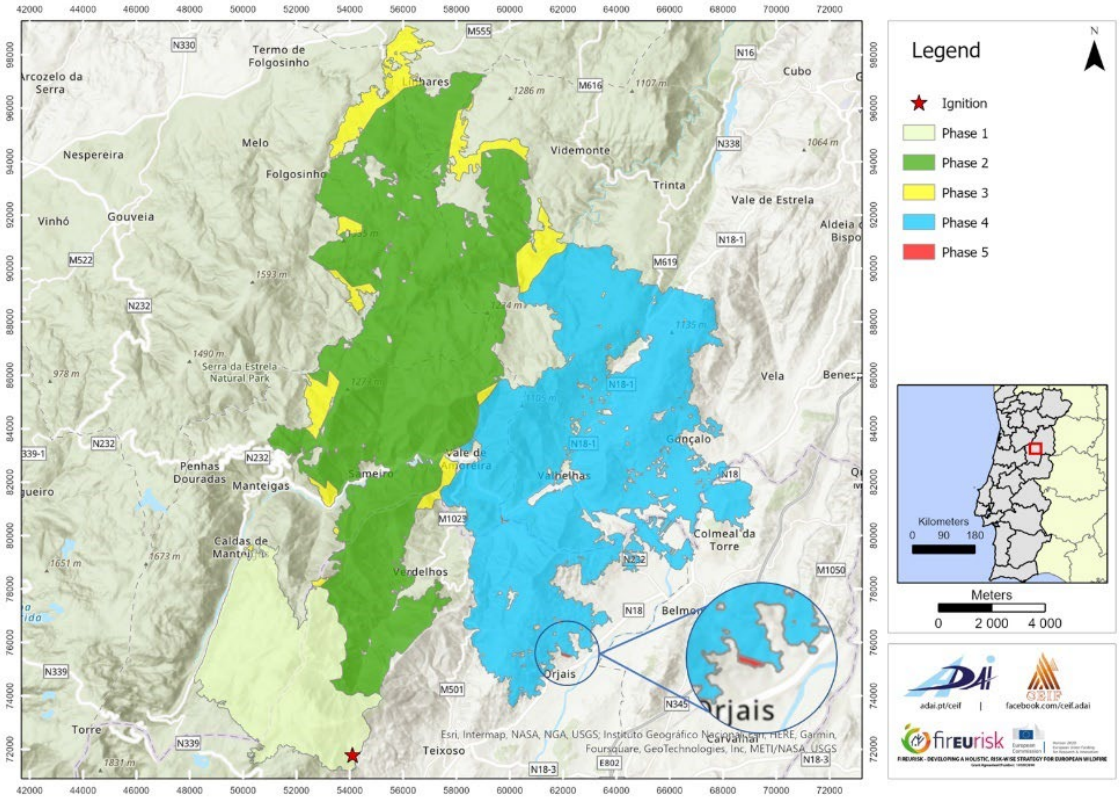
Data source: ANEPC

In total, this wildfire had allocated 2,272 human resources complemented by 1,733 ground vehicles and 539 aircrafts. In the initial phase of the fire, the arrival of ground and air resources to the fire event was high with their maximum occurring on August 12th with 1,470 human resources, 466 vehicles and 14 aircrafts (13:17). On August 15th, when the fire was close to be dominated, the number of resources also decreased. However, the rekindling observed in the afternoon of this day triggered a new large operational mobilization.

7.3.5 Fire behaviour

As expected, due to the rugged terrain, strong winds, and low fuel moisture content, the Serra da Estrela Fire was rich in episodes of extreme fire behaviour and relevant circumstances that can provide valuable lessons. To facilitate the presentation of the fire behaviour, the fire event was divided into five main phases of fire development (Figure 45), which will be detailed below.

Figure 45. Evolution of the Serra da Estrela fire divided in five phases.

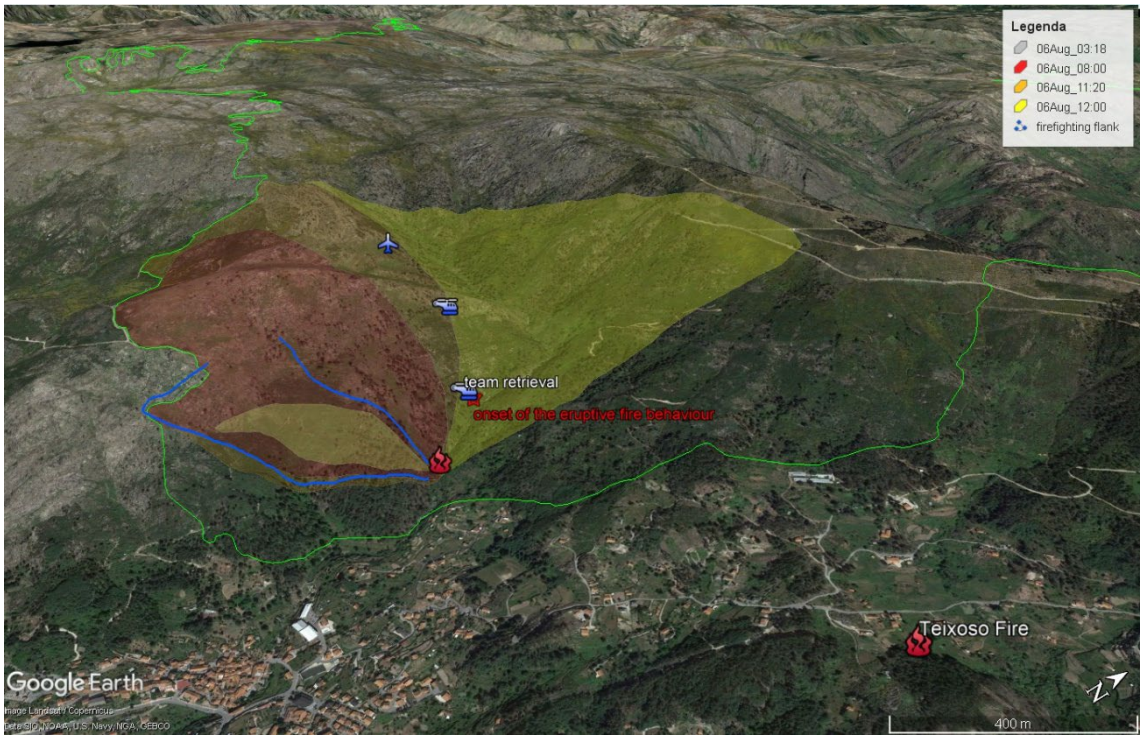


7.3.6 Phase 1: Initial fire spread [06Aug; 03:18 – 08Aug; 18:15]

As previously mentioned, the initial alert for this fire was given at 03:18, near the river beach in Vila Carvalho. The first means arrived on the scene about 30 minutes after the alert, finding a burning area of about 6 ha (Figure 46), so they immediately called for reinforcements.

The wind was not intense, but the fire was spreading in an area with a steep slope and difficult access, especially on the right flank where even sapper combat, particularly at night, was almost impossible. Consequently, the left flank firefighting was being well succeeded, but the right flank was progressing almost unhindered during the night. In the morning of August 6th, the aerial firefighting resources heliborne teams arrived allowing firefighting in the most difficult access areas such as the former left flank, which, with the increasing intensity and rotation of the wind's, became the head of the fire.

Figure 46. Evolution of the Serra da Estrela Fire until 12:00 of August 6th.



The fire crossed the water line and assumed the eruptive behaviour typical of a gorge.

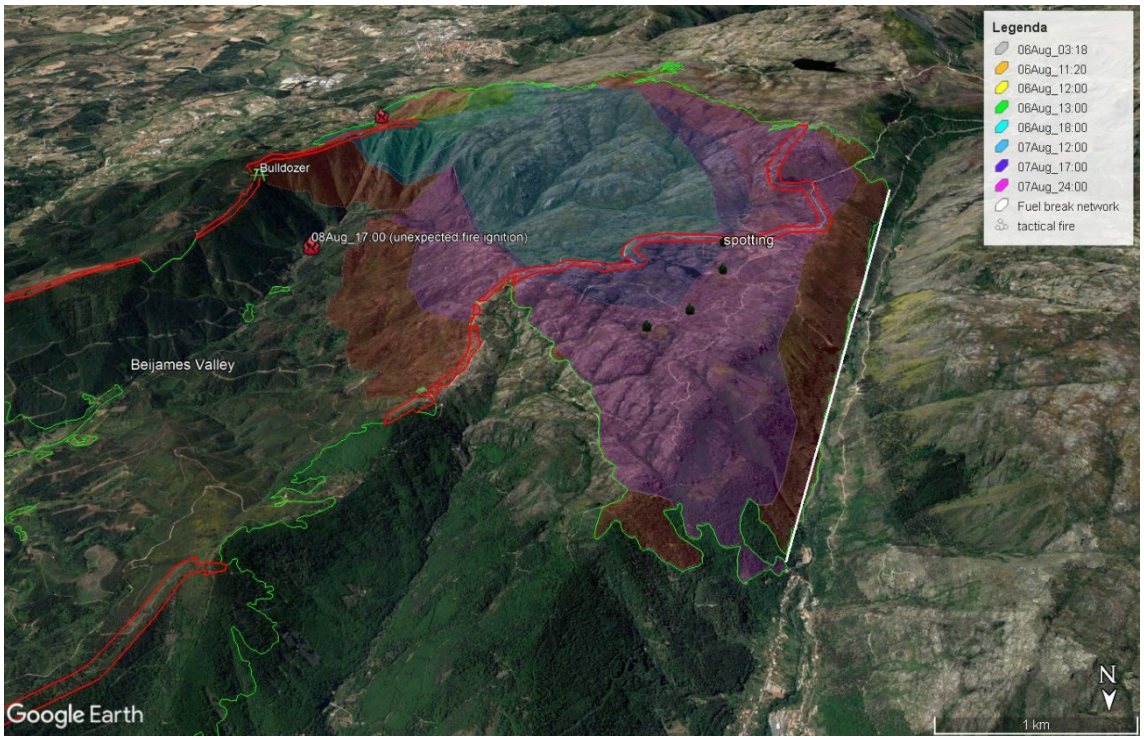
By 11:20, the fire was practically contained, and expectations for a quick resolution were high. The area that required more attention was the right flank, parallel to the water line, which was being extinguished by a heliborne team using sapper equipment, supported by helicopter water drops (Figure 46). Although a longer operation was anticipated for this aerial resource, given the elevation difference and associated fuel consumption, by 11:30, this helicopter, along with its heliborne team, had to leave the fire scene to refuel. During the team's retrieval at the point indicated in Figure 46, turbulence was created, causing the fire to surpass the water line. It was not possible to determine whether the fire crossed the water line through spotting or direct heat transfer, but once it reached the opposite slope, the fire spread eruptively without any possibilities of control. Additionally, at around 11:40, about 1.3 km away, a new fire event emerged (Teixoso Fire), diverting firefighting resources. This new occurrence was promptly extinguished, but the Serra da Estrela Fire was out of control.

The fire spreads down the slope into the Glacier Valley and a tactical fire operation is carried out.

After spreading throughout the canyon in an eruptive behaviour, the fire moved towards NE, driven by the strong winds that decreased in intensity during the night. In this period, it crossed a 130 m wide fuel break, mainly through spotting. By the end of August 7th, the fire was slowly and with low intensity descending the slope of the Glacial Valley.

The fire history in this region indicates that when the fire crosses the Glacial Valley, it drives to a large and difficult-to-control fire. Since the wind was calm and expected to increase in intensity the following morning, a tactical fire operation was decided upon, across approximately 5 km parallel to the valley (Figure 47). The interaction between the low-intensity flames of the fire event and the flames caused by the tactical fire manoeuvre resulted in a high-intensity burn along the entire versant. This manoeuvre was successful in stopping the fire's spread in that area; however, the severe effects of the intense burn damaged the soil structure, making it susceptible to rockslides onto the road. Because of it, this road remained closed for several months with huge impacts on tourism. This is one of the cascade effects that will be addressed in Subchapter 3.6.

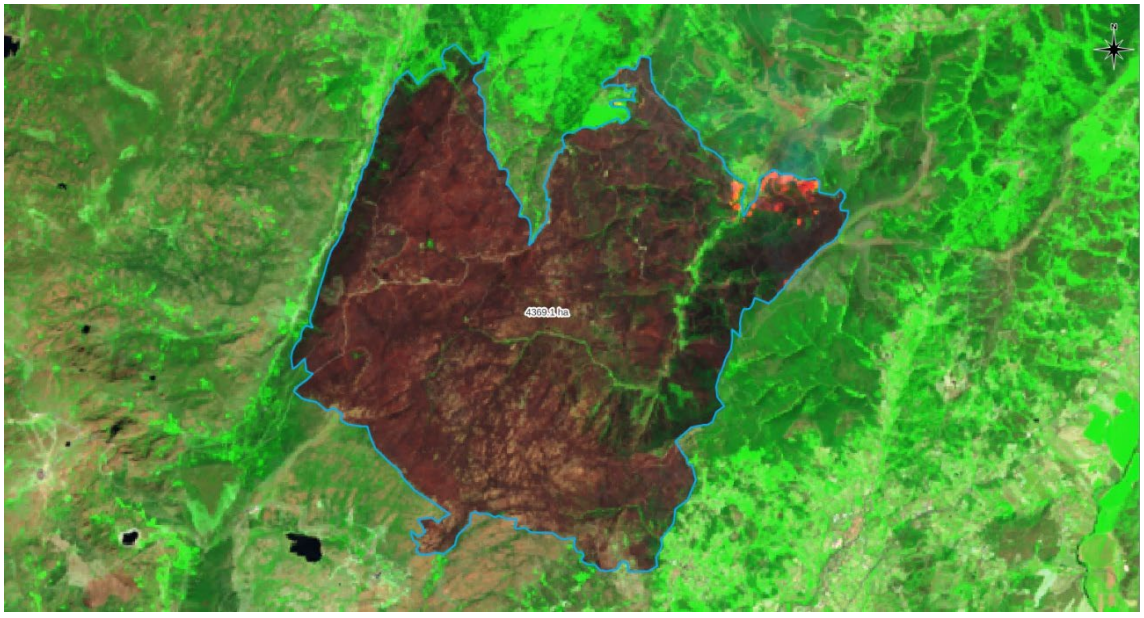
Figure 47. Evolution of the Serra da Estrela Fire until 17:00 of August 8th.



Interaction of the fire front with an unexpected fire hotspot, resulting in a new loss of fire control.

On the afternoon of August 8th, the fire spread was once again favourable. Using bulldozers, hoses, tactical fire techniques, and sapper equipment, at this time, the most active part of the fire was limited to two fronts at NE in the entrance of the Beijames River Valley (Figure 47 and Figure 48).

Figure 48. MODIS satellite image of the fire situation at 11:08 of August 8th. It is possible to see the most active fire perimeter at the entrance of the Beijames Valley, NE of the burnt area.



Unexpectedly, around 17:00, a new fire ignition occurred (Figure 47), allegedly caused by citizens seeking to protect a structure they believed was threatened by the fire. This ignition started to interact with the two fire fronts, leading to the loss of control over the situation and putting the safety of people at risk.

The effect that this new fire ignition may have had on the loss of fire control can be questioned, as the interaction of the two approaching fire fronts could have resulted in a similar episode. To clarify this doubt, two laboratory-scale tests were conducted. The scenario of the first test (Figure 49– top row) included only the two fire fronts that progressed nearly in parallel with late merging and interaction. In the second test (Figure 49 – bottom row), it is possible to observe the evident effect of the added ignition triggering a much more rapid and intense fire development. Thus, the unexpected new fire ignition had a decisive role in the abrupt fire intensification that was observed. In the field, once again, the fire event control was lost again.

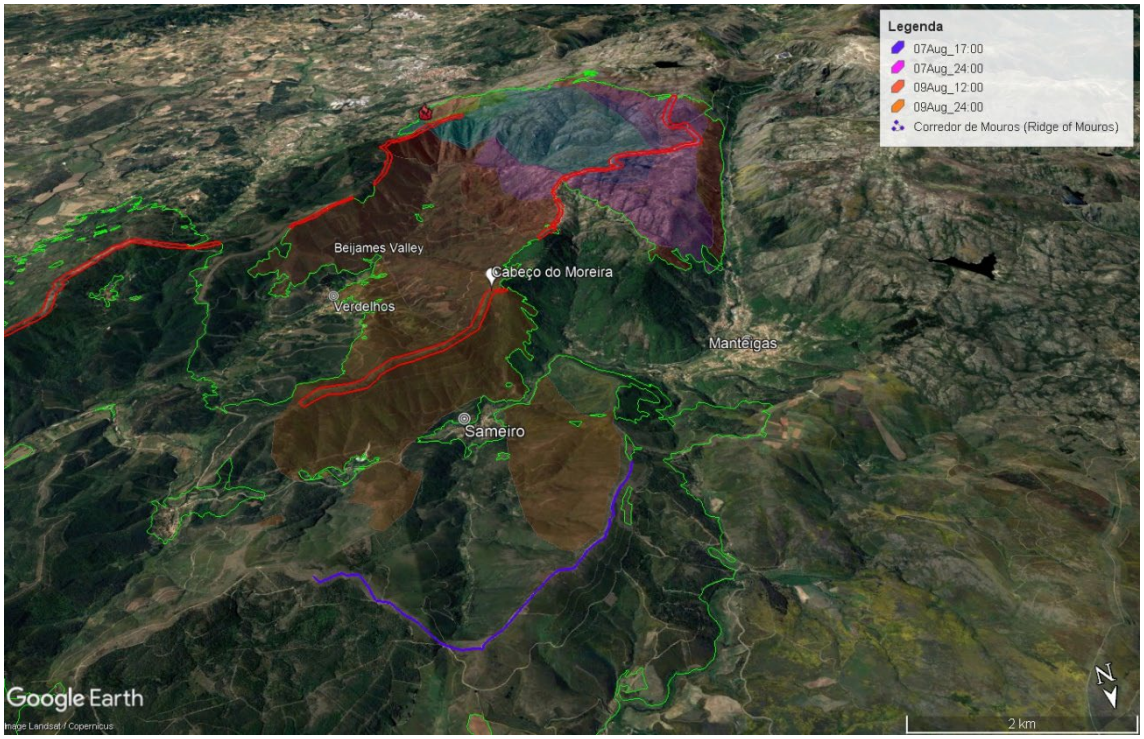
Figure 49. Sequence of frames from two laboratory tests in a canyon (water line slope: 15º; versant slopes: 30º) with the same fuel conditions: top row - two fire fronts; bottom row – two fire fronts and a fire ignition.



7.3.7 Phase 2: Fire spreads to NNE [08Aug – 12Aug]

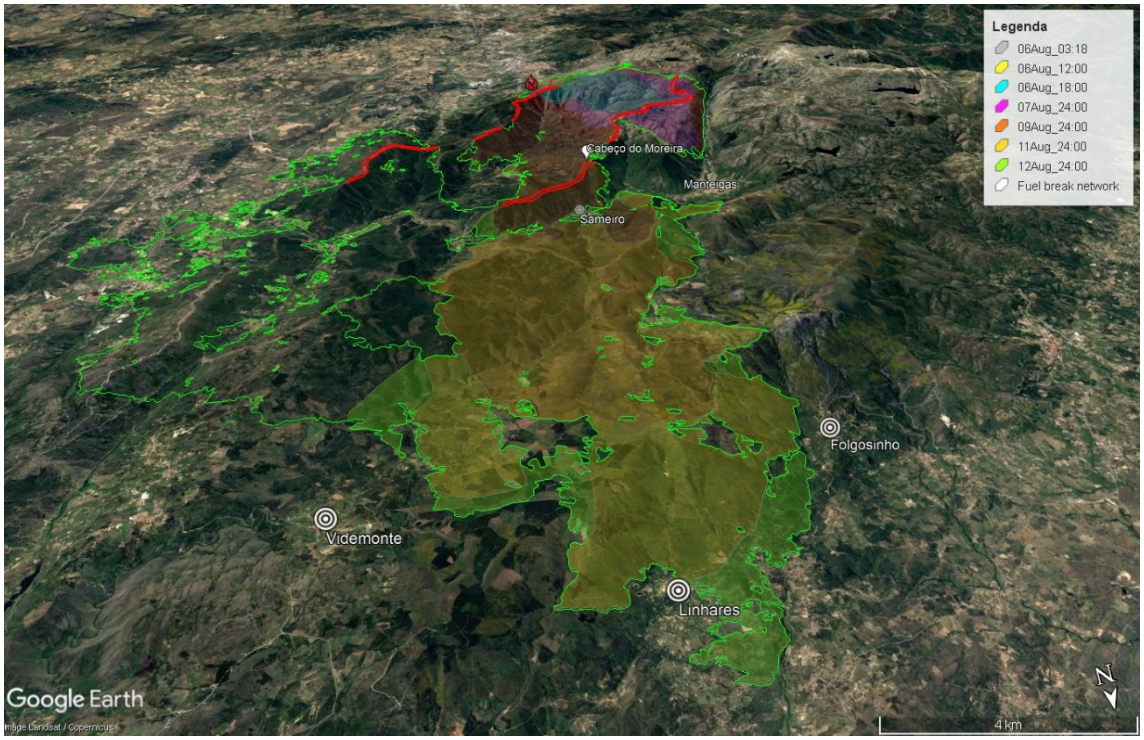
The fire spreading throughout the Beijames Valley, opened up on the two versants due to the firefighting efforts to protect the village of Verdelhos, which was located in the centre of the valley (Figure 50). By the 24:00 on August 8th, due to the terrain configuration and the prevailing southwest wind, the fire reached the ridgeline in "Cabeço do Moreira" with great intensity. Then, by the mid-day of August 9th, a short distance group of spot fires appear in descending slope after the ridgeline, and a long-distance group of spot fires started near the village of Sameiro at about 2.5 km. These more distant spot fires moved to NNE, driven by the wind. The short distance spot fires spread parallel to the ridgeline, possibly influenced by the flow induced by a horizontal vorticity resulting from the wind parallel to the ridgeline (Sharples & Hilton, 2020). Afterwards, when this fire front lost the vorticity influence, it started spreading to NNE driven by the wind, parallel to the fire front established by the spot fires that initiated near Sameiro. These two fire fronts merged after the canyon that culminates in Corredor de Mouros.

Figure 50. Evolution of the Serra da Estrela Fire until 24:00 of August 9th.



Although the two fire fronts merged, the fire continued spreading towards NNE with two main fire heads in direction to Videmonte and Linhares da Beira (Figure 51). Due primarily to the terrain configuration, a new fire front was also formed, heading towards Folgosinho.

Figure 51. Evolution of the Serra da Estrela Fire until 24:00 of August 12th.



7.3.8 Phase 3: Intermediate resolution [13Aug – 15Aug]

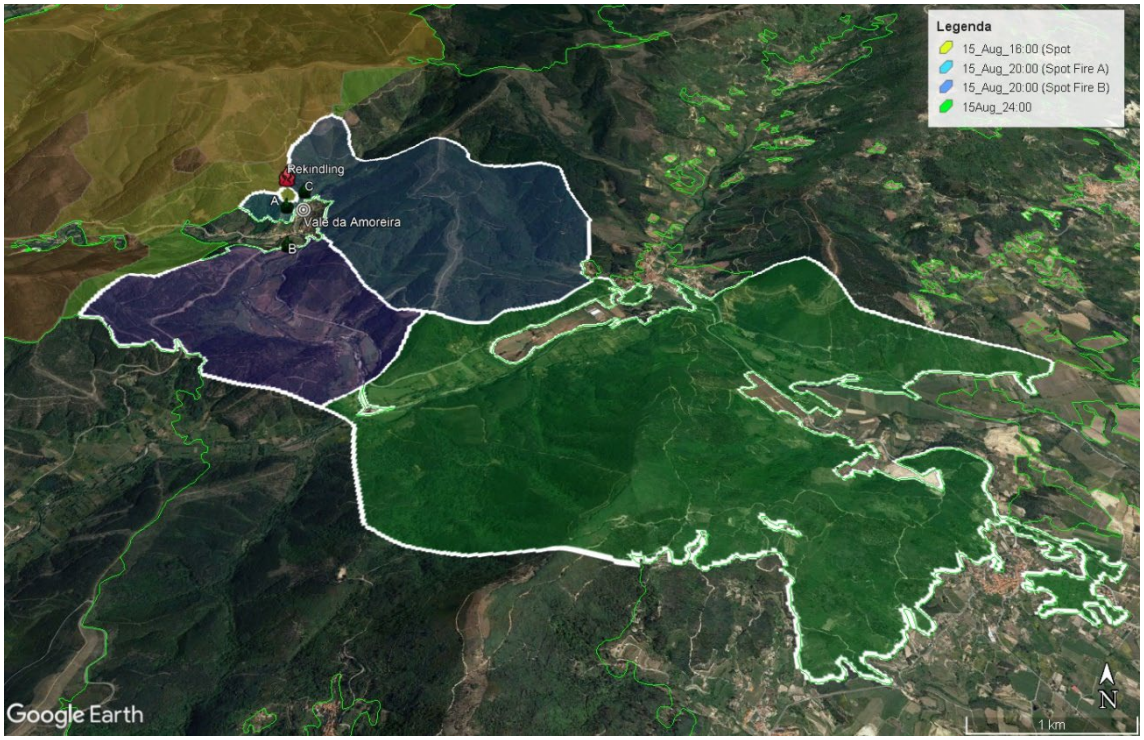
Although the fire perimeter was very extensive, on August 13th, the fire was finally yielding to the fire management strategy. As mentioned earlier, the hottest points were in the fire fronts of Videmonte, Folgosinho, and Linhares da Beira, although there several rekindling spots were observed. The firefighting resources were deployed to fight the active fire fronts and to consolidate the less active fire perimeter using water, bulldozers, and tactical fire. The typical daytime wind slightly decreased in average intensity, although some gusts were still being recorded. Some firefighting resources start leaving the fire scene. On August 15th, at 15:44, the fire event was categorized by the authorities as "under control".

7.3.9 Phase 4: Rekindling, fire spreads to SEE [15Aug – 17Aug]

Several rekindlings were recorded in the previous days in Vale da Amoreira and there was awareness that a new ignition in that area could rise a new fire front that would be difficult to control. Therefore, this zone was considered critical, and many firefighting resources were pre-allocated in this area. Additionally, a double pass of a bulldozer was carried out along the perimeter of the burned area to create a fuel break so minimizing the possibility of an eventual ignition spreading to unburned areas. This double fuel break was inappropriately made mid-slope, separating the burnt and unburnt area. This had influence on the rekindling that we will describe next. Perhaps the right thing to do in that situation would have been to burn the rest of the versant – the bottom part – but the intend was to avoid exposing that population to more fire and smoke.

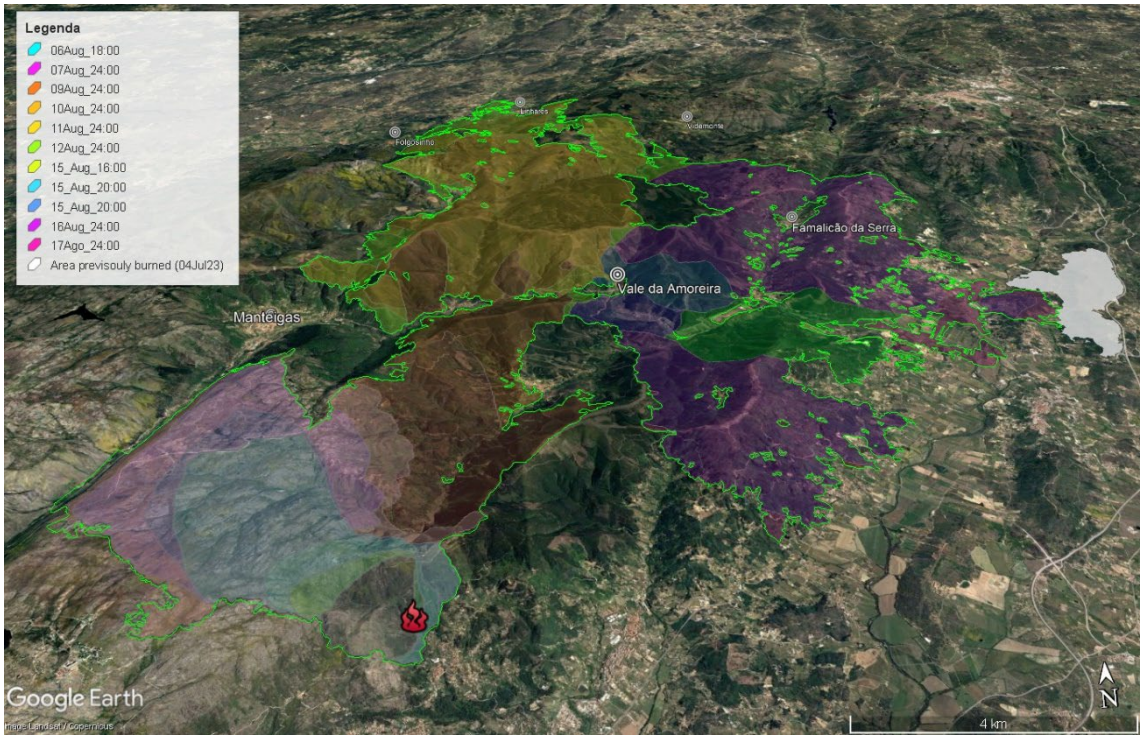
At 15:47 on August 15th, just 3 minutes after the fire was reclassified as "under control," a rekindling was registered near the village of Vale da Amoreira. According to witnesses, a firefighting helicopter responding to this episode caused significant turbulence in the area that drove to several spot fires. Three new ignitions stood out which followed distinct initial paths. The Spot Fire A (Figure 52) was promptly fought against and, although interacting with the initial front, it was confined to a small area. The Spot Fire B, approximately 750 m from the original fire front, started in a grassland with an initial spread very fast, mainly to SE but covering the entire gorge where it was located. Driven by the topography and the turbulence caused by the meteorological wind in the Vale (Valley) da Amoreira, the Spot Fire C climbed the gorge to the north, gaining more prominence on the eastern slope. When the prevailing NW wind overlapped with the local turbulence, it pushed this fire front to SE, merging with Spot Fire B. A situation, which previously seemed under control, became completely uncontrolled, given the rate of spread and intensity with which the fire progressed.

Figure 52. Evolution of the Rekindling at Vale da Amoreira by the 15:47 of August 15th. Fire perimeter by the 24:00 of August 15th.



Pushed by the wind, the fire continued to spread south-eastward, opening up new fronts to the northeast and southwest, guided by the topography, particularly the hydrographic basin of the Zêzere River, towards Famalicão da Serra, and the Sarzedo valley (Figure 53). In general, the fire was pushed into an extensive agricultural land strip along the Zêzere River. In this terrain flatter and more humid, firefighting conditions become more positive. The relative humidity and air temperature also become more favourable on August 17th.

Figure 53. Evolution of the Serra da Estrela Fire – approximate final perimeter by the 24:00 of August 18th.



7.3.10 Phase 5: Final resolution [17Aug - 03Sep]

By August 17th, the situation was progressing encouragingly. The most concerning hotspots remained in Videmonte and in the fire front of approximately 5 km parallel to the Zêzere River. In this area, the priority was the defence of structures, as it was expected that the fire would drastically decrease in intensity when it reached the agricultural fields. There was still an area where the fire crossed the agricultural strip and the Zêzere River, but it encountered an area burned in the previous month, so easily solved. The situation was more complicated near Videmonte, but the significant presence of firefighting forces was sufficient to resolve it.

The fire was definitively considered under control at 21:30 on August 17th. Naturally, several resources remained in the area to respond to the various rekindling that occurred. The fire of Garrocho – Serra da Estrela was declared closed at 21:00 on September 2nd.

7.4 Fire management at the WUI

Despite the extensive burned area and sporadic progression of the fire with high velocity and intensity, the damages to infrastructure were relatively low. However, several houses were burned down, and various other equipment were destroyed. There are surely other damages that were not reported or to which we did not have access, but as presented in Table 17, in three out of the six directly affected municipalities, the recorded direct losses amounted to nearly 24 million Euros.

Table 17. Damages registered in the municipalities affected by the Serra da Estrela Fire.

Municipality	Damages registered
Celorico da Beira	Municipal/public infrastructures and equipment* Agricultural equipment and materials
Covilhã	Municipal/public infrastructures and equipment* (€5,128k) Equipment and industrial infrastructures in three villages (€433k) Dwellings in in six villages (€520k) Agricultural equipment and materials (€3,160k)
Gouveia	No information was obtained
Guarda	Municipal/public infrastructures and equipment* (€8,000k) 3 family tourist business (€250k) and 2 companies with damages to exterior equipment (€150k) 30 second dwellings and 6 primary dwellings (€1,000k)
Manteigas	No significant impacts recorded
Belmonte	No information was obtained

** Mostly composed by paths and municipal roads, traffic signs, municipal buildings and constructions, public drinking water distribution systems, solid waste collection containers, vehicles and other municipal vehicles.*

The utmost impacts resulting from a wildfire are usually associated with the loss of human or animal lives, and buildings. Fortunately, no fatalities or serious injuries directly related to the fire were recorded among people, and the loss of animals and buildings was relatively low considering the extensive burned area and the conditions in which the fire spread. This is largely due to the fire management strategy prioritizing the protection of houses and communities, especially during the day when the wind was stronger, and firefighting was more difficult. On the other hand, compared to recent years, there was a preference for confining people to the villages rather than carrying out mass evacuations. This confinement was facilitated by the existence of shelters or safe havens in most villages. These shelters and safe havens were predefined priorly under the national program "Safe Village, Safe People" (https://aldeiasseguras.pt/).

Even so, there were areas that had to be evacuated due to various reasons. In some cases, it was determined that there was enough time to safely evacuate the residents and move them to secure locations, considering the expected fire intensity. Moreover, certain tourist establishments with occupants who were presumed to have greater difficulties regarding the fire in a region less familiar to them than to residents were also evacuated. Table 18 shows the main people management actions to which we had access.

Table 18. Main actions of people management during the fire in Serra da Estrela.

Municipality	Damages registered
Celorico da Beira	Withdrawal of the most vulnerable people to hostels
Covilhã	From August 15th to August 17th, 71 people were displaced from Sarzedo, Vale Formoso and Aldeia do Souto
Gouveia	No information was obtained
Guarda	From August 15th to August 17th, people from Seixo Amarelo, Quinta da Sra. da Misericórdia and surrounding farms were displaced. In other settlements, several people were sheltered in place, while some people preferred to remain in the protection of their properties and goods.
Manteigas	On 10August a hotel was evacuated for a few hours.
Belmonte	No information was obtained

Tens of dwellings were identified as having been severely damaged by the fire. In most cases, the roof was the construction component that first ignited, confirming the conclusions of Ribeiro et al. (2020). It is possible to observe that the burned structures are scattered, meaning that the fire did not spread continuously through the communities, destroying multiple buildings. Naturally, in addition to the protection provided by the firefighting agents, fuel management in the surrounding areas of the communities was crucial in preventing devastating effects caused by the fire. Figure 54 presents an example of the effectiveness of fuel management in a village surrounding, which prevented the fire from spreading and ensured that no damages were recorded to the buildings in that village.

Figure 54. Image of the village of Sameiro (Manteigas) when threatened by a fire front (a) and after the passage of the fire (b). The effect of fuel management can be observed, as it delimited the burned area, ultimately saving the village (photos cordially provided by Manteigas City Council).

(a) (b)



7.5 Cascading effects

This fire was part of a sequence of events commonly referred to as a cascade effect. Upstream of the cascading chain, the heatwave and drought experienced in 2022 in Portugal and several European countries played a significant role in the fire season, as previously described, and particularly in this fire. Among several subsequent events of the Serra da Estrela Fire, two stand out due to their strong economic, social, and environmental impacts.

Flash flood in Sameiro

During the fire, there was a major concern regarding the protection of the Bosque das Faias (Beech Forest) in São Lourenço, Manteigas. This forest was planted in the second half of the XIX century with the aim of protecting the Village of Manteigas from the common flash floods of that time. During this fire, preserving this forest became crucial, not only for its natural value but also to prevent the cascade effect that would be exacerbated by the severe erosion often observed after fire events. However, to the east of São Lourenço lies the hydrographic sub-basin (Figure 55) that includes Sameiro, which was seriously affected by high intensity fires.

According with the climate report from IPMA, in September 2022 the precipitation occurred from 12th to 15th, during the passage of the Cyclone Danielle, was significantly high in the interior Central of Portugal, especially in Covilhã region where the total precipitation values accumulated in these 4 days (188.4 mm) exceeded by 3 times the average value of the month (58.9 mm). On September 14th the highest daily values of precipitation in 24 hours in the country were exceeded in Covilhã (92.5 mm) and Guarda (42.3 mm). Also, the amount of precipitation that occurred in 6 hours is higher than the normal value for the month. In Covilhã, from 09:00 to 15:00 the amount of precipitation was 60.9 mm, and in Guarda from 04:00 to 11:00 the amount was 42.3 mm (IPMA, 2022). These were the magnitude of precipitation amount in Manteigas, a region close to Covilhã and Guarda. Steepest areas where the fire one month before had spread with high intensity experienced significant erosion, and large amounts of ash, soil and burnt vegetation remnants were carried by the waters, causing floods and landslides of earth and rocks. One area where this impact was particularly experienced was the Sameiro sub-basin and specifically in the village with the same name. In here, the Sameiro Stream, a tributary of the Zêzere River, overflowed, causing extensive destruction in the village, including the sweeping away of vehicles and damage to various infrastructures (Figure 56).

Figure 55. Orographic framing of the Bosque das Faias (Beech Forest), the Manteigas sub-basin and the Sameiro sub-basin.



Figure 56. Images showing the flash flood impacts in Sameiro. September 13th (a) and October 17th (b).

(a) (b)



Rockslides in the Glacial Valley demands road cut off

Manteigas is a village where tourism plays an important role in the economy. All year seasons attract a large influx of tourists, as it offers nature and adventure tourism, as well as snow tourism. The Serra da Estrela Fire had significant impacts on the tourism sector, not only due to the transformation of the landscape but also due to the destruction of tourism supporting infrastructure (e.g., ATMs), which were quickly restored, as well as the destruction of some facilities such as campsites or the artificial ski slope (Figure 57).

Figure 57. Images showing some direct impacts of the Fire of Garrocho on tourism infrastructures.

(a) (b)





Located in the heart of the Serra da Estrela, many people use Manteigas as a logistical base. One of the most frequently used roads for tourist circulation is the Glacial Valley Road (EN338), which connects Manteigas to Torre – the highest point in mainland Portugal at an altitude of 2,000 m and a popular destination for winter sports.

Previously was mentioned the tactical fire action along the Glacial Valley Road, which was successful in blocking the fire spread in than flank but resulted in an episode where the fire spread intensely along the slope. This episode greatly weakened the soil, which, following the hard rainfall on September 13th described earlier, experienced significant erosion. As a result, numerous rockslides occurred, endangering users of the Glacial Valley Road. Consequently, the road had to be closed for several months until the slope achieved sufficient stabilization. This measure had a severe impact on the local tourism sector, particularly in Manteigas, as it drove to a much longer and time-consuming access route to Torre. This may have been one of the most significant economic impacts that Manteigas experienced as a result of the fire. At the time this chapter is being written, 10 months after the fire, there is still no forecast of when this road will be reopened.

7.6 Conclusions and lessons learned

The Serra da Estrela Fire was a highly challenging management event, as it aligned strong winds, rugged terrain, and very low vegetation moisture content. Fortunately, no human casualties were reported, which is the most positive outcome to register. There were several learning opportunities that can be extract from this fire. Next, we will resume some of the most important ones, considering the international scope of this publication.

Helicopter operations in critical areas should require special precautions. This statement was confirmed by two situations at least – at 11:30 on 06th August and the reactivation in Vale da Amoreira (15:47 on 15th August) – in which the fire was close to resolution but ended up again out of control. It is relatively common to see helicopter manoeuvres causing a great turbulence that increases the fire and complicates the firefighting operations, as it was confirmed here. It is important to study this phenomenon and the best way to carry out this type of manoeuvre, passing the lessons on to the pilots of these aircraft.

Tactical fire operations must consider the indirect impacts that result from them. The use of tactical fire is highly effective, especially in areas that are difficult to access and where ground-based methods are complex. However, it is important to consider that these operations, when leading to episodes of high-intensity fire, can trigger cascading effects such as erosion and rockslides, as observed on the Glacial Valley Road. It cannot be stated that this maneuver was entirely wrong because it ultimately halted the fire's spread in that front, especially considering the forecasted strong winds the following morning. However, that manoeuvre, which began around 23:00, could have possibly been delayed allowing the fire to descend most of the slope with low intensity, thus avoiding nearly the entire hillside being exposed to the intense interaction of both fire fronts – the wildfire and the tactical fire.

The use of fire not authorized by the event general commander can be highly negative to the firefighting strategy and can endanger people's lives. Some citizens and civil protection agents resort to actions of tactical fire without the required approval of the general operations commander. In Portugal, the unauthorized use of tactical fire is considered a crime, except in exceptional situations such as the emergency defence of

people's life. It is crucial to understand that an operation of this nature, when not properly coordinated, can jeopardize the entire fire management strategy and put the lives of people in the vicinity at risk. This is a challenge that requires a social action plan for its resolution, as sometimes it is deeply rooted in society's culture.

Fuel management around communities is effective in protecting populations. As mentioned, there have been no situations of inhabited villages being devastated by the fire, even when it reached a large scale and great intensity and speed. Here, an example was presented of several situations where the crucial role of fuel management zones around villages prevented the fire from entering the settlement. In certain cases, particularly when this zone was narrower, it enabled more effective action by civil protection agents who were safeguarding the communities.

References

CISE. (2023). Parque Natural da Serra da Estrela. Https://Www.Cise.Pt/Pt/Index.Php/Serra-Da-Estrela/Parque-Natural.

ICNF. (2022). 8.o Relatório provisório de incêndios rurais - 2022. 8.o RPIR/D, 14. https://www.icnf.pt/api/file/doc/4e8a66514175d0f7

IPMA. (2022). Boletim Climático Portugal Continental - Setembro 2022. https://www.ipma.pt/pt/media/noticias/news.detail.jsp?f=/pt/media/noticias/arquivo/2022/Boletim_climatologico_setembro.html

IPMA. (2023a). IPMA no apoio ao Sistema Nacional de Protecção Civil. http://multisites.ipma.pt/anpc/malha_regular_novo/

IPMA. (2023b). mf2 - Perigosidade Meteorológica de Fogos Rurais. http://mf2.ipma.pt/about

Lopes, S. (2013). Modelos de previsão do teor de humidade de combustíveis florestais. University of Coimbra.

Mendonça, J. M., Máguas, C., Pereira, J. M. C., Fernandes, P., Xavier Viegas, D., Tedim, F., Keizer, J., Silva, J. S., & Al., E. (2023). Relatório Final do Grupo de Peritos dos Incêndios Rurais.

Pordata. (2023). Estatísticas sobre Portugal e a Europa. Https://Www.Pordata.Pt/Home.

Ribeiro, L. M., Rodrigues, A., Davi, L., Viegas, D. X. (2020). The impact on structures of the Pedrógão Grande fire complex in June 2017 (Portugal). https://doi.org/10.3390/fire3040057

Sharples, J. J. & Hilton, J. E. (2020). Modeling Vorticity-Driven Wildfire Behavior Using Near-Field Techniques. http://dx.doi.org/10.3389/fmech.2019.00069

Viegas, D. X., Reis, R. M., Cruz, M. G., Viegas, M. T., Doutoramento, B. De, Silvicultora, E., Coimbra, U. De, Engenharia, D. De, & De, P. (2004). Calibração do Sistema Canadiano de Perigo de Incêndio para Aplicação em Portugal. Silva Lusitana, 12(1), 77–93. http://www.scielo.oces.mctes.pt/pdf/slu/v12n1/12n1a07.pdf

8 Fire of Murça (Portugal)

Authors

Domingos Viegas	ADAI
Carlos Ribeiro	ADAI
Tiago Rodrigues	ADAI
Luís Mário Ribeiro	ADAI
Daniela Alves	ADAI



8.1 General Description

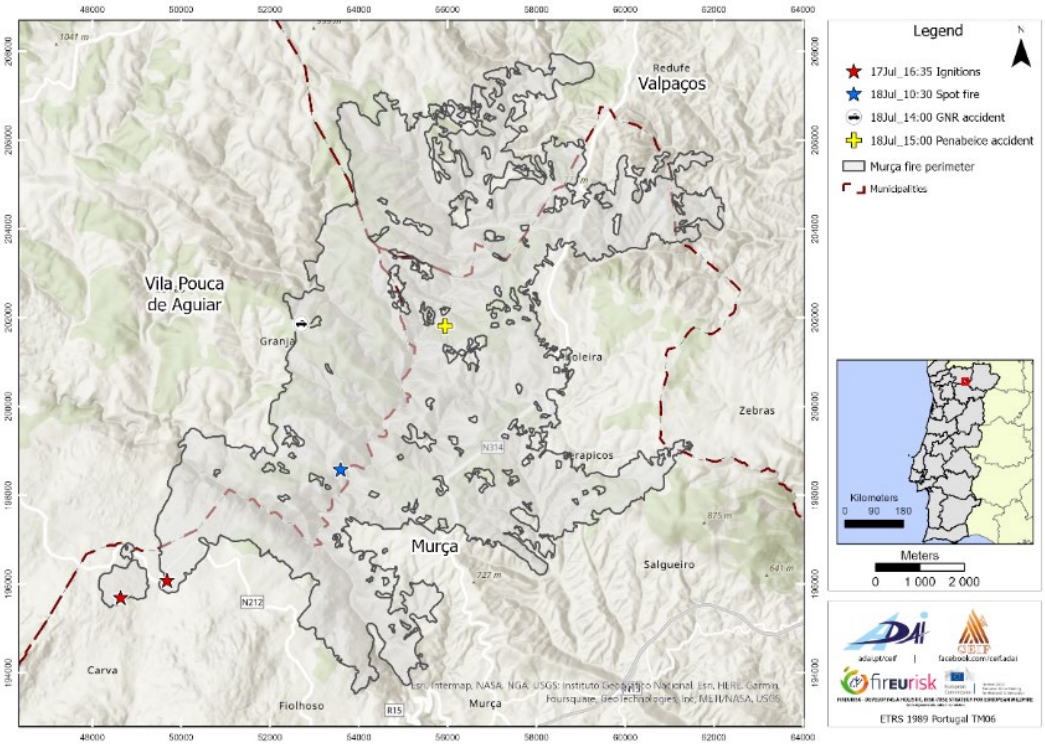
The alert for the fire of Murça was given on the July 17th by 16:35 near the settlement of Carva, in the municipality of Murça, district of Vila Real, in the Northeast of Portugal (see map in Figure 58), and its extinction was registered on the July 21st, by 15:35, after having spread in an area of 7185.78 ha, making it one of the largest fires in the year 2022 in Portugal.

This fire developed in a territory with diversified vegetation cover, with some periods of very intense fire spread. In this fire the only two fatalities associated directly to the fires of 2022 occurred, contradicting the goal of "zero deaths in forest fires", proposed in the National Program of the Portuguese Government.

The study of this fire will deal mostly on its propagation during its first day, in the afternoon of the July 17th and in the late morning and afternoon of the July 18th, during which, with its violent propagation, it was a serious threat to the safety of the population and of the operational agents and caused the death of two civilians.

In Figure 58 the general evolution of the fire from its origin on the July 17th to its resolution on the 21st is shown. The phases of more intense propagation occurred on the July 17th and the July 18th.

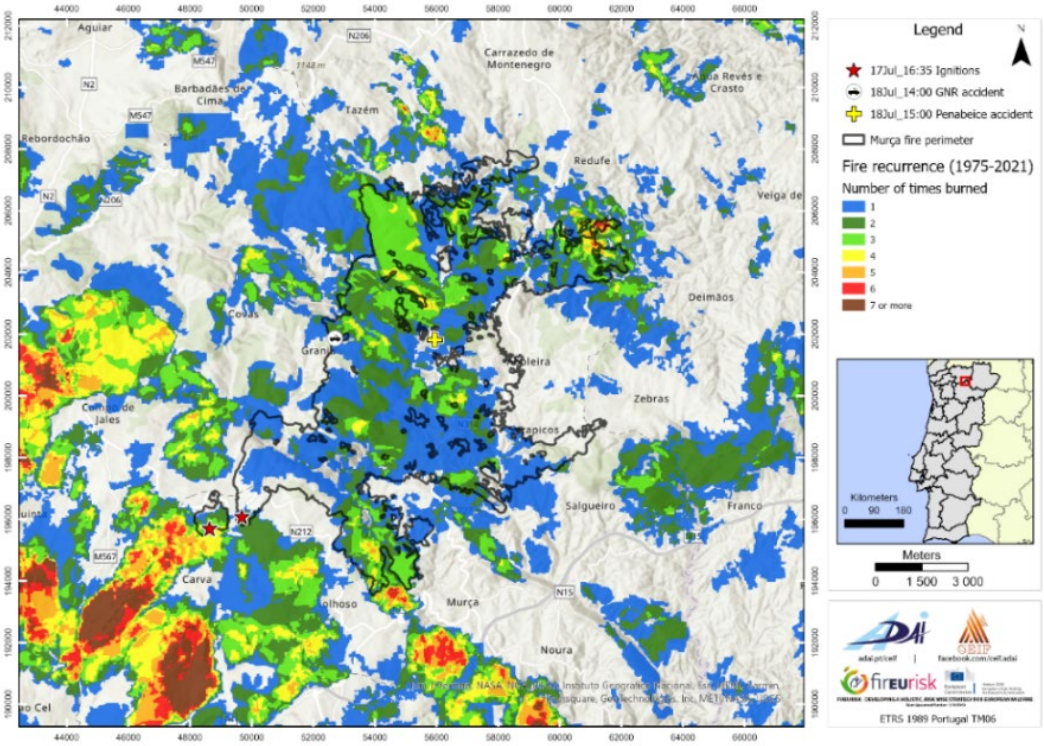
Figure 58. The final perimeter of the Murça fire from the 17th of July to the 21st, with a total area of 7185.78 ha. The two ignition points are marked in the map. The yellow cross indicates the location of the two fatalities and the vehicle symbol marks the location of the incident with a fire truck that was destroyed by the fire. In the inset map the location of Murça in the Northeast of Portugal is shown.



8.2 Characterization of the affected area

The number of times that Murça region was burned (fire recurrence) between 1975 and 2021 is presented in Figure 59.

Figure 59. Fire recurrence in the region affected by the wildfire of Murça between 1975 and 2021.

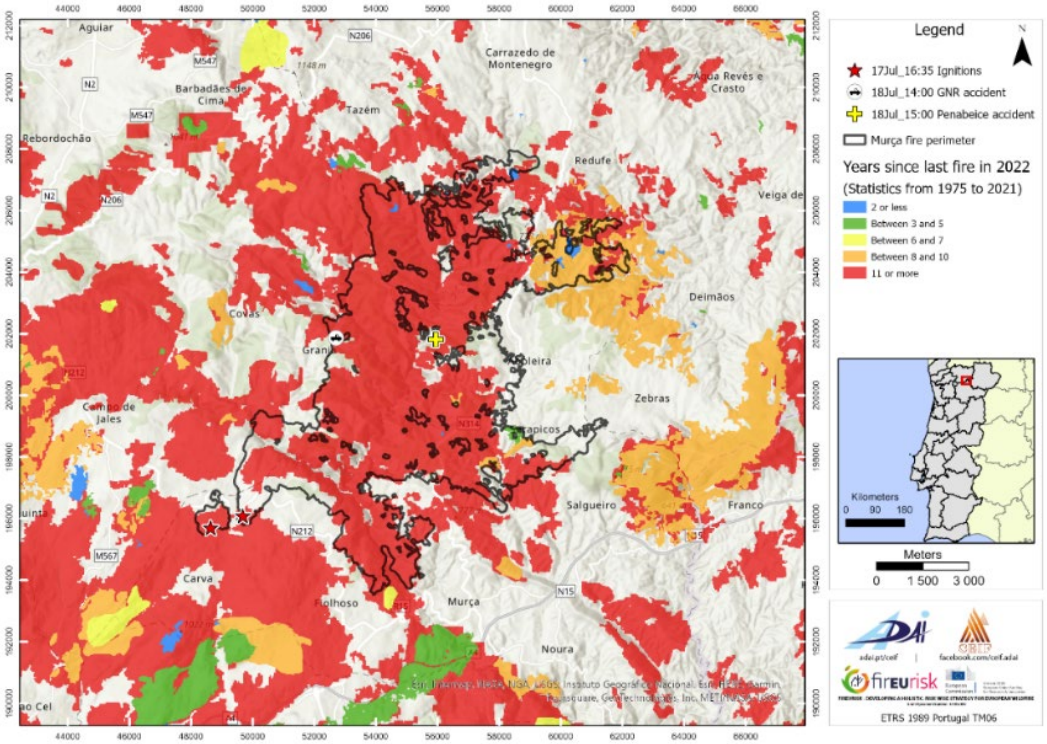


The area where Murça wildfire occurred was not affected by many fires from 1975 to 2021. It is observed that most of the burned area in 2022 had only burned once since 1975. The number of times that an area

burned in the region is larger on the SW side of the fire perimeter, namely where one of the ignitions occurred.

The number of years without wildfires until 2022 in the region of Murça (statistics from 1975 to 2021) is presented in Figure 60.

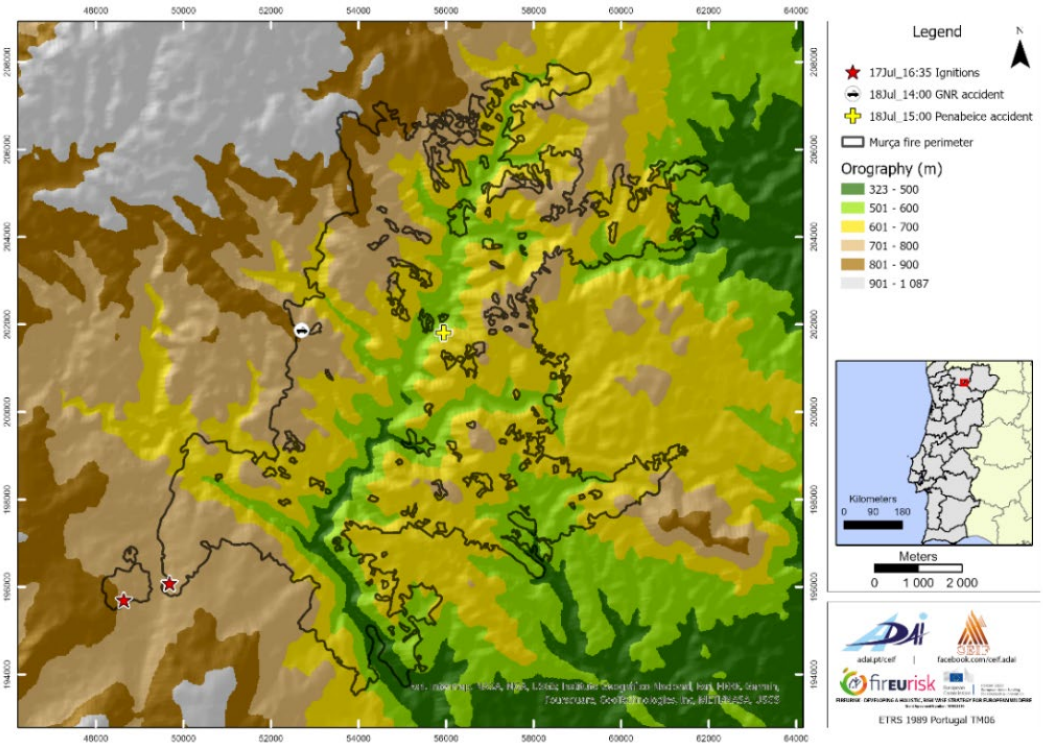
Figure 60. Number of years since the last wildfire in Murça in 2022 (statistics from 1975-2021).



Most of the area had not burned at least since 2010 or before (11 years or more without fires). In 2022, the amount of fuels in this area and the meteorological conditions in the Portuguese territory (drought and the passage of a heatwave) that led to a higher dryness state of the fuels, contributed to the high intensity fire propagation that was observed in the wildfire of Murça.

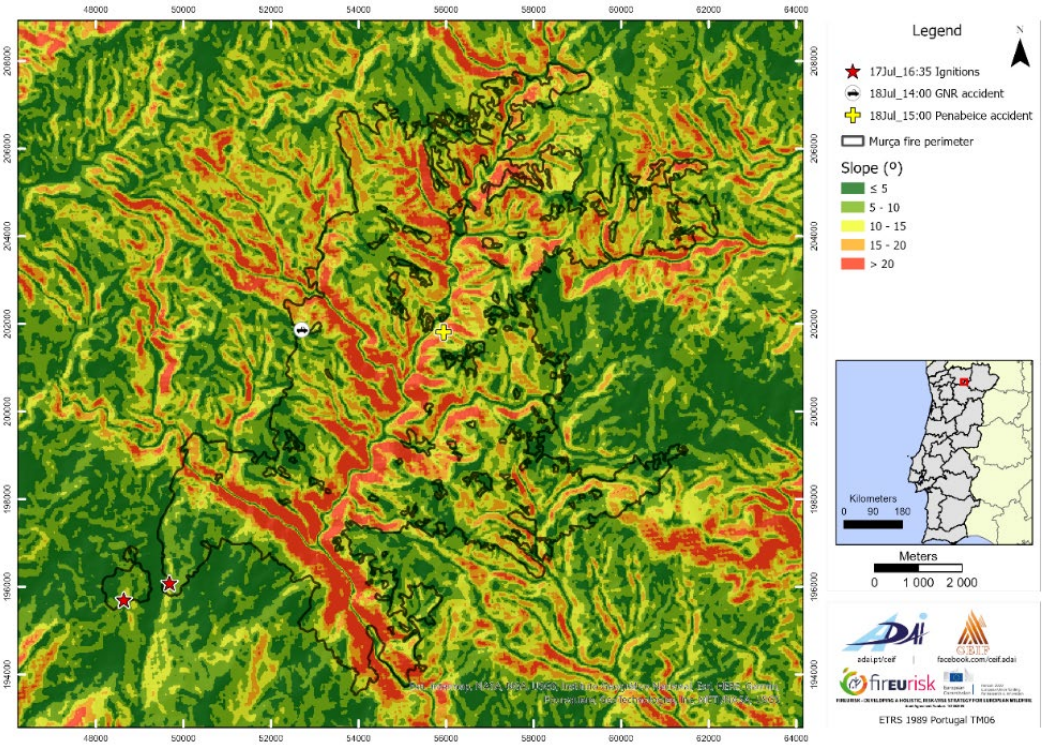
The orography in the area affected by the wildfire of Murça is very heterogeneous (Figure 61). The fire propagation occurred mainly in areas with altitudes between 323 m and 900 m.

Figure 61. Orography in the area of the wildfire of Murça.



The slope in the region of the wildfire of Murça is presented in Figure 62. The slopes are also very variable in this region. The ignitions occurred at 10º to 15º which also is the most represented slope class in the burned area. The GNR accident occurred in a slope of around 5º and the Penabeice accident occurred for the highest slope class (15º-20º).

Figure 62. Slopes in the area of the wildfire of Murça.



The characterization of the land use in the area of Murça wildfire is presented in the map of Figure 63. The map was carried out using thematic maps provided by the Portuguese General Directorate of the Territory

(DGT), namely the conjunctural land use chart that has been updated for 2021 (COSc 2021) having an annual production and update frequency, and a raster format with 10 m pixels. Table 19 presents the respective percentage values of land use. The most representative land use classes in the region are: shrubland, maritime pine and spontaneous herbaceous vegetation.

Figure 63. Land use in the area of the wildfire of Murça.

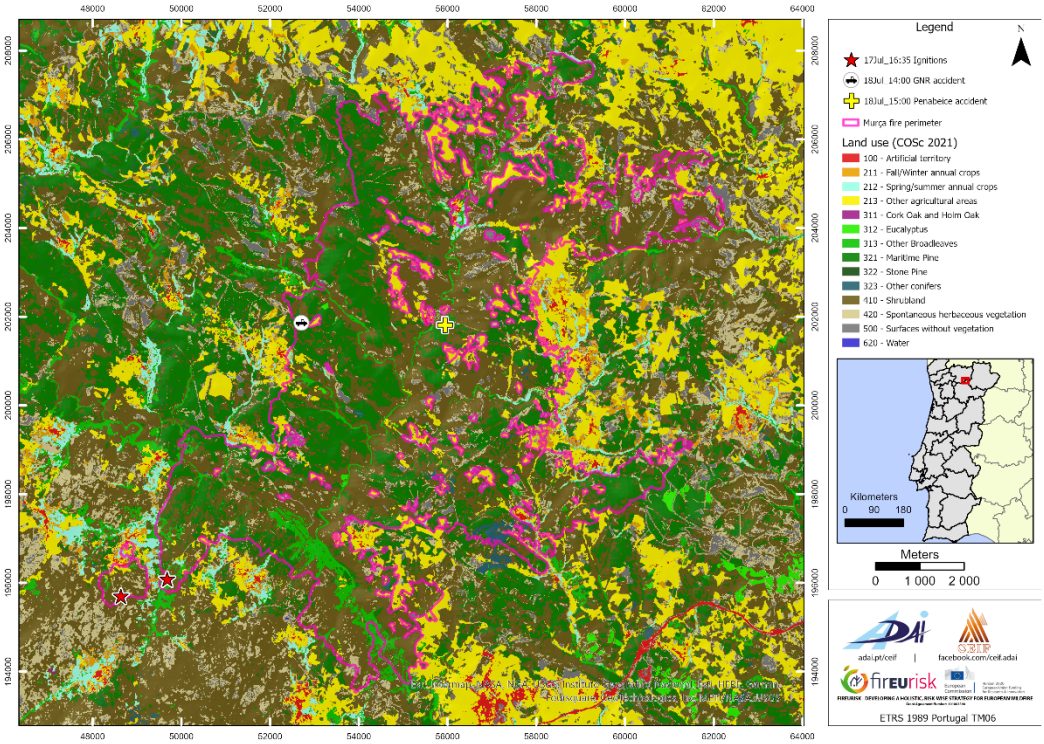


Table 19. Percentage per class of land use in the area of the wildfire of Murça (ordered from the highest to the lowest value).

Class of land use	Percentage of land use
410 - Shrubland	54.06%
321 - Maritime Pine	25.74%
420 - Spontaneous herbaceous vegetation	6.99%
313 - Other Broadleaves	4.47%
213 - Other agricultural areas	4.27%
500 - Surfaces without vegetation	2.28%
323 - Other conifers	0.92%
212 - Spring/summer annual crops	0.71%
211 - Fall/Winter annual crops	0.44%
312 - Eucalyptus	0.09%
100 - Artificial territory	0.01%
620 - Water	<0.01%
322 - Stone Pine	<0.01%

Fire propagation occurred mainly in shrub land areas (54%), forest areas (Maritime Pine – 26%) and herbaceous areas (7%). Also, broadleaves (4.5%) and agricultural areas (4.3%) are representative of the wildfire area in Murça.

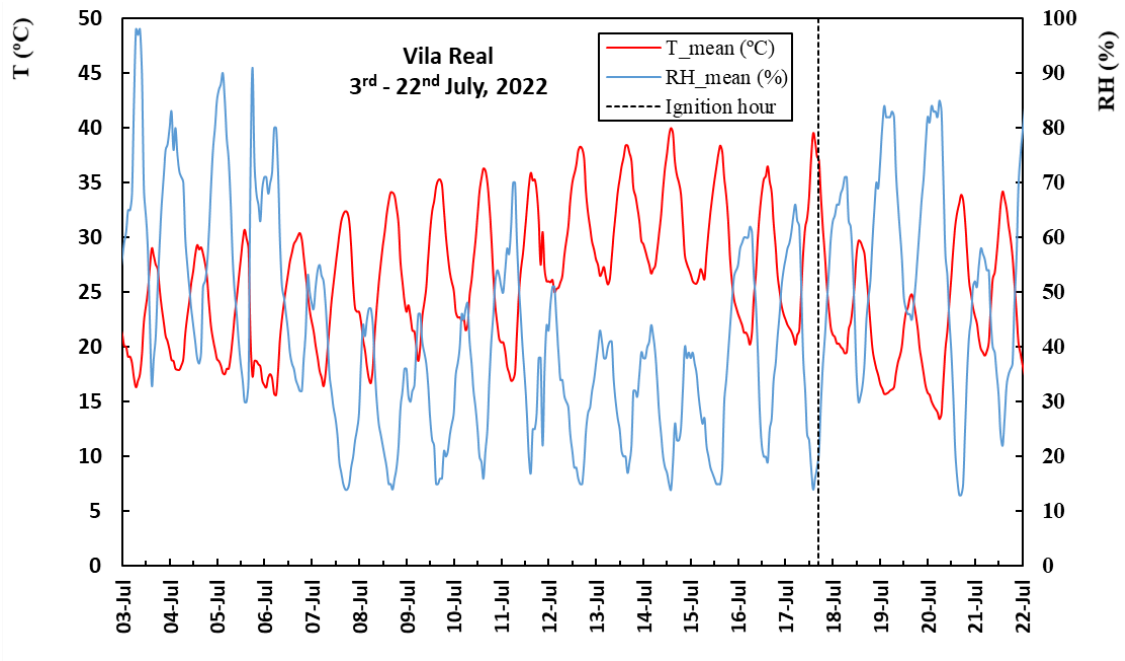
As can be seen in Figure 63 and although the fire affected some agricultural areas, the fire propagation stopped in these areas namely to the north, east and south of the perimeter of the fire.

8.3 Fire conditions

8.3.1 Meteorological Conditions

The weather station of the Portuguese Institute of Sea and Atmosphere (IPMA) located in Vila Real (ID: 567), approximately 23 km from the ignition point, was used to analyse the conditions during the wildfire period. Figure 64 presents the temperature of the air (T) and the relative Humidity (RH) between the July 3rd and July 22nd.

Figure 64. Temperature of the air (T) and Relative Humidity (RH) registered by the meteorological station of Vila Real (ID:567) between the 3rd and 22nd July.



Data source: IPMA

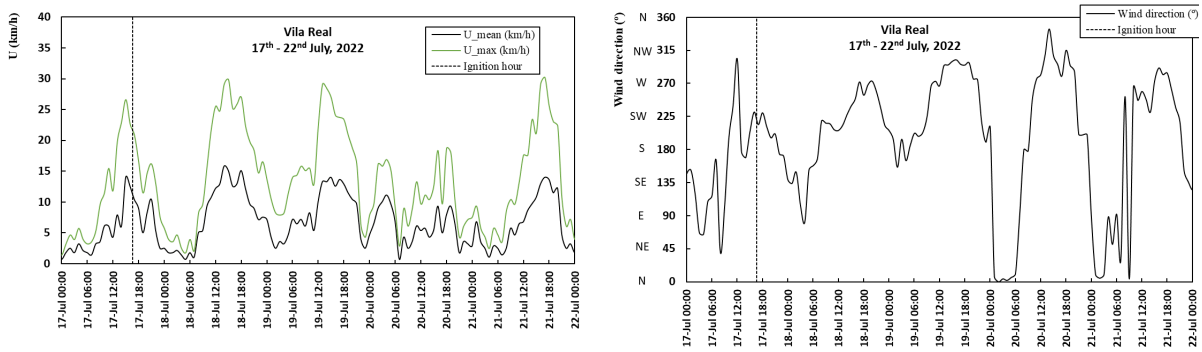
In the period from the 3rd to the 17th of July, the air temperature in the Vila Real region had been increasing, with maximum values of 28ºC on the 4th to 39.5ºC on the 17th. The relative humidity of the air ranged between 15 and 48% (July 12th and July 16th), corresponding to very low values. These meteorological conditions in the days preceding the wildfire were driven by the heatwave that the country was facing between July 2nd and July 18th.

The wildfire started on the July 17th at 16:35 where the temperature reached a maximum value of 39.5ºC, with the relative humidity dropping to 14%. On the July 18th the maximum temperature was 29.7ºC and the minimum humidity was 30% at 13:00.

In Figure 65a) and in Figure 65b) the hourly evolution of the average and maximum wind speed (U), and the direction of the wind, respectively are presented. Wind data is important to understand the fire spread, for this reason the data are presented from the ignition day.

Figure 65. Wind data registered by the meteorological station of Vila Real (ID:567) between 16th and 22nd July: a) Wind speed (U) in km/h, and b) Wind direction in degrees (º).

(a) *(b)*



Data source: IPMA.

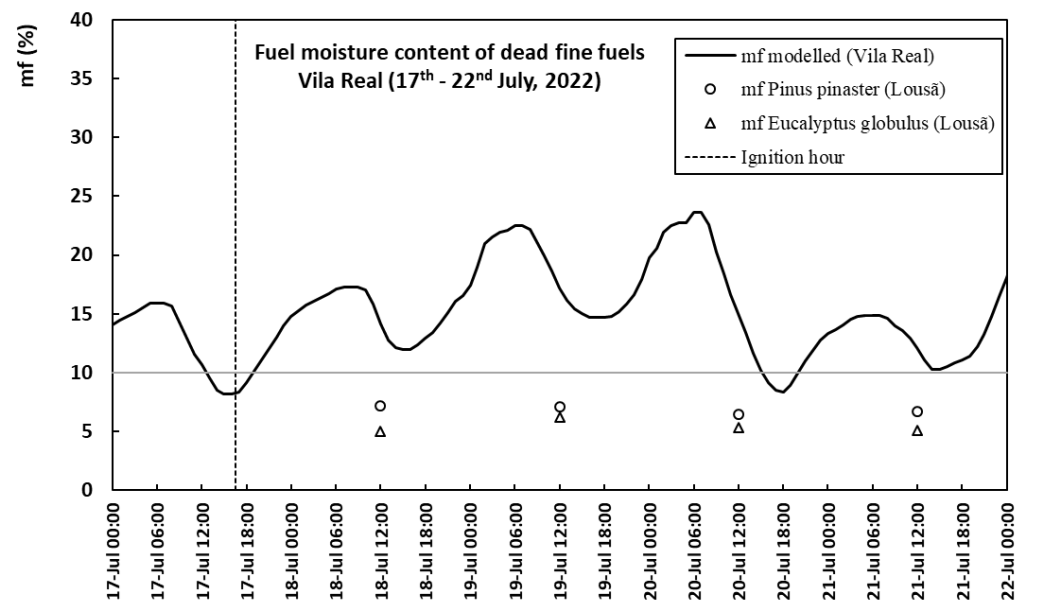
As can be seen, from the difference between the average (U_mean) and the maximum (U_max) values, there were periods with gusty winds (U_max), which have a strong effect on fire propagation. On the afternoon of the July 17th, at this station, the wind was blowing from the Southwest (SW), turning to the South (S) and then, during the night, to the East (E), with a maximum value of around 13 km/h, gradually decreasing to about 2 km/h at early morning on the July 18th. On this day, the wind speed gradually increased to around 16 km/h, at 15:00, and remained at that level of intensity until around 19:00, while its average direction changed from East, at 04:00, to South around 9:00 then to West, at 17:00.

8.3.2 Fuel moisture content of dead fine fuels

Dead fine fuels moisture content were modelled using hourly meteorological data (air temperature and relative humidity) registered by the meteorological station of Vila Real (ID:567), according to the methodology described in Lopes (2013). Figure 66 presents these results for the period from July 17th to July 22nd. Additionally, in the same figure, the fuel moisture content variation for dead needles of *Pinus Pinaster* and dead leaves of *Eucalyptus globulus* measured daily (12:00) in Lousã, a Central region in Portugal, is presented as a reference for observed values.

As can be seen the predicted values of moisture content are higher than the measured values. It must be noted that our model does not consider the effect of solar radiation, therefore the predicted values tend to overestimate the actual values of fuel moisture content.

Figure 66. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from July 17th to July 22nd.



Data source: IPMA and ADAI/MCFIRE (PCIF/MPG/0108/2017).

The amplitude of the daily cycle of moisture content variation on the July 17th was very low, between 7 and 15%. According to our model the moisture content must have reached a maximum of 24% only on the end July 19th.

Several studies carried out by ADAI indicates that dead fuels *mf* values lower than 10% are associated with highly danger conditions and *mf* values of around 6 to 7% can led to events of extreme fire behaviour. These were the danger conditions on the wildfire period, especially on July 17th and on 20th with *mf* lower than 10%. An indication of that extreme danger conditions in these days in Portugal is given by the *mf* measured in Lousã that reached very low value on July 18th: 7.2% for *Pinus pinaster* and 4.9% for *Eucalyptus globulus*.

8.3.3 Fire danger

In Portugal, in accordance with current legislation (DL nº 82, of October 13, 2021), the RCM (Conjunctural and Meteorological Risk) is used to define the fire danger level of a region. The RCM is usually called the "Rural fire danger index" and is mainly addressed to the population.

The RCM is calculated daily and results from the combination of two components (IPMA 2020):

- Conjunctural and structural component given by cartography of the land use, slopes and burned areas of the last 10 years (from 2020, the burned areas of the last 3 years are also considered) – updated every year by ICNF.
- Meteorological component given by the Fire Weather Index (FWI) from the Canadian system (Van Wagner, 1987) that represents the intensity of the fire front, defined as energy per unit length of the flame front – updated every day by IPMA;

The integration of the two components is performed by applying a weighting matrix. RCM is rated on a 5-level fire danger scale (Low, Moderate, High, Very High and Maximum) and it is available at municipality and district level.

The interpretation of the FWI value is also made using a danger scale where the increase in FWI corresponds to an increase in fire danger. Table 20 presents the FWI danger level according to two classifications: IPMA 2023 and Viegas et al. (2004). The first considers a single scale (limit values of FWI for each level) to define the level of danger for the entire territory of Portugal (IPMA, 2023). The second classification considers a danger scale for each district of the country since the authors consider each of these classes has a relative interpretation, which changes from one district to another (Viegas et al., 2004). Despite this comparison, we highlight that the classification made by IPMA (2023) is the official one used in Portugal.

Table 20. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Vila Real, and FWI description according with IPMA (2023).

Level	Limit values of FWI		Description according to IPMA (2023)
	IPMA (2023) for Portugal (a)	Viegas et al. (2004) for Vila Real (b)	
1	<8.2	<13	Surface fires.
2	17.2	20	
3	24.6	30	High fire intensity with crown fires
4	38.2	50	
5	50.1	>50	Exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control.
6	64.0	-	Exceptional fire intensity with extreme difficulty of control
7	>64.0	-	

In Table 21 we compare the level of fire danger given by the FWI values and the RCM. This table presents the observed values for July 17th and the predicted values at 24h, 48h, and 72h for July 17th in Vila Real.

Table 21. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for July 17th in Vila Real. The red colour in RCM indicates the maximum danger classification.

Day	FWI observed and predicted				RCM observed and predicted			
	Obs.	Predicted			Obs.	Predicted		
		24h	48h	72h		24h	48h	72h
July 17th	42.6	48.5	53.6	49.9	5	5	5	5

On the July 17th in Vila Real, the predicted and observed fire danger level according with RCM was classified as *Maximum* (level 5).

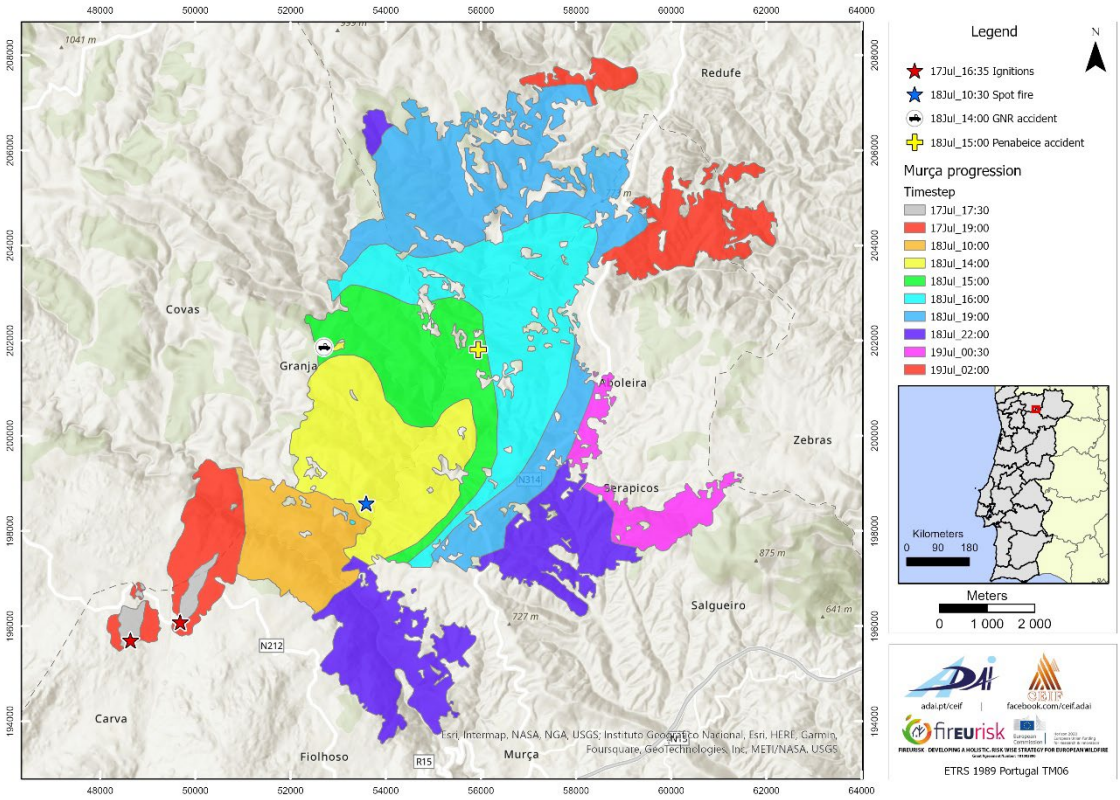
The predicted FWI at 48h (53.6) was also classified as *Maximum* according with IPMA (2023) and Viegas et al. (2004). For these FWI values the fire is characterized by "exceptional fire intensity with crown fires active, potential for spot fires and high difficulty of control" (IPMA, 2023).

The FWI at 24h (48.5) and the observed FWI (42.6) were classified as Maximum according with IPMA (2023) and Very High according with Viegas et al. (2004). According to IPMA (2023), the limit FWI value that defines the change to the Maximum level is 38.2 and, as shown in the Table 20, all forecasts (and the observed FWI) were above this value. Although this level corresponds to the serious reality of the day in Vila Real, in general this classification is more penalizing, putting any region of the country with FWI>38.2 at Maximum fire danger. The concept of danger scale must have an interpretation or relative character as proposed by Viegas et al. (2004), for example a given value of FWI can mean a Maximum danger level in Vila Real (North region), but not in Faro (South region).

8.4 Fire Behaviour

The evolution of the perimeter of the fire of Murça since its ignition on the 17th of July till its extinction on the 21st is shown in the map of Figure 67. The location of the fire perimeter at given times gives an indication of the fire growth in some periods of the fire which are described below.

Figure 67. Evolution of the fire perimeter since the ignition on the July 17th till the extinction of the fire on the July 21st.



8.4.1 Fire ignition and spread on the July 17th

The fire of Murça had two ignition points that were detected on the July 17th at around 16:25, near an electrical 15kV line (Figure 68). One point was close to the Road N212, and the other one was close to Cortinhas.

Figure 68. View of the location of the East ignition point, close to the electrical post shown in the photo near the road N212.

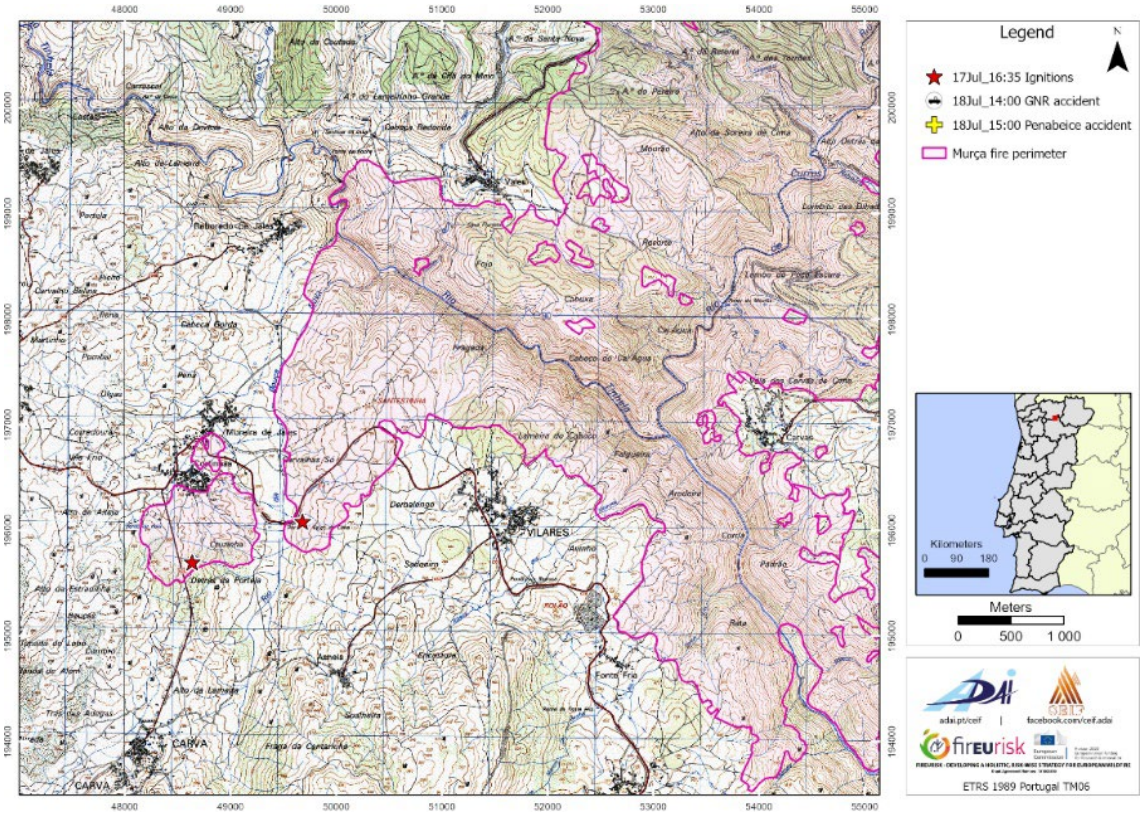


The initial attack was performed by five Firefighter Corporations. Two helicopters were dispatched as well, although one of them did not take off due to mechanical problems.

The ground forces of the initial attack were split into two forces to attack both ignitions. The suppression of the West ignition was achieved after a couple of hours but that was not the case of the Eastern ignition. This fire spread towards Vilares and a back burn had to be made near the road N212, to protect this village. Soon afterwards the fire entered the Municipality of Vila Pouca de Aguiar.

Figure 69 presents the location of the two ignition points and the perimeter of the fire in the SW section of the fire perimeter.

Figure 69. Location of the two ignition points and the perimeter of the fire in the SW section of the fire perimeter.



As can be seen in the images by the reconnaissance aircraft *Óscar 2*, around 17:26 on July 17th that are shown in Figure 70, less than one hour after its start, the two ignitions had already an important development, having covered around 668 m the West ignition and around 1,700 m the East ignition, corresponding to ROS of 0.73 km/h and 1.82 km/h, in that period of time. These values are indicative of the difficulty of the initial attack, especially for the East ignition. In figure m there is a set of three spots ahead of the Western fire. At a certain stage it was assumed that these were intentional ignitions, but it was realised that they must have been spot fires caused by the main fire, similar to one that can be seen near its head.

Figure 70. IR and video images from the fire of Murça obtained by the observation plane *Óscar 2*, around 17:26 on July 17th.

(a) *(b)*



Data source: ANEPC

There was a great effort by the Fire Brigades of Murça and of V. P de Aguiar, supported by other forces, to contain the fire on the west side of the river Tinhela to avoid that it could endanger the North of the Municipality of Murça. Despite the very difficult conditions of the terrain on the west bank of the river, due to the steep slope and rocky terrain, the fire was actually contained on this side of the river.

8.4.2 Propagation on the July 18th

In the dawn and morning of the July 18th, with a reduction of the wind velocity the fire evolved to East along the West bank of River Tinhela and to the South of it.

Around 10:00 some spot fires produced a fire escape on the left flank of the fire containment near the river. As this fire was not contained if spread and around 10:30 produced one or two spot fire on the other bank of the river Tinhela.

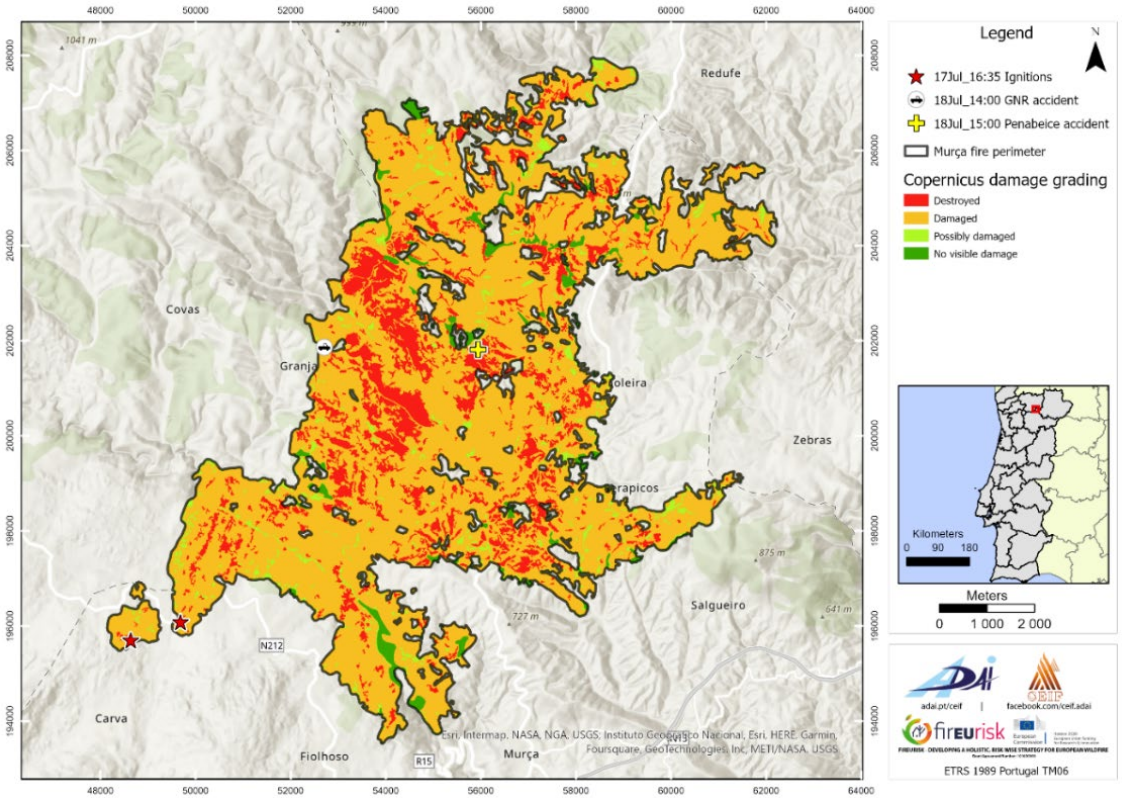
As was already remarked after 7:00 the wind velocity started to increase and its direction veered from East, then to South and Southwest, turning to West by 21:00. The wind between 14:00 and 18:00 had velocities around 15 km/h and gusts of 30 km/h. With the increased wind velocity these spot fires spread out of control, towards North and the same happened to the fire perimeter in the Municipality of Murça, which also spread out of control in the same direction.

This was the worst phase of the fire in which there were two fire fronts spreading on both sides of the valley of River Curros that merged near Penabeice and Curros, spreading like a junction fire as described by Viegas *et al*., (2012) and Raposo *et al*. (2018). Groups of broken trees were found near Jou. This effect is characteristic of the strong convective processes that occur in this type of fires as had been observed in Pedrógão Grande, in June 2017, as it is reported in Viegas et al. (2017) and analysed in Pinto et al. (2022) and Viegas et al. (2023).

As it is shown in Figure 67 between 12:30 and 16:00 the fire reached and average ROS of 1.37 km/h which corresponded to peak values of the ROS possibly of the order of 3 km/h and fire line intensity (FLI) of the order of 16 to 30 kW/m, that corresponds to a fire completely out of control and of the capacity of suppression by direct attack.

The level of damage grading provided by the Copernicus satellite (Figure 71) is consistent with the observation of a very high intensity fire in this area of the fire.

Figure 71. Level of damage grading provided by *Copernicus* satellite.



At the end of the July 18th the fire spread along two fingers in the Southeast direction reaching almost its final perimeter.

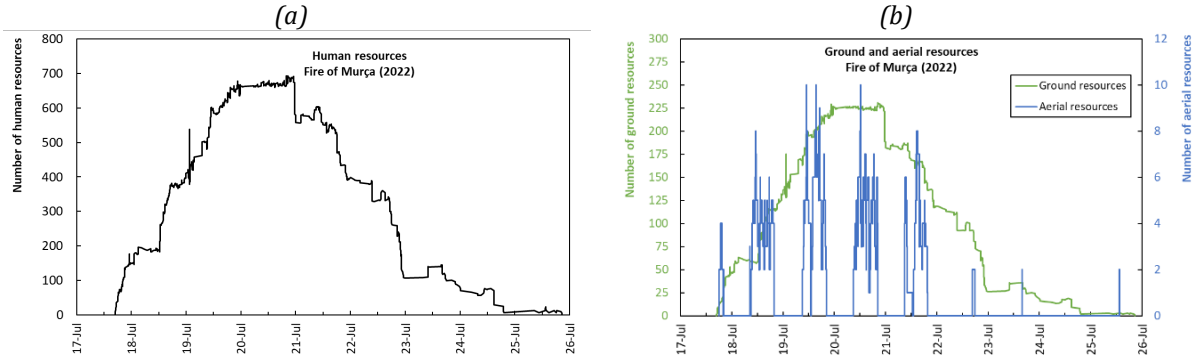
On the July 19th there were many resources to fight the fire that was mostly controlled along its entire perimeter. The difficulty to access some parts of the perimeter led to some rekindling during the night of the July 19th and the fire did not spread more after 2:00 of the July 20th.

8.4.3 Fire Suppression resources

On the July 17th there was another fire in Bustelo, Chaves, district of Vila real that involved several firefighting resources not only from the district but also from neighbour districts, including several elements of the District Command which may have affected the conditions of the initial attack of the fire of Murça.

Based on data provided by the Portuguese Civil Protection Authority (ANEPC), the Figure 72 presents the variation of the firefighting resources allocated to the fire of Murça: a) human resources (firefighters and other civil protection agents), and b) ground and aerial resources. The allocation in the fire started on July 17th at the time of the first ignition until the closure of the occurrence report (July 25th). Resources with incomplete information in the occurrence report were excluded (e.g., resources without date of departure).

Figure 72. Evolution of the resources in the fire of Murça: a) human resources, b) ground and aerial resources.



Data source: ANEPC

In total, this wildfire had allocated 1,859 human resources complemented by 661 ground vehicles and 134 aerial resources. These aerial resources include the combat aircraft, heli-transported teams and the fire monitoring aircrafts.

8.5 Fire Safety Issues

8.5.1 Operational Agents Safety

Since its start the fire of Murça created an important danger for the safety of the operational agents and for the population, with various personal accidents being registered, plus the loss of vehicles and residence houses.

On the July 17th at around 18:00 two firefighters had to be taken to the Hospital of Vila Real with light injuries. Although we do not know the nature of the injuries it must be remarked that this event happened barely in the first hour of the fire suppression activities. At 22:00 there is another register of a firefighter hurt by inhalation of gases, without indication of the severity of the problem.

On the July 18th after the end of the morning and the beginning of the afternoon the safety conditions aggravated. At 14:05 there is a register of a fire fighter with burns in his feet.

At around 14:00 a fire truck from the National Guard (Guarda Nacional Republicana) was trapped and destroyed by the fire near Tresminas. The vehicle and its crew with other two fire trucks were preparing to attack the fire that was spreading on a gentle slope below them, when this incident occurred. The terrain shape was that of a bowl, causing a fire acceleration that caught the agents by surprise giving them barely the time to escape on foot, abandoning the vehicle that was destroyed by the fire. There were no personal casualties, but this incident gives an indication of the quick spread of the fire from this hour on.

At 16:30 the Command Post was transferred from Vilares to Murça, for safety and to have better access conditions and remained installed there from 17:30 onwards.

At 16:52 it is registered that the fire is out of the extinction capacity and safety is recommended to all operational agents. At 19:42 another firefighter with light injuries is registered in Ribeirinha.

On the July 19th by 10:47 one other firefighter was hurt when he was caught by a falling tree that was downed by a discharge from a Canadair. On this day by 16:40 there is a register of a firefighter hurt by inhalation.

8.5.2 Citizens Safety

Besides the accidents that involved operational personnel that were referred above, the fire threatened the population since its initial stage endangering the villages of Carvas, Cortinhas and Vilares. As was said above this situation affected the effectiveness of the initial attack and created problems to the attack of the two starting fires.

Nevertheless, it was on the July 18th that this threat was more extensive and dangerous, leading the authorities to promote the evacuation of various villages.

At 11:05 the evacuation of eight houses in Carvas is demanded; at 13:50 the evacuation of Mascanho and Penabeice is requested due to projections, GNR and the Civil Protection of Murça started this operation with the support of a bus. At 14:30 the Municipality of Murça activated the Municipal Emergency plan to allow the mobilization of all available resources, to face the situation.

At 14:39 it is registered that the National Road 314 is cut between the crossroad of Carvas and Vale de Égua and between Carrazedo de Montenegro and Murça. This indicates that other roads might be inaccessible to traffic or about to become so.

At 14:42 a GRIF from Guarda is sent to Penabeice to protect this village. Slightly later the help of military forces available in the area is requested to support the evacuation of Penabeice and Mascanho.

At 15:10 there is an indication of residence houses burning in Penabeice. At 15:12 the presence of the Medical Emergency Services (INEM) is requested to support the evacuations and at 15:42 it is reported that in Mascanho there are operational agents and civilians surrounded by the fire.

At 16:03 the presence of the National Guard is requested in Penabeice and at 16:57 also in Mascanho as the fire was spreading towards this village with great intensity.

At 17:11 one civilian informed by phone that the fire is very close to the village of Jou and that there are five aged persons and no firefighting resources.

8.5.3 Fatal Accident

In this fire two fatal victims occurred on the July 18th, around 15:00, near the village of Penabeice (Figure 73).

Figure 73. Map of Penabeice, with the road (CM1176), that goes up from the village to the road ER314, that gives access to Murça. The yellow dot indicates the place where the car went out of the road to its left side falling in the ravine.



The two victims were a couple that lived in a house near the western limit of the village. The house had very good habitability conditions, it was very well built and surrounded by other constructions that provided good safety conditions (Figure 74a). As the house was located above a slope towards the approaching fire the two persons had the perception of its very strong advance and decided to leave the village using their own vehicle.

The municipality of Murça was carrying out an operation of evacuation of some citizens from Penabeice, with the support of the firefighters. A bus was parked in the main square of the village with some citizens but as the fire was approaching it was decided to suspend the evacuation, due to the lack of conditions.

A reinforcement group of around 10 vehicles and more than 40 firefighters that had arrived at the scene of the fire had been mobilized to protect Penabeice. In spite of the relatively small size of the village this force was deployed inside and around the village providing a very effective support and protection to its citizens and to their houses.

It was recommended to all persons to remain in the village but unfortunately this message did not reach the couple that was affected by the fire. Several citizens had left the village during the two hours before the accident, including some persons that lived near the couple.

There are indications that at least one of the members of the couple deployed some hoses in the courtyard behind the house, overviewing the area from where the fire was coming, trying to wet the scarce vegetation that existed in that part of the terrain. At a certain time, possibly slightly before 15:00, the couple went in their car to get out of the village and away from the fire. They went along a lateral street that bypassed the main square and were not spotted by the authorities. They left the village, crossed a small bridge over the river Curros and started to drive along the road CM 1176 that went up along a relatively steep slope on the other side of the valley, opposite to Penabeice.

Going up this road they did not realize that the fire was climbing the slope behind them. After a turn they must have been engulfed by smoke, losing visibility. The vehicle veered to the left side and went out of the road, falling on the slope. The car was immobilized with its wheels up and the two occupants did not manage to get out of it before the fire reached the vehicle (Figure 74b).

In this case the two citizens decided to escape from their house very late, with the fire approaching the village of Penabeice in a very violent form. They probably underestimated the rate of spread of the fire, especially going upslope and, above all, they possibly did not consider the effect of the smoke that caused their disorientation and ultimately their death.

Penabeice is a village that participates in the National program of Safe Villages and Safe Citizens, but we do not know to what level this participation impacted in the training of the villagers and in particular of the two victims.

Figure 74. a) A view of the house where the couple lived; b) A view of the place where the vehicle fell.

(a) *(b)*



8.6 Conclusions and Lessons learned

In the fire of Murça several issues were identified. We list here the most relevant ones that can provide lessons to be learned:

- In the initial attack there was possibly a delay in the launching of the alert which was compounded by the existence of another fire in the region which limited the available resources, namely of aerial means.
- There were two ignition points with very important spread due to the wind, causing multiple spots, challenging the fire suppression strategy and the safety of the operational agents.
- There was a lack of coordination between the several agencies in presence, namely with the aerial means during the second and third day of the fire, given the extension of the fire and the intensity of fire propagation.
- Regarding the protection of the people during the fire, namely in the late morning and in the afternoon of the July 18th, the authorities took the right measures to protect the citizens. The decisions to evacuate the villages or other places in peril were taken with prudence and in their execution the required agencies were involved.
- It is necessary to intensify the preparation of the populations to deal with fires of great intensity that can surprise them and overcome their predictions based on their past experience with fires in the region. It was found that the populations are now more receptive to the instructions or orders given by the authorities, but they are more in favour of the decision of sheltering in place instead of leaving their homes and villages. It was also found that the population helped the firefighters in all that was requested including the support of firefighting operations. It was felt that the fuel management operations that were performed by the citizens around their houses after the 2017 fires had declined and that a new effort was needed to increase the motivation.
- It was mentioned that some sectoral meetings of the various commands during the fire could have been made online. The displacements required for the face-to-face meeting at the main command post represented a waste of time that could be avoided. It was mentioned that there was a need to verify the follow up of some orders that were given at the tactical level.

- The lack of water due to the drought at some water sources and scooping areas created some problems to the fire suppression effort, namely for the aerial means, increasing the distance to collect water and the time between drops.

References

Instituto Português do Mar e da Atmosfera. (2020). Nota Metodológica - Cálculo do Índice de Risco de Incêndio Rural (RCM). 1–8.

IPMA. (2023). mf2 - Perigosidade Meteorológica de Fogos Rurais. http://mf2.ipma.pt/about

Lopes, S. (2013). Modelos de previsão do teor de humidade de combustíveis florestais. University of Coimbra.

Mendonça, J. M., Máguas, C., Pereira, J. M. C., Fernandes, P., Xavier Viegas, D., Tedim, F., Keizer, J., Silva, J. S., & Al., E. (2023). Relatório Final do Grupo de Peritos dos Incêndios Rurais.

Pinto, P., Silva, Á. P., Viegas, D. X., Almeida, M., Raposo, J., & Ribeiro, L. M. (2022). Influence of Convectively Driven Flows in the Course of a Large Fire in Portugal: The Case of Pedrógão Grande. Atmosphere, 13(3), 1–34. https://doi.org/10.3390/atmos13030414

Raposo, J. R., Viegas, D. X., Xie, X., Almeida, M., Figueiredo, A. R., Porto, L., & Sharples, J. (2018). Analysis of the physical processes associated with junction fires at laboratory and field scales. International Journal of Wildland Fire, 27(1), 52. https://doi.org/10.1071/WF16173

Van Wagner, C. E. (1987). Development and structure of the Canadian forest fire weather index system. In Forestry.

Viegas, Domingos X., Raposo, J. R., Davim, D. A., & Rossa, C. G. (2012). Study of the jump fire produced by the interaction of two oblique fire fronts. Part 1. Analytical model and validation with no-slope laboratory experiments. International Journal of Wildland Fire, 21(7), 843–856. https://doi.org/10.1071/WF10155

Viegas, Domingos X., Ribeiro, C., Almeida, M., Pinto, P., Ribeiro, L. M., & Silva, Á. (2023). Field and laboratory analysis of the junction fire process in the catastrophic fire of Pedrógão Grande in June 2017. International Journal of Wildland Fire, June 2017, 951–967. https://doi.org/10.1071/wf22161

Viegas, D. X., Reis, R. M., Cruz, M. G., & Viegas, M. T. (2004). Calibração do Sistema Canadiano de Perigo de Incêndio para Aplicação em Portugal. Silva Lusitana, 12(1), 77–93. http://www.scielo.oces.mctes.pt/pdf/slu/v12n1/12n1a07.pdf

Viegas, Domingos Xavier, Almeida, M. F., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Jorge, H., Rodrigues, A., Lucas, D., Lopes, S., & Silva, L. F. (2017). O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017. Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA).

9 The Fires of Sierra de la Culebra (Zamora, Spain)

Authors

Emilio Chuvieco UAH

Patricia Oliva UAH

Mariano García UAH



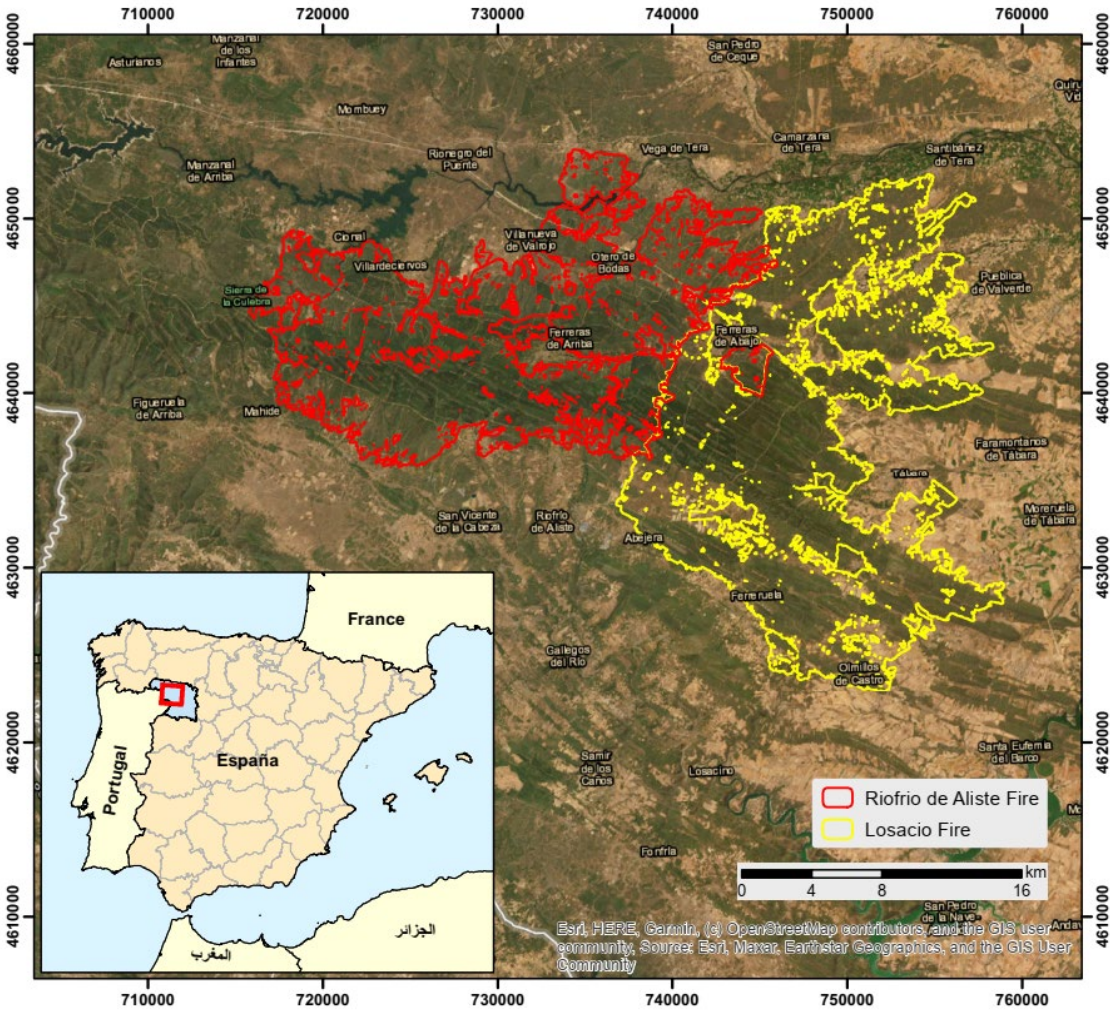
9.1 General description

The Sierra de la Culebra region is a low populated region in the western part of the province of Zamora, in Northwest Spain (Figure 75), one of the historically most affected areas by wildfires. The region is characterised by steep hillsides and wide valleys, with altitude ranging between 747-1205 m above sea level. The climate is Mediterranean, with mean annual temperature and precipitation of 11ºC and 750 mm, respectively (Ninyerola et al. 2005). The conifers are distributed preferentially in the high and sloping areas, while the broadleaves occupy the low and flat areas. Most of the burned area occupied by broadleaves is located in the northern region of the fire.

Two very large fire events occurred in this region in the summer of 2022. The two large fire events occurred one month apart, and they finally merged into a single burned patch, which totals more than 55,000 ha, therefore being one of the largest burned patches in the European historical records (Figure 76).

The first fire event (Ríofrío de Aliste Fire) started on June 15th between the municipalities of Ferreras de Arriba and Sarracín de Aliste, in the western region of the province. The ignition was caused by several lightning strikes produced by an electric storm as 18 lightings were detected in the area, with six of them reporting ignition of fires between 19:00 and 21:00. The fire spread fast due to intense and erratic winds. The alert was given at 22:20 of the same day by the *Castilla y Leon* Forest Firefighting Department. Considering the magnitude of the fire, the regional government requested support from the Military Emergency Unit and reinforcements from several other regional governments. The fire was controlled on the June 24th after burning 24,738 ha, although most of the area was burnt during the first three days. Fortunately, there were no human victims to mourn, but among the impacts are some cultural heritage sites and the disturbance of population from 17 localities who had to be evacuated. More than 560 firefighters worked in the extinction event, supported by 22 helicopters and 18 aircrafts.

Figure 75. Location of Sierra de la Culebra Fires (Riofrio de Aliste Fire in red and Losacio Fire in yellow).

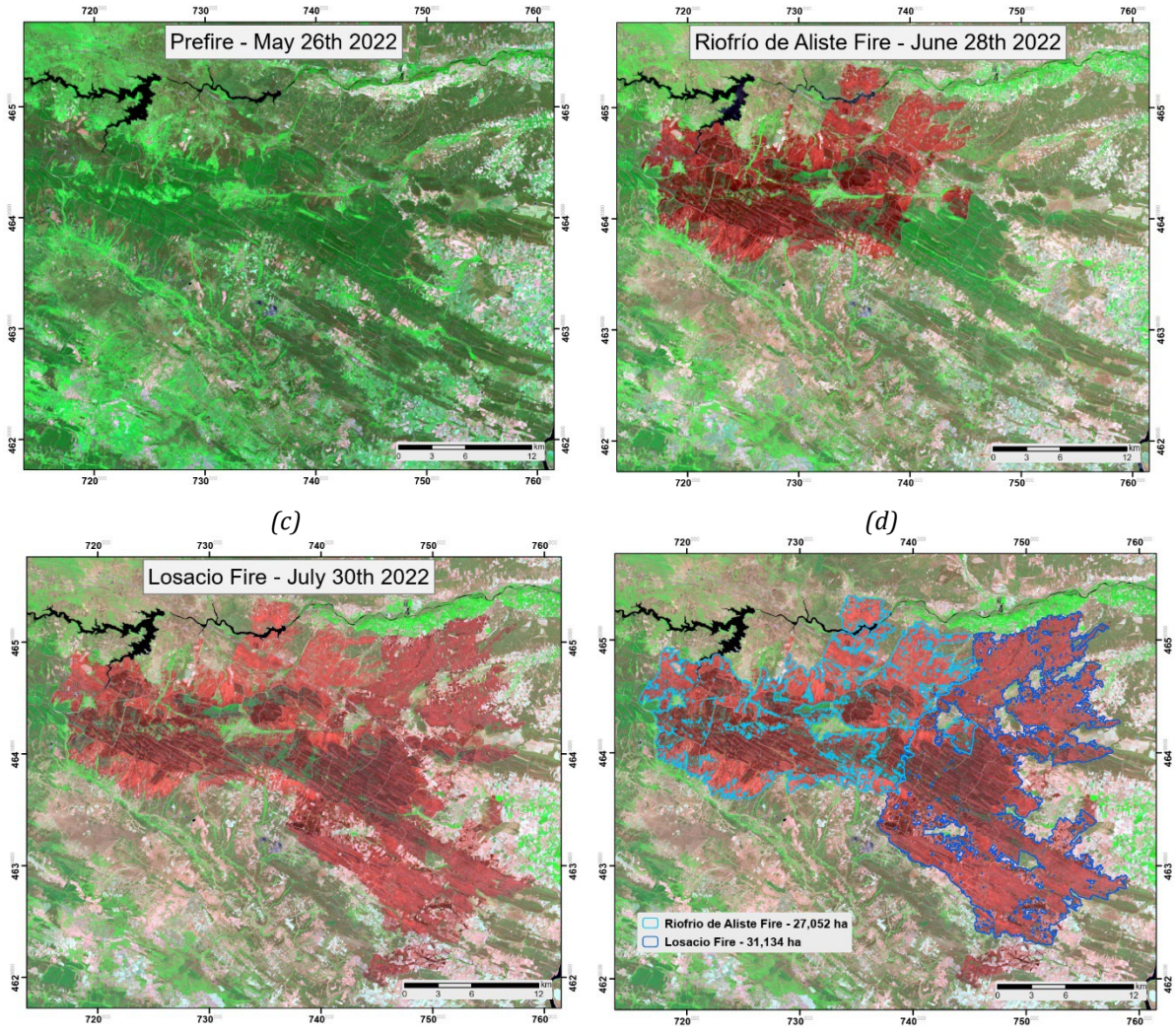


The second fire (Losacio Fire) occurred about one month later, on July 17th. It was also caused by lightning, and it was active for five days, causing a total burned area of 34,473 ha, with higher spread rate on the July 18th due to strong winds (>35 km/h) and extreme fuel drought. The fire started a few kilometres from the perimeter of the first large fire and finally merged with it. The fire was considered extinguished on August 14th. The propagation of this fire was very intense (10,000 ha were estimated to be burned in just four hours), which recommended the evacuation of 28 villages in the area. One firefighter died during the first day of the fire, and a shepherd perished on the following day, both trapped by the flames. Two more civilians died some weeks later as a result of the wounds caused by these fires. More than 450 firefighters worked in the fire extinction, helped by 15 helicopters and 12 aircrafts.

A third fire event occurred on July 24th, called Losacino Fire, affecting a non-contiguous area of the same province, covering around 1,600 ha. We will not cover this third fire event in here, as only the two large fires firstly mentioned have been analysed.

Figure 76. Sentinel 2 images acquired before the fires occurred on May 26th, after the Riofrío de Aliste Fire on June 28th, and after the Losacio Fire on July 30th. The colour composite used (SWIR-NIR-RED) shows the vegetation in green tones, with light greens for growing crops and darker greens for forested areas; the burned areas are shown in magenta tones, areas with sparse or no vegetation are shown in light pink colour. The bottom right image shows the fire perimeters of both fires with the estimated burned area from satellite images.

(a) *(b)*

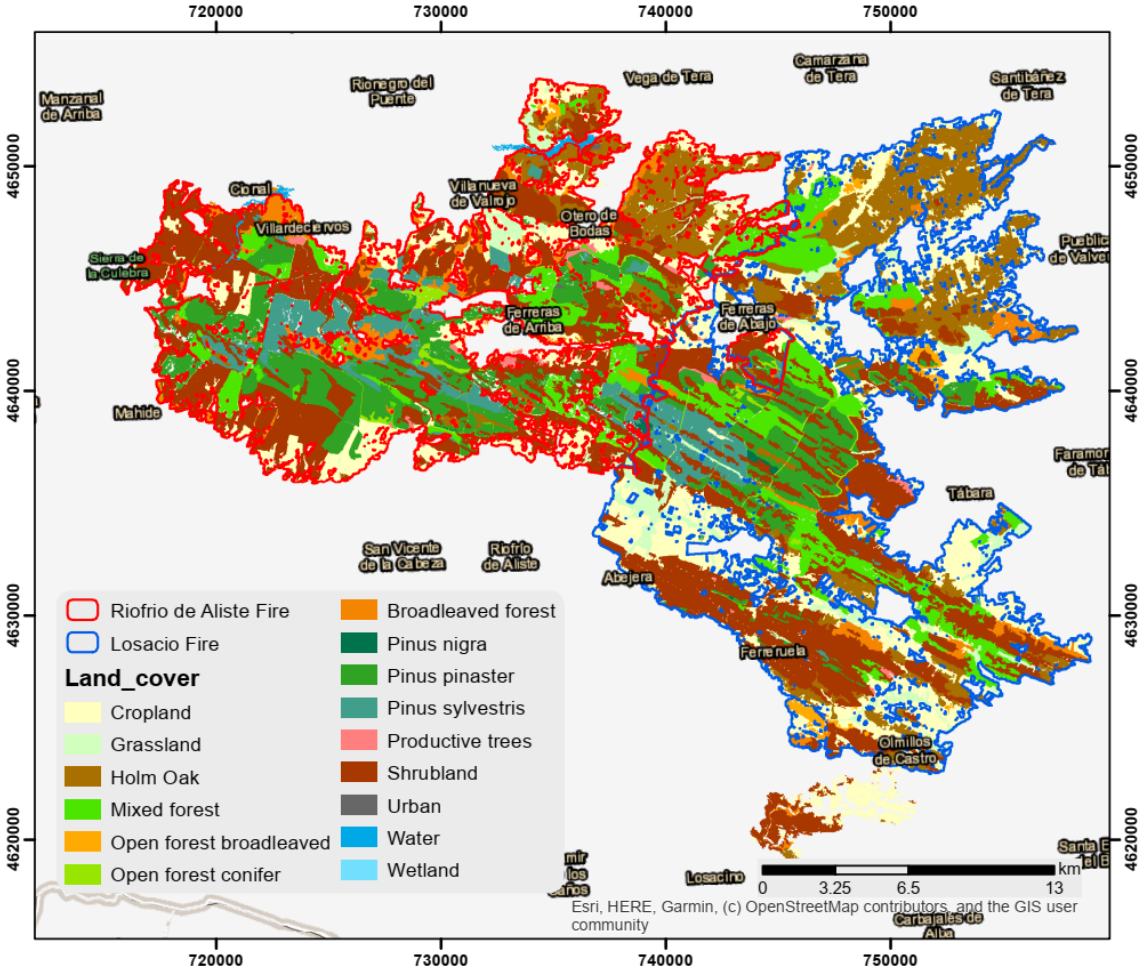


9.2 Characterization of the affected area

The Riofrío de Aliste Fire implied the evacuation of 18 communities of the region. In terms of land cover (Figure 77), the fire mainly affected forested areas (13,000 ha), followed by shrublands (7,839 ha) and grasslands (742 ha), with a minimal area of agricultural areas (453 ha). The affected forested area includes both natural forests (61,63 %) and plantations (38,37 %) (Figure 77). The main tree species affected were *Pinus pinaster* (maritime pine), *Pinus sylvestris* (Scots pine), *Quercus ilex* (holm oak), *Quercus pyrenaica* (Pyrenean oak) and *Castanea sativa*. The shrublands were dominated by *Cistus ladanifer L.*, *Pterospartum tridentatum* (L.) Willk., *Erica australis L.*, and *Halimium lasianthum subsp. alyssoides* (Lam.). Four protected areas included in the Natura 2000 network were inside the perimeter of the fire (Lagunas de Tera y Vidriales, Riberas del Río Aliste y afluentes, Riberas del río Tera y afluentes and Sierra de la Culebra). Also, a part of the biosphere reserve called Transfronteriza Meseta Ibérica was affected by the fire.

The Losacio Fire was even larger than the first one, affecting a total of 31,134 ha across 38 municipalities. The land covers affected were forested areas (14,760 ha), followed by shrublands (4,601 ha) and grasslands (6,820 ha), with a significant share of agricultural areas (4,955 ha) (Figure 77). Two protected natural areas were affected by the fire: Lagunas de Tera y Vidriales and Sierra de la Culebra. Species burned included *Quercus ilex, Quercus suber, Pinus pinaster, Pinus sylvestris, Quercus pyrenaica, Quercus faginea, Pinus nigra, Pinus pinea and Populus x canadensis.*

Figure 77. Land covers affected by the Sierra de la Culebra fires (Riofrio de Aliste and Losacio).



9.3 Fire conditions of *Riofrio de Aliste* Fire

Regarding the meteorological conditions, the winter of 2021-2022 was the fourth warmest and second driest winter recorded in Spain. The spring of 2022 was also unusually dry. In particular, the month of May 2022 was the second warmest and second driest on Spanish records.

In June, a heat wave occurred in Europe which in Spain lasted from June 12th to 18th, making it the second earliest heat wave ever recorded. The Spanish weather service's (AEMet) weather station at Villardeciervos (Figure 78) recorded a maximum temperature during the heatwave of 35.8°C on June 15th, while on the night of June 17th- to 18th the minimum temperature was 17.5°C. By comparison, the average minimum temperature for June at that weather station is 11°C. In these circumstances, AEMet warned of an extreme risk of fires from June 14th in most of peninsular Spain and, in particular, in the north-west of the province of Zamora. These weather episodes led to very favourable conditions for the spread of the fire on June 15th.

The high temperatures, both during the day and at night, and very low relative humidity resulted in a situation of marked and progressive hydric stress of the vegetation, resulting in a very high probability of ignition of the fine fuels (Figure 78 and Figure 80).

On June 15th, the day the fire started, a low-pressure centre began to form on the west of the Iberian Peninsula, associated with the DANA (Isolated depression at high elevation of the atmosphere) (Figure 79), with high atmospheric instability, which produced a cold front and dry storms over the west of the community where the fire started. This cold front and the storms produced strong winds that caused the fast spread of the fire during that evening.

In the following days, from June 16th to 20th, the movement of the DANA located to the SW of the Iberian Peninsula towards the NE generates a situation of strong winds of 30 to 35 km/h with gusts of up to 70

km/h, which rotate from E to W during the first days of the fire. The winds conditioned the main directions of fire spread, which together with the conditions of very high temperatures, very low relative humidity and low vegetation moisture content caused the fire to spread quickly triggering a large burned area.

Figure 78. Meteorology station of Villardeciervos – 2775X, at 850 m above sea level. A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB). Sources: AEMet and Castilla y León Forestry Department.

(a)

(b)

(c)

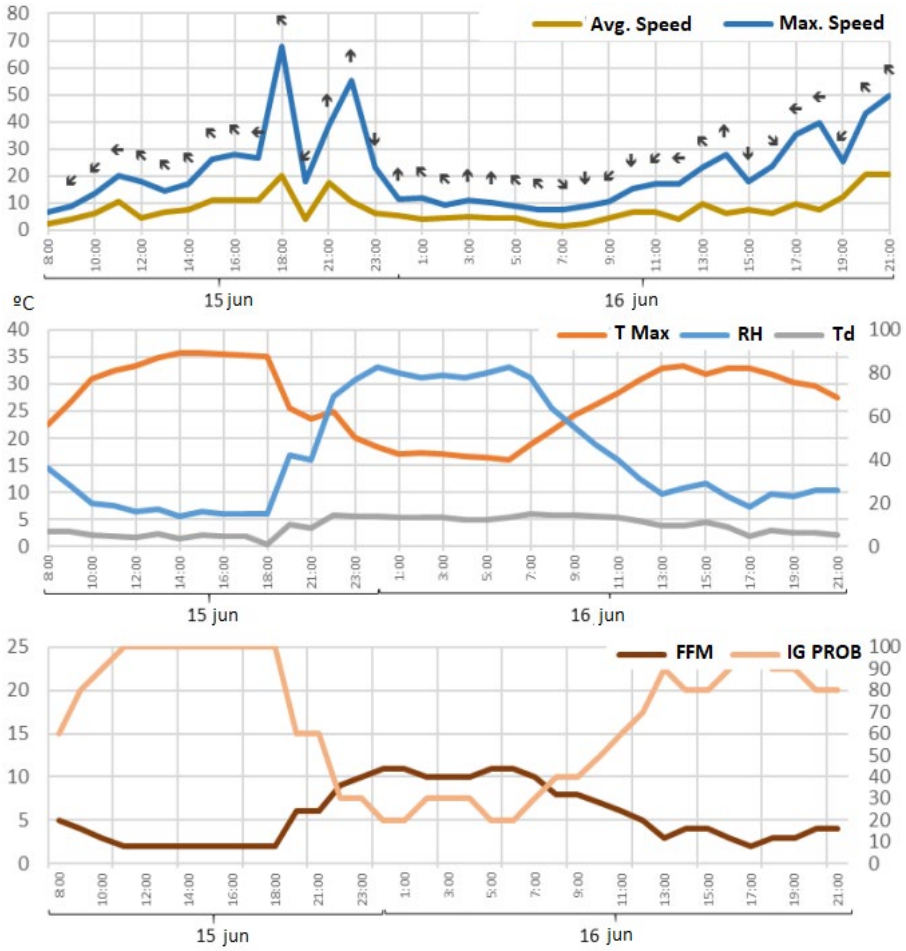
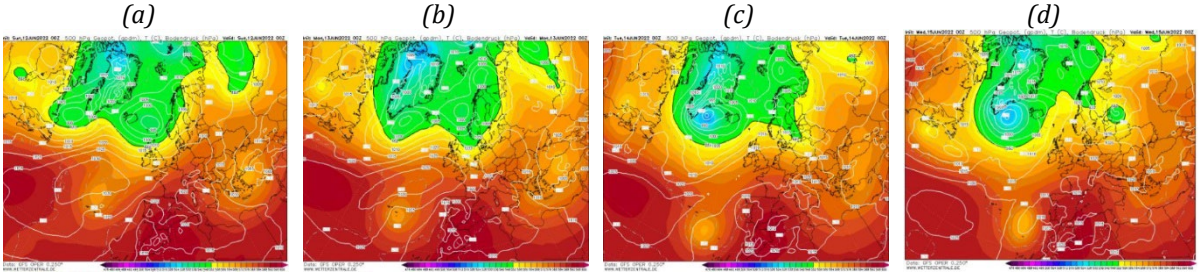


Figure 79. Geopotential pressure at 500hPa at 00z from July 12th to 15th and dominant synoptic situations during the week of June 13th to 19th.

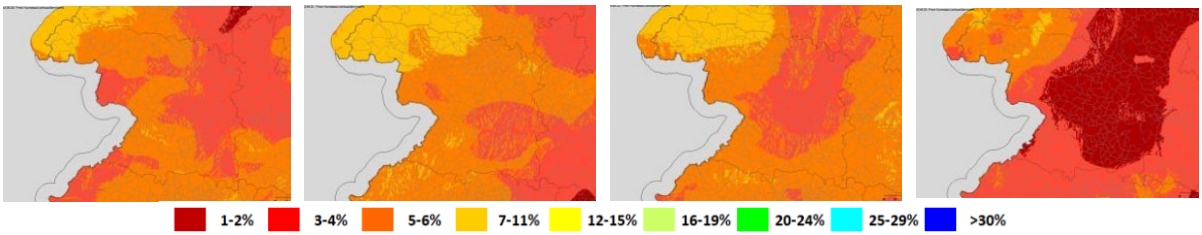
(a) *(b)* *(c)* *(d)*



Source Wetterzentrale and AEMet

Figure 80. Fuel moisture content of dead fine fuel from June 12th to 15th.

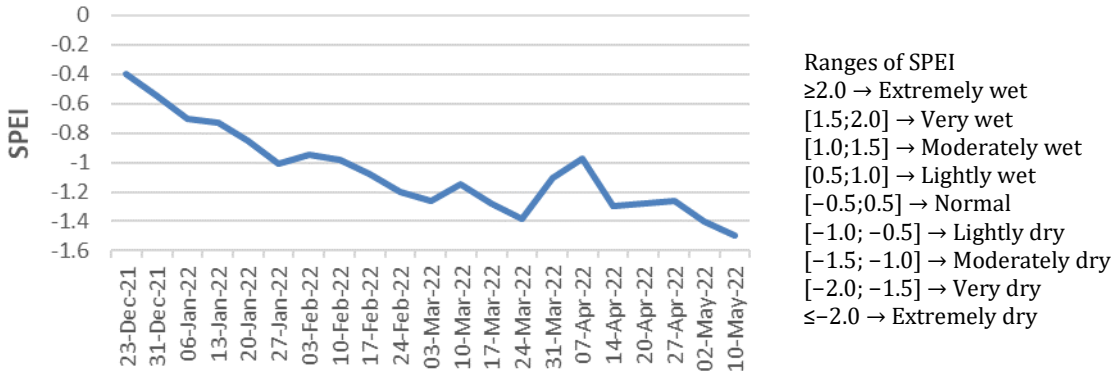
(a) *(b)* *(c)* *(d)*



Source: METEOSIG

The Standardized Precipitation-Evapotranspiration Index (SPEI) shows the drought conditions including intensity and duration, over a region. The data was calculated using the meteorological data of the area. Figure 81 shows the drastic descent of the water content starting in December 2021, not modified by the Spring season (which is regularly the wettest in the region). The continued drought conditions produced a sharp decrease of fuel moisture content, increasing fire risk in the area. The fuel moisture content of dead fine fuels is relevant for the analysis of the ignition conditions, the potential of spotting and for the understanding of the initial fire propagation. The values of dead fine fuel moisture stayed below 6% in the region and decreased to 1-2% on the day of the fire, producing very favourable conditions for fire occurrence.

Figure 81. Standardized Precipitation-Evapotranspiration Index (SPEI) in Zamora during the six months prior to the Riofrio de Aliste and Losacio fires occurrence.



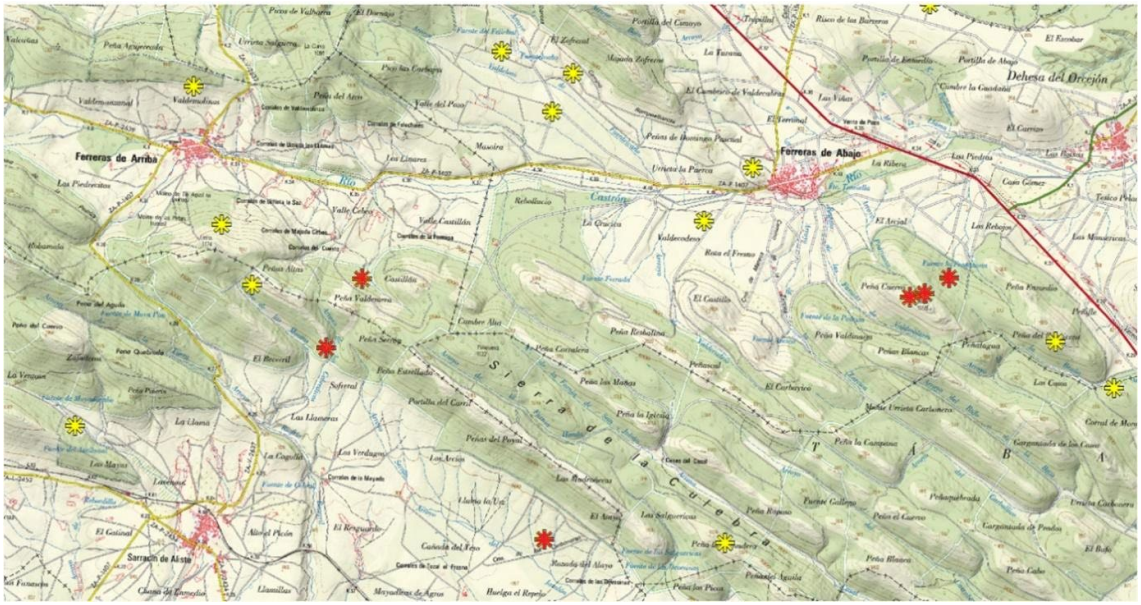
Sources: AEMet and Castilla y León Forestry Department.

9.4 Fire behaviour of Riofrío de Aliste Fire[2]

In the late afternoon on the June 15th, 18 lightning strikes were detected in the Sierra de la Culebra produced by an electric storm. Eleven of these lightings generated ignitions, but only six turned into active fires (Figure 82). The fire was detected at 20:08 of June 15th and was declared extinct at 21:00 of June 21st.

[2] We have used for this section the report prepared by fire authorities of *Junta de Castilla y León*, courtesy of Angel Manuel Sánchez and Francisco Javier Ezquerra.

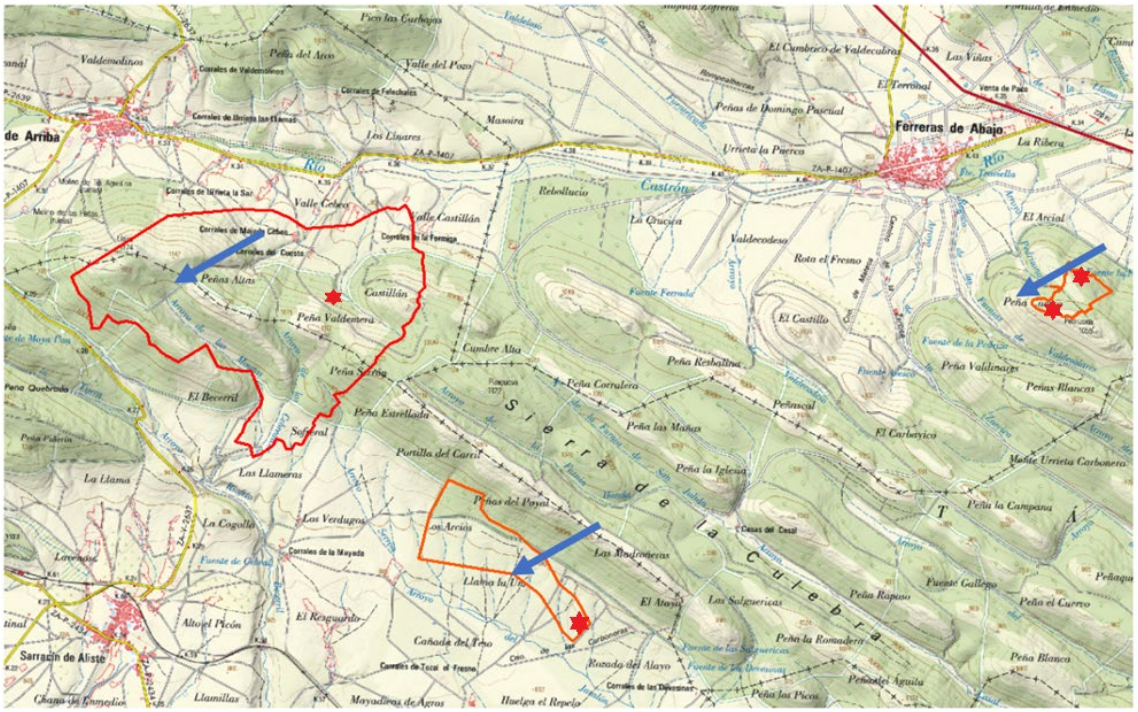
Figure 82. The map shows the lightnings strikes occurred in the region on June 15th in yellow and the lightning strikes which turned into active fires in red. Source: Report of the Forest Firefighting Service of JCyL.



During the night of the lightning strikes, the fire quickly propagated influenced by strong winds of more than 50 km/h, burning more than 500 ha. During the following day, the fire stabilized in the early morning. However, in the afternoon it started progressing rapidly and intensively again influenced by low humidity and high atmospheric instability, with wind changing direction and gusts of more than 50 km/h, particularly at late afternoon and early night (Figure 83). On the June 17th, there strong winds blowing towards southeast with an average speed of 25 km/h, and gusts of 40 km/h, were observed. The eastern ignition was stabilized but the western fire flank advanced very quickly and out of control. The wind conditions were constant until 4:00, when the wind rotated to South direction, moving toward populated areas such as Cabañas de Aliste, Torres de Aliste and Pobladura de Aliste. Consequently, the protection of the populated areas was prioritized, involving firefighting resources (Figure 84).

By 5:30 the wind changed direction again, turning to the East and threatening the town of Mahide. The population of Mahide was evacuated. In the afternoon, the wind changed again to the South component reactivating the northern fire flank. The towns of Villardeciervos, Villanueva de Valrojo and Otero de Bodas were evacuated as the fire approached the populated areas. Again, the priority was to protect the villages.

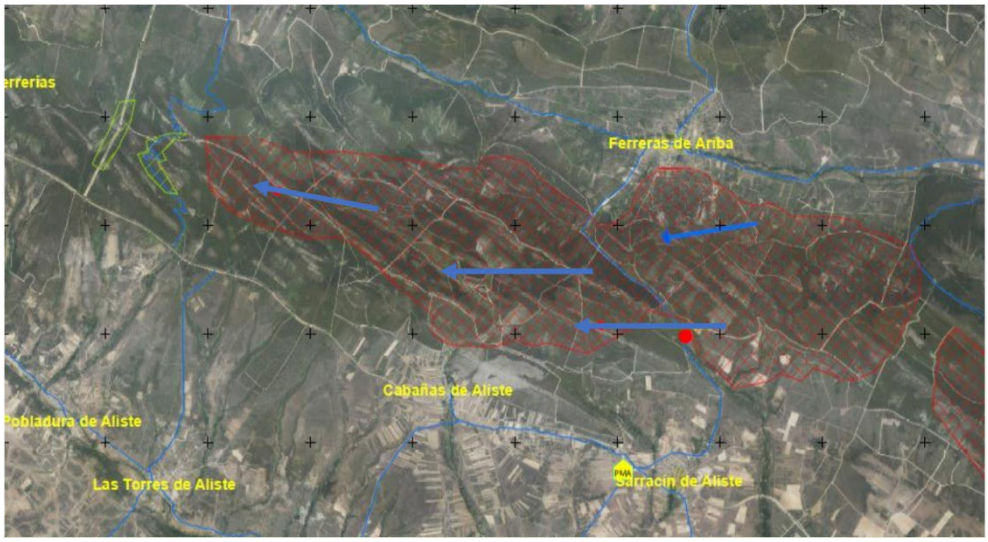
Figure 83. Fire growth and dynamic on June 16th. Red stars mark the location of the ignition, blue arrows indicate the direction of the wind, and the red polygon indicates the size of the affected area.



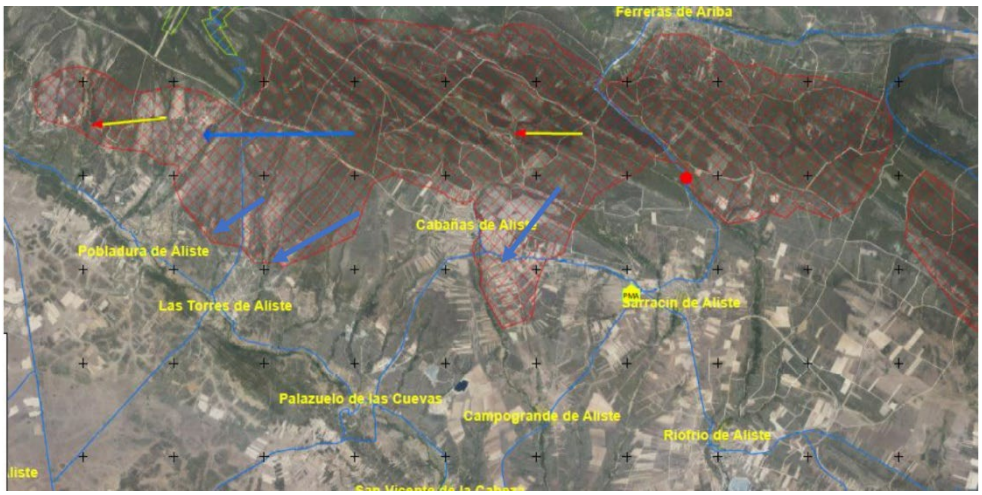
Source: Report of the Forest Firefighting service of JCyL.

Figure 84. Fire growth and dynamic on June 17th: a) Shows the fire growth at 3:00, b) the fire growth at 5:00, and c) shows the fire growth at 8:00.

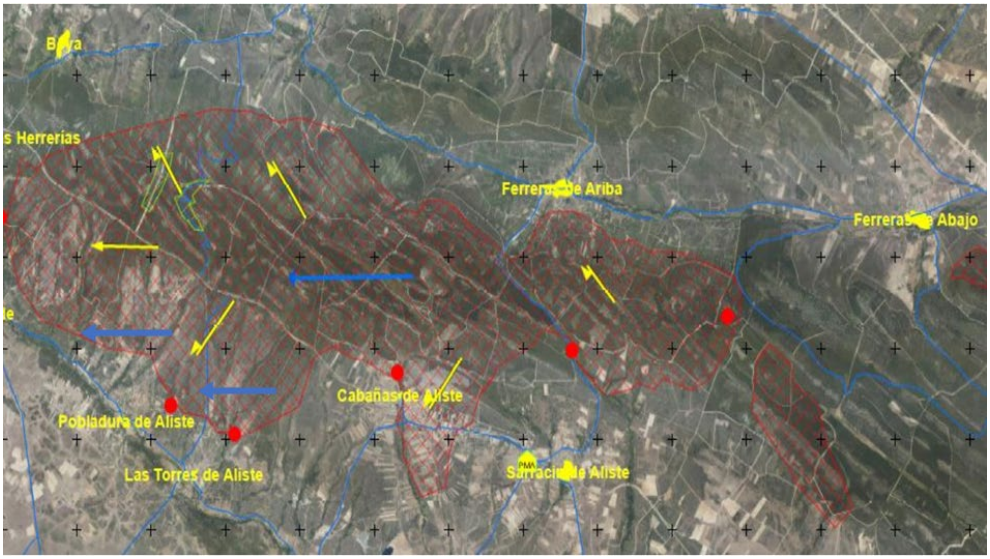
(a)



(b)



(c)

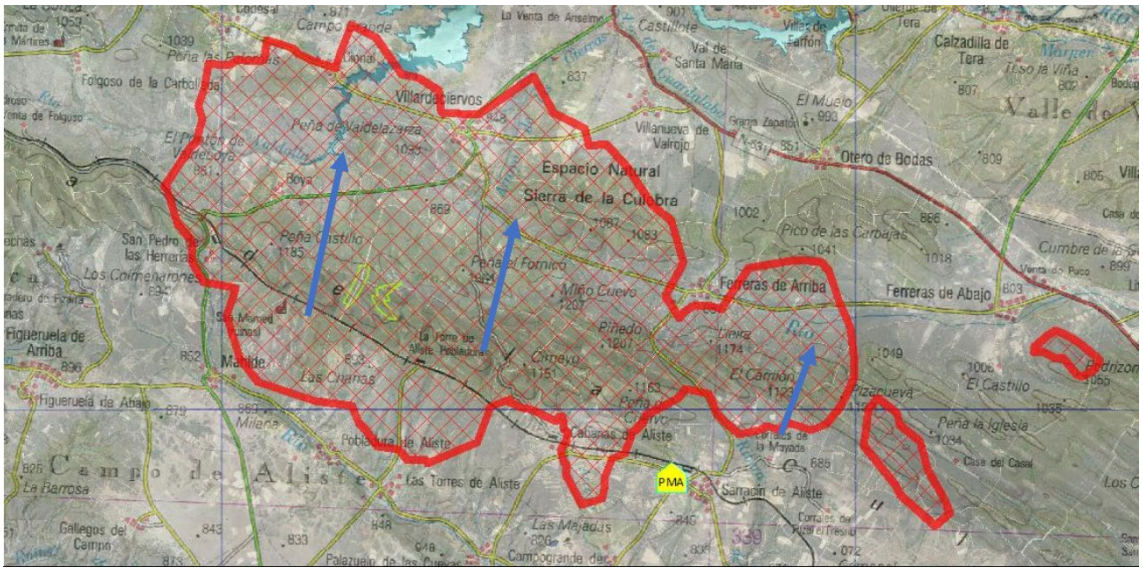


Source: Report of the Forest Firefighting Service of JCyL.

On June 18th, the fire crossed the highway N-631 advancing in southwest direction quickly and out of control (Figure 85). More villages were evacuated: Melgar de Tera, Olleros de Tera, Calzadilla de Tera, Pumarejo de Tera, Junquera de Tera, Milla de Tera, Vega de Tera and Val de Santamaría.

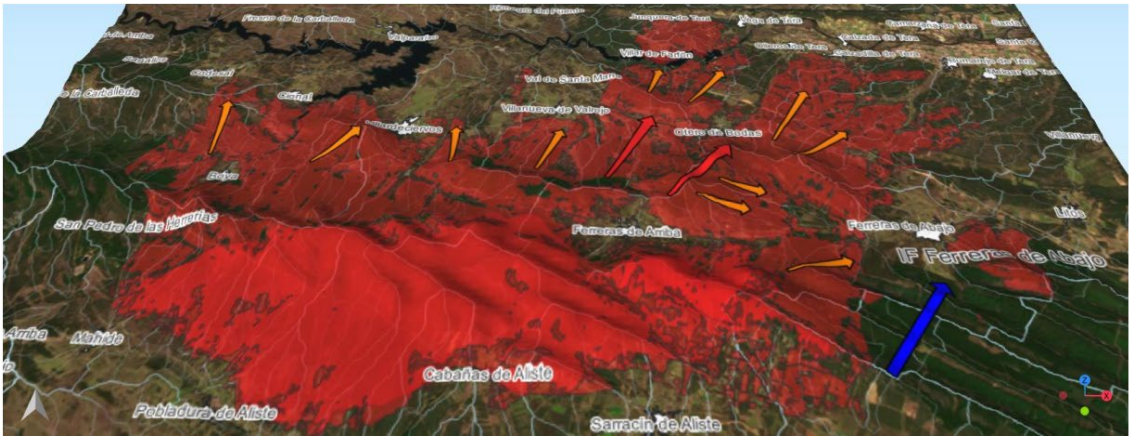
On June 19th, the wind changed direction again towards west-southwest direction moving towards the towns of Villanueva de las Peras and Litos (Figure 86). However, the wind slowed down, and the firefighting brigades could control the fire by the end of the day. The fire continued burning in some areas until the June 24th, but the fire spread was stabilised, and the fire perimeter varied little.

Figure 85. Fire growth and dynamic on June 18th. Blue arrows indicate the direction of the wind, and the red polygons mark the extension of the burned area.



Source: Report of the fire extinction service of JCyL.

Figure 86. Fire growth and dynamic on June 19th. Blue arrow indicates the direction of the wind, red and orange arrows mark the fire spread.



In summary, during the four days that the fire was active, the atmospheric conditions were very instable and unfavourable for extinction, with maximum temperatures above 30º C, no rain, low humidity levels and strong winds. However, the local weather conditions were not those measured by the weather stations, but rather those observed at the fire front, which were more extreme, since the fire created its own wind whirls and thermal conditions, exacerbating the difficulty of extinction. During many hours the fire was outside the extinction capabilities, with strong convective winds. Propagation was facilitated by those fast winds, with spotting registered up to 500 m.

Table 22. Summary of fire propagation parameters for the Riofrío de Aliste Fire.

Date/time	Time since prev. obs.	Area (ha)	Increase (ha)	Speed (ha/h)	Length (km)	Rate of Spread	
						(km/h)	(m/s)
15/06/2022 20:08	--	0	0				
16/06/2022 12:00	15:52	800	800	50.42	4	0.25	4.2

16/06/2022 20:00	08:00	1195	395	49.38	1	0.13	2.08
17/06/2022 08:00	12:00	7378	6183	515.25	13	1.08	18.06
17/06/2022 22:30	14:30	15702	8324	574.07	7	0.48	8.05
18/06/2022 12:00	13:30	17761	2059	152.52	1	0.07	1.23
18/06/2022 21:00	09:00	29185	11424	1269.33	7	0.78	12.96

Source: Report on the fire by Junta de Castilla y León.

9.5 Fire conditions of *Losacio* Fire

As commented in the previous section, winter and spring were unusually warm and dry inducing the hydric stress of vegetation in peninsular Spain. During the summer of 2022 a continuous condition of heat wave took place since mid-June, with very high temperatures and low relative humidity, which added to the drought conditions occurring since winter. In fact, the average temperature of July in the region was 4.5º higher than the average of the reference period (1981-2010).

This situation was produced by the lifting of a DANA located to the west of the peninsula, producing a cold front and dry storms over the west of the community, affecting to a greater extent the provinces of León, Zamora, Salamanca and Ávila.

One of the most important factors for the high propagation speed of this fire was the intensity of the wind, which during the 17 to 20th of July had an average speed of more than 25 km/h in the central hours of the day, reaching peaks of more than 60 km/h (Figure 87). Moreover, on the afternoon of July 18th, the day of greatest spread of the fire, the average wind speed was over 35 km/h from 15:00 to 19:00 hours, which caused the fire to be very difficult to control by the firefighters.

Figure 88 shows the moisture content of the dead light fuel on the day of the start of the fire and subsequent days. As can be seen, the FFMC varied from 1 to 4%, which are extremely low values that facilitate the ignition of the vegetation.

Figure 87. Fuel moisture content of dead fine fuel from July 17th to 20th. Source: METEOSIG.

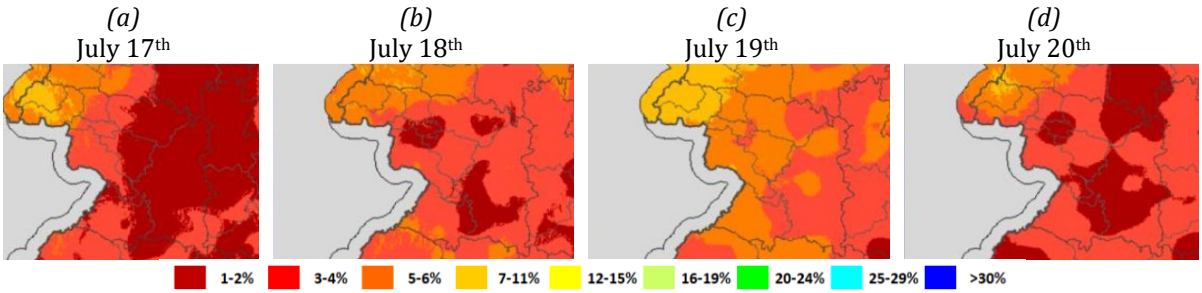
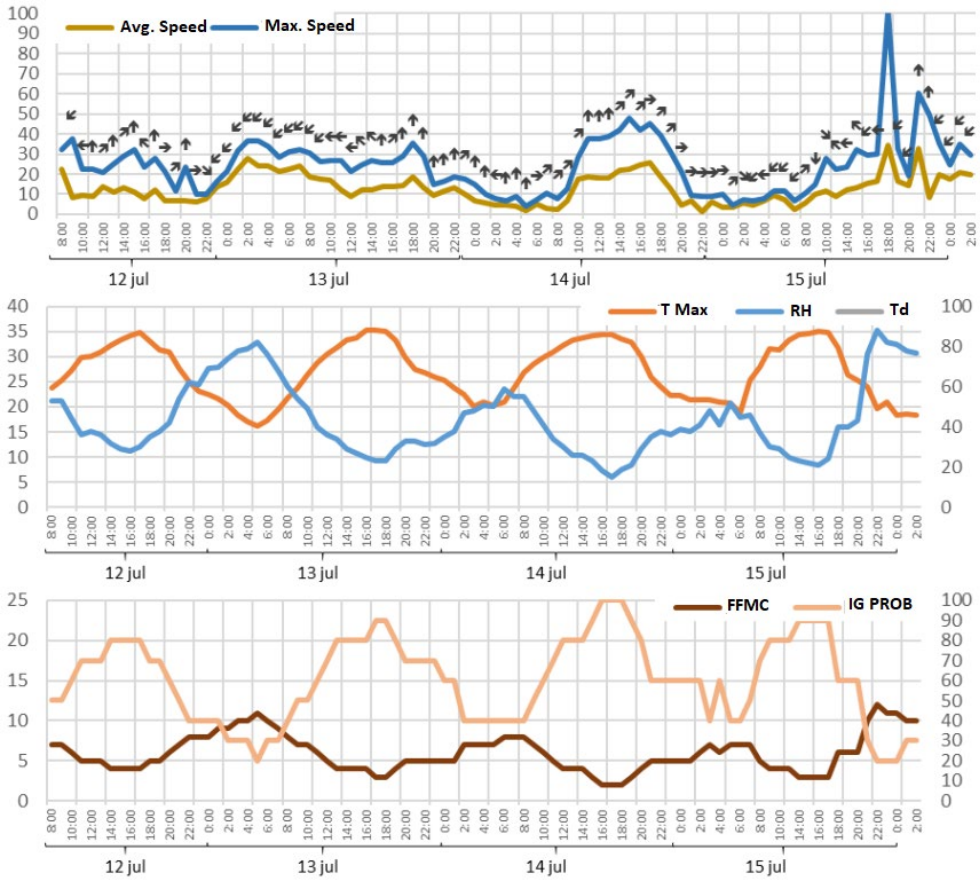


Figure 88. Meteorology station of Alcañices – 2966D, at 840 m above sea level (Right), during the previous days to the Losacio Fire (started on July 17th). A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB).

(a)

(b)

(c)



Sources: AEMet and Castilla y León Forestry Department.

9.6 Fire behaviour of Losacio Fire[3]

Fire propagation analysis was based on images and videos recorded by the coordination aircrafts during the fire suppression activities, as well as field information from fire brigades and forest rangers. Estimations of fire rate of spread are approximated, as propagation sometimes was very dispersed. However, a more detailed analysis of the fire propagation conditions, similar to the Riofrío fire, is not available.

It was observed that the fire had very diverse propagation pattern, with high propagation speed during the first hours of activity (Table 23 and Figure 89). The peak of extreme behaviour was observed in the second day of the fire, particularly between 17:30 and 19:00 of July 18th, when more than 3,300 ha/h were observed. Winds were predominantly from the South, and they changed directions several times during the extinction period.

Table 23. Summary of fire propagation parameters for the Losacio Fire.

1st hour	2nd hour	Area burned				Propagation			
		Total (ha)	Δ	Δ%	Speed (ha/h)	Main axis	Speed (km/h)	Speed (m/min)	Class
17/07/2022 18:00	17/07/2022 20:00	187.27	187.27	100.00	93.64	2151.26	1.08	17.93	High

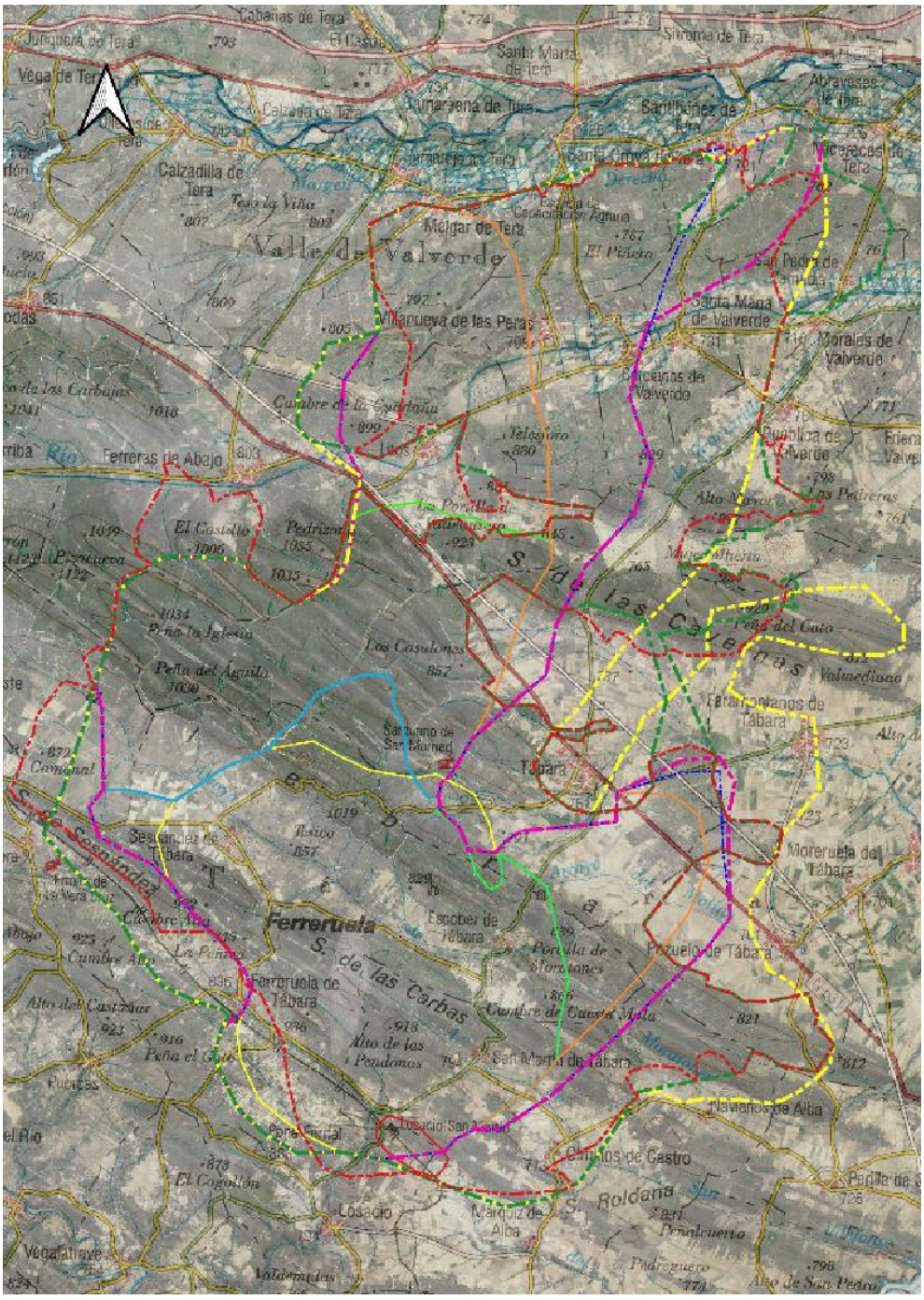
[3] We have used for this section the report prepared by fire authorities of *Junta de Castilla y León*, courtesy of Angel Manuel Sánchez and Francisco Javier Ezquerra.

17/07/2022 20:00	18/07/2022 3:00	8918.65	8731.38	97.90	1247.34	10635.05	1.52	25.32	High
18/07/2022 3:00	18/07/2022 8:00	9852.67	934.02	9.48	186.80	2535.5	0.51	8.45	High
18/07/2022 8:00	18/07/2022 13:30	15982.43	6129.76	38.35	1114.502	4890.74	0.89	14.82	High
18/07/2022 13:30	18/07/2022 17:30	22029.96	6047.53	27.45	1511.88	8561.27	2.14	35.67	Extreme
18/07/2022 17:30	18/07/2022 19:00	27102.1	5072.14	18.71	3381.43	6484.99	4.32	72.06	Extreme
18/07/2022 19:00	18/07/2022 22:00	28317.85	1215.75	4.29	405.25	4527.24	1.51	25.15	High
18/07/2022 22:00	19/07/2022 5:00	40277.11	11959.26	29.69	1708.47	3959.44	0.57	9.43	High
19/07/2022 5:00	19/07/2022 15:00	35941.66	-4335.45	-12.06	-433.55	-2519.15	-0.25	-4.20	Adjusted
19/07/2022 15:00	20/07/2022 15:00	33932.56	-2009.1	-5.92	-83.71	-3237.82	-0.13	-2.25	Adjusted

Source: Report on the fire by Junta de Castilla y León.

Figure 89. Fire growth of the Losacio fire following aerial photography and field reports. Yellow line: July 17th at 03:00; Light Blue line: July 18th at 08:00; Green line: July 18th at 13:30; Brown line: July 18th at 17:30; Dark Blue line:

July 18th at 19:00; Magenta line: July 18th at 22:00; Discontinuous yellow line: July 19th at 05:00; Discontinuous green line: July 19th at 15:00; Discontinuous red line: July 20th at 15:00.



Source: Report of the Forest Firefighting Service of JCyL.

9.7 Fire damage and burn severity

As indicated earlier the two large fires – Riofrío and Losacio Fires - were among the most extreme occurring in Spain, burning more than 25,000 and 34,000 ha, respectively, and creating a continuous immense burned patch. The fires caused four deaths and the evaluation of more than 3,000 persons in around 30 villages.

Our research group has performed field work over the affected area, to estimate combustion completeness (biomass consumed by the fire), mainly focused on the Riofrio de Aliste Fire and post-fire severity measured in both fires. Measures were taken almost one year after the fire, in May and June 2023.

Field measures allowed us to observe a great diversity of burning conditions in the huge area affected by the fire. The most intensively burned areas were located in moderate to high fuel loads and short pine trees, which were almost completely burned (Figure 90). Lower severities were found in those areas where coniferous forest was taller. These areas showed varying understory density, the lower density of understory was found in managed forests with higher tree heights, as the effect of the shadow limits the growth of shrubs. There were also areas where the fire showed lower intensity as indicated by the less affected understory formed mainly by heather (*Calluna vulgaris or Erica L.*) (Figure 90).

Burn severity was measured following the GeoCBI (Composite Burn Index) (De Santis and Chuvieco 2009). The GeoCBI considers a list of variables that are adapted to temperate and Mediterranean forests. It follows the hierarchical structure of CBI (Key and Benson 2006) dividing the vegetation in 5 strata (Soil and litter, vegetation < 1 m, vegetation 1-5 m, vegetation 5-20 m, and vegetation > 20 m), also introducing the consideration of the fraction covered by each stratum inside the plot.

In addition to GeoCBI estimates, we collected inventory measurements over 18 plots distributed across different burn severities, as well as unburnt plots. Field measurements included: diameter at breast height (DBH) of all the trees taller than 2 m, tree height of 10-20% of the trees, identification of species, and visual estimation of the percentage of biomass consumed in different biomass fractions (foliage, trunk, and branches diameter classes of: <2 cm, 2-7 cm, and > 7 cm). Moreover, four subplots of 2×2 m^2 were analysed in each plot to account for understory vegetation. These measurements will be used to estimate above ground biomass before and after the fire. In addition to these inventory field measurements, the plots were scanned using a terrestrial LiDAR system (TLS) and a drone Lidar system, to complement the field measurements for biomass estimations.

Figure 90. a) Post-fire situation in the central valley of the Riofrío de Aliste fire showing intense severity; b) Post-fire situation in the Southern mild slopes of the Riofrío de Aliste fire showing medium fire severity. (photos taken by Emilio Chuvieco in November 2022).

(a) *(b)*

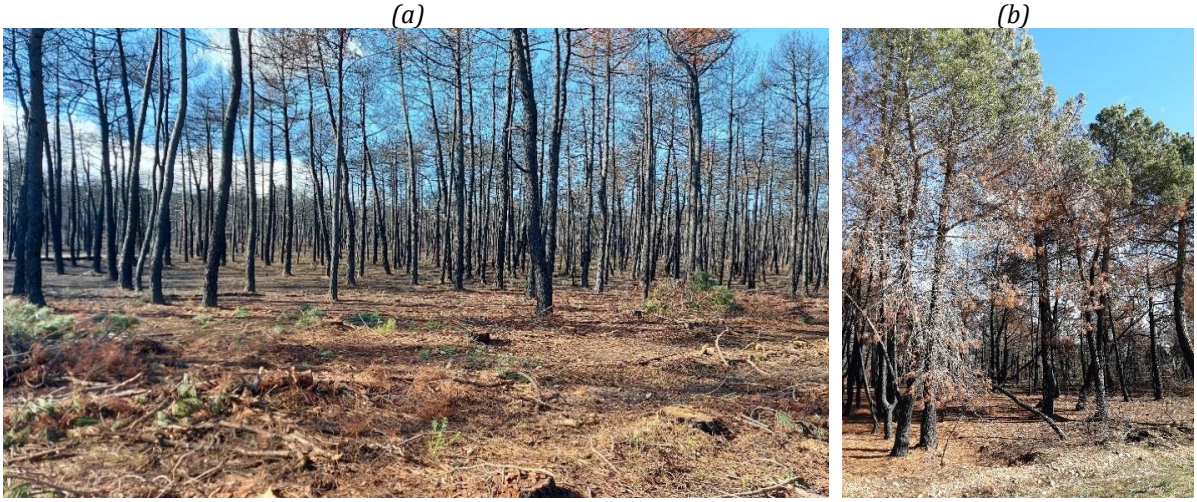


Figure 91. a) Post-fire situation in the north of Losacio fire showing intense severity; b) Post-fire situation in the North East of Losacio fire showing medium fire severity. (photos taken by Patricia Oliva in June 2023).

(a) *(b)*



Burn severity was computed following a simple approach based on changes in reflectance of two spectral bands after the fire. Following a standard procedure initially proposed by the USGS ((Key and Benson 1999)), we have used the changes in the Normalized Burn Ratio (NBR), which is a spectral index closely related to post-fire effects and defined by:

$$NBR = \frac{\rho_{SWIR} - \rho_{NIR}}{\rho_{SWIR} + \rho_{NIR}} \qquad \text{[Eq. 1]}$$

Where SWIR refers to the reflectance values in the SWIR (2-2 μm) and NIR (0-7-0.9 μm) bands. In this case, we used bands 11 and 8A from Sentinel 2 images, respectively. The burn severity then was computed as the temporal difference of NBR (dNBR) from before (t1) and after (t2) the fire:

$$dNBR = NBR_{t_1} - NBR_{t_2} \qquad \text{[Eq. 2]}$$

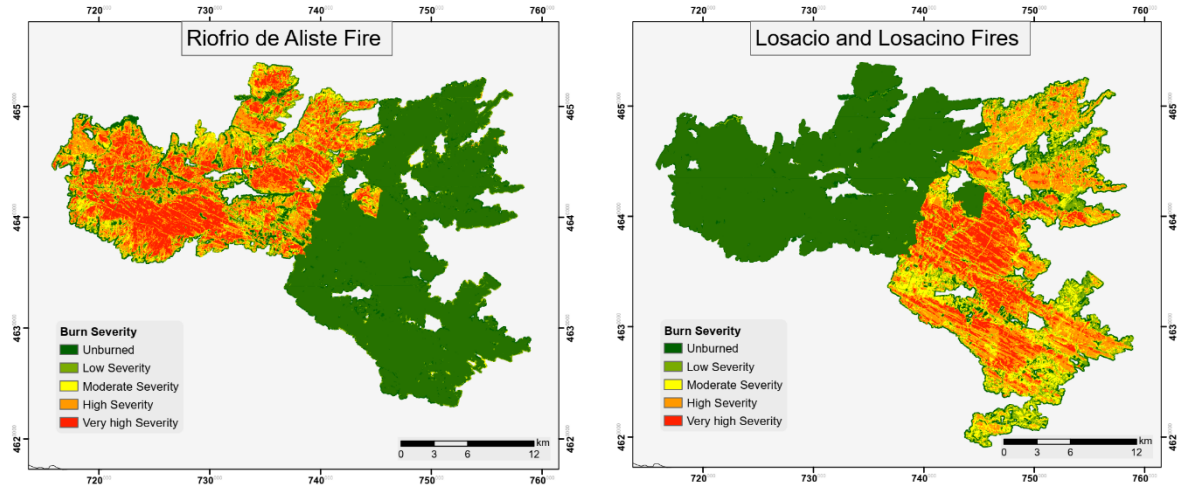
Once the difference was computed, the severity levels were classified using intervals adapted to the burn severity measured as CBI in the field based on the standard intervals of USGS (Key et al., 2006) (Table 24 and Figure 92).

Table 24. Burn severity classes derived from dNBR values obtained from Sentinel 2 data.

Severity level	dNBR range
Unburned	-0.1 - 0.99
Low severity	0.1 - 0.26
Moderate severity	0.27 - 0.469
High severity	0.47 - 0.66
Extreme severity	> 0.66

Figure 92. Burn severity estimation based on the difference in NBR for the Riofrío de Aliste fire (left) and Losacio fire (right), based on Sentinel-2 images. The Riofrio de Aliste estimation was computed by the difference between the NBR in the prefire date of May 26th and the postfire date of June 28th. The Losacio burn severity estimation was computed by the difference between the pre-fire image of June 28th and the postfire image of July 30th.

(a) *(b)*



In the Riofrio de Aliste Fire higher severities were found in dense forested areas mainly composed of *Pinus pinaster*, and shrublands. Lower severities were found in deciduous species such as *Quercus faginea* and in conifer forests with trees higher than 20 m. In the Losacio Fire higher severities were also found in dense conifer plantations located in areas with steep slopes. Lower severity values located in the north of the fire affecting holm oak (*Quercus ilex*) and cork oak (*Quercus suber*) forests and agro-forestry areas (*dehesas*) (Figure 93Figure 93)

The Riofrio de Aliste Fire affected a considerable area of productive forests in the region, mainly chestnut plantations, and mushroom production, which reduced the income of the people living there. We estimated an area of 354 ha of chestnuts plantations and 2,630 ha of *Pinus pinaster* plantation used for mushroom and wood production.

Figure 93. Affected chestnuts plantations in the Riofrío de Aliste fire were already resprouting in November 2022 on the right. (photos taken by Patricia Oliva in November 2022).

(a) *(b)*



1.1 Fire damage to cultural heritage

Even though most of the buildings in the affected area were protected from the fire, there were numerous effects over the cultural heritage present in the region. The Unit for Risk Management and Emergencies in Cultural Heritage (UGRECYL) from the Castilla y León regional government performed a thorough revision of the cultural heritage affected in Zamora by the fires of 2022. The cultural heritage considered are all the categories included in the protection law, which are: ethnographic heritage, architectonic heritage, historic

roads, cultural landscapes, industrial heritage, geologic and palaeontologic heritage, and archeologic heritage.

Fires have a direct impact on the cultural heritage, but it can also have an indirect effect due to an increase in the level of erosion over time that make them more susceptible to atmospheric and biological agents thus, increasing their degradation and hampering their conservation (Escudero 2023). On the other hand, some of the damages observed in cultural heritage is due to the operation activities of firefighters. These damages are related to the use of heavy machinery and the chemical retardant used to control the fire front.

The UGRECYL reported 73 cultural heritage sites affected in the Riofrio de Aliste fire and 43 in the Losacio fire, including Roman roads, ethnographic and architectonic heritage, and archeologic heritage. Figure 20 shows the severity of the damage inflicted upon historic buildings used for cattle.

Figure 20. Effect of the fire in architectonical heritage sites in Riofrio de Aliste fire.

(a) *(b)*



Data source: a) UGRECYL; B) Plataforma por la Defensa de la Arquitectura Tradicional de Aliste.

9.8 Lessons learned

Large Fires of "Sierra de la Culebra" occurred in very anomalous atmospheric conditions, with intense heatwaves and long dry periods, weeks before the fires, with one of the historically driest months of May in the region. Fires were fuelled by strong winds and benefited by anomalous high temperatures and night, which further complicated the extinction works.

Civil protection services were efficient. Evacuation was done in an orderly and timely manner, and therefore no major civil causalities occurred. One firefighter died in the extinction activities and 3 civilians died because of severe wounds in trying to protect their own properties.

Post-fire severities observed were very dependent on the managing conditions of the forest. Those areas where forest management favoured the cleaning up of heliophilic shrubs, which greatly reduced the understory density, and where pine-trees were more mature had much less severity that areas with more understory and lower pine trees. Even with a dense cover and drought conditions, deciduous trees were less affected by the fire than pine trees. Within deciduous, chestnuts plantations were generally much less affected, as they are more intensively managed and therefore had much less understory than natural broadleaf forest.

The impacts on cultural heritage must be considered in the analysis of the fire effects since due to the rich historic culture of Europe there are many ethnographic, architectonic, and archeologic heritage dispersed in the rural areas. To improve their preservation the fire brigades should be informed of the most vulnerable areas to avoid their destruction.

References

De Santis, A., & Chuvieco, E. (2009). GeoCBI: A modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data. Remote Sensing of Environment, 113, 554–562.

Escudero, C. (2023). Forest fires and cultural heritage: protection strategies in Castilla y León. In ProCultHer-Net Technical Bulletin. Union Civil Protection Knowledge network. European Union. Issue 2, pp. 54-66. (https://civil-protection-knowledge-network.europa.eu/system/files/2023-06/PROCULTHER_NET_TECHNICAL_BULLETTIN_N2.pdf)

Junta de Castilla y León (2022): Informe simplificado del incendio forestal Riofrío de Aliste (Zamora).

Junta de Castilla y León (2022): Informe simplificado del incendio forestal Losacio (Zamora).

Key, C., & Benson, N. (1999). The Normalized Burned Ratio, a Landsat TM radiometric index of burn severity incorporating multi-temporal differencing. In: U.S. Geological Survey (http://www.nrmsc.usgs.gov/research/ndbr.htm).

Key, C.H., & Benson, N. (2006). Landscape Assessment (LA). Sampling and Analysis Methods. In D.C. Lutes, R.E. Keane, J.F. Caratti, C.H. Key, N.C. Benson, S. Sutherland, & L.J. Gangi (Eds.), FIREMON: Fire effects monitoring and inventory system. Integration of Standardized Field Data Collection Techniques and Sampling Design with Remote Sensing to Assess Fire Effects (pp. LA1-LA51). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Ninyerola, M., Pons, X., & Roure, J. (2005). Atlas climático digital de la Península Ibérica. Metodología y aplicaciones en bioclimatología y geobotánica. Bellaterra: Universidad Autónoma de Barcelona. In: Spain: Universidad Autónoma de Barcelona (http://www.opengis.uabes/wms.

10 Fire of Karst (Italy/Slovenia)

Authors

Ramona Velea	ISIG
Riccardo Laterza	ISIG
Marco De Lucia	ISIG
Paola Lorenzoni	ISIG
Bachisio Arca	CNR-IBE
Michele Salis	CNR-IBE
Valentina Bacciu	CNR-IBE
Liliana Del Giudice	CNR-IBE
Grazia Pellizzaro	CNR-IBE
Pierpaolo Duce	CNR-IBE



10.1 General Description

10.1.1 Introduction

The Karst wildfire (Carso – Italian, Kras – Slovenian) refers to the set of main wildfires that affected the Karst region, located between Friuli Venezia Giulia (Italy) and Slovenia, in the period from July 15th to the first days of August. The Karst wildfire is in fact the result of different and independent fire events, some of which converged into the same area/burned perimeter in the Slovenian and in the Italian territories. The Karst wildfire affected an area of about 4,450 ha, the majority of which (about 3,600 ha) was in Slovenia: in fact, this wildfire represents one of the worst events ever observed in in the cross-border Karst area and overall, in Slovenia. Moreover, a significant portion of the burnt area by the Karst wildfire is part of Natura2000 sites.

The Karst area is historically known for the violent battles between Italian and Austro-Hungarian troops, during World War I. This explains the presence of unexploded bombs, many of which originated detonations and posed safety issues to the operators who were working to contrast the fire spread in both Italian and Slovenian areas. For instance, according to the estimations and data provided by the Slovenian fire management forces, over 500 detonations were detected at the fire sites in Slovenia during the suppression interventions.

The wildfire affected several municipalities in Italy (namely Doberdò del Lago, Savogna d'Isonzo, Monfalcone, and Duino Aurisina) and Slovenia (Renče- Vogrsko, Komen, Miren – Kostanjevica) (Figure 94). The municipality that was mostly affected by the Karst wildfire was Miren – Kostanjevica, with about 3,000 ha of burned area, that is approximately 48% of its municipal area. On the Italian side, the most affected municipality was Doberdò del Lago, with about 589 ha burned (22% of the municipal territory).

10.1.2 Note on the methodology

The present report outlines some of the main features related with the 2022 Karst wildfire. The complexity of this event, due mainly to its cross-border dimension (further described in this report), led to the following methodological choices:

- Use of both qualitative and quantitative data sources.
- Need of validation of the emerging analysis with a representative panel of experts.

Moreover, the data collection and validation were based on the following steps:

- Identification and review of relevant official and technical documents provided by agencies and institutions involved in different ways in the issues at stake (such as Friuli Venezia Giulia Region Forestry Corps, or Slovenian firefighters – Gasilci).

- Organisation of in-depth, semi-structured interviews with Italian and Slovenian emergency operators and validation of the related contents. The interviewees are mentioned in the Acknowledgements at the beginning of the report.
- Organisation of further feedbacks activities involving the above-mentioned interviewed operators, and other relevant actors in the field are foreseen after the publication of the Report.

The above descripted structure is designed to address the overall complexity and some specificities of the selected case study, namely:

- The complexity and the peculiarities deriving from the cross-border dimension of both the physical and socio-economic context of action, the wildfire dynamic, and the firefighting response envisioned and operationalised in the field. Such complexity encompasses the articulation of the multi-agency emergency response governance structure.
- The novelty of the event in the Karst context, giving the fact that, despite the relatively low impact of the wildfire (no loss of human lives and low impact in terms of destruction of anthropic areas), the area has never witnessed a fire of this magnitude in recent history. This feature oriented the research towards more qualitative findings, rather than quantitative/technical data, focusing for instance on land uses or the reaction of local population to the event.

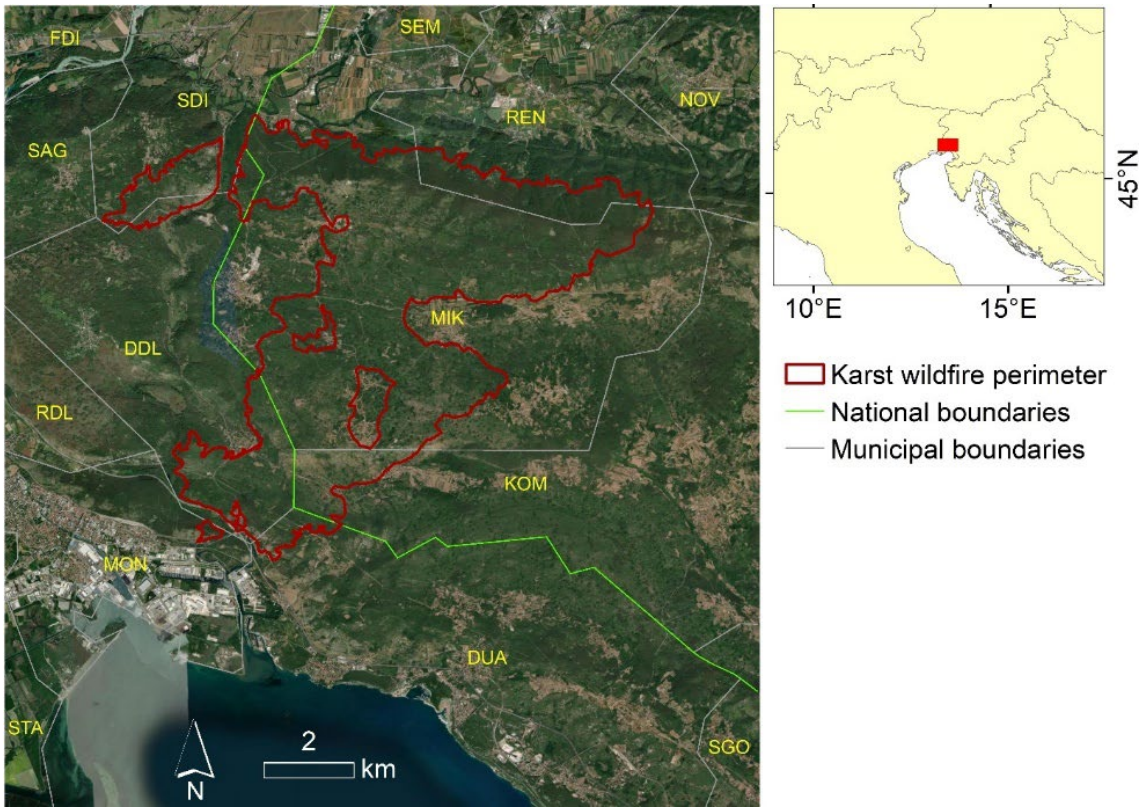
10.2 Topography, vegetation, and land uses of the affected area

The Karst region is a rocky calcareous plateau extending from north-eastern Italy (Friuli Venezia Giulia) to southwestern Slovenia. The Karst tends to gradually rise in elevation from the southwestern area (Gulf of Trieste area) to the northern and western parts of the plateau. The average elevation of the Karst plateau is approximately 330 m a.s.l., with a large part of the area presenting elevations between 100 and 450 m a.s.l. The highest peak of the Karst is represented by the Trstelj hill, which reaches approximately 640 m a.s.l (Figure 95a).

Due to the high presence of superficial stones and rocks and the reduced presence of soil, these areas tend to dry-out rapidly in the summer months and after the occurrence of heat waves. The dryness conditions of the summer months, the limited land and forest fuel management, and the occasional windiness (in fact, although not a constant nor stable variable, the strong ventilation represented one of the crucial factors contributing to the intensity of the Karst wildfire) make the area one of the most fire-prone in Slovenia and Friuli Venezia Giulia (Italy).

Figure 94. General map of the Karst area, including the 2022 wildfire perimeter and the administrative municipal boundaries. DDL = Doberdò del Lago, FDI = Farra d'Isonzo, MON = Monfalcone, RDL = Ronchi dei Legionari, SAG =

Sagrado, SDI = Savogna d'Isonzo, STA = Staranzano, DUA = Duino Aurisina, SGO = Sgonico, SEM = Šempeter- Vrtojba, REN = Renče- Vogrsko, KOM = Komen, MIK = Miren – Kostanjevica, NOV = Nova Gorica.

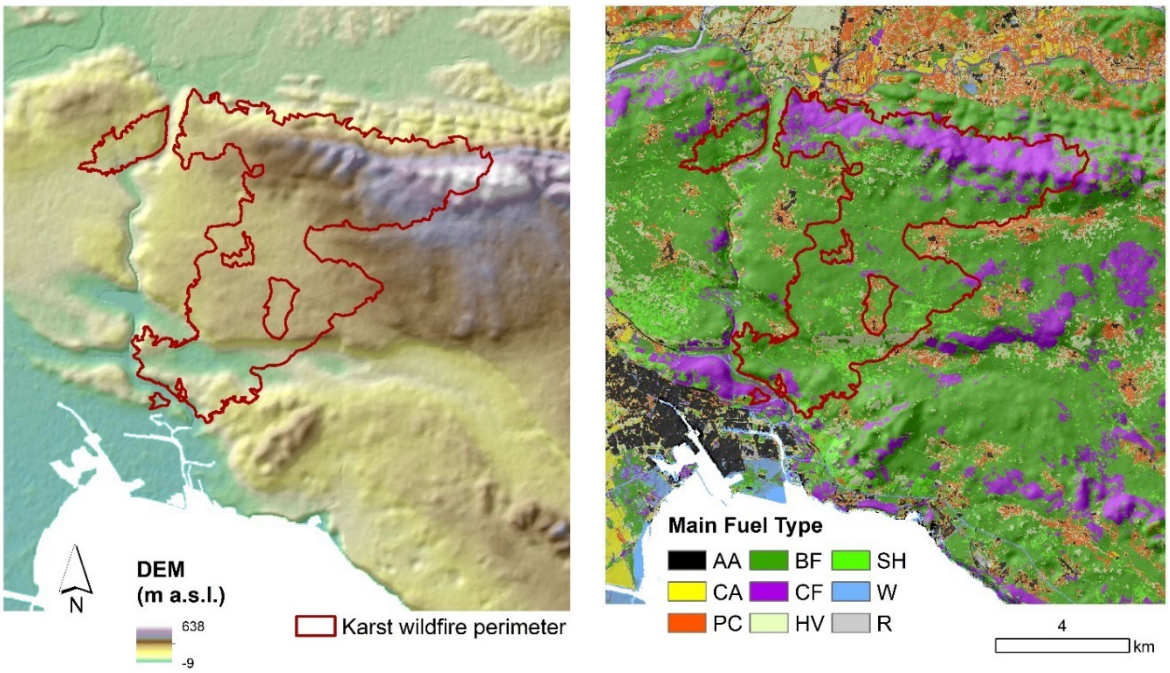


Data Source: Esri, Maxar, GeoEye, EarthStar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Fire perimeter based on EFFIS Data and Reports of burned areas provided by the FVG Region.

Regarding the vegetation, the Karst region has changed profoundly over the past centuries. Until about a century and a half ago, the Karst was a relatively bare plateau largely covered with herbaceous fuels (dry in the summer months) and a few shrublands. Agriculture was mostly characterised by pastoralism and stable livestock; vineyards and olive groves were confined in the most fertile and in the less exposed to winds areas. Around the mid-19th century, under Austro-Hungarian rule, a process of afforestation with black pine was carried out in some areas of the Karst: this species was able to adapt well to the weather and soil conditions of the stony plateau. The original black pine plantations were regular and covered only a few areas of the Karst region. As agricultural and pastoral activities in the area decreased over time, with the inherent decrease in herding, wood cutting and fuel control, forests and shrubs progressively occupied the Karst lands and moved closer to urban and anthropic areas. Another recent change to the Karst vegetation is related to Juniperus spp., once very present in the Karst but now less widespread, and often replaced by Rhus spp. (sumac), which presents high potential in promoting spot fires.

Figure 95. a) Digital elevation model of the Karst area. b) Main fuel types of the area affected by the Karst wildfire. AA = anthropic areas; CA = cultivated areas; PC = permanent crops; BF = broadleaf forests; CF = conifer forests; SH = shrub vegetation; SV = sclerophyllous vegetation; W = wetlands; R= rocks. The map is derived from the Land Use Map of Europe 2017.

(a) *(b)*



Data Source: Malinowski et al. 2020.

Nowadays, the Karst vegetation is dominated by black pine forests, low-height trees, and shrubs, which are expanding rapidly and covering the former grasslands and meadows. Grasslands and meadows are quite fragmented and are not as extensive as in the past. Mature broadleaf forests are primarily represented by *Quercus petraea* and *Carpinus betulus*, even if they cover limited extent of lands; *Quercus pubescens*, *Ostrya carpinifolia* and *Fraxinus ornus* are also present in the Karst region. Another element to highlight is the high anthropization of the territory, which affects as arson fires as well as fire ignitions due to accidental causes and negligence. For instance, the railway between Monfalcone and Trieste was a source of fire ignitions due to malfunctioning train braking equipment, which can promote multiple ignitions distributed over hundreds of meters.

The Karst wildfire mainly affected forest fuels (Figure 95b): about 2,850 ha of the burned area was covered by broadleaf forests and about 930 ha by coniferous forests. Shrublands accounted for about 7% of the burned area. The remaining fuel types (8% of the burned area) affected by the event were herbaceous vegetation, permanent crops, and cultivated areas.

The Karst territory is highly anthropized: at the same time, relevant changes in the use of forest areas through decades have had an important influence on both the dynamics of fire ignition and its development into actual fires, as well as over the possibility of implementing traditional fire risk management strategies. The abandonment of the territory, and the decrease of traditional economic activities such as herding and wood cutting, does not have a specific influence on the triggering of the fire, but rather on its speed of development and on its intensity, as well as on the difficulty of tackling it and protect local population from its direct and indirect impacts. In fact, such traditional economic activities, which used to have an important role in controlling local fuel availability, have decreased over time. Nowadays the pastures, which once constituted the most frequent wildland-urban interface, are replaced by highly flammable vegetation, such as shrubs. The abandonment of territory, thus, results in a greater surface area and a greater quantity of fuel available for fires. Furthermore, forest paths and roads which used to be cleaned and maintained for the benefit of local populations, are now less used; this determines less accessibility to high-risk areas, especially for rescue services. Moreover, the abandonment of Karst environment determines a lower awareness of fire risk by local population, as the natural areas are less experienced.

The presence of the railway line, which runs in Italian territory between Monfalcone and Trieste, is another relevant feature when discussing about Karst land uses. Very often fires are caused by malfunctioning train braking equipment, which generates sparks or leaks of incandescent material in multiple spots along the railway line.

Another statement expressed during the interviews is that, taking into consideration the decrease in caring towards the land by local populations, laws often do not enforce public authorities in implementing

practices that used to be traditionally carried on by local inhabitants – such as prescribed burnings – and that would still contribute nowadays to fire risk prevention.

10.3 Fire weather conditions

To better understand the state of dryness of the vegetation in the Karst area, one of the primary factors in this event, a summary of the weather conditions in the months before the Karst event is presented.

In terms of precipitation, the Regional Agency of Environmental Protection of Friuli Venezia Giulia estimated that the cumulative rainfall over the period July 2021-June 2022 was 50% or more lower than the average values observed in the past 10 years.

As far as temperatures are concerned, the months of May, June, and July were approximately 2-2.5°C warmer than the average values recorded in the past 10 years. On July 21st, 22nd, and 23rd, the most of meteorological stations in Friuli Venezia Giulia observed the highest temperatures for the year 2022; for some of them (Pordenone; Cividale; Bicinicco), the new historical maximum temperature records were observed in those days.

The largely above-average temperatures are confirmed in Slovenia: July 2022 was the second warmest month since 1961, with average temperatures 2.5°C above the climatological values at the Country level, and peaks of +4°C than the average monthly values in Nova Gorica: in this town, temperatures above 35°C for seven days in a row were observed in the second half of July.

The month of July 2022 started with a strong heat wave, caused by the extension of a North African anti-cyclone to the Alps. In mid-July, synoptic conditions were characterised by strong stability, thanks to the protrusion of the anti-cyclone from the west over the Alps: the thermal zero had risen to over 4500 m altitude and the sky was basically clear. Very high temperatures were recorded in the lowlands on July 15th, with almost 35°C, but a few thunderstorms were observed in the mountains. From July 17th to 20th, the weather conditions were stable with clear or slightly cloudy skies, maximum temperatures around 35°C in the plains and in the range 30-32°C on the coastal areas. From July 21st to 25th, the North African anti-cyclone reinforced its presence in Italy and neighbouring Countries, causing a phase of protracted heat wave, with 20°C at 850 hPA in eastern Friuli Venezia Giulia, and maximum temperatures at the ground in the range 35-40°C in the plains and 30-35°C on the coast. Only on July 23rd, some scattered thunderstorms affected the mountains and partially also lowlands and coastal areas.

To describe the meteorological conditions during the main phases of the Karst wildfire, weather data were gathered from a meteorological network of weather stations of ARPA Friuli Venezia Giulia. The main station used is in the municipality of Gradisca d'Isonzo, in a flat area located about 7 km west of the eastern perimeter of the Karst wildfire; this weather station was considered a good representative of the weather conditions that influenced the Karst wildfire, due to of its proximity to the area affected by event. In addition, data from reanalysis ERA5-LAND referred to the central area of the Karst plateau were used.

On July 15th, during the early stages of the Miren event, the weather conditions provided by the Gradisca station were moderately severe, with maximum temperatures of 32°C and minimum relative air humidity around 26% (Figure 98). Maximum wind intensities recorded were around 4 m/s, with prevailing directions around 240-280° (Figure 99). The second step of the Miren fire (July 19th to 20th) was characterized by more severe weather conditions, particularly those recorded by the Gradisca station, with temperatures around 35-36°C and much lower minimum relative humidity (22-23%) than the previous days (Figure 98). The wind speed was slightly higher, with 5 m/s intensity and prevailing directions fluctuating between 250° and 300° (Figure 99).

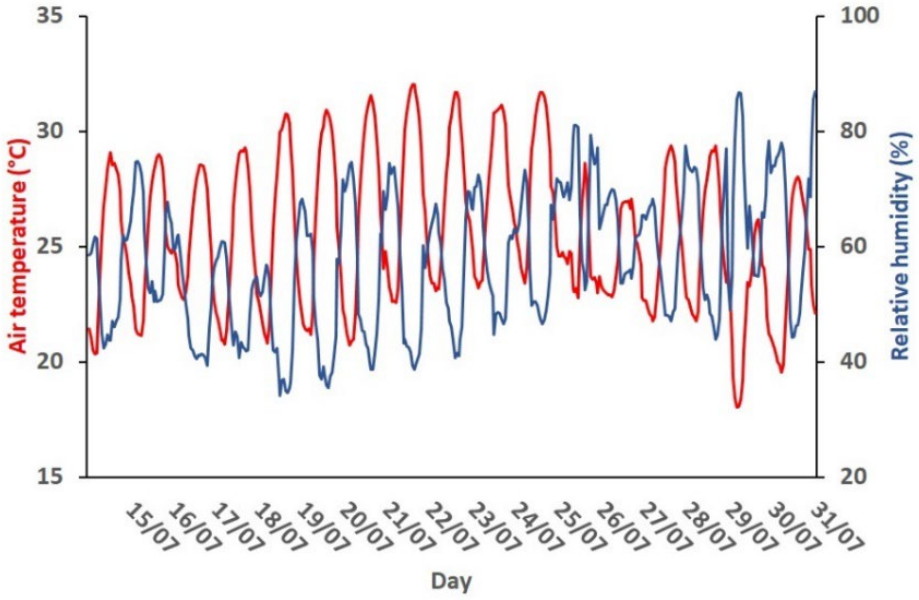
The Renče fire, which propagated simultaneously to the to the Miren fire, was characterised by more severe wind intensity conditions on the first day (July 17th), during which the Gradisca weather station detected wind intensities of 6-7 m/s, later decreased to 5 m/s in the afternoon, and prevailing directions from NE-ENE (Figure 99). Due to these conditions and the orography of the Karst plateau, the wildfire in fact spread in a westerly direction, with a sustained spread rate and generating an elongated ellipsoidal burned area. The wind field conditions were also confirmed by the ERA5-LAND reanalysis data, which indicated wind intensities of 6 m/s and prevailing wind directions around 70-100° (Figure 97).

Regarding the Monfalcone fire, which later joined the other fires contributing to the final perimeter of the Karst wildfire, severe temperature conditions were observed on July 20th, 21st and 22nd, with increasing temperatures (above 35°C) and very low minimum relative humidity values (22-24%). Wind conditions, on

the other hand, were moderate, with intensities on the order of 4-5 m/s and prevailing directions from the southwest, rotating from the eastern quadrants on July 24th.

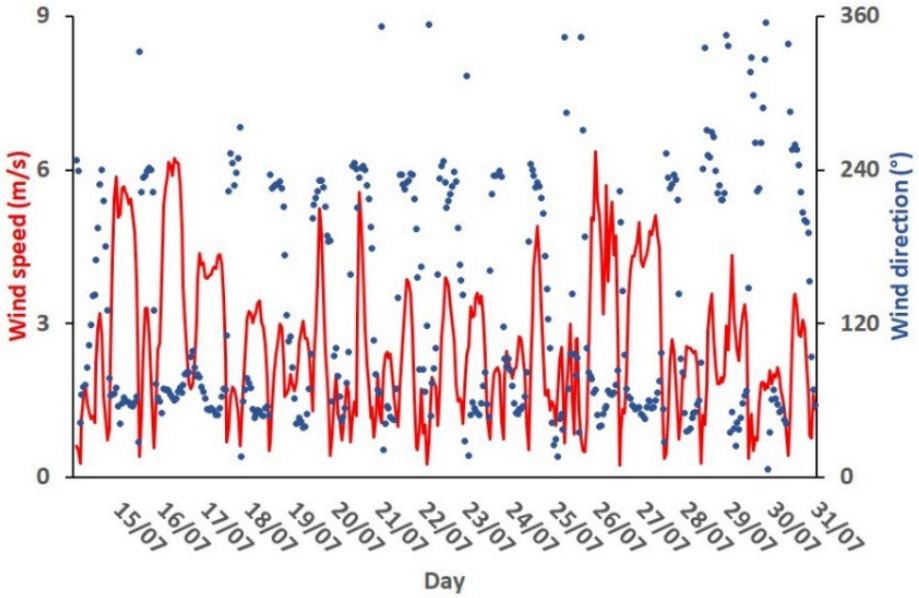
The last step, represented by the Brestovec fire (July 27th-29th), took place with initial severe conditions of wind intensities (6-7 m/s) and prevailing directions from the eastern quadrants, which contributed to the prevailing west-south-west propagation of the fire; while on July 29th a wind rotation to southwest, with significantly lower intensities (3-4 m/s), was observed. During this final day, the conditions of maximum temperatures (31-33°C) and relative humidity (32-38 %) were not particularly severe.

Figure 96. Hourly values of air temperature and air relative humidity provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st.



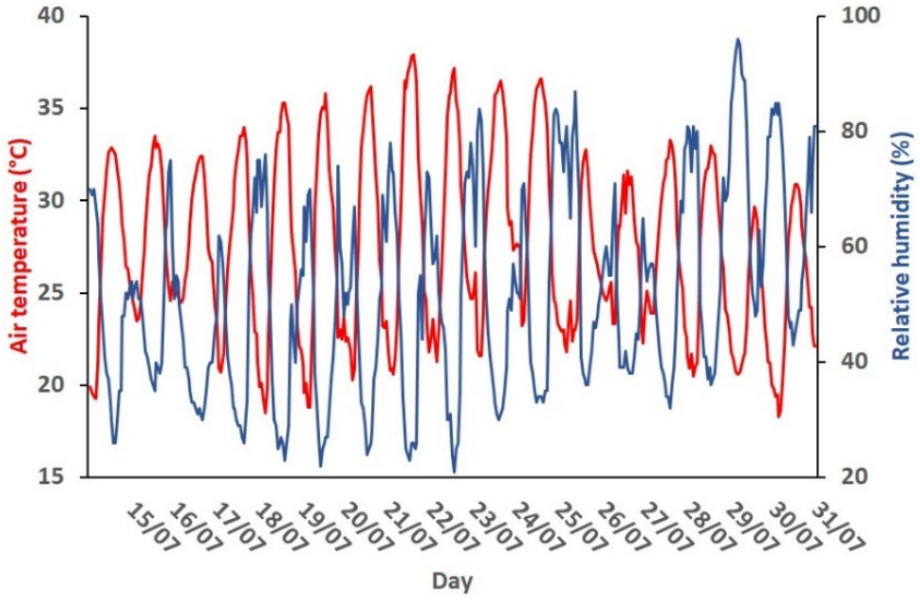
Data Source: Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Figure 97. Hourly values of wind intensity and direction provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st.



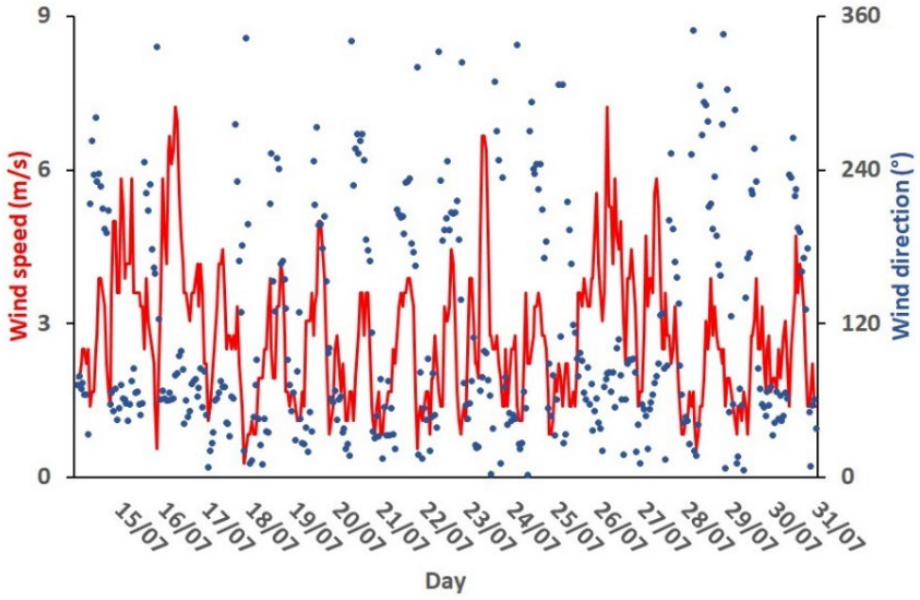
Data Source: Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Figure 98. Hourly values of air temperature and air relative humidity measured by the weather station of Gradisca from July 15th to 31st.



Data Source: Regional Meteorological Observatory, Regional Environmental Agency (ARPA) of Friuli Venezia Giulia.

Figure 99. Hourly values of wind intensity and direction measured by the weather station of Gradisca from July 15th to 31st.



Data Source: Regional Meteorological Observatory, Regional Environmental Agency (ARPA) of Friuli Venezia Giulia.

10.4 Fire Development and Operational Response

As anticipated in the introduction, the Karst wildfire indicates several independent but converging fires, which affected a transboundary area between Slovenia and Italy from mid-July to the first days of August, and together contributed to affect a burned area of about 4,450 ha, mainly located in the Slovenian territory.

To describe the Karst wildfire development, we will differentiating four main sub-events of the whole wildfire[4]:

1. The first fire that occurred on July 15th in the municipality of Miren-Kostanjevica, in Slovenia, along the road Miren-Opatje Selo (Miren fire, see 10.4.1).
2. The fire that occurred on July 17th along the Renški vrh-Temnica road, in Slovenia (Renče fire, see 10.4.2).
3. The fire that occurred on July 19th along the Trieste Monfalcone railway line, in Italy (Monfalcone-Jamiano fire, see 10.4.3).
4. The fire that occurred on July 27th in the municipality of Doberdò del Lago, close to the Brestovec mountain, in Italy (Brestovec fire, see 10.4.4).

In the following paragraphs, each fire will be presented in more detail, based on the analysis performed by Commander Simon Vendramin (Vendramin, 2022).

It is worth noting that the general setting of the operational response has been structured along the main objectives of protecting human lives (including those of the operators) and secondly protecting, as far as possible, material assets and the environment, keeping in mind the close connection between the former and the latter, especially in a WUI area such as the Karst. Implicitly, another objective has been to avoid the emergence of further emergency scenarios, especially with respect to critical infrastructures.

The strategy for achieving these objectives had to measure itself against four characteristics of the Karst wildfire:

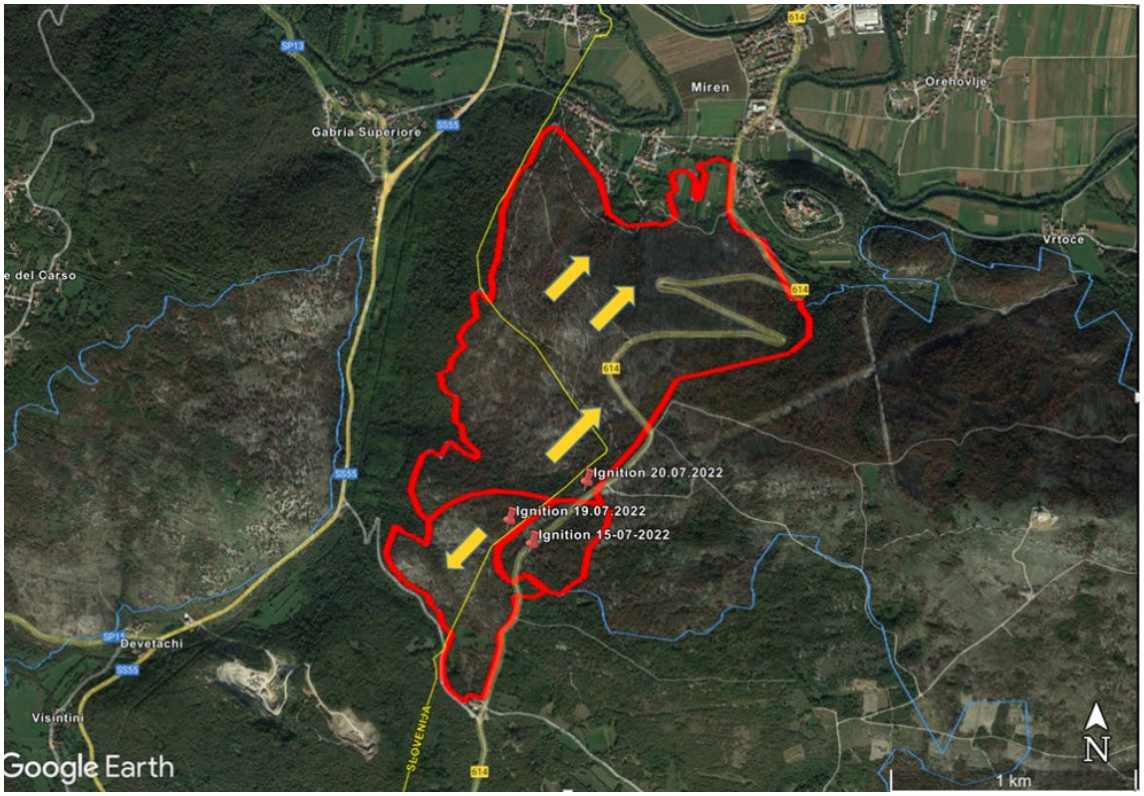
- The emergence of numerous widespread fire triggers, deriving from spotting fires, i.e., sparks which, with the help of the wind, travel even tens of meters away, triggering new outbreaks.
- The strong speed of propagation of the fire determined not only by the weather conditions (temperature, wind), but also by the peculiar conformation of the Karst Plateau.
- The presence of critical infrastructures (highway, state road, railway, power lines, methane pipelines) in the "bottleneck" of the Lisert area, between Monfalcone and Duino.
- The serious risk posed by the presence of unexploded war devices along the war front that ran through the Karst area.

10.4.1 Miren Fire

The first event, the Miren fire, was ignited in the municipality of Miren-Kostanjevica, near the regional road Miren-Opatje Selo, in Slovenia. The fire started on July 15th at about 16:10 in different points between the intersections of the villages of Cerje and Lokvica, in Slovenia at a very short distance from the border and close to the 400kV high-voltage international transmission line Redipuglia–Divača (Figure 104a). Several firefighting units were rapidly activated by the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief – Regional dispatch center (112), and the fire was contained and was defined under control in the evening hours and supervised during the night and the following day. The burned area during this first event was of about 11 ha, consisting mainly of mixed deciduous and coniferous forests and located entirely in the Slovenian territory (Figure 100). Two helicopters of the Slovenian Armed Forces and of Friuli Venezia Giulia Region contributed to successfully limiting this fire. The activation of the intervention of the Friuli Venezia Giulia Region helicopter was possible thanks to the Protocol on Cross-Border Cooperation between the Protection and Rescue Administration of the Ministry of Defence of the Republic of Slovenia and the Civil Protection of the Autonomous Region of Friuli Venezia Giulia.

[4] Other wildfire events involved areas close to Trieste, in the Italian Municipalities of Monrupino/Repen, Trieste, Sgonico/Zgonik, and San Dorligo della Valle/Dolina. Between 9th and 12th August, a significant cross-border wildfire hit the area of San Dorligo della Valle/Dolina. Being detached from the other fires described in the following paragraphs, these events were not considered for the purpose of this report, for the sake of brevity.

Figure 100. Map of the three main steps of propagation of the Miren fire (in red). The ignition points of the different steps are showed, together with the main directions of propagation. The final perimeter of the Karst wildfire is also showed (in blue).



Data Source: Image elaborated by CNR based on information collected from Vendramin (2022).

In the morning of July 19th, at about 12:00, there was a re-ignition of the Miren fire, in the proximity of the power line (Figure 100). The fire immediately turned into a crown fire and started spreading towards south-west and crossed the Italy-Slovenia border. Given the extent of the event, and the fact that forces on the ground were previously deployed in firefighting activities in the southern fire front area, it was agreed that the Slovenian forces would take over the fire. The fire extinguishment operation was supported by two helicopters and a PC-6 of the Slovenian Armed Forces and a helicopter of the Slovenian Police, and later by a helicopter and a Canadair from Italy. On the eastern side of the fire area, along the main road Miren–Opatie Selo, a backfire was carried out, all buildings were protected, and the main vehicles were moved to the Lokvica-Devetaki road, where the fire was contained.

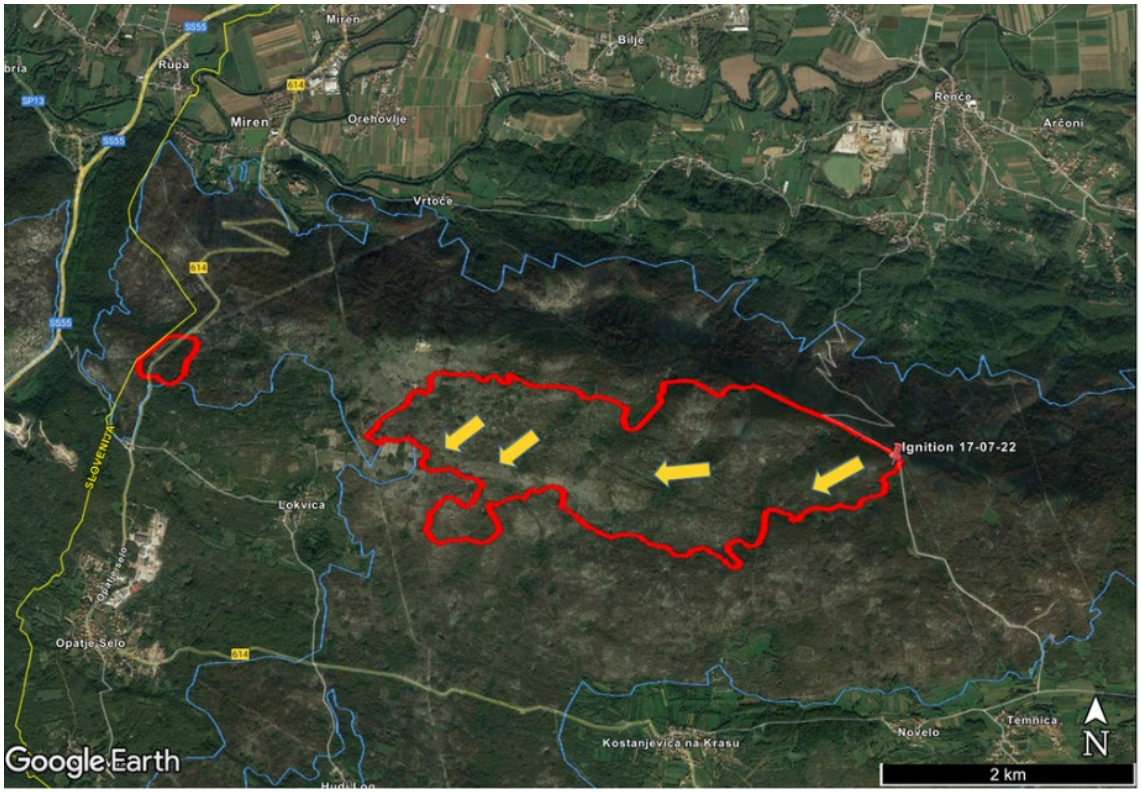
A new re-ignition of the Miren fire was observed on July 20th, at around 14:15. The fire crossed the Miren-Opatje Selo Road and propagated at high spread rates in the direction of Miren (Figure 104b). The fire took only 15 minutes to reach the valley from the top of the slope and the village was reached by the flames in the evening. An evacuation order was issued for people staying in the area immediately adjacent to the road Miren-Opatje Selo, nearby Miren. Some tankers arrived on the scene and were deployed to the fire front. On the whole, the Miren fire affected an area close to 185 ha.

10.4.2 Renče fire

The second event, the Renče fire, occurred on July 17th at about 09:50, near the Renški vrh-Temnica road, in Slovenia, 12 km east of the first fire of Miren (Figure 101 and Figure 104c). Immediately after the fire detection, two firefighting units from the Miren-Lokvica fire station were diverted to this fire and based on the assessment of the fire and the smoke column, a request to activate additional forces was made. Due to the windy conditions and the fuel dryness, the fire affected with high intensity the understory of the pine forest, and in some parts also spread as crown fire and started to spread very quickly towards west. Firefighting units from the nearby Fire Brigades Municipalities (Vipava, Ajdovščina, and Komen) and from the North Primorye Firefighting Region were activated. Air forces were also activated, namely a helicopter

of the Slovenian Army and another one from Friuli Venezia Giulia Region, in accordance with the protocol on cross-border cooperation. However, the available activated forces were unable to contain the fire spread. Therefore, at 13:30, the activation of the National Plan for Major Fire in the Natural Environment was requested. In this context, the activation of other Unions Brigades (Postojna and Karst) as well as the firefighting units from the Notranjska Firefighting Region was requested, to replace the forces that were in the field overnight. A request for a Canadair was also made through the EU assistance mechanism. The National Unit for Unexploded Ordnance (NUS) went to the area due to presence of old unexploded weapons in the fire area. Due to the danger posed by these weapons, the complex terrain, the limitations in safely accessing and moving in the area with fire trucks, and the fire spread rates, the firefighting tactics were set to stop the fire nearby roads. The rate of spread of the fire was approximately 8.5 m/minute and, shortly after 16:00, a Croatian Canadair plane flew over the fire site for the first time. Effective firefighting interventions were carried out in the NE flank of the fire, where (due to favourable weather conditions) the hill ridges were secured with a tactical wildfire of about 1.5 km in length. The fire was successfully contained in the late evening of July 17th.

Figure 101. Map of the three main steps of propagation of Renče fire (in red). The ignition point of the fire, together with the main directions of propagation, is also included. The final perimeter of the Karst wildfire is showed in blue.



Data Source: Image elaborated by CNR based on information collected from Vendramin (2022).

Mop-up of the fire perimeter began in the night, although the fire rekindled in the western front (near the Borojević chair) and spread towards the village of Lokvica. The fire brigades stopped the fire 500 m before the village of Lokvica and along the road Lokvica-Cerje. Further clearing and watering of the fire area were carried out during the next day, with the aerial assistance provided by five helicopters (two from the Slovenian Army, tow from Friuli Venezia Giulia and one from Slovenian Police). In the morning of July 19th, the fire was under control. Overall, the Renče fire burned about 350 ha of land.

10.4.3 Monfalcone-Jamiano fire

On July 19th, at about 10:00, fire ignitions and smoke columns were observed in the eastern side of the Monfalcone municipality, in Italy (Figure 104d). The fires occurred along the Trieste-Monfalcone railway line, in three distinct outbreaks near the villages of Duino, Aurisina, Sistiana, and Medeazza (Figure 102).

Italian firefighters from the station of Monfalcone, with the support of aerial forces, extinguished almost all the fires along the railway line where rail traffic was previously suspended. This operation saw the coordinated intervention of many operational forces coordinated by the Gorizia Rescue Coordination Centre. In the area close to Medeazza the fire continued to spread towards north-west (near Sablici, where the advanced command point was established, and where 15 residents were evacuated) and in the evening overcame the Italy-Slovenia border, descended downslope towards the Jamiano-Brestovica road, and threatened homes in Jamiano the following day at 12:00. In more detail, Jamiano, a hamlet of Doberdò del Lago, in Italy, was heavily affected by this fire, with the flames spreading across the local cemetery and menacing several houses and buildings, and the need of temporary evacuation of houses at risk.

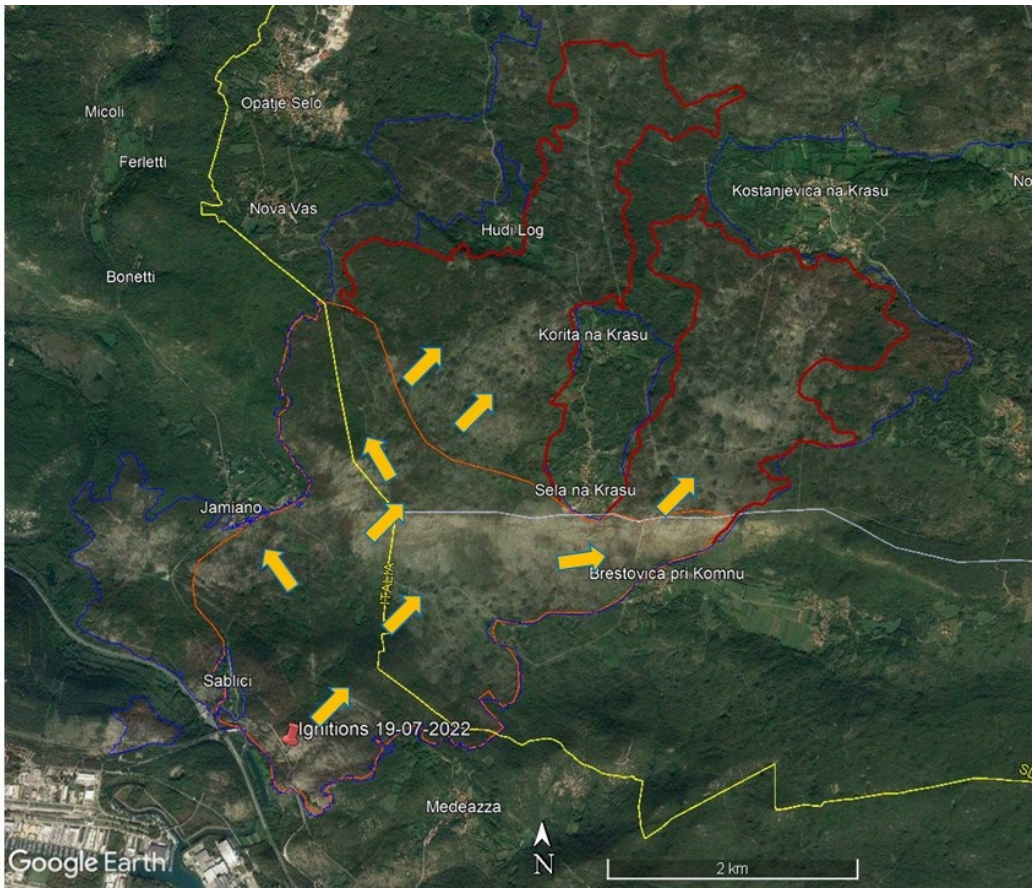
During the same morning, three helicopters started operating to extinguish this fire front in Slovenia. As the fire was approaching the villages on the plateau very quickly, an evacuation order was issued for the villages of Korita na Krasu, Hudi Log, Sela na Krasu. The event venue in Opatje-Selo was designated as an evacuation site. An additional request for air support from foreign countries through the Union's protection and rescue mechanism was made by Slovenian authorities. At around 13:05, the first houses in the village of Sela na Krasu were already threatened by the fire and, due to the high level of smoke in the area, the requests of emergency medical needs,ong firefighters and citizens, increased. Additional units, including medical personnel, were activated. At 14:10, the fire jumped across the road at Brestovica pri Komnu and, at 14:40, the fire also jumped the Sela na Krasu - Vojščica road.

On July 20th, at 14:00, the general situation was particularly critical, mainly for the front originated by the Monfalcone fire, which was advancing rapidly (Figure 102), and for the other active fronts in the Miren and in the Renče fires. Due to the shortage of firefighting units and the reduced water supply, the primary strategic objective of the Slovenian authorities was to protect the people and the villages; so, all incoming forces were diverted solely to protect the villages. The tankers arrived on the scene were deployed to the fire sites according to the needs. In cooperation with the Slovenian Forest Service, the personnel involved in logging and forestry machinery activities was mobilized to carry out specific forest management measures. At 16:35, the fire also jumped the Opatje selo - Kostanjevica road, in Slovenia. Due to the high danger, an evacuation order was issued for the village of Lokvica and the hamlet of Segeti. An order to clear the area around the industrial facilities and to disconnect the Redipuglia-Divača international power line was provided. About 1,000 firefighters were on the ground to contrast the fire. At 18:05, 4 Croatian tankers arrived on the scene and were deployed to resupply the helipads. At around 19:15, a Canadair also arrived with the priority to extinguish the fire front, which was approaching the villages of Lokvica, Sela na Krasu, Hudi Log, Korita na Krasu and Kostanjevica na Krasu. Only Lokvica and the hamlet of Segeti remained evacuated, as the fire in this area was still threatening the villages.

Additional interventions were established on July 21st: a backfire was set at Brestovica; the village of Vojščica was evacuated; the cutting of the firebreak on the Kostanjevica - Vojščica road was started. As the fire was approaching the villages of Kostanjevica na Krasu and Temnica, and due to the very high smoke level, an evacuation order was issued at 10:45 for the villages of Temnica, Vojščica and Novelo. At about 17:45, a spot fire allowed the fire to jump the Renški vrh - Temnica road for the first time, but the firefighters were able to contain the fire. Immediately afterwards, a second spot fire occurred a little further south from the first spot fire, but the firefighters could not control it and the fire started to spread towards Trstelj. The fire moved in this area with a tilted smoke column in the direction of the wind for 200-250 m. The forces on the Renški vrh - Temnica road were powerless to stop the fire propagation. The fire front in the direction of the Kostanjevica - Vojščica road was finally under control in the evening.

Figure 102. Map of the burned area by the Monfalcone fire on July 20th (in orange) and on Juli 21st (in red). The ignition point, indicating the area where most of the fire ignitions near the railway line were observed, is also showed,

together with the main directions of propagation and the Italian-Slovenian border. The final perimeter of the Karst wildfire is showed in blue.



Data Source: Image elaborated by CNR based on information collected from Granata (2022) and Vendramin (2022).

At nighttime, the fire intensified towards the village of Lokvica and spread further north towards Cerje. Due to the activity under the Redipuglia - Divača power line, a request for disconnection of the power line was made again. During the following morning, on July 22nd, the fire also reappeared at Hudi Log. The close Renče fire spread further south towards Kostanjevica na Krasu. Due to the airborne firefighting in this area, a request was also made to disconnect the Renče - Temnica power line. Later on, additional firefighting units from the Primorje Firefighting Region arrived. As the fire was approaching the villages, Opatje selo, Hudi Log and Nova Vas were evacuated very quickly. Depending on the availability of forces at the time, the firefighting operations were diverted to the protection of the villages; firefighting activities in the area of Cerje were therefore reduced. Assistance was provided by residents with agricultural machinery – tankers. In the afternoon, a new front line began to descend eastwards across Cerje. The fire spread rapidly down the slope. The forces on the ground were limited and the activated forces had not yet arrived on site. Due to the approach of the fire to the hamlets, an order of evacuation was issued for the threatened areas with buildings located in the forest belt (namely Merljaki, Martinuči, Vinišče, and later Mohorini and Oševljek). The lack of visibility for the smoke did not allow to see the fire area. During the night, the fire spread eastwards down the slope, and it merged with the Renče and Miren fires that had crossed the valley, further east at Cerje. Fire watches were established overnight in those hamlets. At Miren Castle, the fire was already in the valley, and by the morning of July 23rd was under supervision. Due to the size of the fire, and consequently the visibility and management of the interventions, a sub-station in front of the village of Lipa was established to manage the fire from the Renški Vrh - Temnica road.

On July 23rd, the most of extinguishment activities were in the eastern part of the fire area, in the hills of Stola and Trstelj. Overnight, there were several spot fires that were successfully contained. During the day, most of the air force was diverted to this area, and an additional helicopter drop-off point was established. By the 18:00, the fire in this area was basically blocked. Intensive mopping-up and watering operations in the fire edge were carried out.

On July 24th, in the morning, a short weather front with precipitation passed over the fire area, and this temporarily improved the situation. However, strong winds started to blow and soon dried up the fire area. Smaller hot spots, which were soon extinguished, appeared throughout the fire area during the day. The fire presented some intense conditions only in the area nearby Stol and Trstelj, on the northern side of the hill slope. With extensive air support, the fire was finally extinguished.

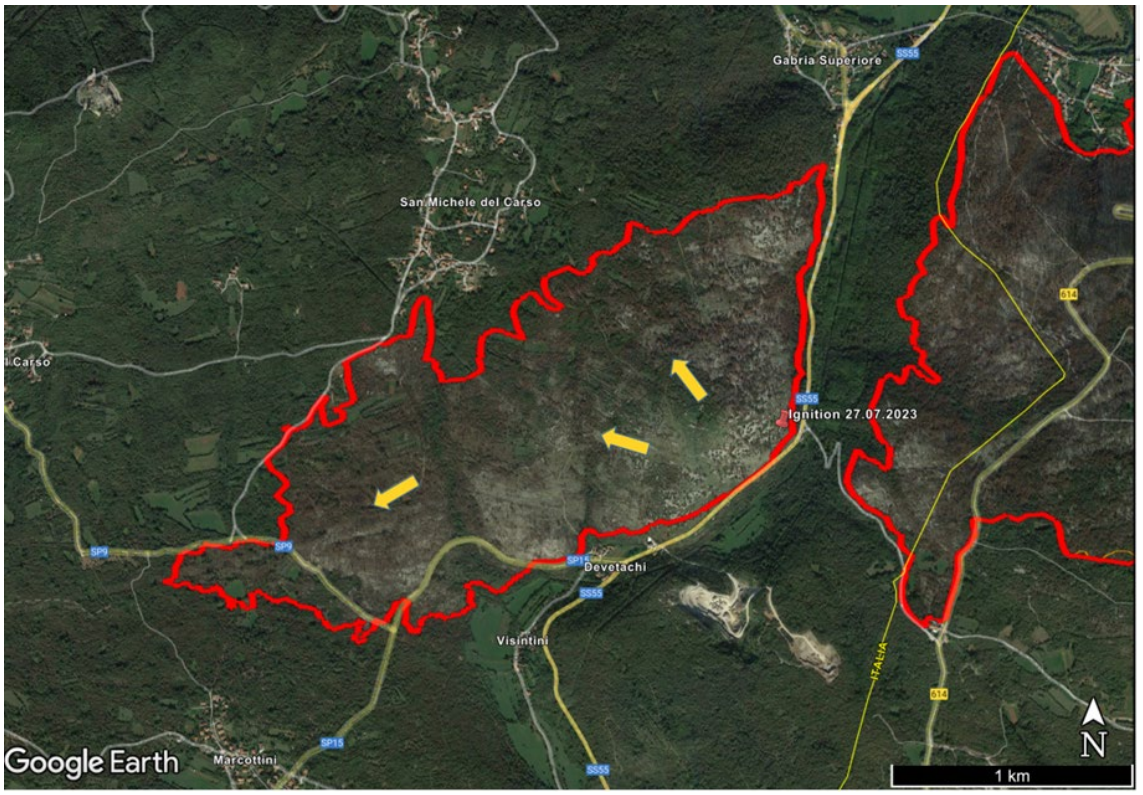
Starting from July 25th, the situation on the whole Slovenian burned areas was quite under control. Occasional hot spots or rekindling appeared throughout the fire area and were soon extinguished by aerial and terrestrial forces. Inspections of the burned area to identify hot spots were performed by helicopters equipped with thermal imaging cameras. Small and episodic hot spots and rekindling were still observed in the coming days.

On August 1st, the situation at the fire sites was under full control. The fire was declared extinguished in late afternoon, and at 19:00 the National Fire Plan for major interventions in natural fires was interrupted and all units were dismissed.

10.4.4 Brestovec fire

On July 27th, at about 13:30, a new ignition was observed in the municipality of Doberdò del Lago, in Italy, nearby the Brestovec mountain (Figure 103). The fire was ignited near the National Road no. 55, less than 300 m from the western edge of the Miren fire. From 13:45, the personnel of the Monfalcone forestry station, volunteer firefighters and National fire brigades operated to limit the fire propagation. However, due to the slope conditions, the fire quickly moved upslope, enlarging the front, and spreading in several directions. The fire threatened several villages, on which San Michele del Carso, that was temporally evacuated, Marcottini and Gabria Inferiore, all in the Italian territory. Through the cross-border cooperation protocol, firefighter units from Slovenia (Gasilci) were called to provide support in extinguishing the fire fronts and defending anthropic areas and buildings. The advanced command point was established in S. Michele. To allow aerial forces to operate in safety conditions, two electric power lines were disconnected. The fire affected about 239 ha, entirely in the Italian territory, and mainly burned conifer and deciduous forests (172 ha) and herbaceous areas. The fire, which mostly spread on July 27th, was extinguished on July 29th, at 20:00, but mop-up and control of rekindling continued until August 8th.

Figure 103. Map of the burned area by the Brestovec fire (left polygon, in red). The ignition point is also showed, together with the main direction of propagation. On the right, the western side of the Miren fire.



Data Source: Image elaborated by CNR based on information collected from Granata (2022) and Vendramin (2022).

Figure 104. Pictures of the fires: (a) Initial propagation phase of the Miren wildfire (July 15th); (b) The wildland urban interface threatened by the Miren fire (July 20th); (c) View from north of the initial propagation of the Renče wildfire (July 17th). The are of ignition is located on the left; (d) View from north-east of the initial propagation phase of the Monfalcone fire (July 19th).

(a) *(b)*



(c) *(d)*



Data Source: Vendramin, 2022.

10.5 Cross-Border dimension and related dynamics

10.5.1 Cross-Border Organisational Setting

Cross-border cooperation between Friuli Venezia Giulia Region and the Republic of Slovenia in the field of emergency management is regulated by two main Protocols:

- The Memorandum of Understanding on cross-border cooperation between the Civil Protection of the Ministry of Defence of the Republic of Slovenia and the Civil Protection of the Autonomous Region of Friuli Venezia Giulia, for forecasting, prevention, and mutual assistance in emergency situations. The Memorandum was signed in 2006.
- The Agreement on cooperation between Fire Brigades in the cross-border area between Italy and Slovenia. The Agreement was signed in July 2022, just few days before the Karst wildfire, as a result of the INTERREG Ita-Slo CROSSIT SAFER Project and substitutes the previous Agreements between the Trieste Fire Brigade and the Koper Fire Brigade (2008) and between the Gorizia Fire Brigade and the Nova Gorica Fire Brigade (2009).

The following table summarises the main aspects of the above-mentioned acts.

Table 25. Content of the 2006 Civil Protection MoU and 2022 Fire Brigades Agreement.

	2006 Civil Protection MoU	2022 Fire Brigades Agreement
Signatories	Civil Protection Services of Slovenia and Friuli Venezia Giulia.	Firefighting Services of Slovenia, Slovenian Municipalities, and Regional Direction of the Firefighting Services.
General scope	Cross-border cooperation for forecasting, prevention, and mutual assistance in emergency situations.	Collaboration in the cross-border border area between Italy and Slovenia.
Objective(s)	Increase and encourage cross-border cooperation in the Civil Protection sector (...) to safeguard the safety of neighbouring populations, animals, assets, cultural heritage, settlements and the natural environment, in the event of emergency situations that occur in neighbouring areas. [art. 1].	Provide mutual assistance for more effective action in the case of urgent relief interventions in border areas. [art. 1].
Area of application	Friuli Venezia Giulia Region (Italy) and Republic of Slovenia.	20km band across the border [art. 2].

	2006 Civil Protection MoU	2022 Fire Brigades Agreement
Means	- Exchange of information and data via telecommunication channels in real time for the purpose of predicting and preventing disaster events, timely communication of information relating to conditions occurring in the event of an emergency - Mutual assistance in cases of emergency and coordination of relief efforts for affected neighbouring populations [art. 2]	Mutual assistance in firefighting and emergency technical rescue interventions in general, in various operational scenarios [art. 3].
Activation procedure	Mutual commitment to promptly communicate the looming emergency risk or the ongoing emergency [art. 5]. In emergency situations that may involve neighbouring populations, it is possible to request mutual assistance through the reference Operational Centres [art. 7]. The Civil Protection requesting assistance must ensure adequate logistical and linguistic support and is responsible for the direction and coordination of operations [art. 8]. The Civil Protections undertake to provide mutual collaboration in activities aimed at extinguishing forest fires [art. 10]. The Protocol allows aircraft to fly across the border, subject to authorization from the Operations Centre and in compliance with air navigation regulations [art. 9].	After gathering information on the critical event, the territorially competent Fire Brigade Command may ask the corresponding Command in the cross-border area for help in terms of personnel, equipment, and resources [art. 4]. The requested Command can approve or refuse the request for intervention, without any consequences of any kind [art. 5]. Once the request for help has been accepted, the competent Command provides a Liaison Officer to guarantee a contact between the two organisations. The Liaison Officer will go to the agreed border crossing point and accompany the operators mobilised by the Command that accepted the request for help to the place of intervention [art. 6]. Qualified personnel from the country, in which the intervention is carried out, will oversee the intervention. In the event of an incident that affects the territories of both countries or with a cross-border impact, appropriate operational management will be established, including the possible activation of a joint command [art. 7].
Technical means and provisions	Mutual aid may consist, depending on availability, in: - Sending specialized technicians - Sending teams of volunteers and other civil protection units with adequate means and equipment - Dispatch of aircraft - Sending assistance items (food, medicines and others) to the affected population - Any other civil protection activity useful for overcoming emergency situations [art. 8]	Commitment to implement the interoperability of technical means, vehicles, and equipment in case of joint interventions, starting from an exchange of information on the state of the art [art. 11].
Costs	Mutual aid is provided free of charge, the side requesting help covers logistical costs and guarantees insurance coverage [art. 11].	The intervention costs remain under the responsibility of each party, except for any logistical costs which are guaranteed by the host territory [art. 8].
Exchange of information and common training	The Operational Centres are connected to each other in order to exchange relevant information and co-organise training [art. 3]. The collaboration programs are established on an annual basis [art. 6].	Fire brigades undertake to exchange information on hazards and risk of possible cross-border impact, including statistical data, as well as to participate in joint projects in the field of research and planning of emergency mitigation measures [art. 10]. A joint training and education programme on the operational scenarios included in the

	2006 Civil Protection MoU	2022 Fire Brigades Agreement
		Protocol can be set up to make cross-border cooperation more effective [art. 9].
Validity	No time limitation [art. 16]	Five years from the signing, with renewal by tacit consent. Possibility to withdraw from the agreement by giving written notice [art. 12].
Previous agreements	The usual collaboration between border municipalities regarding civil protection in cases of emergency remains unchanged [art. 12].	The agreement replaces the previous agreements signed in 2008 (between firefighters of Trieste and Koper) and in 2009 (between firefighters of Nova Gorica and Gorizia) [art. 12].
Controversies	Any disputes must be resolved out of court and through negotiation [art. 13].	N. A.

All the interviewees underlined that in many cases, included the one explored in this Report, the joint commitment informally preceded the activation of the Protocols, and that the most determining factor in the ability to activate a joint response at a cross-border level, beyond formal agreements, is the existence of a common and reciprocal interest in the protection of areas and people affected by fires. It has also been highlighted that there are areas in which informal activation is possible, while for others the operations are inevitably more complex to coordinate on a cross-border level: air interventions, for example, respond to different maps and authorisation, support and check; this complexity was highlighted, during the Karst wildfire, above all when aircraft from third countries (for example, Republic of Serbia) were also present on the field.

The difficulties encountered in implementing the formally reached agreements derive mainly from different operating systems and practices between Italy and Slovenia. The differences relate to the following aspects:

- Organisational scale. In Italy, for instance, operate both national bodies, such as the Fire Brigade, and entities organised on a regional or local scale, such as the Regione Friuli Venezia Giulia Forestry Corps and the Regione Friuli Venezia Giulia Civil Protection. This results in different chains of command, different modalities of operational response, and different access to tangible and intangible resources at the respective level of competence.
- Composition in terms of human resources. Organisations involved in the firefighting response can be exclusively professional (Italian Fire Brigades), or mainly composed by volunteers coordinated by professional personnel (Regione Friuli Venezia Giulia Forestry Corps, Regione Friuli Venezia Giulia Civil Protecion, Slovenian Gasilci). The composition is reflected in the organisational structures, in the degree of "freedom of movement" in relation to (less or more) legal responsibilities, as well as in the kind of knowledge/expertise/experience which can be rely upon during the emergency phase.
- Function within the emergency governance structure. The Civil Protection is focused on providing logistical support to operations. Other actors, such as Fire Brigades, Regional Forestry Corps, or Gasilci, are involved in the direct intervention in relation to fire.

There are also significant differences in the approach to the firefighting operations. In the choice on how to deal with the fire in order to extinguish it, approaches applied between Italy and Slovenia partially differs: some of them – especially in Italy – derive from a tradition of intervention which is focused on the direct aggression of the flame in order to avoid the risk of excessive extension of the fire; others ones – especially in Slovenia – are more defensive, providing for example the use of foaming agents or backfires as a tool for the preventive elimination of the fuel, as well as for orienting the fire route far from sensitive targets.

The interviews highlighted the fact that a high degree of difference in organisational models could account for fragmentation and hinder the capability of a system to properly respond to an emergency, complex systems, if properly coordinated, retain the appropriate degree of internal diversification and redundancy which is highly relevant during emergency scenarios. To positively exploit the features of this complex system, however, it is necessary to have a high awareness of roles and competencies attributed to every actor involved.

In addition to the activation of the bilateral Protocols mentioned above, Slovenia requested international assistance by calling for the Union Civil Protection Mechanism (UCPM), asking for aerial firefighting

aircrafts and additional firefighting units, and activated another bilateral military-to-military Protocol with Hungary.

As reported by the Slovenian Gasilci, a total of 9 helicopters (from Italy, Hungary, Croatia, Austria, Slovakia, and Serbia), 5 aircrafts (from Croatia, Romania, and Slovenia) and 1 firefighting unit (4 vehicles and 9 operators, from Croatia and a team of Slovak firefighters to support a Slovak helicopter with a 20,000 liter fire vehicle) operated in Slovenia, both through the UCPM and as a result of bilateral agreements.

10.5.2 Population Response

On both sides of the border, the local population is reported to have been very much cooperative and keen to help emergency operators. However, not much direct participation in the firefighting response activities has been registered.

The impression, from the Italian point of view, is that while for minor fires that occurred in the area in the past there have sometimes been issues related with population low levels or lack of risk awareness, in this situation, despite the unprecedented magnitude of the event, the level of preparation and knowledge of people was higher than before. This impression is confirmed also by Slovenian operators, who recalled that Karst people already know how to move in an emergency, both in terms of individual protection (for example in field cleaning operations carried out with tractors) and in collaboration with evacuation operations.

People's solidarity towards the emergency operators has been shown also in terms of voluntary supply of resources to first line operators.

During the firefighting operations, evacuations, there was necessary not only to put the population in a safe condition, but also to make the firefighting activities more operational, in fact they allowed the operators to concentrate more on the fire, and not on the protection of civilians.

Both in Italy and in Slovenia, even though the official decision is taken by the mayor, evacuation operations are requested by emergency operators:

- In Italy, evacuation operations arise from specific requests from emergency operators, shared in the Prefecture also with the civil authorities and formalised by a municipal ordinance. The sheltering facilities are identified among those that each Municipality surveys as part of the Civil Protection Plan. In this case they were all fixed structures, specifically school gymnasiums, in Monfalcone, Savogna d'Isonzo, and Gradisca d'Isonzo.
- In Slovenia, the Mayor authorizes the evacuation which is then implemented concretely by the Police and the Civil Protection. In this case, the destination of the evacuees was Šempeter, in the Sport Centre Hall, because the entire Karst area was impacted by smoke.

In both cases, the evacuations are not mere formal acts. Beyond the issuance of the formal order there is a dimension of operational implementation through which people must be put in a position to actually be able to evacuate safely (which includes leaving their properties with enough guarantees).

The first evacuation took place in the town of Sablici (Municipality of Doberdò del Lago) already on July 19th, with 15 people evacuated. In the case of San Michele del Carso (Municipality of Savogna d'Isonzo), the sheltering solution organised in the gymnasium was chosen by 20-30 people out of the 250 evacuees; the others found a private solution, for example being hosted by relatives or friends. Different Civil Protection groups took care of different tasks, according to their previous professional experience: sheltering sites, for instance, were monitored by volunteers from the Carabinieri Association (retired police forces), while food was provided on site by the Alpini Association (retired military forces). Support for materials and provisions was organised starting from the centralised warehouses of the Civil Protection. Basically, Civil Protection was primarily concerned with the safety of the population (including safe transportation and availability of sheltering sites) as well as planning issues such as setting the correct time to evacuate based on objective evidence, for example those on the wind forecast.

The reaction of the population to the need to evacuate was on average very cooperative, even if there were some tensions. Obviously, emotional factors also emerge in situations like this, as every individual has their own reaction to emergency events, and someone is inevitably more reluctant to evacuate. More than regret at having to leave one's home, it seemed that the strongest feelings were dedicated to the environment and elements of the landscape (e.g., the tree that "has seen the person who lives nearby grow"). There was also widespread concern about the integrity of properties that needed to be abandoned due to the evacuation.

For this reason, for instance, in Italy some volunteers from the technical-logistics sector of the Civil Protection kept a garrison in the emptied towns.

2.5.4 Human Resources

On the Italian side, 3,044 man/days of work were recorded between July and August. This effort was performed by around 54 volunteers including firefighting and technical-logistics operators. 1,634 man/days were recorded in Gorizia and 832 in Trieste: essentially 80% of the regional workforce was employed in the two Provinces interested by the Karst wildfire. Going at the Municipality level, 1,516 man/days were recorded in Doberdò del Lago (Gorizia), 453 in Duino-Aurisina (Trieste). Also, in terms of forest fire fighting vehicles, out of 1,146 missions, 581 were performed in Gorizia, 353 in Trieste. Within two months only (July-August), the average expense of a whole year of fire-fighting helicopters operations was reached. To this must be added the National Civil Protection airplanes, the Fire Brigade Dragon helicopters, and the AB205s helicopters of the Slovenian army.

From the point of view of the voluntary forces available in Italy, at the time of the fire in Friuli Venezia Giulia 121 Civil Protection groups were registered in 111 Municipalities, with around 1,500 volunteers available. With the strength of these numbers, the Civil Protection has provided broad logistical support to every other involved corps, as well as to the local population.

On the Slovenian front, the estimate is that around 1,400 people were involved in the logistical operation which, given the extent of the fire, was unprecedented in the history of the country.

10.6 Fire Impacts

The impact of the Karst wildfire was more substantial in Slovenia in terms of hectares burned, but it was certainly more critical on the Italian side in terms of critical infrastructures involved.

Luckily, on both sides of the border no deaths or serious injuries have been reported by the competent authorities. In Slovenia 48 firefighters were checked for inhalation and one minor injury was recorded. The balance of the impact of the fire is particularly positive especially if considering the 500 explosions caused by the detonations of unexploded war devices.

10.6.1 Infrastructures

Most of the information presented in this paragraph are related to the critical infrastructure which draw a very dense texture in the area between Monfalcone and Trieste, in the Italian territory.

The safety of the three power lines that cross the Karst area (one of which is 380kV) in the Italian territory was guaranteed not only through deactivation, but also by providing discharges to the ground, which are necessary to guarantee the safety of the personnel working under the line. The decommissioning was carried out to allow for the early re-organisation of energy distribution after the emergency, to avoid uncontrolled and unexpected collapses.

The pipeline has also been placed under special observation, especially near the control stations. However, the most significant problem relating to gas in the Karst area was found in relation to the presence of numerous private LPG deposits, mainly above ground, in several areas where the methane line does not reach.

The water supply network was put under high stress as well, because of the fire extinguishing activities. Reservoirs realised by the Civil Protection after the very warm summer 2003 were deployed to meet the system's need for water.

In the most complex phases of the fire development, the international civil airport of Ronchi dei Legionari (Trieste Airport, Italy) was first shut down, then downgraded to allow the fire extinguishing means operating on the runway to be used in firefighting operations. The main roads (motorway A4 and National road no. 14, also known as "Costiera" road, both connecting Trieste and Monfalcone), the railway towards Venice, and the National road no. 58 (also known as "Vallone" road, connecting the Lisert area with Gorizia) were temporarily closed as well.

10.6.2 Smoke emissions and dispersion

To analyse the effect of Karst wildfires occurred from July 15th to August 1st on smoke emission, several sources of data were exploited. Satellite images monitoring Fire Radiative Power (FRP) observations from

VIIRS instruments onboard the NOAA-20 (https://www.star.nesdis.noaa.gov/) were used to trace fire spread and smoke emissions, while air quality data (PM_{10}) recorded by several measurement stations were downloaded from the Arpa Friuli Venezia Giulia (FVG) network (https://www.arpa.fvg.it/temi/temi/aria/sezioni-principali/). In particular, Arpa FVG, in order to circumscribe the area of actual fire impact, carried out (i) expeditious measurements at various locations of potential fire smoke fallout by means of optical particle counters and (ii) constant hourly monitoring of PM_{10} at the following air quality measurement stations: (a) "Green Area" station in Monfalcone from July 15th (published in the "news" section, https://www.arpa.fvg.it/temi/temi/aria/news/?q=incendi); (b) Trieste-Carpineto, Udine-S.Osvaldo, Tolmezzo stations from July 21st; (c) San Giovanni al Natisone, Trieste - P.zza Carlo Alberto, Trieste - P.zza Volontari Giuliani, Trieste – RFI, Udine - via S. Daniele stations from July 22th.

Satellite images detected a small fire in Slovenia, along the main road Miren – Lokvica, near the Italian borders, on July 17th. However, the closest air quality station, Monfalcone, did not detect any criticality for fine dust in that day. According to Arpa FVG reports, two days later fire smoke affected a large area, evolving vertically in a very dispersed plume shape, but the air quality station in the Monfalcone area did not detect any criticality for fine dust. Indeed, PM_{10} measurements recorded during the morning of July 19th were very low (less than 10 µg/m³), increasing in the afternoon but still well below the threshold of 50 µg/m³.

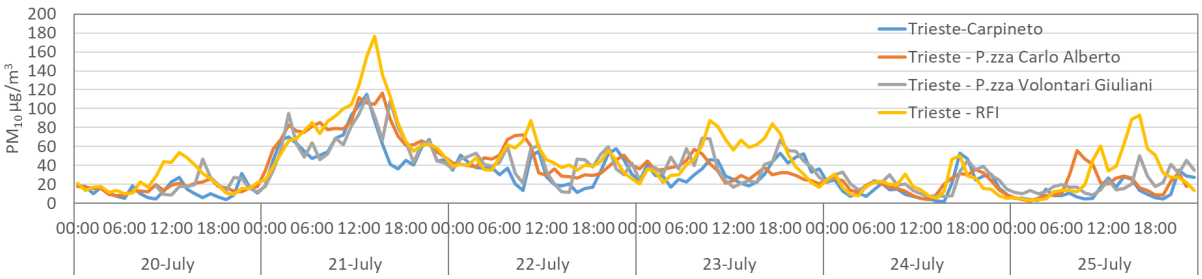
The air quality stations of Monfalcone detected a sudden increase well above the critical threshold during the night of July 19th and the first hours of July 20th, recording a peak of 1600 µg/m³. On July 20th, Arpa FVG and satellite images reported the fire plume raising in altitude and dispersing in a west-south-west direction over a wide area.

On July 21st, the change in wind direction (easterly) moved the smoke plume towards Slovenia and the area of eastern Friuli. The four air quality stations in Trieste recorded their peaks at noon (max. 177 µg/m³, Figure 105). Furthermore, Arpa FVG carried out rapid measurements at various locations using optical particle counters. In this case, Arpa FVG considers more than 1,000 particles with a diameter of less than 1 µm per litre as a reference threshold in the event of a fire. During the night, the values were above the threshold for the cities of Grado, Ronchi dei Legionari, and Gorizia. Indeed, a thermal inversion situation in the low layers was expected, "making the smell of active fires in the Karst perceptible even at considerable distances" (Arpa FVG, 2022a)

On July 22nd, the presence of a weak easterly/northeasterly wind spread the fire smoke towards the area of the Slovenian Karst, while the values measured by the Monfalcone station returned below the critical threshold (from 120 µg/m³ at midnight to 33 µg/m³ at 23:00). During the nighttime, the marked thermal inversion that characterized the previous nights reappeared.

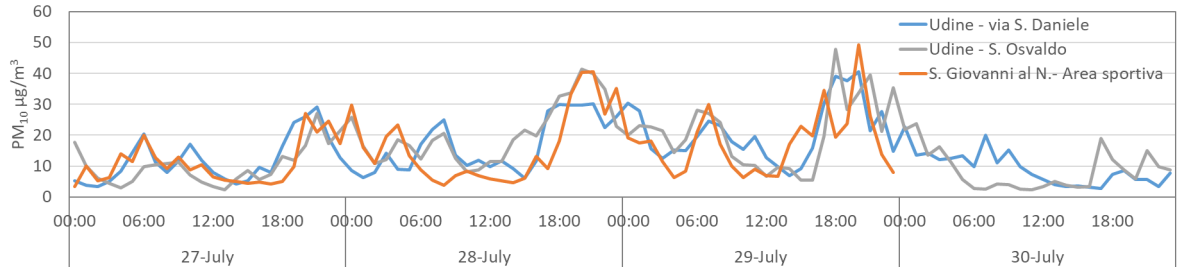
The forecast model of Arpa FVG identified the entry of moderate bora in a North - North-East direction during the night of July 23rd: this pushed the smoke generated by the fire over the Slovenian Karst towards the Friulian plain. Smoke was expected to fall on Gorizia (PM_{10} 32 µg/m³, below the daily mean threshold). Similarly, on July 24th, smoke dispersion from fires in the Slovenian Karst was expected to move towards the Friulian lowlands. On July 25th, the situation regarding fires in Friuli Venezia Giulia was under control and dust levels (PM_{10}) returned to normal values (Figure 105).

Figure 105. PM_{10} (µg/m³) hourly data collected from the four air quality stations in Trieste (July 20th-25th).



Data Source: Based on data from Arpa Friuli Venezia Giulia (FVG) (2022b).

Figure 106. PM_{10} (µg/m³) hourly data collected from the Udine (via S. Daniele and S. Osvaldo) and S. Giovanni al Natisone air quality stations (July 27th-30th).



Data Source: Based on data from Arpa Friuli Venezia Giulia (FVG) (2022b).

Following the new fire that broke out on July 27th in the Dobrevac mountain, during July 28th the fire smoke was dispersed to the west, towards the Friulian lowlands. According to Arpa FVG, the atmospheric turbulence brought the smoke close to the surface, but also diluted its concentrations. On July 29th, Udine (via S. Daniele and S. Osvaldo) and S. Giovanni al Natisone air quality stations detected values near the critical threshold for fine dust after 18:00 (Figure 106).

The fire that broke out on July 27th was declared under control on July 29th. In the morning of July 30th, data from the air quality stations did not show any exceedances of PM_{10} dust particles. Therefore, the extraordinary hourly monitoring and other control measures in the area were suspended.

10.7 Cascading effects

As already anticipated, a significant issue in the case of the Karst wildfire is that of unexploded war ordnance, a presence well known in the territory on both sides of the border that has suffered two World Wars, but perhaps underestimated. The Karst wildfire was characterised by a higher frequency of both the discovery of bombs and their explosions, compared to past episodes. The phenomenon has affected the local population as well as the operators who find themselves in the areas characterised by these explosions.

The Slovenian interviewees report that a similar scenario (in terms of the number of explosions and discoveries) had already occurred in the Montesanto/Sveta Gora fire of 2012. After that episode the Slovenian operating protocol in the event of the presence of unexploded war ordnance was reviewed and partially modified. Up to that moment, indeed, after the first explosion the emergency operators had to move 1 km away, without proceeding with the extinguishing operations, while no specific operational indications were given with respect to the evacuation of people and goods. The regulation currently in force, on the other hand, provides that it is forbidden to proceed immediately with the reclamation operations in the area affected by the explosions for 48 hours, but it is possible to continue with the extinguishing operations. This approach is preferable because it protects operator safety while allowing firefighting activities to proceed.

10.8 Lessons learned and Conclusions

10.8.1 Lessons Learned

10.8.1.1 Organisation of Working and Volunteering Forces

In Italy, following the ex-post assessment of what happened in the Karst wildfire, the 2023/2024 Forest Campaign saw the deployment of an additional Fire Brigade team for each Province, dedicated to fighting forest fires and financed with a regional agreement, operating on shift 08:00 – 20:00. A new Civil Protection Regional air service contract has also been activated in Friuli Venezia Giulia, which includes an automatic detection system with the use of thermal imaging cameras during the flight, therefore in real time. This will facilitate future shutdown operations by sending infrared map and visible map information directly to DOS. In November 2022, a drone which, traveling at lower altitudes, is important for reclamation operations, was purchased.

In Slovenia, at the corps organisation level, the squad activation plan has changed. This will no longer be ordered in relation to the number of people to be mobilised but in relation to the type of intervention to be carried out, according to an organisation in platoons which are supposed to be self-sufficient for the 24h.

This setting was already legally defined in 2006 but never implemented. In addition, 5 aircrafts were purchased, 3 of which are still to be delivered, with both firefighting and monitoring and data collection purposes; prior to that decision Slovenia could only rely on military helicopters and aircrafts for air interventions. Finally, the new Slovenian government presented the new National Anti-Forest Fire Plan in December 2022, simplifying the chain of command in the event of a fire, creating a direct channel between DOS in the field and military forces, and integrating the Single Emergency Number into the firefighting system.

10.8.1.2 Accessibility

During the interviews carried out for this study, the issue of improving the accessibility of areas affected by fire risk was often mentioned as a priority. Several secondary roads that serve as fire trails suffer from a poor degree of maintenance, and in some cases the fire easily overrides them, passing from one side of the road to the other. Another critical issue is represented by isolated settlements connected only by dead-end roads.

The first need is therefore to map the current situation, taking into consideration both the areas already affected by the fire (about 1,700 ha) and those that have not been affected by it. Thanks to this mapping carried out on the Italian territory after the Karst wildfire, the 12 settlements most prone to fire risk in the Province of Gorizia have been identified. This information has been shared with the Municipalities as well, which are primarily responsible in terms of risk communication to citizens.

During the interviews, already planned interventions were reported, for instance the creation of secondary roads and escape routes, interventions which, moreover, can be accompanied by other measures such as better accessibility to water (for example the construction of tanks and deposits). It has been observed that the restoration of secondary road networks could also have positive effects from an economic and tourist point of view.

From the Slovenian standpoint, it is believed that it would also be appropriate to intervene on a legislative level, with clearer laws regarding the characteristics that must be guaranteed, for instance in terms of height and width, for forest firebreak roads. Some positive examples from which to draw inspiration exist, for example in France, or the regional law of Tuscany. Such choices could attract criticism from those who express environmental concerns, because their implementation would require the felling or thinning out of some wooded areas.

10.8.1.3 Self-protection and evacuation operations

Other aspects mentioned several times during the interviews concern the strengthening of self-protection measures, in terms of prevention carried out by citizens, for example the pruning of trees and cleaning of the land with respect for the safety distances between buildings and wooded areas. The work of capitalisation of the lessons learned which was structured in the context of *Carso non arso* (see 10.8.2.2) focuses on these aspects in particular.

From the experience in Slovenian territory, it has emerged that, while organising evacuation operations, the request to take care of the livestock often emerges by local inhabitants. The presence of livestock, especially sheep and goats, in the Karst is an element that generates concern and resistance in the population during evacuation procedures. The evacuation of livestock is a complex procedure that should not only be foreseen by the rules but also made operational.

10.8.1.4 LPG deposits and Unexploded war ordnance

A separate mention is needed for the issue of private liquid gas deposits. Very often in the Karst these tanks are installed above ground as the geomorphological characteristics of the territory make the creation of underground deposits very expensive and complex. Although the safety distances for above ground systems are greater than those for underground systems, the regulations in force are probably not sufficient to guarantee an adequate level of safety, according to the interviewees. This is a case that clearly demonstrates how the rules serve to cover 90% of the risks, but at the same time they risk generating a false feeling of security ("I have complied with the rule, so I safe"). More than interventions on the standard, in this case more common sense and awareness would be needed in the choices of installation and maintenance of these structures.

Regarding the problem of unexploded war ordnance, the Regione Friuli Venezia Giulia Forestry Corps suggests thinking about future action, better if agreed at cross-border level as, for instance: resorting to

indirect attack with the use of retardant products, tactical fire, clearing, setting up planned lines of fire to stop the advancing fronts, setting up 'safe' areas. Also, the Regione Friuli Venezia Giulia Civil Protection called for the necessity, to ensure adequate safety for the emergency operators, to plan a new approach to Karst firefighting, no longer aimed at attacking the fire wherever it is found, but at the creation of reclaimed safe routes along which to set up the garrisons to combat the advance of the fire line.

10.8.1.5 Protocols' Revision, Implementation and Extension

The concrete experience of such a wide-ranging joint and cross-border intervention was also fundamental for putting the international protocols in force to the test. The Protocol has proven to be functional in compressing time requested for certain operations, therefore in helping practitioners to operate with a resource that is always scarce in times of emergency.

In fact, the Safety Operating Procedures require guidelines for different scenarios, but it is equally important to have a structure with adequate organisational flexibility at all levels (including the more purely political and institutional one). From the Slovenian point of view, in practice, even more has been done than what was written down in the Protocol. Somehow the Protocol was always behind reality: therefore, there is a need for simpler tools to implement.

In general, in the opinion of the operators, coordination skills need to be improved more than the procedural aspects. According to all the interviewees, it would be advisable to multiply the opportunities for meeting also in the preventive phase, as well as in the post-emergency phase, to make the necessary assessments; everyone's story, if shared, can create awareness and generate further knowledge useful to all. Mutual knowledge between operators translates into greater cooperation on all levels: this occurs, for example, with joint exercises. In doing so it is important to be aware of the existence of the language barrier.

Sharing sessions would also be functional for developing innovative and co-created approaches to firefighting operations, for example to shift from a purely offensive approach towards more preventive and defensive approaches. The meetings would allow to share strategies, as well as to identify compromise and transition solutions from the old to the new models, including the necessary training in the use of new methods and/or technologies.

The fire also highlighted the need to implement further protocols on other currently less covered fields: an example is the field of risk forecasting, on which interoperability and data exchange between Slovenian and Italian fire susceptibility prediction systems could be evaluated. In other areas, cooperation is currently stronger between Italy and Austria: a few years ago, joint exercises were held at the Carinthian lakes; or in the context of the Single Emergency Number, with a strong relationship between the emergency centres of Palmanova and that of Klagenfurt. Certainly, the recognition of the respective minorities also facilitates cross-border relations.

10.8.2 Capitalising on the Lessons Learned

10.8.2.1 ResiFestGo

In October 2022, right after the Karst fire, Gorizia hosted a series of initiatives within the Italian National Civil Protection Week. One of them was RESIFESTGO, an event which aimed to provide an opportunity for emergency managers and citizens to discuss the issues of resilience and Civil Protection, from a cross-border and European perspective.

The event stemmed from RESILOC - Resilience Europe and Societies by Innovating Local Communities, a Horizon 2020 EU project, started in 2019 and ended in 2022. The project was aimed at improving the resilience of local communities, through research activities and applying a holistic approach to studies, methods and software that combine physical and less tangible aspects associated with human behaviour. The project aimed at improving the level of resilience of local communities, through research activities and by piloting the developed solutions in 4 pilot sites (i.e., Gorizia and Catania in Italy, Tetovo in Bulgaria, West Achaia in Greece).

RESIFESTGO hosted round tables and open debates that provided an opportunity for the exchange of good practices among emergency operators, Civil Protection representatives, and local institutions. The event made it possible to disseminate the principles of self-protection to the local population as well, promoting risk awareness and cooperation. One of the initiatives held within RESIFESTGO was indeed titled "From emergency management to community resilience: European best practices and lessons learnt on the management of wildfires". This technical workshop targeted emergency experts, professionals, researchers,

civil society representatives, and local decision-makers from Slovenia, Italy, and abroad, to share experiences and analyse the impacts of fires in the Italy-Slovenia cross-border area, also in the light of European experiences.

10.8.2.2 Carso non Arso

Carso non arso (literally, "Not burned Karst") is an initiative promoted by the Fire Brigade and shared with the Prefecture, Region, Forestry Corps, Civil Protection, local administrators of the Gorizia area. It was focused on dissemination activities mainly targeting schools and, in a broader sense, at local communities. The starting point came precisely from the Karst wildfire, from what has been done in the field of firefighting but above all on what must be done in terms of prevention.

Carso non arso's aim was to spread the culture of forest fire safety on the population. The intention is to develop an annual appointment, which in the first edition mainly involved schools, with the active collaboration of various institutions. In particular, local administrators were involved with the aim of identifying the best interlocutors at the local level. Also due to issues of time and effectiveness of the intervention, it was decided to focus mainly on schools; out of 7 Municipalities involved, in 6 cases the target was identified in the school population of middle and high schools; only in one case (Sagrado) was instead opted for a meeting with the local community, which took place in San Martino del Carso.

Each meeting was structured as follows:

- An illustrative part relating to the risks that are run during a fire, supported by video interviews made after the Karst wildfire with an evacuated person, a local administrator and an official of the Fire Brigade.
- A more specific part on fire risks, introduced with the help of a presentation.
- An informative part with useful information especially for residents of isolated houses.

The presentations were followed by a moment of debate with questions and answers.

- Finally, an exhibition and demonstration section on firefighting operations.

The first initiative of the 2023 cycle was organized in Gorizia in collaboration with the Slovenian firefighters (Gasilci). Furthermore, the leaflet containing the most operational information, in particular those related to the maintenance of isolated buildings, was translated into Slovenian, as were the posters of the events. The intention was to carry out the entire initiative on a cross-border level, but for the first edition some difficulties were encountered relating to the planning of school activities in Slovenia, which has earlier times than in Italian schools.

10.8.3 Conclusions

Events such as the Karst wildfire confront political decision-makers, managers, emergency operators and stakeholders with the question of how to make people's lives safe in the interface areas, given that zero risk does not exist. The Friuli Venezia Giulia Region Forestry Corps has highlighted how, in critically understanding these phenomena, the greatest difficulties are encountered due to widely diffused single-disciplinary view of the subject, for example on the ecological functions performed by trees. If the vegetation, even the bushy one, can in fact on the one hand constitute a risk factor for the spread of a fire, on the other hand it guarantees the stability of the soil and therefore is an important factor in the prevention of landslides. Such nuances need to be taken into consideration when performing risk analyses.

According to the Fire Brigade, the event, unprecedented due to its scope and duration, today would meet a more prepared system, because direct experience of these episodes is always more valuable than any training. In fact, prior to the Karst wildfire an entire generation of operators have had never directly dealt with a fire of this magnitude. This also applies to the local population, although they were quite prepared thanks to the strength and structure of the Civil Protection mechanisms.

In any case, it is the unanimous opinion of the interviewees that, just as the fire had no boundaries in its development, the response to the fire was also organised on the same level, the cross-border one.

References

ARPA FVG (2022a). Incendio sul Carso Monfalconese – Lisert: aggiornamento misure 20/7 e 21/7 2022. Available at: https://www.arpa.fvg.it/temi/temi/aria/news/incendio-sul-carso-monfalconese-lisert-

aggiornamento-misure/#:~:text=Le%20polveri%20potranno%20concentrarsi%20presso,che%20ne%20disturber%C3%A0%20la%20formazione (last access 11/12/2023)

ARPA FVG (2022b). Incendio Carso: i dati dei monitoraggi Arpa FVG. Available at https://www.arpa.fvg.it/temi/temi/aria/sezioni-principali/download-indicatori-e-dati-aria/indicatori-giornalieri-qualita-aria/ (last access 11/12/2023)

Corpo Forestale del Friuli Venezia Giulia (2022, various). Fogli Notizie Incendi Boschivi / News Report Wildfires

Granata, A. (2022). Forest fire emergency in the province of Gorizia from 19 July to 04 August 2022. Firefighters Service Report for the Ministry of Internal Affairs, Italy.

Memorandum of understanding for cross-border cooperation between the Civil Protection at the Ministry of Defense of the Republic of Slovenia and the Civil Protection of the Autonomous Region of Friuli Venezia Giulia, for forecasting, prevention and mutual assistance in emergency situations (2006)

Vendramin, S. (2022), Poročilo o intervenciji - Požar Kras 2022 - 15.7-1.8.2022 / Intervention report - Karst Fire 2022 - 15.7-1.8.2022, Gasilska Enota Nova Gorica.

11 Fire of Bohemian and Saxon Switzerland (Germany / Czech Republic)

Authors

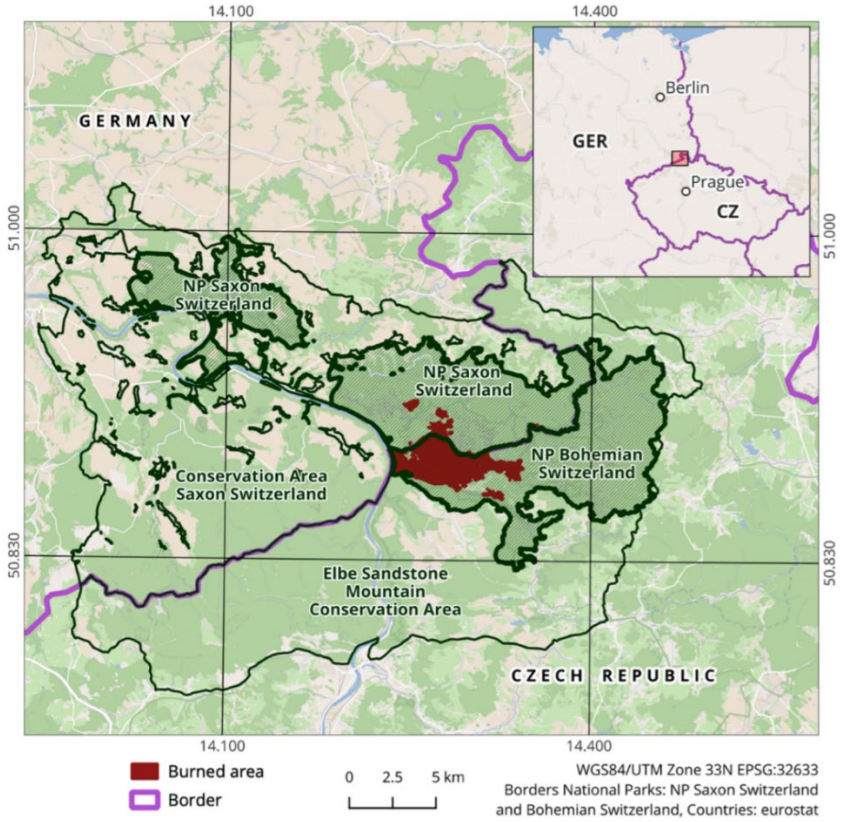
Christopher Marrs	TUD
Matthias Forkel	TUD
Kristina Beetz	TUD
Eric Kosczor	TUD
Markéta Poděbradská	CzechGlobe



11.1 General Description

The fire started on July 24th close to the town of Hřensko in the Bohemian Switzerland National Park, Czech Republic, close to the border with Saxony, in Germany. The location and burnt area can be seen in Figure 107.

Figure 107. Location of the burned area in the two national parks on the border between Germany and the Czech Republic.



The cause of the ignition is now known to be arson and the fire was first identified in the morning of July 24th by rangers from the Saxon Switzerland National Park patrolling on the German side of the border. By

the July 25th, the fire was considered to be out of control. In total 1,215 ha of forest was burned, 115 ha or 1.3 % of the Saxon Switzerland National Park was affected, and 1,100 ha or 14 % of the Bohemian Switzerland National Park on the Czech side was impacted. The fire was the largest recorded in the border region and followed a smaller fire just weeks before.

The fire was eventually suppressed on the August 12th. Steep terrain, weather conditions, the large amount of standing and lying deadwood, limited accesses, underground fires and distant water sources all played a part in length of time needed to extinguish the fires. In addition to this, lack of mobile phone reception also reduced the efficiency of the firefighting effort and coordination of resources.

Fortunately, there was no loss of human life during the event, though three firefighters were injured, one seriously. During the fire, around 2,050 emergency service workers were engaged in fighting the fire and 14 aircraft from Germany, Czech Republic, Slovakia, Poland and Italy were deployed. Specialist pilots trained in fighting fires from Sweden also arrived. Around 450 people were evacuated from nearby settlements of Hřensko Mezná, Janov, and Mezní Louka.

In the small settlement of Mezná (CZ) three houses were lost to the flames, the village was however saved from destruction as a result of the firefighting action of the Czech Fire Brigades, which had to withdraw at one stage to avoid being surrounded by the fire. The village is on a hilltop accessible by only one road. Hřensko nestles in a narrow and high gorge surrounded by forest, much of which contained large amounts of deadwood. The vertical cliffs above the village made for difficult firefighting conditions, though its location on the rivers Elbe and Kamenice ensured that access to water was easily available.

11.2 Characterisation of the affected area

The area affected was predominantly forested land located in the Bohemian and Saxon Switzerland National Parks. As such, the area is sparsely populated within the burnt area, though several settlements are located on its periphery. The area is very popular with tourists and the international railway between Dresden/Berlin and Prague passes through the area making it accessible to large numbers of people, whether as day visitors or those choosing to stay and hike in the area. Whilst it is difficult to provide an accurate number of tourists visiting the parks, current estimate is between 3-4 million annually for the German side of the park. The tall and precipitous sandstone stacks are a key attraction for visitors, but in turn proved to be difficult and dangerous conditions in which to fight a fire (Figure 108).

Figure 108. The Richterschlucht, a popular walking trail through the Saxon Switzerland National Park.



The forest itself contains Norway spruce (*Picea abies*) plantations, European beech (*Fagus sylvatica*), Scot's pine (*Pinus sylvestris)* and European larch (*Larix europea).* Understorey vegetation varies with dominant tree species, but with exception of the beech stands it is for the most part is grasses and bilberry (*Vaccinium myrtillus*). The park and its surroundings are home to wild boar (*Sus Scrofa*), roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*) and pine marten (*Martes martes*) amongst other fauna. Within the national parks hunting is forbidden and as such relatively high numbers of game species reside within the parks.

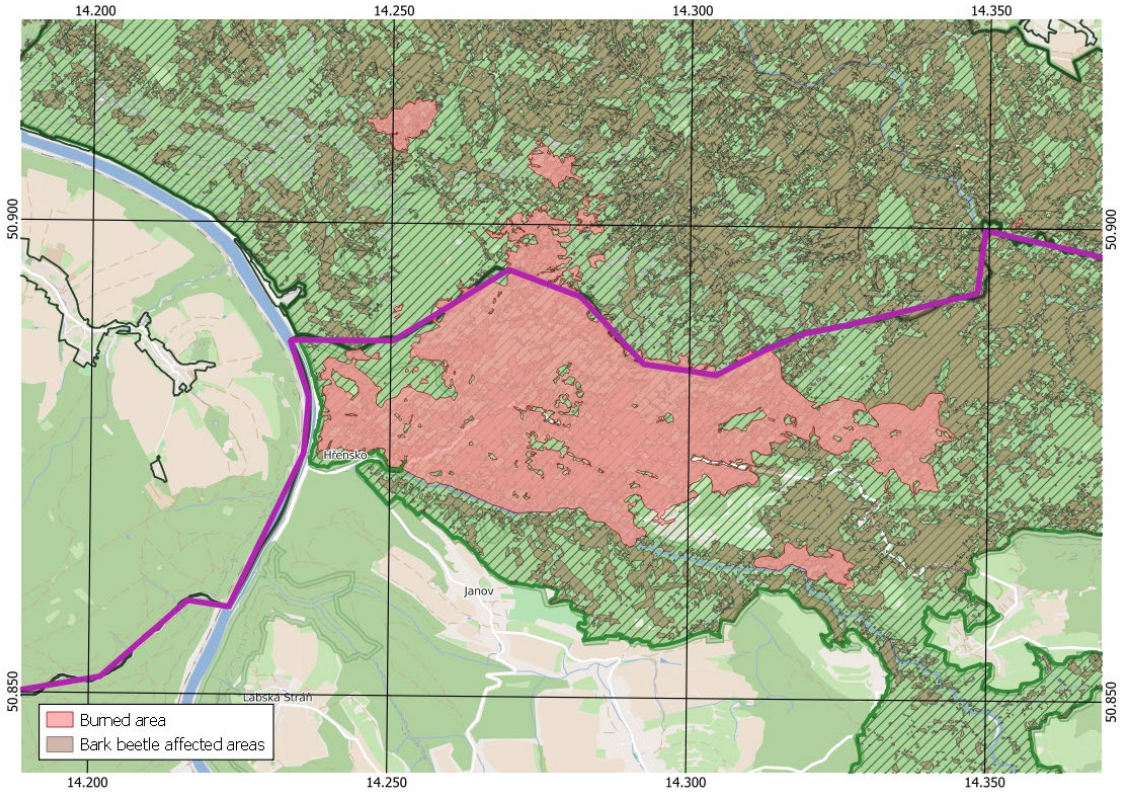
Figure 109. Dead standing and lying Norway Spruce (*Picea abies*).



Both Germany and Czechia have a strong and historical commercially based forestry sector, however, within the national parks an absolute bare minimum of tree felling takes place, and only where absolutely necessary such as maintaining access or to reduce hazards for visitors. Large areas of the spruce plantations have succumbed to increasingly damaging infestations of bark beetle since 2017, exacerbated by drought conditions which weaken the tree and reduce their ability to survive the effects of bark beetle infestation.

Once affected by the bark beetle the trees are normally dead within around three years. This has led to large areas of standing deadwood as well deadwood on the ground (Figure 109). The large amount of deadwood in the park and the proximity of settlements to it has become a cause of concern for residents and remains so.

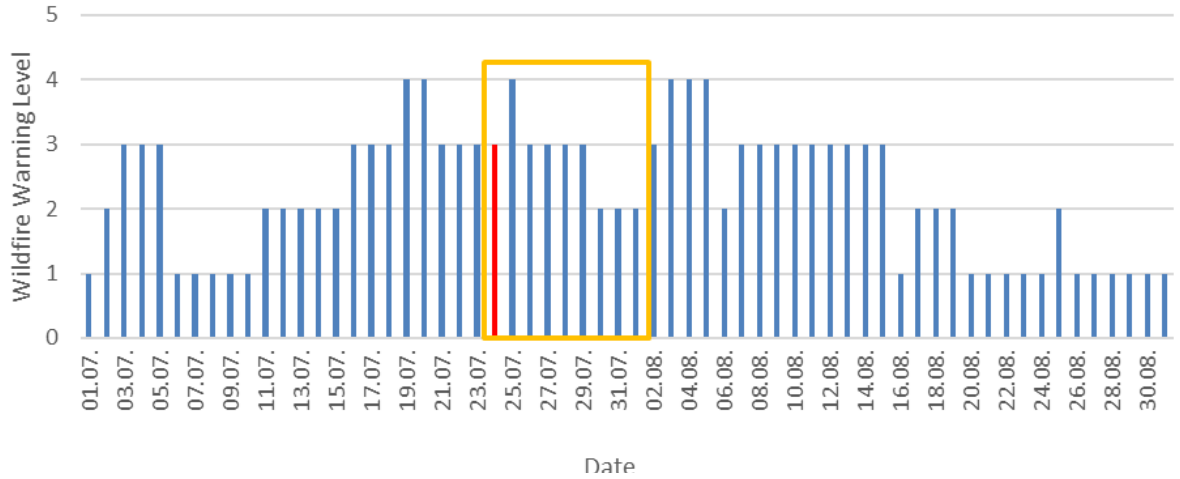
Figure 110. Bark beetle affected areas in the two national parks with overlay of burned area.



11.3 Fire conditions

Like several other countries in Europe, Germany and the Czech Republic experienced a major heatwave in mid-July 2022. Temperatures rose to 40°C in some locations and the number of sunshine hours hit a new monthly record, leading to long periods without cloud cover and very little precipitation. The two national parks were also affected by these dry conditions with very little rainfall being recorded by weather stations in the weeks prior to the fire. Despite these conditions the fire warning level (*Waldbrandgefahrenstufen*) on the day of the fire was set at Level 3, medium risk on a scale of 1 to 5, with 1 being the lowest (Figure 111).

Figure 111. Fire warning levels Saxon Switzerland National Park (according to the German Waldbrandindex) from July 1st to August 31st, i.e., before, during and after the fire. The red column indicates the date of the ignition and the orange box the period of the main fire spread.



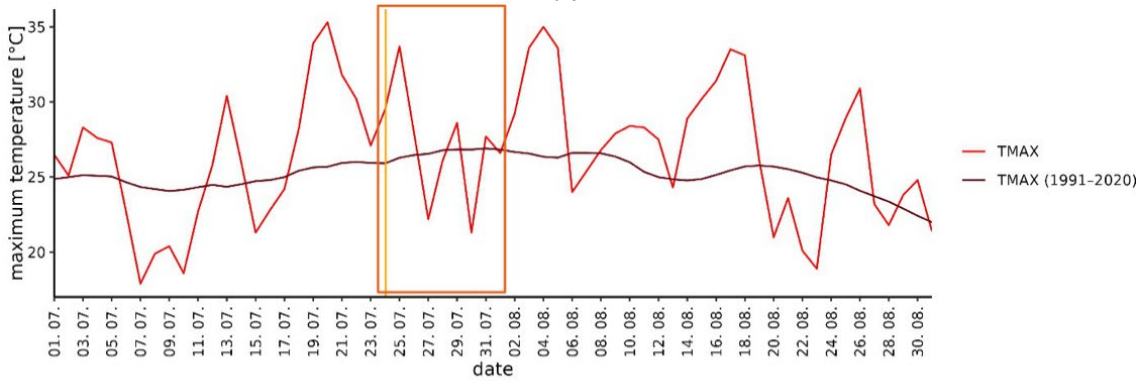
The Saxony fire warning level is based on the German National Weather Service (*Deutscher Wetterdienst*) predictions, and the state is split geographically into three regions (high, medium and low forest fire danger). The lowest spatial unit is the *Gemeinde* (a German administrative unit) with a mean average area of 45 km^2, though actual area varies considerably. The high and medium risk areas are in the north of Saxony are monitored by the Automatic Forest Fire Early Detection System (AWFS) which uses cameras, and by employing overlapping fields of view, cover almost all the high and medium risk areas. However, in the south of Saxony where this particular fire occurred there are no cameras monitoring the forests.

The Czech fire warning levels are based upon a combination of the Fire Weather Index (FWI) developed in Canada and the Forest Fire Danger Index (FFDI) developed in Australia.

As mentioned above, the summer of 2022 was hot for sustained periods. However, temperatures of above 30°C are not uncommon during the summer months in Saxony and northern Czechia. In the month leading up to fire the average daily temperature rose steadily (Figure 112a) and night-time temperatures in the 6 days prior to the fire were on average 15°C. The first days of the fire were characterised by high wind speeds contributing to a fast spread of the fire (Figure 112b). Precipitation in the 10 days leading up to the fire was sporadic and was less than 5 mm in total, leading to very dry conditions for the dead and live fuels (Figure 113).

Figure 112. Daily maximum temperature (a) and maximum speed of wind gusts (b) before, during and after the fire.

(a)



(b)

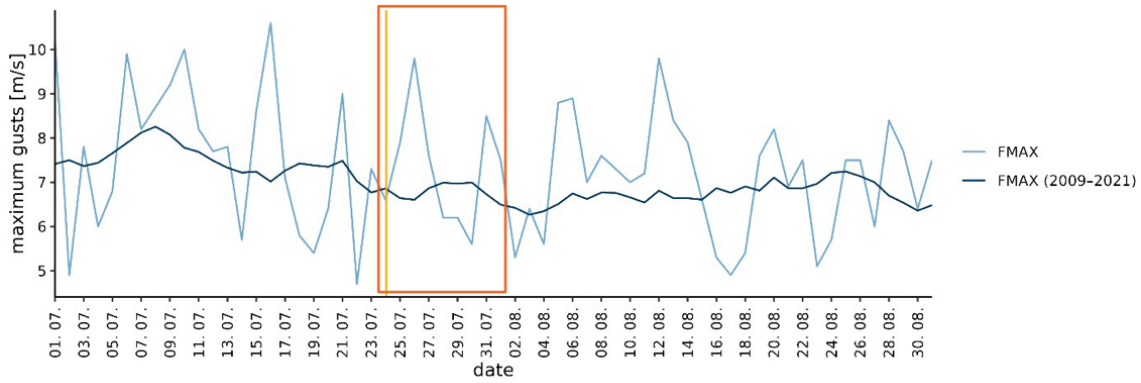
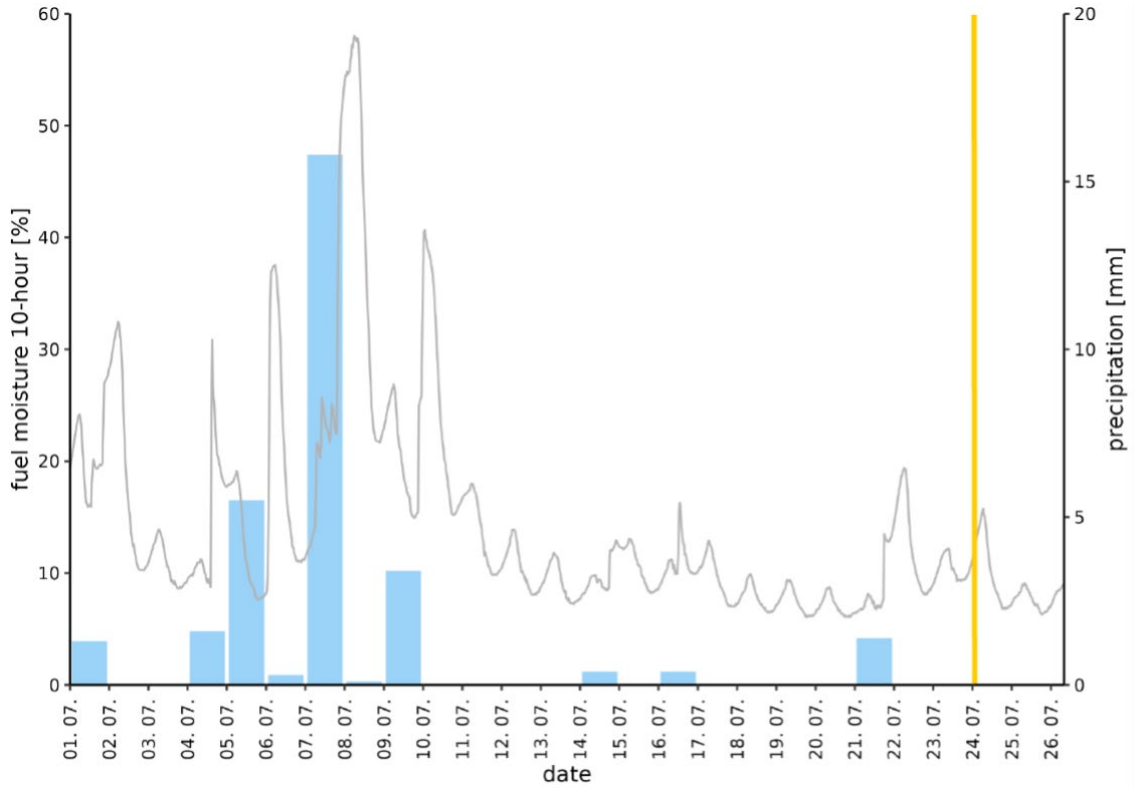


Figure 113. Fuel moisture and precipitation at the fire site. This station was destroyed by the fire on July 26th.



11.4 Fire Behaviour

The fire's relatively small size, compared to larger fires experienced in southern Europe, and the containment efforts of the emergency services, must be taken into account when examining the fire's behaviour. However, research carried out by *Technische Universität Dresden*, revealed a number of key aspects that influenced the fire behaviour.

The stands of dead spruce contained a higher amount of ground-fuels consisting of woody debris (branches, twigs) and fallen needles. This high ground-fuel load was also present in mixed forest where dead spruce could also be found. The spruce remains intact and upright after death until wind or other factors cause the limbs of the tree to fall, at which time they are already dry. The combination of limited rainfall and high fuel loads resulted in these areas burning with more energy and higher flame length than other types of woodland. This meant that adjacent broadleaved woodlands were subjected to a greater exposure to direct flames and flying embers. The dryness of the standing deadwood created the situation where the scorching height or torching was greater. This led to embers being released from a height, travelling further and likely

carried upwards as a result of the updraft from the fire. This caused the occurrence of several spot fires that are disconnected from the main burned area.

The high intensity burning of the dead spruce stands combined with slope meant that embers travelled into the broadleaved forest stands and further away causing spot fires, some of which developed in larger fires, causing extensive damage. The beech woodlands have a generally low amount of ground fuel, at least in terms of large branches and twigs. What they do have is a thick layer of dead leaves carpeting the forest floor. This biomass and the low fuel moisture created the perfect conditions for an ember to ignite fires in the beech woods. All the beech trees that were affected by the flames shed their leaves within days of the fire.

The narrow valleys that lead upwards towards the mountaintops were observed to have burned the most ferociously. Due in fact to slope effectively increasing the flame length and pre-drying fuels and more than likely aided by the wind. It is in these valleys where highest loss of forest occurred.

The forest floor except for the beech stands is covered by a mixture of grasses and bilberry (*Vaccinium sp.)*. Images taken from a camera trap (Figure 114) show that despite the relatively green condition of the bilberry before the fire, almost all green vegetation was consumed fire occurred. Using the images and the timestamps on the images it was calculated that fire spread at around 1.2 m/min in the bilberry and grasses.

Figure 114. Conditions before and after the fire as captured by camera trap (images courtesy of Saxon Switzerland National Park).

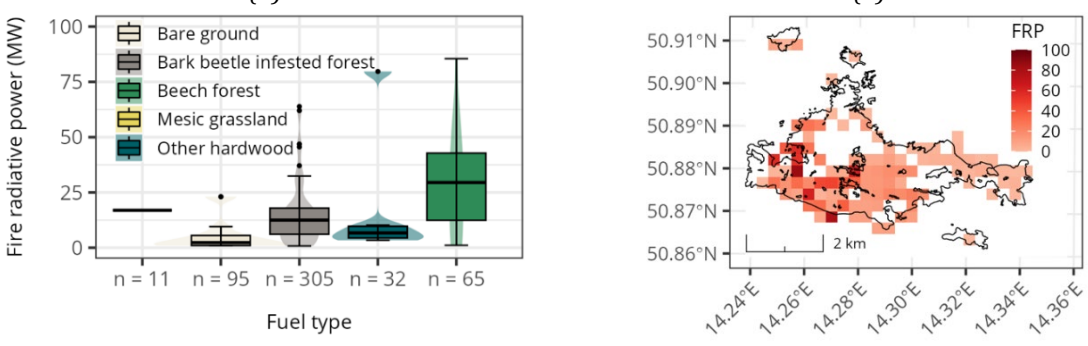
(a) *(b)*



Fire intensity was the highest during the first days of the fire – July 24th – 26th (Figure 115). The highest energy releases in terms of fire radiative power (FRP) were observed in forest stands that were previously affected by bark-beetle infestations with accumulated dead wood. Also, some areas with beech forests had high FRP, which often occurred in beech forest that were in the vicinity of spruce stands. The intensity of the fire was such that large sandstone boulders delaminated and broke apart (Figure 116).

Figure 115. Fire radiative power (FRP) over the burned area as observed by VIIRS satellite sensors between July 24th and 29th. (a) Highest fire energy emissions occurred at forest stands previously affected by bark beetle infestations and in some beech forests; b) FRP over the burned area – July 24th to 29th; c) FRP from July 24th to 29th.

(a) *(b)*



(c)

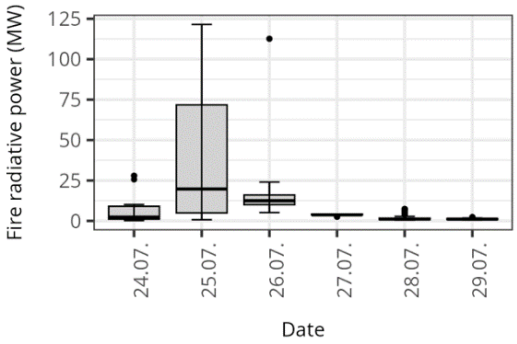


Figure 116. Sandstone affected by high temperatures.



11.5 Fire management at the WUI

The village of Mezná at the border to the Bohemian Switzerland National Park was the only place where three houses were lost to the fire. Other settlements were affected, but firefighting operations meant only Mezná suffered losses. The village sits on a hilltop surrounded on three sides by valley and partly steep gorges which were covered by forests. There is only one road in and out of the village. None of the houses that were destroyed were at the forest/village interface, despite the fact the fire reached the village edge.

There is no pattern to the locations of the destroyed buildings that would lead to any conclusion about the spread of the fire. However, two of the three buildings had a significant amount of vegetation in the gardens surrounding the house, almost all of which burnt. Video footage from the firefighters in Mezná show large firebrands flying at height and along the ground. It is reasonable to assume that the cause of at least two of the house fires could be the result of garden vegetation (coniferous hedgerows) or woodpiles catching fire,

as neither were directly affected by flames (Figure 117). Almost every house in the village has a stock of firewood close to the building and during a visit in 2023, it was observed that houses still have large piles of firewood in the gardens and in some places against the sides of the buildings. The visit to the village also revealed that conifer-type bushes were in the garden of one of the destroyed houses.

Figure 117. House destroyed by fire in the centre of Mezná. The house was not located close to the main burned area. The burning was likely caused by flying embers that ignited the coniferous garden hedges (right side).



Figure 118 also reveals several houses directly at the forest edge, indicating that fear of a forest fire was not a concern during construction, nor afterwards judging by the proximity of the vegetation. In the village of Mezná it is difficult to identify any visible or physical measures taken that would lead one to conclude that the risk from a forest fire to the settlement was a concern for the villagers nor planning regulations. Historical images from the early 20th Century and maps from the 18th Century show that villages and individual buildings were built close to the forest in those times. Historically the village was built by foresters for wood and game production and became a tourist destination in the 19th century.

Figure 118. Fires reached the village-forest interface in Mezná. This image was taken in early June 2023. One house to the left of the photograph was completely destroyed, neighbouring houses were untouched.



11.6 After the Fire

Regeneration of the landscape following the fires has been sporadic and in part related to the fire intensity and the effect on the seedbank in the upper soil levels. For the most part regeneration has been limited to ferns and mosses. The depth of the ferns' rhizome, below the highly scorched earth protected the plants and enabled the relatively quick regeneration, ferns were showing less than two months after the fire. In some areas mosses now carpet the burnt areas (Figure 119). In areas that suffered severe burning there are indications from on-going research that the water absorption ability of the soils has been affected, due to the loss of the organic upper layer of the soil. Tracks from game, mostly boar and deer indicate that the burnt areas do not significantly affect their movement. Indeed, as grasses start to recolonise the area, vigorous growth promoted by the ash and released minerals may actually make these burnt areas a "hotspot" for game.

Figure 119. Regeneration of mosses 8 months after the fire.



The clearing of paths to provide access for firefighters also created some issues. Lack of vegetation means less infiltration of rainfall and increased run-off. The fire was in a core area of the national park, new paths and freed-up access routes enables the public to penetrate the core areas, leading to disturbance for species within them. Measures have been taken to reduce this access but has been considered by some to curtail their perceived entitlement to free access. This discussion about access and the public and the national parks was already an issue before the fires. Resentment amongst locals about newly introduced restriction measures following the fire still requires better communication and understanding between the parks and surrounding communities. In the burnt areas the standing and prone deadwood still remains and to some extent is still an available fuel. However, the small ground-fuels created from fallen branches from the dead trees that helped propagate the fire were consumed. In those areas affected by the bark-beetle but not affected by fire, this ground fuel remains. The effect on the beech stands and their vitality is not yet fully understood. Some trees succumbed to effects of the fires immediately or in the following months. It may be some time before the outlook for the remaining trees is clear and the true losses occurring from the fire are known.

11.7 Conclusions and lessons learned

The forest fire of 2022 was the second fire in the area in that summer, both became the subject of much media coverage, aided in the most part due to the location of the fires in the national parks. Thus, the microscope of public scrutiny became focussed on the actions of all involved in the fire, before, during and after. The National Park administrations have been criticised in some media for allowing the build-up of deadwood stands. The lack of standing deadwood is problem for many forests in Central Europe in terms of biodiversity, and in their defence the park administrations attempted to remedy this by retaining the deadwood stands. However, the amount and location of these stands and the risks associated with such large amounts of fuel in the proximity of more natural woodlands means that this current retention approach is worthy of reassessment. Since the fire the Czech part of the park has started to thin out and remove stands of deadwood close to the village of Doubice.

The media also covered the efforts of a multinational and inter-sectoral group of professionals to combat the fire, though coverage was done at distance and the real story of what was achieved, and the conditions involved could only be understood after the fire. Information about access in the park, for both vehicles and people on foot was not readily available, resulting in firefighters using tourist maps to navigate and several

local guides coming out of retirement to make-up for the deficit in this knowledge. In some places trails and indeed some roads access was restricted by fallen logs, causing delays in getting to the fire front.

Communication, even between responders and agencies from the same country, was fraught with problems regarding connectivity in the hilly landscapes and deep gorges, where sunlight can barely reach, let alone a mobile phone signal. Standing deadwood already weakened and fragile became extremely dangerous when ablaze, creating serious risks for the firefighters. In many places this danger remains, leading to access to some areas being controlled. This restriction of access is not popular with either visitors or locals, though a completely understandable measure in terms of protecting both the vulnerable soils and the visitors themselves.

The fact that the fire was in two national parks on the border of Czech and Germany meant that it was featured in the media and as tragic as the fire was for nature and people who depend upon it for the livelihoods, there is now an increasing realisation that forest fires in Central Europe are a contemporary danger that must be addressed. This needs to be accomplished at a policy, management and community level. Firefighters and other emergency responders are now able to reassess how they deal with large forest fires and where techniques, equipment and preparation needs to be improved. Science, whilst already awake to the increasing threat of wildfires in Central Europe, now has living laboratory where the causes and effects of wildfire on Central European ecosystems can be better understood.

12 Penteli Attica Fire (Greece)

Authors

Nadia Politi	NCSRD
Athanasios Sfetsos	NCSRD
Diamando Vlachogiannis	NCSRD

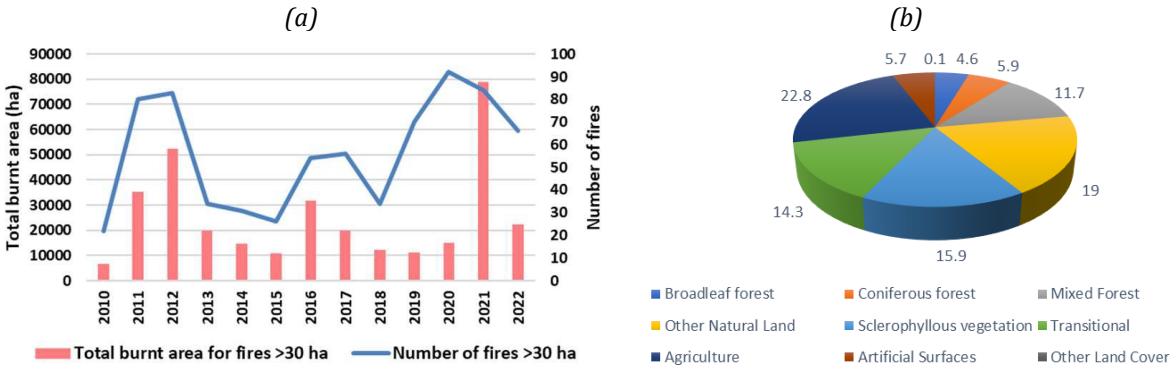


12.1 General Description

In 2022, Greece experienced a unique pattern of wildfire incidents, both in timing and number. From January 1st to October 31st, 9,245 wildfires were recorded, marking a 3.1% increase from the 15-year average of 8,958 fires (2007-2021). Notably, a significant majority of these fires, numbering 5,922, occurred during the peak fire season, from May to October. The total land area affected by these wildfires in 2022 was 23,838 ha, with 22,322 ha burned during the May-October period. This represents a notable decline of 52.42% in burned acreage compared to the historical average of 50,097 ha for 2007-2021. Of the total burned area, 4,288 ha were forested lands, a reduction from the historical average of 9,532 ha.

The Joint Research Centre's first report of 2022 (JRC, 2022) contrasted this year with 2021, noting a return to average levels of fire activity. A total of 23,942 ha was burned in 230 fires, with 9,778 ha affecting Natura 2000 sites, constituting approximately 41% of the total burned area and 0.014% of Greece's total Natura 2000 area. In Figure 120b is provided the distribution of the mapped burnt area by land. Interestingly, a significant number of fires, approximately 3,323, occurred outside the typical fire season. The 2022 wildfire season posed considerable challenges, with the seven most significant fires, mainly in July, accounting for a large portion of the total burned area.

Figure 120. Annual mapped burnt area of fires >=30 ha in Greece (a) and distribution of % total area burnt by land cover types in 2022 (b).

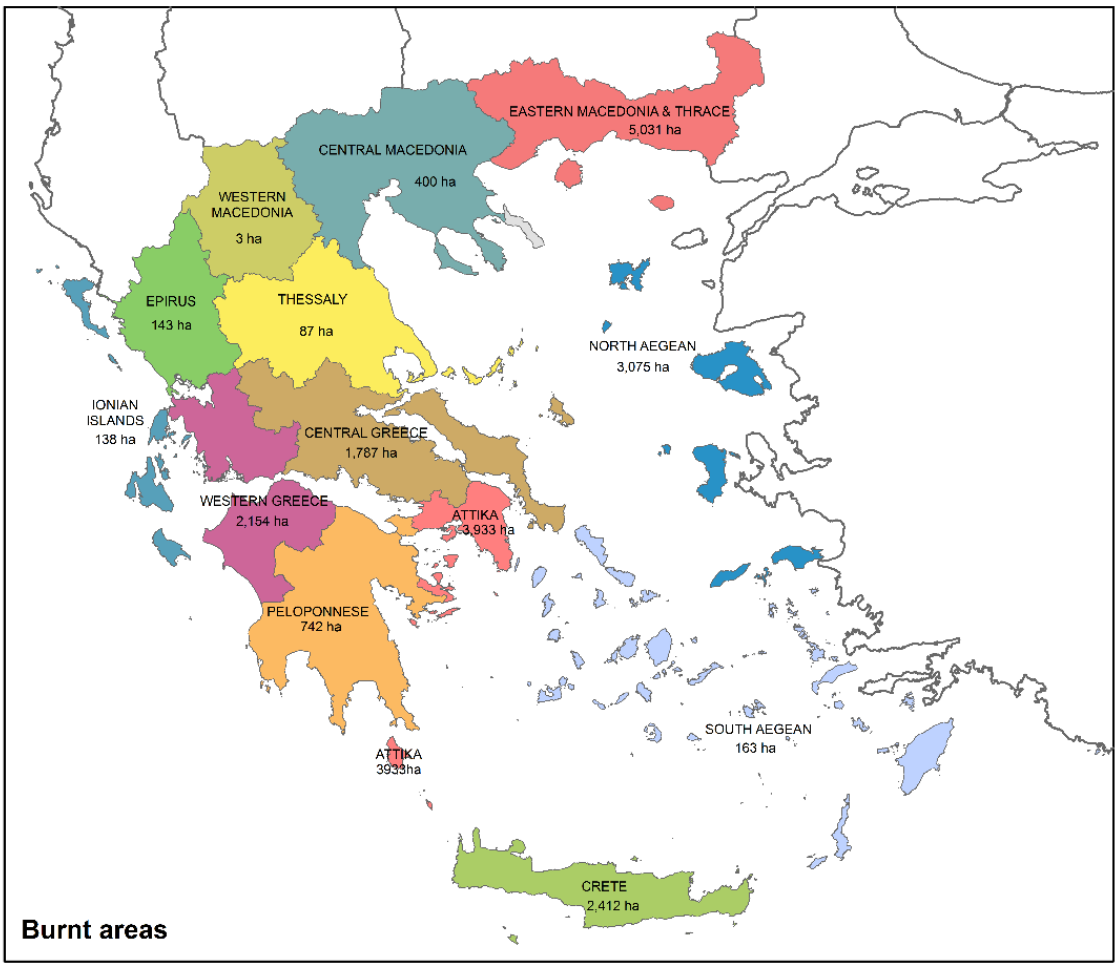


Source: JRC 2022: Advance report on Forest Fires in Europe, Middle East and North Africa 2022, JRC133215

In terms of regional distribution, the following map (Figure 121) illustrates the burned areas across Greece's thirteen administrative regions. The Dadia Forest Fire in the Natura 2000 network area was one of the most significant incidents, consuming 4,604 ha of a total 42,800 ha area. The fire season also saw the challenging Penteli Fire, covering 2,782 ha and rapidly shifting its perimeter through residential and

forested areas. July emerged as a particularly tough month, with the seven largest fires consuming 13,865 ha, which constituted 62% of 2022's total burned area.

Figure 121. Total number of burnt areas (ha) for each of the country's thirteen region of Greece.



Source: EFFIS

Regarding aerial firefighting resources, Greece deployed an aerial fleet of 83 assets, including 48 fixed-wing aircraft and 35 helicopters. The fleet was a mix of 44 leased and 39 national units. This fleet executed 2,925 air sorties, totalling 7,667 flight hours, with 1,193 hours dedicated to preventive surveillance.

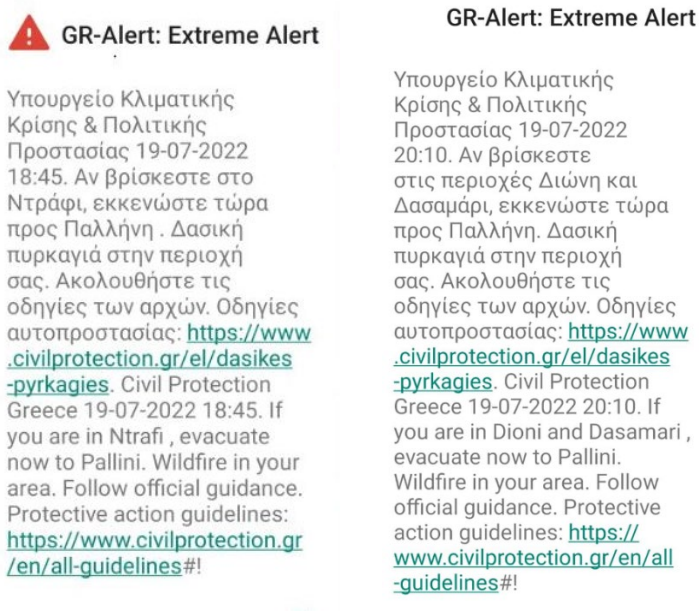
The season's most impactful fires included those in Dadia, Evros (4,604 ha), and Penteli, Attica (2,781 ha), among others. These fires underscored the critical role of proactive measures and the importance of a coordinated response in wildfire management. The Ministry of Climate Crisis and Civil Protection's activation of the "112" service 43 times for forest fire warnings, coupled with preventive evacuations and increased volunteer firefighter numbers, were key strategies in this response.

Overall, the 2022 wildfire season in Greece underscores the necessity for robust fire management strategies, enhanced preventive measures, and coordinated efforts to protect both natural and human resources against wildfire threats.

According to the Fire Service Department, the Penteli Attica Fire, due to the proximity to residential areas, sensitive structures, hospitals, industries, propane and natural gas facilities, it was an extremely difficult fire to manage, as very strong winds were blowing in the area. The fire burned mostly through shrub vegetation, pine trees and parts of agricultural land, leading to impacts on the environment as well. Therefore, in this report, this fire was selected for further analysis.

More specifically, a forest fire broke out on the slopes of Mount Penteli, closed to Ntaou Penteli area, in the northern suburbs of Athens on July 19th (17:19). Due to strong north winds (13.9-20.7 m/s), the fire moved southwards to lower altitudes and spread to the surrounding areas towards Anthousa, Ntrafi, Dioni, Pallini towns, as well as Penteli residential area (Palaia and Nea Penteli) to the west. As the fire was moving southwards, residents of those towns were receiving notification to their cell phones (through the activation of 112 emergency number) to evacuate the affected areas, as the flames approached their houses and as the fire fighting forces were operating in the area with land and aerial units (e.g., of these messages in Figure 24). The fire was extinguished on July 20th.

Figure 122. Examples of the received notifications to geotargeted population to evacuate as the fire approaches to residential areas.



Source: https://www.cnn.gr/ellada/story/321335/fotia-penteli-neo-minyma-ekkenosis-gia-dioni-dasamari-ekkenoste-tora-pros-pallini

12.2 Characterization of the affected area

Mount Pentelicus or Penteli is a mountain in Attica, Greece, situated northeast of Athens and southwest of Marathon. Its highest point is the Peak Pyrgari, with an elevation of 1,109 m. This mountain is covered in large part with forest (about 60 or 70%). Habitations surround the mountain, especially in Vrilissia, Penteli, Kifisia, Ekali, Dionysos and north of Pallini-Gerakas, housing around 169,862 inhabitants according to Census 2021 (https://elstat-outsourcers.statistics.gr/Census2022_GR.pdf).

The latest study of World Wide Fund for Nature (WWF) (Tzamtzis et al., 2022) for the area affected by this fire event indicates::

- *Pinus halepensis* forests were burned;
- Fire spread in sparsely vegetated areas, that concern rocky places and slopes, where a little vegetation cover of grasses and small shrubs dominates;
- There are no burned forest ecosystems not adapted to fire;
- Most of the burned area is double-burned stands (reburned within the last 20 years and specifically in 2009), which have either *Pinus halepensis* forests or sparsely vegetated areas;
- There are a few burnt stands of *Pinus halepensis* some of which they are double burnt, on deep slopes between 50-100%, in which natural regeneration is difficult. There is a notable increase in the number of halepensis pine stands that have experienced double burning and are situated on slopes with a gradient below 50%.

Unfortunately, in Penteli several fire events have occurred in the last 30 years. The most important event, which is extensively described in the study of Xanthopoulos (2002), involved the severe fire in

early July 1995 (July 21st to 24th, 1995) that have severe impacts on the mountain forest – total burned area reached 6,200 ha; about 105 buildings of various types were heavily damaged or fully destroyed. Xanthopoulos (2002) indicated that the smoke emissions were tremendous, nearly covering the entire northeastern are of Athens. The blaze lasted about five days. It burnt three quarters of the Mount Pentelicus, and was the worst wildfire registered in Athens and Greece in the 20th century. Some of the buildings were high quality houses built with reinforced concrete frame, clay-tile roofs etc., whereas most of them were out-houses, mobile homes, small temporary buildings, farm-barns etc. made of flammable materials. Fortunately, and despite the adverse conditions, there was no fatalities registered.

Several other fires occurred from1998 (burned area exceeded 7,500 ha and 1 fatality) to 2018 (Neos Voutzas) by destroying the forest that had remained on the mountain of Penteli after the fire of 1995, and reburned most of the previously burned area reducing the capability for natural regeneration of pine due to lack of seed (Xanthopoulos, 2002). The following years, housing development occurred in the eastern part of the mountain, resulting in the depletion of its remaining natural elements. The streets in this area are designed in a grid and circular pattern. The northern half remains heavily forested.

12.3 Fire conditions

12.3.1 Fire Danger

The fire season report (May 1st –October 31st) which was presented by the Minister of Civil Protection (https://www.kathimerini.gr/society/562144600/5-922-pyrkagies-antimetopistikan-to-22/) in November, citing statistics for high-risk days of meteorological conditions (a combination of high temperatures and wind), mentioned 20 high risky days in July and 12 days in August. It should be noted that Etesian northerly winds (also known as Meltemi wind) are prevailing during summer in the eastern part of Greece and usually playing an important role in fire behaviour. They result from a high-pressure system over the Balkans area and a relatively low-pressure system over Turkey, affecting mainly the Aegean Sea and its islands.

The wildfire danger conditions for July 19th and July 20th were analysed using the fire behaviour indexes of the Canadian Fire Weather Index System (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index), as well as the moisture code sub-indexes, provided by EFFIS and depicted in Table 27. These indices can be interpreted on a danger scale where an increase in the index corresponds to an increase in fire danger based on the classification included in the following Table 27 associated with the colour's legend.

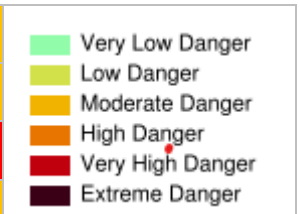
Table 26. Fire Danger classes for the FWI and its sub-components by EFFIS

Fire Danger Classes	FWI	FFMC	DMC	DC	ISI	BUI
Low	<11.2	< 86.1	< 27.9	< 334.1	< 5.0	< 40.7
Moderate	11.2 - 21.3	86.1 - 89.2	27.9 - 53.1	334.1 - 450.6	5.0 - 7.5	40.7 - 73.3
High	21.3 - 38.0	89.2 - 93.0	53.1 - 140.7	450.6 - 749.4	7.5 - 13.4	73.3 - 178.1
Very High	38.0 - 50	>=93.0	>=140.7	>=749.4	>=13.4	>=178.1
Extreme	>= 50					

Table 27. Fire Danger behaviour indicators.

Fire Weather Index (FWI)	67.7 – Extreme danger	Low Danger Moderate Danger High Danger Very High Danger Extreme Danger Very Extreme Danger
Fine Fuel Moisture Code (FFMC)	92 – High **danger**	

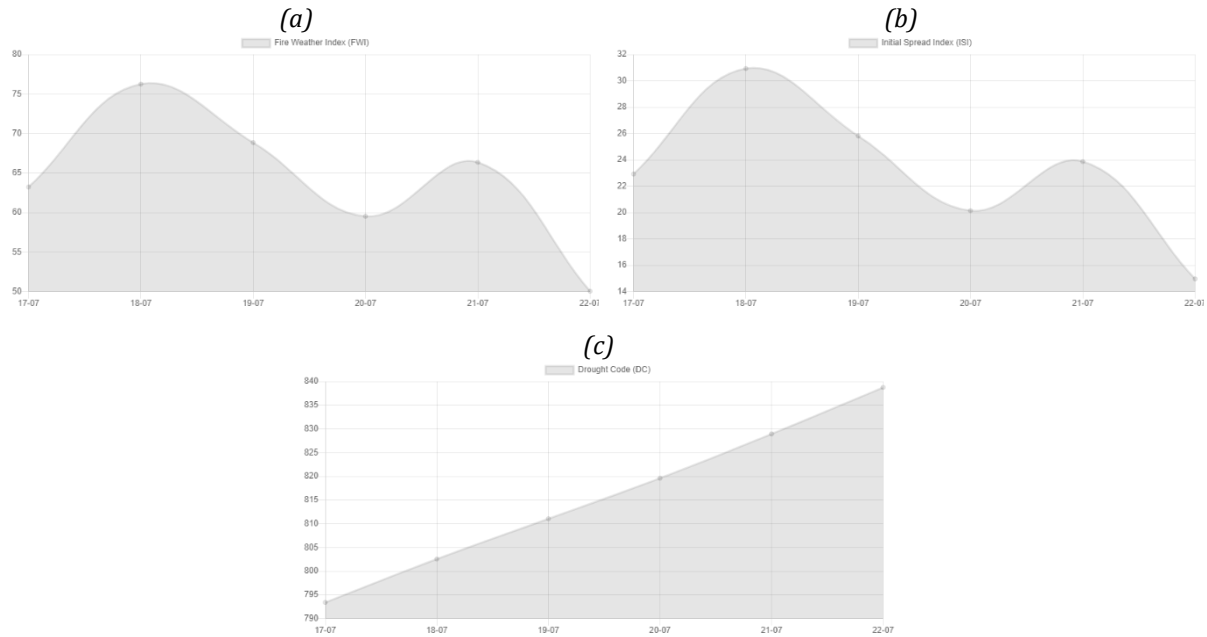
Duff Moisture Code (DMC)	94.8 - High **danger**
Drought Code (DC)	535.3 High **danger**
Initial Spread Index (ISI)	19.9 – Very High **danger**
Build Up Index (BUI)	131.4 – High **danger**
Anomaly	1
Ranking	92.4



Source: EFFIS application, https://effis.jrc.ec.europa.eu/apps/effis_current_situation/index.html

The following graphs in Figure 123, downloaded by EFFIS, provided the fire behaviour indices evolution, two days before the fire-starting date, and during the period that the fire broke out. The indexes assumed extremely high values, as well as the day before of the fire-starting date by yielding extremely high FWI values between 76 and 68. This magnitude of FWI means that any eventual wildfire would be expected to have an exceptional intensity with extreme difficulty of control.

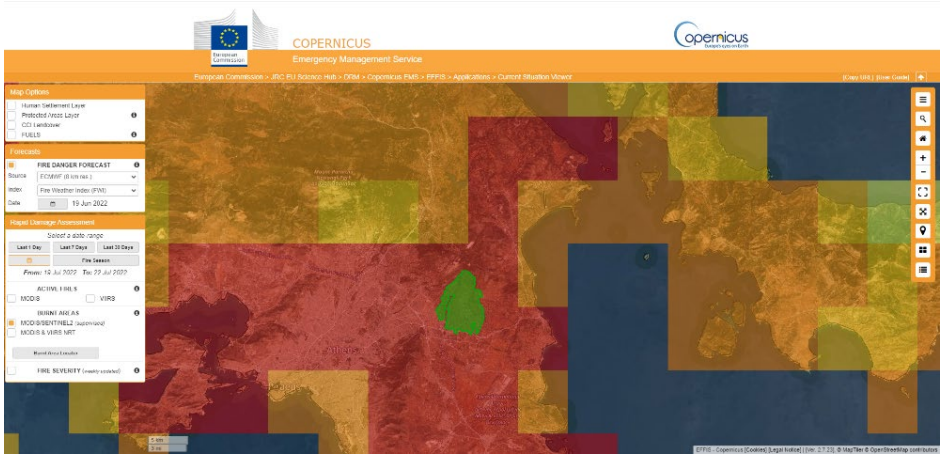
Figure 123. Daily evolution of a) Fire weather index, b) initial spread index an c) drought code provided by EFFIS before and after the fire occurred in the burnt area of Penteli.



Source: EFFIS application, https://effis.jrc.ec.europa.eu/apps/effis_current_situation/index.html

In addition, in Figure 124 is pointing out spatially the total burnt area (in green color) of Penteli Attica fire by MODIS/SENTINEL2 (supervised) and MODIS & VIIRS NRT, in the area of Mount Penteli along with the FWI background in the day (extreme value) that the fire has started.

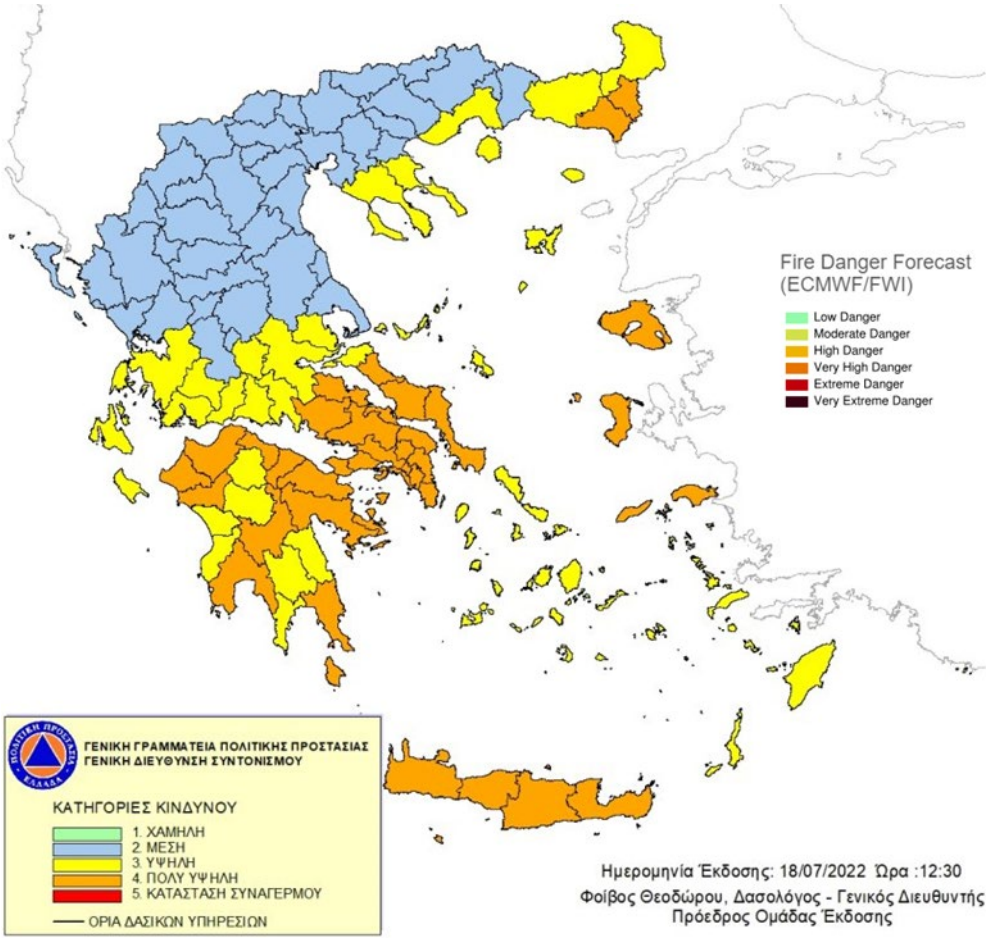
Figure 124. Spatial depiction of FWI index and Total burnt area by MODIS/SENTINEL2 (supervised) and MODIS & VIIRS NRT in the affected area (in green) of Mount Penteli.



(Source: https://effis.jrc.ec.europa.eu/apps/effis_current_situation/)

Moreover, according to the Fire Risk Prediction Map (Figure 125) for Tuesday July 19th, provided by the General Secretariat of Civil Protection of the Ministry of Climate Crisis & Civil Protection (https://civilprotection.gov.gr/), a very high risk of fire (category number 4 in the map, orange colour) was predicted for the whole Attica Region. This map was issued on July 18th at 12:30.

Figure 125. Fire Risk Prediction Map for Tuesday, July 19th. The legend on the bottom left corner classifies by colour the fire risk in 5 categories, as (1.low, 2. moderate, 3. high, 4. very high and 5. alert situation). The black lines show the boundaries of local forest services).



Source: https://civilprotection.gov.gr/arxeio-imerision-xartwn

12.3.2 Resources allocation

Overall, during the fire season, 2,925 aerial vehicle sorties were made, and a total of 7,667 flight hours were carried out, of which 1,193 hours were for surveillance in the framework of strengthening prevention. In what concerns the actions towards the Penteli Attica fire, the elements provided by the Fire Service Department (https://www.fireservice.gr/el_GR/synola-dedomenon), reported that this wildfire event had allocated in total, 2,485 firefighters, assisted by 28 ground teams and several volunteers, as well as by 120 fire engines, five CL-425 water-dropping planes, three CL-215 aircrafts and thirteen helicopters.

12.4 Fire management at the WUI

The burnt area provided by MODIS is estimated of 2,836 ha as depicted in Table 28 which also includes the percentage of the estimated affected land cover.

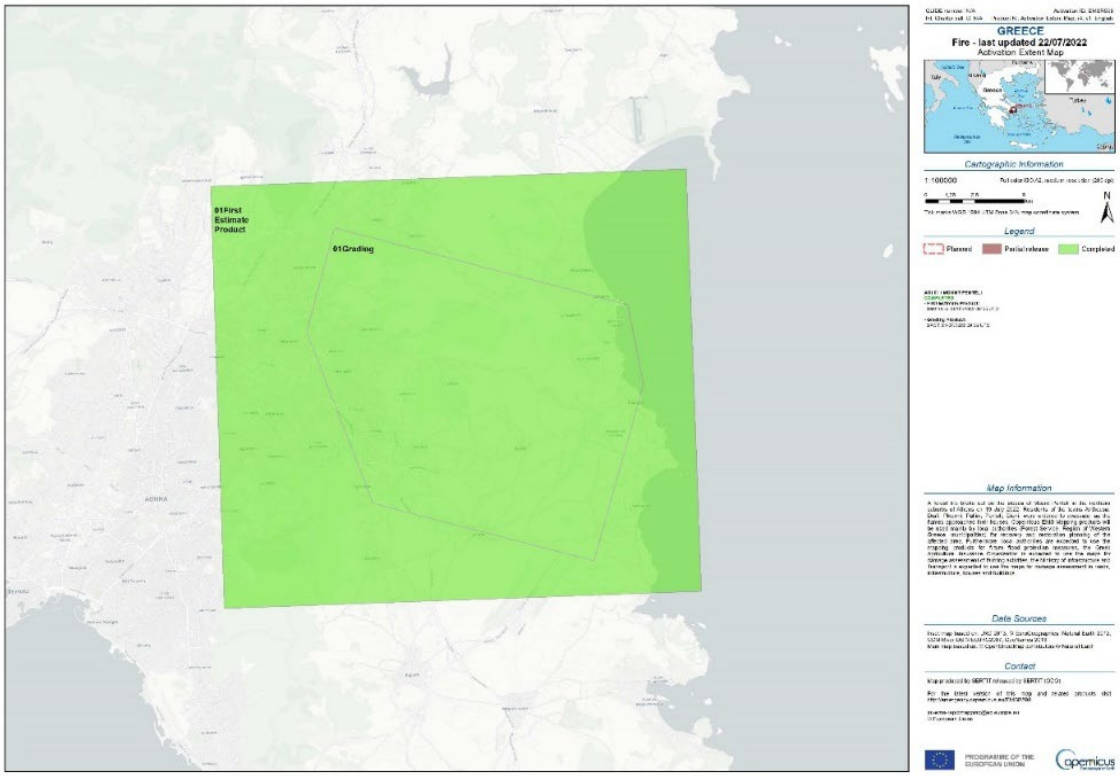
Table 28. MODIS burnt area detailed layer information for Penteli Attica Fire.

Start Date	July 19th
Last Update	July 20th
Country	Greece
Province (NUTS3)	Regional Unit of North Athens (Northern Sector of Attica Prefecture)
Location	Local Municipality of Penteli
Total Burnt Area (ha)	2,836
Forest: broadLeaves (%)	0
Forest: coniferous (%)	0
Forest: mixed (%)	0
Sclerophyllous Vegetation (%)	13.8
Transitional Woodland-shrubland (%)	35.5
Other Natural Areas (%)	1.6
Agricultural Areas (%)	3.4
Artificial Surfaces (%)	45.7
Natura 2K (%)	0
Other Land Cover (%)	0

Source: EFFIS application, https://effis.jrc.ec.europa.eu/apps/effis_current_situation/index.html

In these two days, the emergency Copernicus system (https://emergency.copernicus.eu/mapping/list-of-components/EMSR598) and EMS Mapping products were used mainly by local authorities (Forest Service, Region of Western Greece, municipalities) for recovery and restoration planning of the affected area. Furthermore, local authorities are expected to use the mapping products for future flood protection measures, the Greek Agricultural Insurance Organization is expected to use the maps for damage assessment of farming activities, the Ministry of Infrastructure and Transport is expected to use the maps for damage assessment in roads, houses and buildings, among other infrastructures.

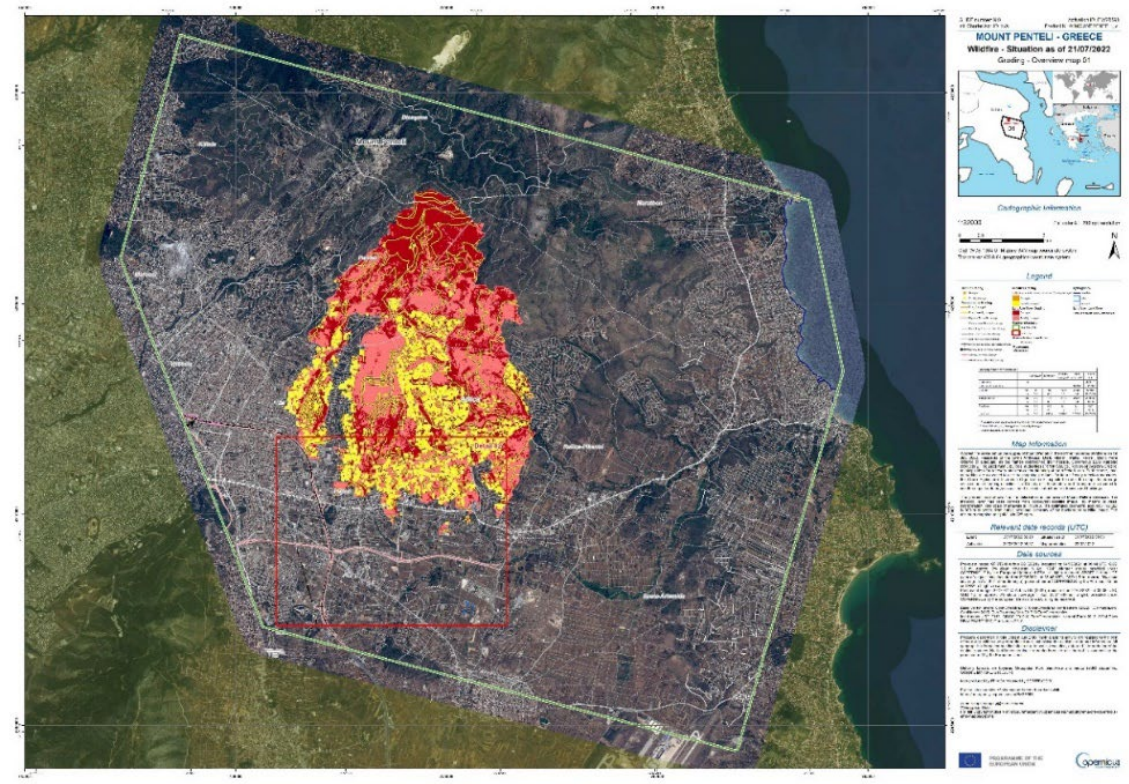
Figure 126. First estimate product from the activation of emergency Copernicus focusing on Mount Penteli.



Source: EFFIS

The following two maps in Figure 127 and Figure 128 show the fire delineation in the area of Mount Penteli and presented the situation on July 21st at 12:06 after the fire event. The thematic layer has been derived from post-event satellite image by means of visual interpretation. The scale analysis is 1:10,000. The second map is focused on a sub-area of the previous map to depict the potential damages in residential areas in more detail.

Figure 127. Fire delimitation in the area of Mount Penteli provided under Copernicus by the European Union and ESA



Legend

Built Up Grading
- Damaged
- Possibly damaged

Transportation Grading
- Road, Damaged
- Road, Possibly damaged
- Highway, No visible damage
- Primary Road, No visible damage
- Secondary Road, No visible damage
- Local Road, No visible damage
- Cart Track, No visible damage
- Long-distance railway, No visible damage

Facilities Grading
- Damaged
- Possibly damaged

Land Use-Cover Grading
- Damaged
- Possibly damaged

General Information
- Area of Interest

Administrative boundaries
- Municipality

Placenames
- Placename

Hydrography
- Lake

Land Use - Land Cover

Features available in the vector package

Data sources

Pre-event image: SPOT6 © Airbus DS (2021), (acquired on 04/03/2021 at 08:44 UTC, GSD 1.5 m, approx. 0% cloud coverage in AoI, 10.4° off-nadir angle), provided under COPERNICUS by the European Union and ESA, all rights reserved. SPOT7 © Airbus DS (year of acquisition), (acquired on 22/06/2021 at 08:48 UTC, GSD 1.5 m, approx. 0% cloud coverage in AoI, 6.9° off-nadir angle), provided under COPERNICUS by the European Union and ESA, all rights reserved.
Post-event image: SPOT6/7 © Airbus DS (2022), (acquired on 21/07/2022 at 09:06 UTC, GSD 1.5 m, approx. 0% cloud coverage in AoI, 28.2° off-nadir angle), provided under COPERNICUS by the European Union and ESA, all rights reserved.

Base vector layers: OpenStreetMap © OpenStreetMap contributors (2022), Wikimapia.org, GeoNames 2015, EuroBoundaryMap 2017 © EuroGeographics.
Inset maps: JRC 2013, GISCO 2010 © EuroGeographics, Natural Earth 2012, CCM River DB © EUJRC2007, GeoNames 2015.

Disclaimer

Products elaborated in this Copernicus EMS Rapid Mapping activity are realized to the best of our ability, within a very short time frame, optimising the available data and information. All geographic information has limitations due to scale, resolution, date and interpretation of the original sources. No liability concerning the contents or the use thereof is assumed by the producer and by the European Union.

Delivery formats are Layered Geospatial PDF, GeoJPEG and vector (ESRI shapefiles, Google Earth KML, GeoJSON).

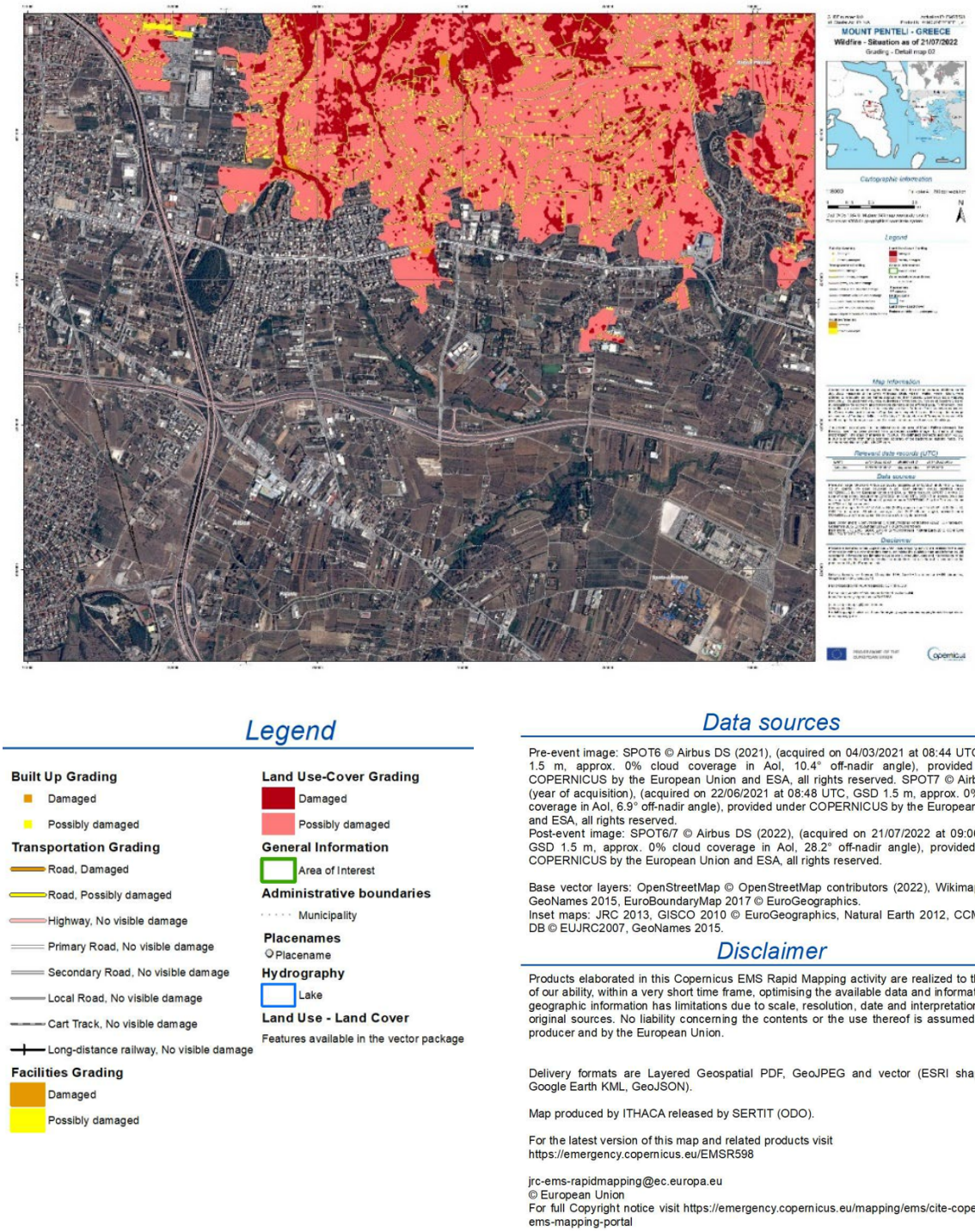
Map produced by ITHACA released by SERTIT (ODO).

For the latest version of this map and related products visit
https://emergency.copernicus.eu/EMSR598

jrc-ems-rapidmapping@ec.europa.eu
© European Union
For full Copyright notice visit https://emergency.copernicus.eu/mapping/ems/cite-copernicus-ems-mapping-portal

(Source:EFFIS)

Figure 128. Fire delination in the area of Mount Penteli provided under Copernicus by the European Union and ESA.



(Source: EFFIS)

The wildfire also severely scorched 54 houses, five businesses, seventeen warehouses and one religious' structure, according to the Ministry of Infrastructure and Transport (https://www.yme.gr/2013-01-31-06-37-23/2013-01-31-07-00-49/item/10388-aftopsies-apo-mixanikoys-tou-ypourgeiou-ypodomon-kai-metaforon-se-ktiria-ton-pligenton-dimon-pentelis-pallinis-pallini-gerakas-anthoysa-kai-rafinas-pikermiou-logo-tis-pyrkagias-tis-19is-iouliou). An 84-year-old man, from Penteli, decided to end his life after seeing his house destroyed by the fire (Lekkas et al., 2022). Thirty people were taken to the hospital, three of whom with skin burns. Most of the people suffered respiratory problems and minor injuries, including three firefighters from the Pallini, Gerakas, Anthousa and Penteli regions

(https://www.euronews.com/video/2022/07/20/wildfire-rages-in-athenss-northeastern-suburbs-for-a-second-day). The two following photos exemplify how this fire impacted ethe residential areas.

Figure 129. Houses (a) and a car (b) are engulfed by flames during the Penteli Attica Fire – in Pallini, near Athens, Greece July 20th. REUTERS/Costas Baltas.

(a) *(b)*



Source: Reuters

12.5 Conclusions and lessons learned

- The Penteli Attica Fire of July 19th was one of the most severe and dangerous fire events because of its proximity to residential network, with significant impacts on the environment, vegetation, infrastructures and one indirect fatal victim.
- Due to strong north winds, the fire front moved southwards and later westwards with high velocity in low-vegetation areas to the towns of, Anthousa, Gerakas, Pallini, Dioni and Palaia Penteli.
- Difficulties were observed on fire suppression because of the geomorphological conditions of the area and the strong north winds especially during the night.
- Increased risk of landslides and flood risk are expected due the geomorphological characteristics of the burnt area along with runoff and erosion conditions, which will worsen in the south and southeast slopes of Penteli Mt (Lekkas et al., 2022). This risk must be taken into consideration, since it can be reinforced, due to the already burdened landscape affected by past fires the last 25 years in the same area.
- Reinforcement of psychological support to those who lost the house, so avoiding dramatic situations that can lead to suicides.
- Geotargeted citizen information: The timely information of citizens about the risk they face due to an upcoming forest fire cannot, in any case, be solely based on the sending of emergency messages 112, but on a series of measures and actions that will have been defined in advance in the particular plans of the Municipality and the Region, to be launched, if there are reasons, by the competent institution at the local level.
- It should be emphasized that the measure of the total organized preventive evacuation of citizens can be applied only when the time of approach of an upcoming fire in a residential area provides scope for timely information and evacuation.
- Education for increased awareness and preparedness of populations living in fire-prone regions is very important as part of the prevention activities.

References

JRC 2022: San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Libertá, G., Oom, D., Branco, A., de Rigo, D., Ferrari, D., Roglia, E., Scionti, N., 2023. Advance report on Forest Fires in Europe, Middle East and North Africa 2022, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/091540, JRC133215.

E. Lekkas, S. Lozios, I. Parcharidis, M. Diakakis, S. Mavroulis, N.-I. Spyrou, M. Gogou, T. Falaras, K. Vorgiopoulou, M. Vassalou, K. Lymperopoulos, I. Aliferis, K.-N. Katsetsiadou, E. Kotsi, A. Berkovits, E. Stamati, S. Moraitis, I. Zikeloglou. The July 19-20, 2022 Penteli (Attica, Greece) Wildfire ISSN 2653-9454 Issue No. 27, July 2022

Tzamtzis I., Kokkoris I.P., Samaritakis V., Ganatsas P., Tziritis El., Georgiadis N., 2023. Mapping study of the areas affected by forest fires in the fire season 2022. WWF Greece, Athens. pp. 506 & 88 Annexes. https://wwfeu.awsassets.panda.org/downloads/wwf_wildfires_2022.pdf

Xanthopoulos, G. 2002. The forest fires of 1995 and 1998 on Penteli mountain. Pp 85- 94. In proceedings of the International Workshop on "Improving Dispatching for Forest Fire Control". December 6-8, 2001. Chania, Crete, Greece. G. Xanthopoulos, editor. Mediterranean Agronomic Institute of Chania, Chania, Crete, Greece. 162 p

URL:

https://emergency.copernicus.eu/mapping/list-of-components/EMSR598

https://effis.jrc.ec.europa.eu/apps/effis_current_situation/

https://www.kathimerini.gr/society/562144600/5-922-pyrkagies-antimetopistikan-to-22/

13 Dadia National Park-Evros Region Fire (Greece)

Authors

Georgios Eftychidis	AUTH
Dimitris Stavrakoudis	AUTH
Vassiliki Varela	AUTH
Ioannis Gitas	AUTH



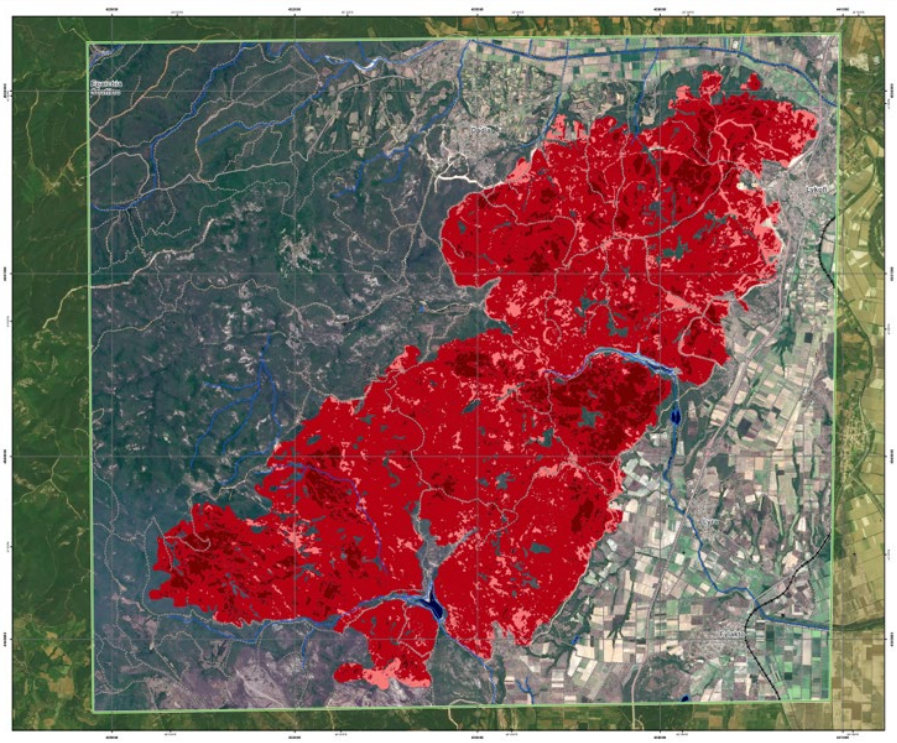


Copernicus Sentinel-2 image (ESA)

13.1 General description

In July 2022, a severe wildfire erupted in the northeastern section of Dadia National Park, situated within Greece's largest Natura 2000 site, which also harbours a significant colony of black vultures. This incident marked one of the park's most devastating fires, particularly alarming due to the area's ecological sensitivity and history of wildfires.

Figure 130 Copernicus EMS Mapping product depicting Dadia's 2022 fire extend and damage.



Data source: AUTH, NOFFi | National Observatory of Forest Fires.

The incident started at approximately 14:30 pm local time near the Lyra Dam, located within the Evros and Dadia Delta National Parks' Management Unit. The fire burned between July 21st and 27th approximately 4,600 ha of the park's extensive 42.80 ha area within the Natura network. According to data from the

Natural Environment & Climate Change Agency (N.E.C.C.A./OFYPECA), only half (2,219 ha) of the total affected area (4,541 ha) has been completely burned. The type of destruction, combined with the absence of human activity in the forest, raises hopes that nature will recover quickly.

Initial investigations point to a lightning strike as the likely cause of ignition. This wildfire posed a critical threat to the park's biodiversity, particularly affecting its population of over 200 endangered black vultures. Since 2016, black vultures in the park have been fitted with tracking transmitters for ongoing monitoring. This monitoring has provided valuable data, showing that these vultures have started to resettle in park areas, hopefully not affected by the fire.

During the wildfire, the behaviour of the fire was quite unusual and extreme in certain places. In some areas, the pine forest was completely burned, while in others, the fire moved along the ground burning only low vegetation, leaving the trees mostly unaffected. In some of these cases, the thick fuel bed on the ground, along with its high bulk density, caused a prolonged and creeping burn that lasted for days, leading to problems due to rekindling caused by changes in the wind speed and direction. The fire's paths in the National Park were serpentine, creating a mosaic of burned and unburned areas.

Fortunately, the larger of the two cores of the national park (zone A1) was not affected by the recent fire and remains intact. However, the second core of the park (zone A2) has suffered significant damage, with almost half of the southern region burned. The total burnt area is less than 10% of the national park. Despite the damage, there are still some patches of unburned vegetation that are expected to aid in the natural recovery of the area.

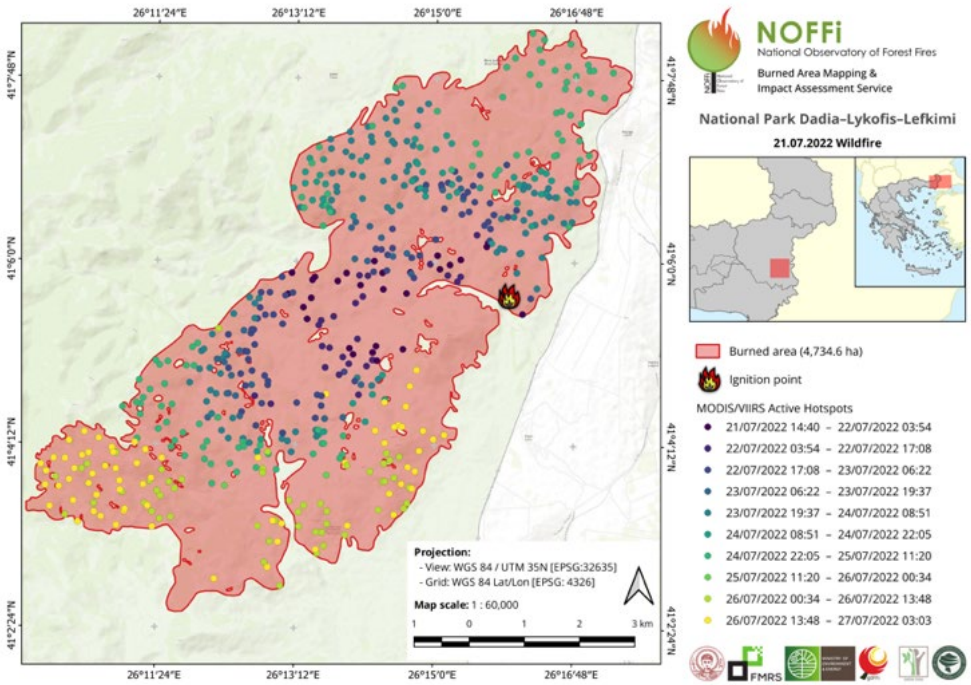
The Hellenic Fire Brigade, EMAK (Hellenic Fire Service's Special Disaster Response Unit), Forest Service, Forest cooperatives, locals, villagers, volunteers, conservationists, and other involved units, both aerial and ground-based, made a concerted effort to contain the fire. They all joined forces to save the threatened villages and the core of the National Park. Their hard work was instrumental in achieving this goal.

13.2 Incident Progression

The fire broke out on July 21st at around 14:30 pm local time, near the Lyra Dam in the Evros region. Within a short time, a secondary fire front emerged south of the Lyra Dam, which required a reallocation of firefighting resources. This development made the situation more complex and raised concerns about the potential magnitude of the fire. Despite the combined efforts of multiple agencies, including the Fire Brigade, forest services, military units, civil protection of the Region, the municipality of Soufli, and local volunteers, the fire continued to spread. Initial attempts to contain the fire were unsuccessful, and the perimeter extended several kilometres.

The figure below shows the active hotspots recorded by MODIS/VIIRS during the fire duration.

Figure 131. Dadia fire active hotspots – July 21st to 27th.

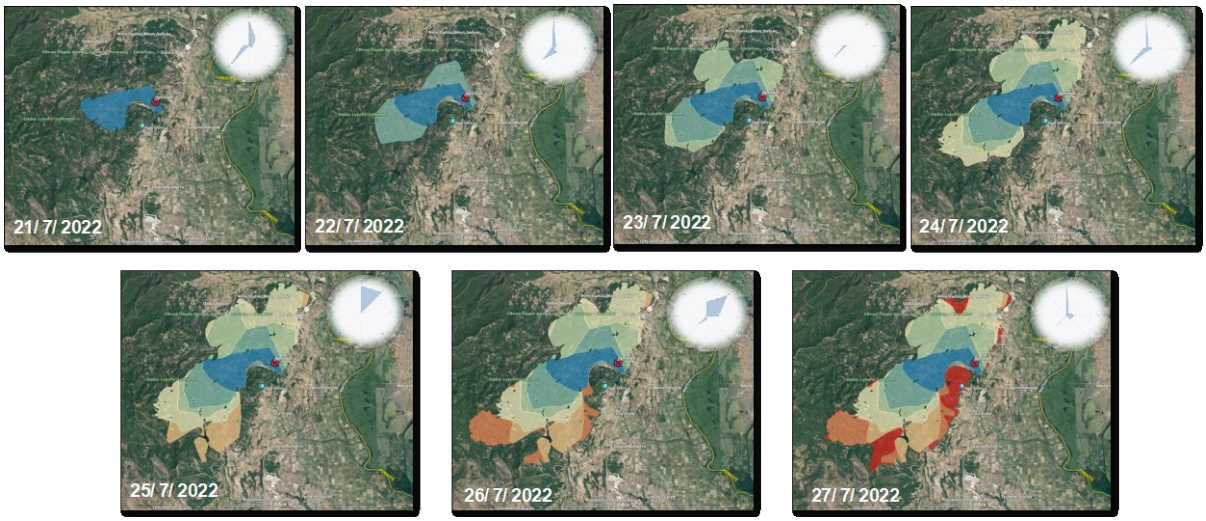


Source: MODIS/VIIRSA: NOFFi | National Observatory of Forest Fires.

The Hellenic Fire Service acted promptly to the Dadia wildfire by deploying a significant number of resources. The operation involved 102 firefighters, 4 groups of ground forces, 29 vehicles, 6 water-bombing aircraft, 5 helicopters, and municipal water tanks. Despite this strategic deployment, the wildfire could not be adequately suppressed and managed.

The progression of the Dadia fire over seven days is shown and analysed next. The fire initially spread towards the southwest, in the direction of the prevailing winds that blew from the north and northeast (ePADAP). However, it is essential to note that the fire's path changed during the seven days due to alterations in wind direction and speed. Figure 132 provides a series of daily fire propagation patterns, accompanied by a wind rose diagram for each day, which depicts these changes.

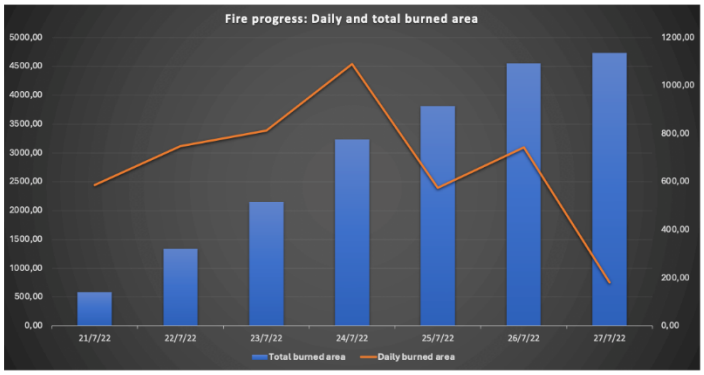
Figure 132. Daily progress of the Dadia fire – July 21st to 27th.



Source: AUTH, NOFFi | National Observatory of Forest Fires.

Presented below are the daily and total burned areas between July 21st and July 27th, in both graphical and tabular formats.

Figure 133 Daily burned areas in Dadia fire – July 21st to 27th.



	Total burned area (ha)	Daily burned area (ha)
21/7/22	586,74	586,74
22/7/22	1333,62	746,88
23/7/22	2147,12	813,50
24/7/22	3236,00	1088,88
25/7/22	3809,89	573,89
26/7/22	4553,11	743,22
27/7/22	4734,59	181,48

Data source: AUTH, NOFFi | National Observatory of Forest Fires.

Analyzing wildfire data from Dadia National Park provides insights on daily fire behaviour and growth (ePADAP).

Day 1: July 21st

- Fire growth: 586.74 ha burned.
- Meteorological conditions: Average temperature of 29.4°C and peak wind speed of 20.5 km/h from 240°.
- Impact: The rapid spread of the fire on the first day was likely due to high temperatures and strong winds from the north and south-southwest, which made firefighting challenging due to increased fire intensity and spread rate.

Day 2: July 22nd

- Fire growth:160.14 ha more than the first day burned (total burn for the day 746.88 ha).
- Meteorological conditions: Slightly cooler with average temperatures around 30°C, wind speeds up to 16.6 km/h, winds shifting from south-southwest to west-southwest (240° to 250°).
- Impact: Despite a slight decrease in temperature, the persistent strong winds caused a significant increase in the burned area due to abundant fuel.

Day 3: July 23rd

- Fire growth: 66.62 ha more than the previous (second) day burned (total burn for the day 813.50 ha).
- Meteorological conditions: Temperatures peaked at 34.6°C with 18.4 km/h winds from the southwest (240°).
- Impact: The fire's behaviour was likely worsened by high temperatures and gusty winds, causing it to spread further and making containment more challenging.

Day 4: July 24th

- Fire growth: Significant increase, with 275.38 ha burned more than the previous day (total burn for the day 1,088.88 ha).
- Meteorological conditions: Temperatures reached 34°C with variable wind speeds up to 20.5 km/h.
- Impact: This day saw the largest daily increase in burned area, possibly due to shifting winds that exposed new fuel and flanks of the fire to combustion.

Day 5: July 25th

- Fire growth: The fire's daily spread was reduced by almost 50% from the previous day, with a total burn of 573.89 ha for Day 5.
- Meteorological conditions: Slightly cooler temperatures around 30°C with wind speeds up to 18.4 km/h from varying directions.
- Impact: The slight improvement in weather conditions enabled firefighters to slow the rate of spread.

Day 6: July 26th

- Fire growth: There has been a 169.33 ha increase in the daily burned area compared to the previous day, bringing the cumulative total from Day 1 to 4553,11 ha.
- Meteorological conditions: Temperatures peaked at 33°C with south-southwest winds at speeds up to 22.3 km/h.
- Impact: The wind's persistence and strength, in combination with high temperatures, likely caused the fire to continue spreading, especially in areas with a large amount of fuel.

Day 7: July 27th

- Fire growth: A decrease in wind speed and change in direction reduced fire spread to only 181.48 ha burned while extinguishing active fire fronts.
- Meteorological conditions: High temperatures reached 35°C with 20.5 km/h south-westerly winds.
- Impact: Despite the hot weather, the reduced wind speed may have contributed to a smaller increase in burned areas. This could be due to effective firefighting efforts or the fire reaching natural barriers or areas with less fuel.

The most challenging days for firefighting during the Dadia National Park wildfire were July 21st and July 24th. On July 21st, the fire spread rapidly due to high wind speeds and temperatures, making it difficult to control. The situation continued to worsen, and on July 24th, the fire burned the most area in a single day. This was made worse due to a significant change in wind direction, complicating containment efforts. Both days were marked by weather conditions that significantly influenced the fire's behaviour and posed substantial challenges to firefighting strategies.

13.3 Operational Challenges and Strategy Shifts

The firefighting efforts in Dadia National Park were compounded by the stringent restrictions imposed by the park's protected status, which posed additional challenges to the wildfire containment strategies. The National Park's designation meant that any firefighting measures had to be carefully balanced to prevent ecological damage, complicating efforts to manage the wildfire while preserving the habitat of species such as the rare black vulture.

The deep beds of forest fuel, typical of untouched natural reserves like Dadia, offered abundant combustible material, exacerbating the fire's intensity and persistence. The topography of the park, characterized by rugged terrain and dense underbrush, further hindered the effectiveness of traditional firefighting methods and equipment. To mitigate this, heavy earthmoving machinery was utilized to carve out firebreaks, a critical action in containing the spread of the fire from Zone A2 to the more sensitive Zone A1, where the core of the forest and the black vulture colonies reside.

The operation was a testament to coordination and collaboration, bringing together 320 firefighters, 13 hiker teams, 75 water trucks, 5 aircraft, and 9 helicopters. These forces worked in unison, supported by the robust assistance of the Hellenic National Defence General Staff (HNDGS) and the Regional Unit of Evros, which provided additional machinery and water trucks. The integral efforts of local foresters and volunteers were pivotal; their in-depth knowledge of the terrain allowed for strategic firebreak placements and fuel thinning while maintaining the ecological balance.

Despite the coordinated response, the unpredictable nature of wildfires, fuelled by dry conditions and variable winds, led to a prolonged engagement with the fire. The operation was further challenged by the need to ensure that the actions taken to control the fire were in line with the conservation goals of the

national park, avoiding unnecessary harm to the protected environment. The firefighting forces were hampered by the direction and not so much the speed of the wind, as well as the area's topography.

The firefighting teams' commitment to safety and conservation was evident in their adaptive strategies, which were responsive to the dual imperatives of combating wildfire and preserving the park's natural heritage. They demonstrated an unwavering dedication to the task, even as they faced the continuous threat of re-ignition and the logistical complexities of managing an extended operation in a sensitive and protected landscape.

In conclusion, the firefighting operation in Dadia National Park highlighted the critical importance of integrating conservation principles into wildfire management. It underscored the effectiveness of collaborative efforts and the value of local expertise in protecting natural ecosystems and human interests. The experience from Dadia provides valuable insights for future wildfire management in protected areas, where the balance between immediate threat mitigation and long-term ecological preservation is of paramount concern.

13.3.1 Objectives and Defensive Measures

The Dadia National Park wildfire required a strategic approach that included both offensive and defensive measures due to the challenging conditions presented by the limited water supply from the Lyra Dam. Unfortunately, the dam's compromised capacity, caused by unresolved leakage issues, severely impacted water availability for firefighting. This underscored a critical gap in disaster preparedness and preventive measures. Despite prior knowledge of the dam's state and a previous incident at the neighbouring Provatonas Dam, the necessary maintenance to ensure water availability had not been prioritized. This demonstrated a shortfall in proactive management and risk assessment.

The operational strategy had two main protection goals. The first goal was to defend Dadia village, which was located dangerously close to the northern front of the fire. A comprehensive fire defence perimeter was quickly established, involving a coalition of regional fire units, military personnel, and expert local forestry workers. Although residents were evacuated as a precaution, they played an active role in the firefighting efforts. This collaborative defence effort culminated on the evening of July 23rd, with the village emerging unscathed from the immediate threat.

A robust defence line for Zone A1, a biodiversity hotspot and sanctuary for numerous predatory species, was a top priority. A meticulous and labour-intensive operation established an extensive firebreak that spanned two kilometres, effectively linking the Airport area to the Lefkimi fire station. The tireless work of the crews over 24 hours resulted in a formidable barrier that halted the fire's progression toward this ecologically critical area. Preserving the predator nests was a significant victory in the face of the blaze, epitomizing the success of the defensive strategy.

The offensive measures, although hindered by the water shortage, were augmented by alternative firefighting techniques and adaptive strategies. These included deploying specialized ground and aerial equipment adapted to the rugged terrain and the need for precision in sensitive ecological zones.

The Dadia National Park firefighting operation serves as a case study of the complexities of wildfire management within protected areas, highlighting the delicate balance between aggressive fire suppression tactics and the imperatives of environmental conservation. The experience underscores the necessity for thorough preparedness, the integration of local expertise, and the importance of maintaining critical infrastructure to ensure readiness for emergency responses.

13.4 Characterization of the affected area

The Dadia-Lefkimi-Soufli Forest National Park (DNP), located in the Evros Prefecture of northeastern Greece, is ecologically significant nationally and internationally. Covering 42,800 ha, this park is part of the Eastern Rhodope Mountains' southeastern hills. The ecological diversity of DNP is remarkable, featuring a blend of pine and oak forests, open clearings, pastures, and agricultural fields. This varied habitat supports a wide range of species, notably raptors, and is home to three of Europe's four vulture species, including the Balkans' only breeding population of Black Vultures. The park's extensive biodiversity includes around 360-400 plant species, 104 butterfly species, numerous amphibians, reptiles, mammals, and over 200 bird species, including 36 European raptor species.

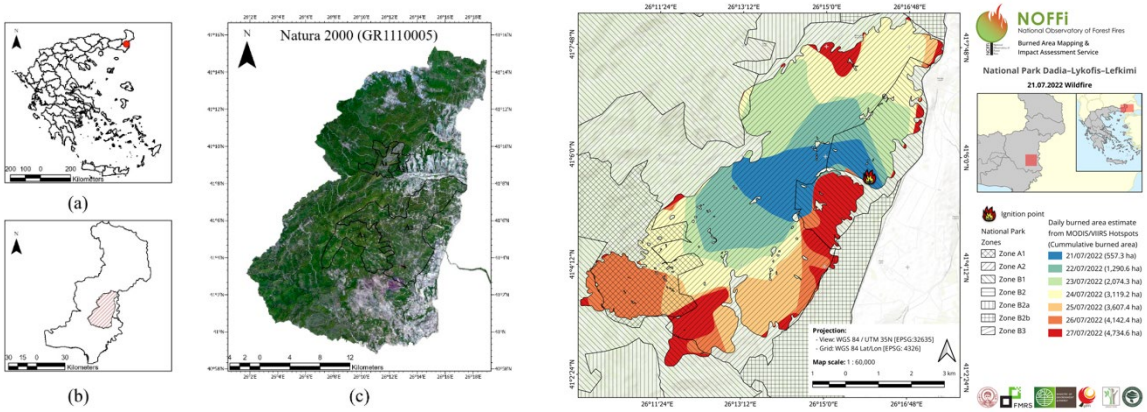
The low-altitude Dadia forest, with its mix of xerophilous deciduous oaks and Calabrian pines, underwent significant changes in the 1970s. Recognized for its high conservation value, especially for birds of prey, the forest saw development projects, including infrastructure improvements and reforestation. Conservation concerns led to the designation of the Dadia Forest as a Special Protection Area or Nature Reserve in 1980, categorized into a buffer zone and two core protection zones, each with distinct management practices focused on protecting threatened bird species.

Since the 1970s, the Dadia-Lefkimi-Soufli forest complex has been managed for timber production, game, and livestock support. However, stricter protection measures implemented since the 1980s, especially in the core zones, led to denser woodlands. In the early 1990s, a shift in management philosophy emphasized a balance between conservation and sustainable use, leading to the park's designation as a National Park and implementing a Forest Management Plan. A monitoring system established in 2000 ensures regular assessment of the forest's health and interventions.

The park administration is shared among several municipalities, with most of the land being public. Only cultivated fields are privately owned. The Forest Service, particularly its Soufli Office, manages the forest. The park was initially designated as a Nature Reserve in 1980, covering about 42,400 ha. By 2006, it had expanded to 42,800 ha and was officially designated as the Dadia-Lefkimi-Soufli Forest National Park (Natura 2000, GR1110005). The park has a zoning structure established before its official designation as a national park. The zoning structure includes a strict protection zone of 7,800 ha and a buffer zone subdivided for various uses such as forest exploitation, agriculture, and grazing. The figure below shows the current zones of the Dadia National Park with the fire perimeter overlay for each day between July 21st and July 27th.

Figure 134 Dadia National area and Park Zones with the daily burned areas during the 2022 fire.

(a) *(b)*



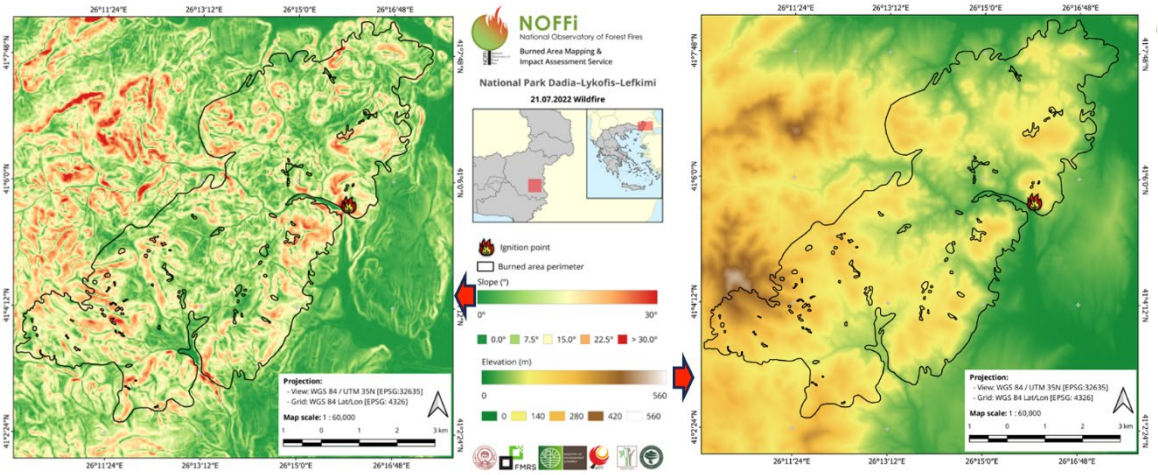
Data source: AUTH, NOFFi | National Observatory of Forest Fires.

Geographically and geologically diverse, DNP is located 36 km from the coast, near the Evros Delta, and at a varied altitude between 10 and 654 m above sea level. Tertiary ophiolite complexes characterize the northern part of the park, while the southern part comprises Paleogene volcanic and sedimentary rocks. The park experiences a modified Mediterranean climate, with northern winds influencing the weather patterns. Historical data from 1964 to 1998 indicates an average annual precipitation of 732 mm, with the dominant vegetation consisting of thermophilous sub-continental deciduous oaks and pine forests (N.E.C.C.A).

The next figures display slope (Figure 135a) and elevation (Figure 135b) maps of the wider park area.

Figure 135. Slope and elevation of the Dadia National Park area.

(a) *(b)*

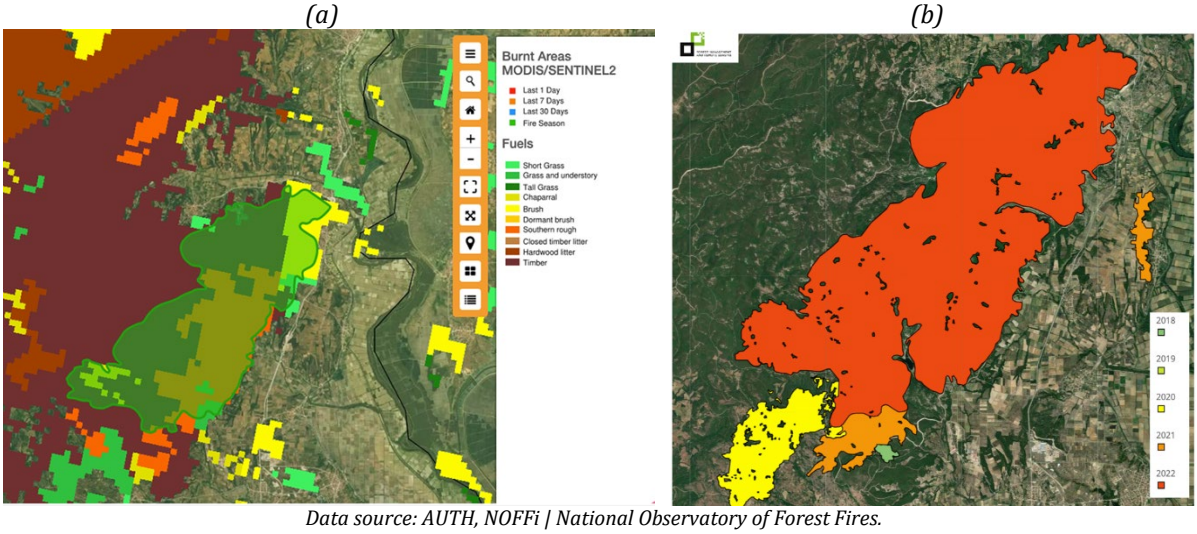


Data source: AUTH, NOFFi | National Observatory of Forest Fires.

The area of the National Park most affected by the fire was predominantly forested, with a vegetation composition primarily of black pine (*Pinus nigra*) and Calabrian pine (*Pinus brutia*), interspersed with oak species (*Quercus spp.*) and various deciduous trees, alongside areas of maquis shrubland. The vegetation in the two protected zones, A1 and A2, covers an area of 7,350 ha. Oak and pine trees make up most of the forested areas. The spatial distribution of the different types of trees in the National Park can be divided into two areas. The centre is covered with pine trees, whereas the north and southwest are mostly oak. The distribution of these fuel types within the impacted zone is illustrated in Figure 136a. Furthermore, the area experienced in the past multiple smaller-scale wildfires in the region, with the subsequent figure detailing incidents from 2018 to 2022 (Figure 136b). During 2019 and 2021, two major fires occurred within the National Park, both in the southern region and the northern part of the village of Lefkimi. The first burst-fire occurred on October 1st, 2020, burning approximately 694 ha, and the second on July 9th, 2021, burning approximately 242 ha (Maniatis et al., 2022).

Figure 136. Recent fire history (a) in the area and fuel types (b).

(a) *(b)*



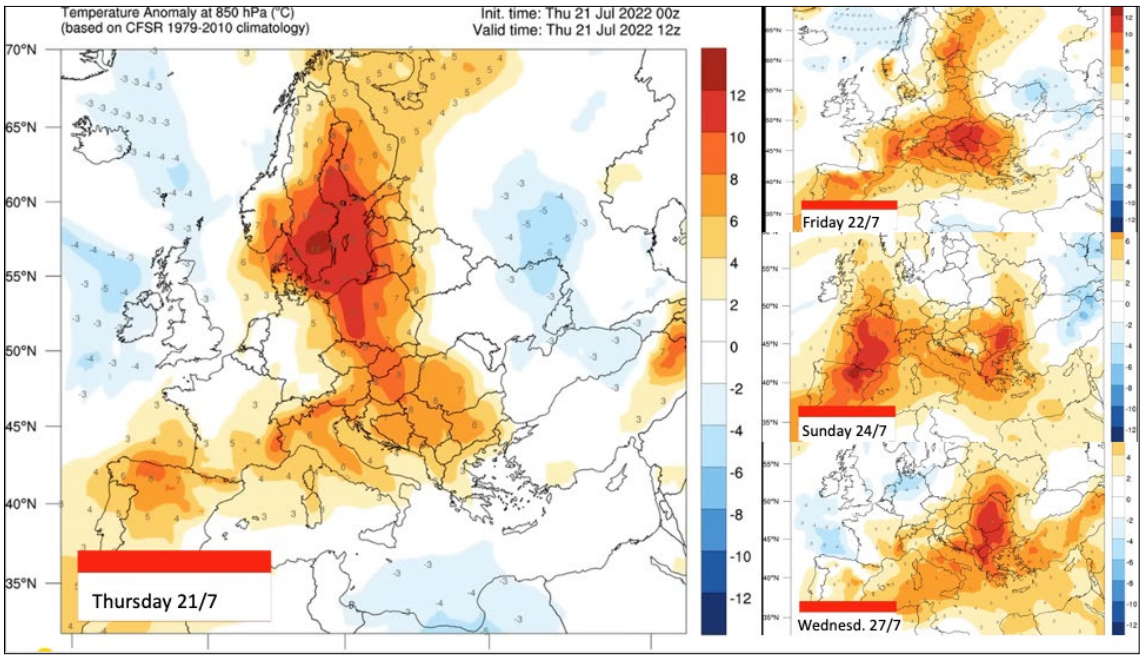
Data source: AUTH, NOFFi | National Observatory of Forest Fires.

13.5 Fire conditions

By the end of July 2022, the cold air masses that had been present over the eastern parts of Europe for the past few days will gradually be replaced by warmer ones. The temperature is expected to rise to 10 degrees above the average climate value of the season. According to the forecast data shared by NoA, the

temperature will start to rise on Thursday, July 21st, and high temperatures are expected to persist until the end of July.

Figure 137. Temperature anomaly over Europe at 1,500m – July 21st to 27th.

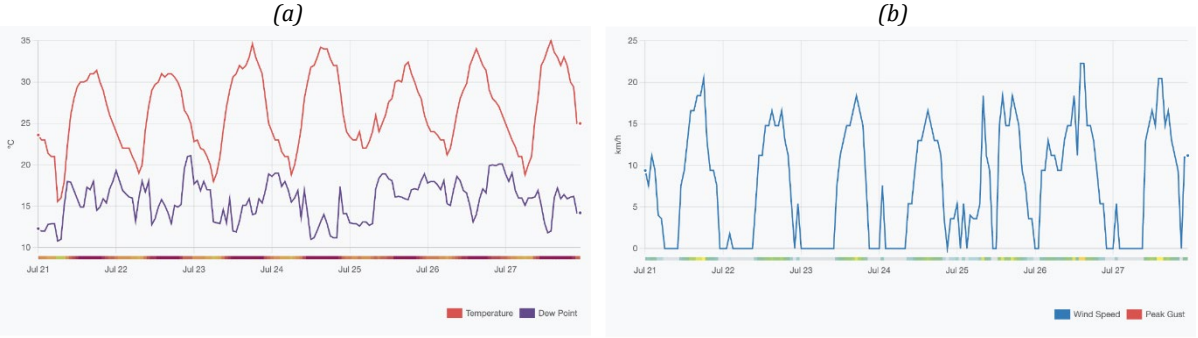


Source: National Observatory of Athens.

Below are charts presenting the temperature and wind speed data recorded during the period of the fire event.

Figure 138. Temperature and wind speed data between July 21st and 27th.

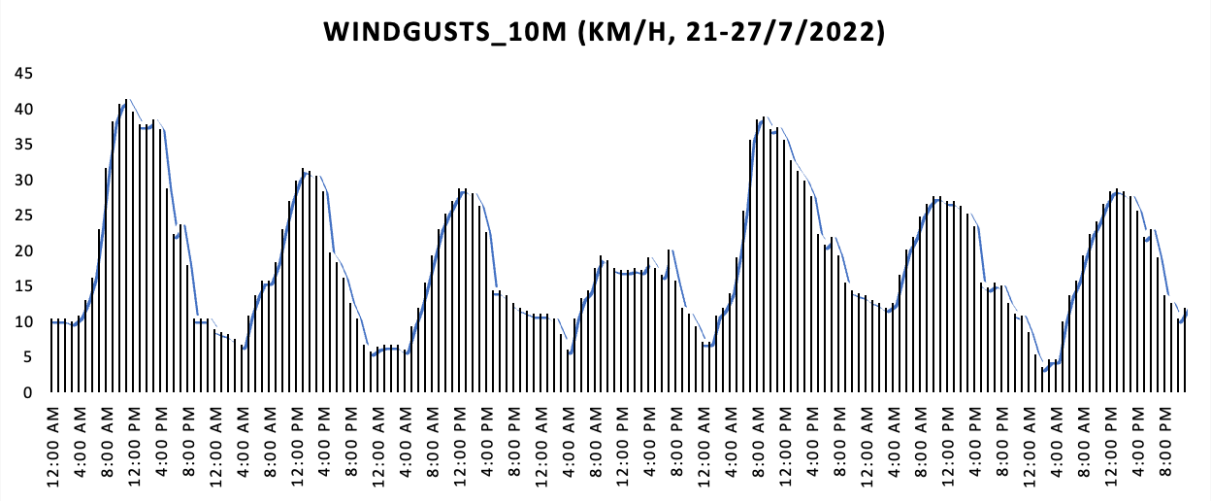
(a) *(b)*



Source: meteostat.net

Based on the data presented, it is clear that the winds were not particularly strong throughout the entire fire incident. The graph below shows the wind gusts during the days of the fire. From the graph, it is evident that the gusts were at their maximum during the morning hours and were more pronounced on the first and fifth day. However, the maximum fire growth occurred on the other five days when the gusts were not as significant. This suggests that the growth of the fire was not heavily influenced by the wind gusts.

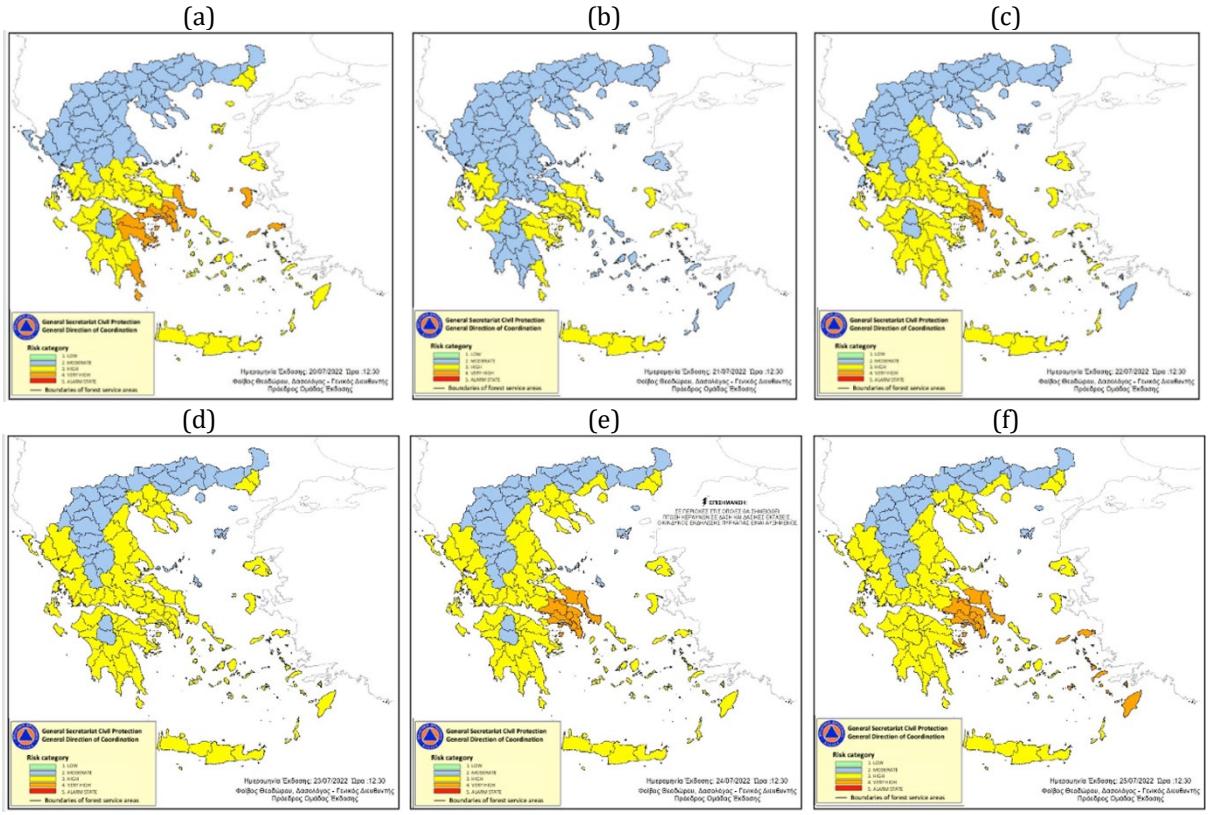
Figure 139. Wind gusts graph in Dadia region between July 21st and 27th.



Source: meteostat.net

The fire risk maps issued by the Greek General Secretariat of Civil Protection indicate that the conditions during the Dadia fire were not associated with high fire risk. However, the difficulties in containing and extinguishing the fire suggest that the excessive fuel load and fuel status were contributing factors to the duration of the fire.

Figure 140. Fire risk map: a) July 21st; b) July 22nd, c) July 23rd, d) July 24th, e) July 25th,) July 26th.

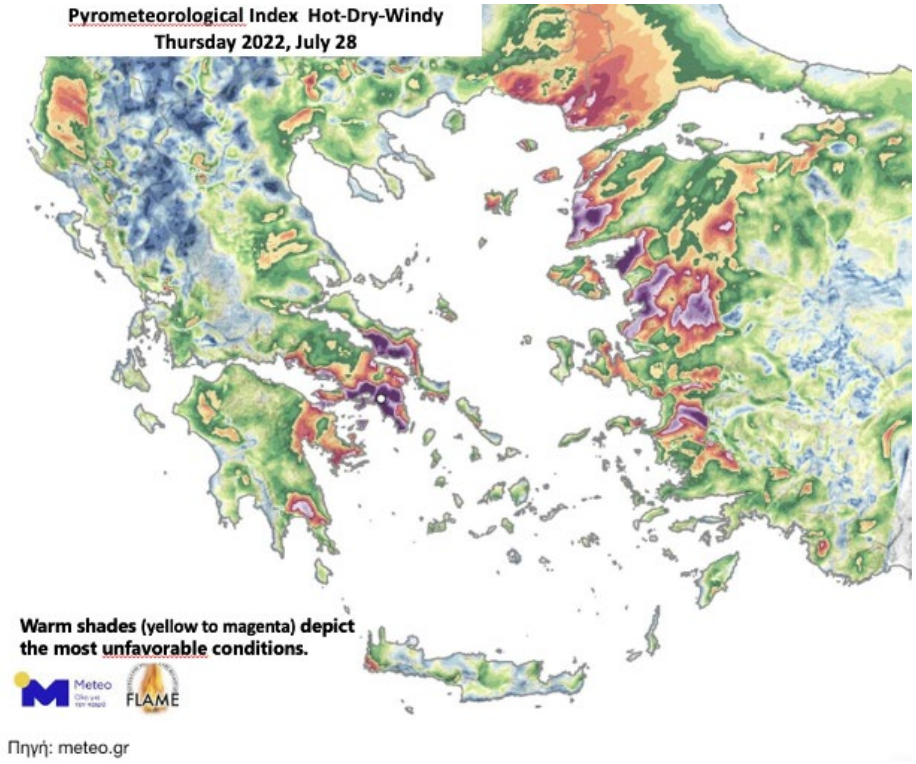


Source: Greek General Secretariat of Civil Protection (GSCP).

13.5.1 Pyrometeorological Dynamics of the Dadia Wildfire

The wildfire spreading in Dadia National Park has become a major concern in the Northeastern part of Greece. The fire has exhibited complex pyrometeorological phenomena that require careful scientific analysis. The FLAME team of the National Observatory of Athens (NOA) has released a Pyrometeorological Index of Fire Propagation Potential based on hot, dry, and windy weather conditions (as shown in Figure 141). This index provided more accurate fire potential estimations compared to the risk map of the GSCP, based on relevant meteorological conditions.

Figure 141. Pyrometeorological index (hot-dry-windy) for July 28th.



Data source: FLAME project, National Observatory of Athens.

Based on meteorological data, the region of Dadia experienced mainly Northeastern winds blowing at a speed of 12-19 km/h during the fire. The temperature reached 34-35°C, while the fine fuel moisture content remained below 10% for most days. These conditions led to the formation of 'shallow' pyrocumulus clouds (pyroCus), indicating the potential of the fire intensity. The presence of pyrocumulus clouds formed due to strong updrafts caused by the heat released from the fire indicates instability in the atmosphere. It also suggests that a circulation system of air has been created due to the fire. This system had the potential to greatly increase wind speeds in the vicinity of the fire, which could cause the fire to spread more rapidly.

Figure 142. Transient "shallow" pyroclouds over the induction column of the southwestern front of the forest fire in Dadia, Evros – July 26th.



Source: Weather News of Thrace.

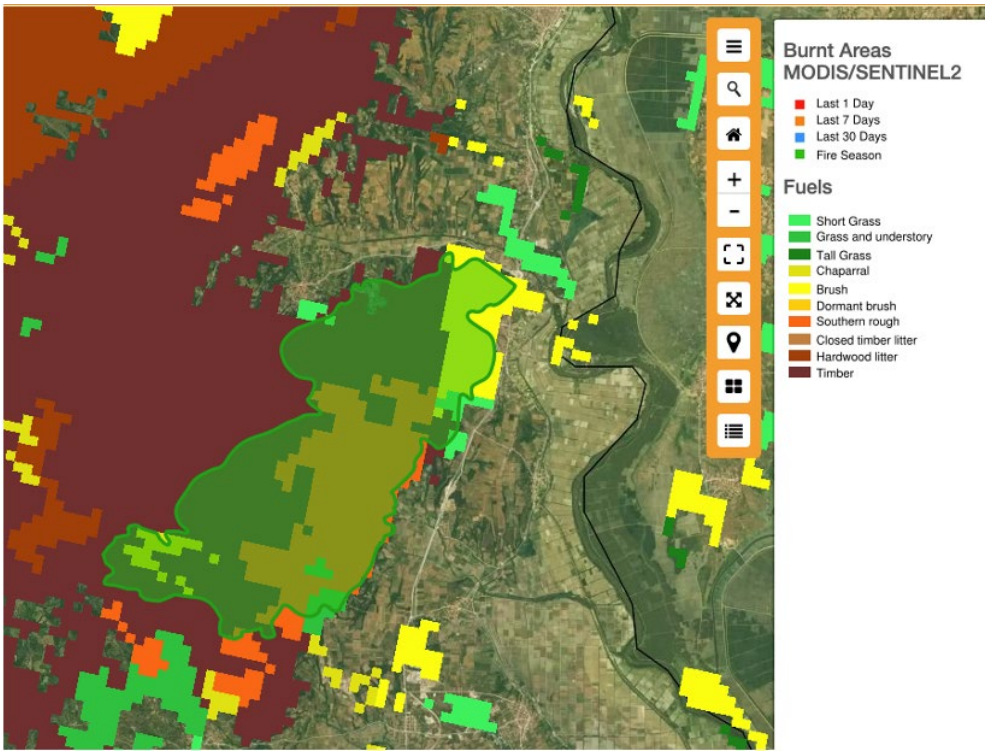
Observations indicate that a wildfire can develop an induction column, causing the fire to behave in a 'self-guided' manner. This phenomenon leads to a more complex fire behaviour as it indicates a significant amount of energy release that can affect local wind patterns and weather conditions. The Dadia wildfire is a result of the intricate combination of fire behaviour and local weather conditions, which create a feedback loop that speeds up the spread of the fire.

13.5.2 Land Cover within the Fire's Perimeter:

The vegetation types that covered the burned areas included:

- Mixed Forest: The dominant land cover type was mixed forest, comprising 61.8% of the burned area.
- Transitional Woodland and Shrublands: This type of vegetation form covered 30.4% of the affected area.
- Other Cover Types: The fire also impacted agricultural areas (2.1%), coniferous forest (1.9%), natural pastures (1.5%), and sclerophyll vegetation (2.4%). No significant impact was recorded on artificial surfaces, broadleaf forests, shrubs, and heaths, open spaces with little or no vegetation, wetlands, or water surfaces.

Figure 143. Fuel types of Dadia area.



Data source: AUTH, NOFFi | National Observatory of Forest Fires (MODIS/SENTINEL2).

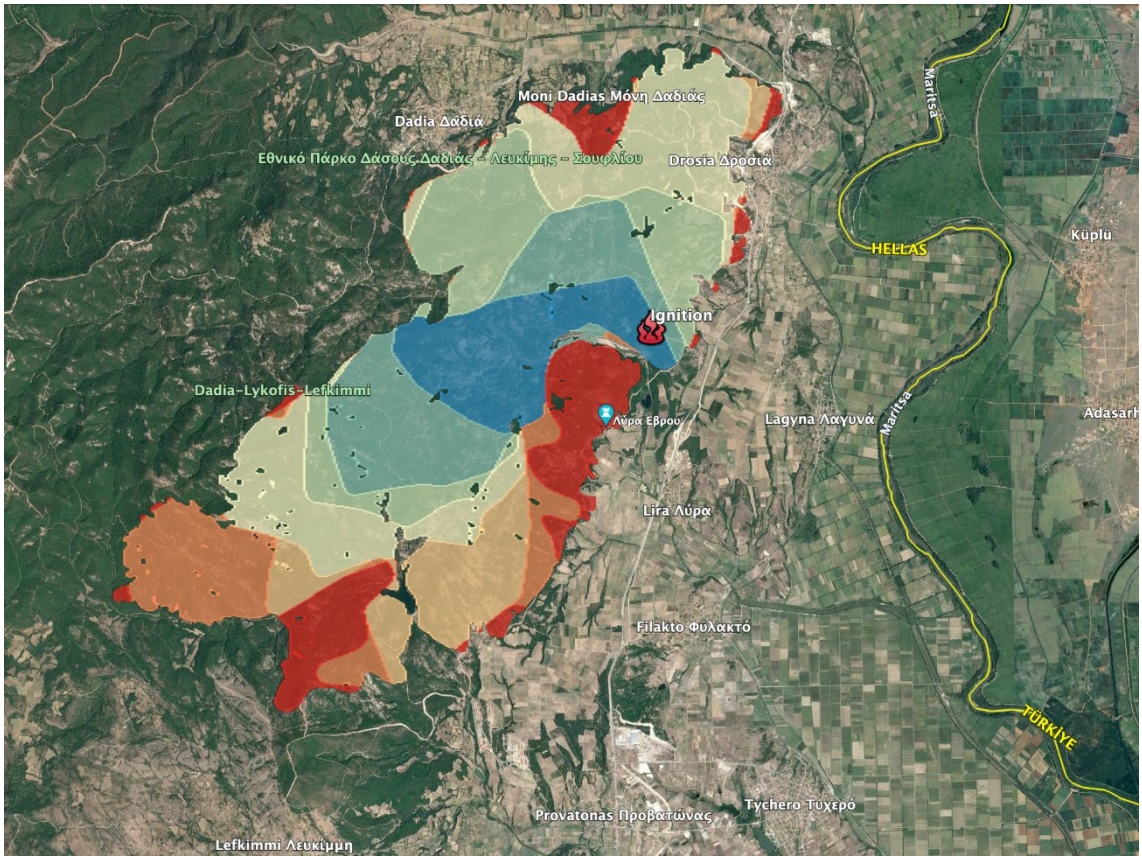
The 2022 Dadia Forest Fire was a significant event that affected a large area with varying degrees of severity. The fire's behaviour and spread were influenced by meteorological conditions, particularly high temperatures, low humidity, and wind patterns. The varying impact on different vegetation types highlights the complexity of forest fire dynamics and emphasizes the need for detailed analysis in post-fire recovery and management strategies (Pleniou, 2022).

13.6 Fire behaviour and smoke dispersion

The wildfire's behaviour was unpredictable due to the thermal-induced wind systems it generated. These winds created a localized inversion layer that trapped smoke close to the ground, reducing visibility and affecting air quality over a vast area. The limited water supply from the Lyra Dam hampered the suppression efforts, allowing the fire to maintain its intensity for an extended period.

As the fire grew, it created a convective column that drew in fresh air from the surroundings, feeding the fire's intensity and enabling the vertical growth of smoke plumes. This self-sustaining system contributed to the long-range transport of smoke particles, impacting not only the immediate area but also regions downwind of the fire. The fire's behaviour showed a marked escalation in the afternoon, aligning with peak temperatures and lower relative humidity, leading to greater fire spread rates and increased smoke production.

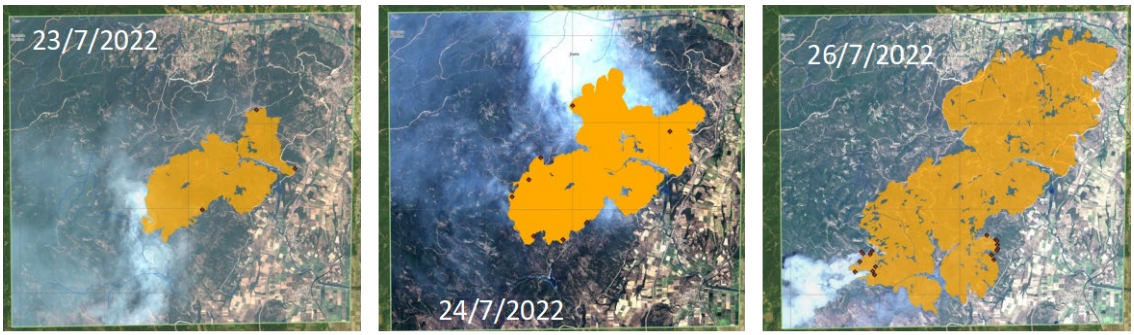
Figure 144. Patches of area burned during the seven days Dadia fire.



Data source: AUTH, NOFFi | National Observatory of Forest Fires

Satellite imagery from the Copernicus service on July 23rd, 24th, and 26th provided evidence of how smoke from the Dadia National Park fire was dispersed by the wind. The images showed that the direction of the smoke changed as the wind changed. On July 23rd, the smoke was blown southwest by the north wind. On July 24th, the smoke was redirected northwest by the southern wind. Two days later, on July 26th, the smoke was again blown in a different direction by the northeastern wind. These observations show that smoke dispersion is influenced by local wind patterns and can change quickly. The satellite data provides direct visual evidence of how wind affects smoke behaviour, which can help decision-makers manage air quality and public health advisories during wildfires.

Figure 145. Wind-driven smoke dispersion pattern of Dadia fire on July 23rd, 24th and 26th.



Source: Copernicus EMS.

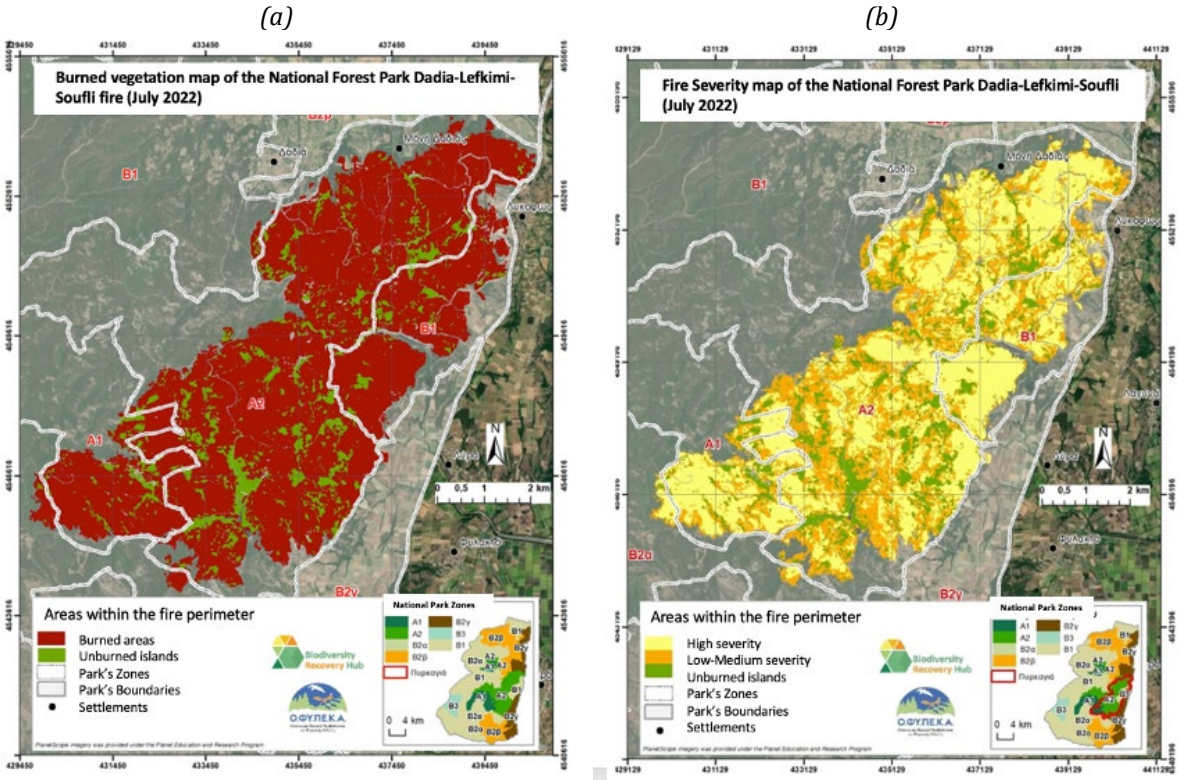
The Dadia National Park fire's behaviour underscores the importance of understanding the multifaceted nature of wildfires and the necessity for integrated fire management and air quality monitoring systems, particularly in areas of ecological significance.

13.7 Direct fire impacts

The wildfire in Dadia, which raged from July 21st to 27th, has left deep ecological scars (Vasilopoulos & Survas, 2022). The persistent flames over such an extended period resulted in severe ecological degradation, affecting plant life, wildlife habitats, and the soil microbiome. This has had several critical consequences:

- The forest's natural regenerative capabilities have been impaired, making it likely that human intervention will be necessary to assist in ecological restoration.
- The demand for prolonged firefighting efforts drained the resources and taxed the capacity of the responding agencies, both in terms of logistics and human capital.
- The area's biodiversity suffered, with the potential loss of endemic and endangered species due to the long-term exposure to high heat and destruction of habitat.
- The fire has also likely led to soil sterilization and disruptions in the hydrological patterns of the region, heightening the risk of erosion and landslides.
- The carbon sequestration function of the forest stands compromised which may have implications for climate change mitigation strategies.
- Finally, the extended duration of the fire could have set off a series of cascading ecological effects, disrupting predator-prey dynamics, nutrient cycling, and overall ecosystem services. Figure 24 offers a detailed mapping that delineates the wildfire's impact on vegetation and natural assets within the Dadia National Park, utilizing color coding to signify varying degrees of severity. This color-coded system used by the Greek Natural Environment & Climate Change Agency (N.E.C.C.A.) of the Ministry of Environment and Energy aids in understanding the extent of damage and facilitates targeted rehabilitation efforts.

Figure 146. a) Map of the fire-affected area, encompassing 45,412 ha; b) Map detailing the fire's severity and impact on vegetation.



Data source: Greek Natural Environment & Climate Change Agency (N.E.C.C.A.).

The orange-coloured areas covering 1,607 ha experienced a fire impact primarily at the ground surface level. The fire here consumed forest fuel directly contacting the ground, including dry leaves, needles, small

branches, grasses, and low-lying shrubs. Notably, in these areas, the tree canopy largely remained intact or suffered only minimal damage. This suggests that while ground-level vegetation was affected, the overarching forest structure and canopy were preserved to a considerable extent.

Areas coloured in yellow, encompassing 2,210 ha, witnessed a more intense level of fire impact. The fire in these zones was severe enough to consume almost all available vegetation, ranging from the subfloor to the tree canopy, in some cases leading to the complete annihilation of vegetation. This level of intensity indicates extensive damage to both the understory and the canopy, significantly altering the ecological balance and necessitating more intensive restoration efforts.

Finally, 615.3 ha coloured green depict patches that remained entirely unburned. The presence of these untouched areas within the impacted zone is crucial for ecological recovery, serving as refuges for wildlife and seed sources for natural regeneration.

The fire notably impacted the park's A2 zone, where 2,637 ha were scorched. This area is significant due to its biodiversity and ecological value. More critically, the A1 zone, known for its high density of Black Vulture nesting sites, experienced fire impact over 459 ha. The damage to this zone is particularly concerning given the conservation status of the Black Vulture.

The existence of approximately 50% of the area remaining unburned or subjected to low to moderate fire severity provides a hopeful perspective for biodiversity conservation. These areas could be pivotal in the park's ecological resilience, benefiting rare predatory and scavenger species. Additionally, many regions experienced low fire severity, warranting further study to identify surviving plants that could contribute to natural reseeding processes. The fire's effect on vital bird habitats necessitates evaluations by specialists knowledgeable about local species to ensure the implementation of effective conservation measures.

In response to these findings, N.E.C.C.A, the relevant authority of the Ministry of Environment, developed a comprehensive post-fire rehabilitation plan for the region, informed by the mapping results. Additionally, these results will be further refined and verified through extensive fieldwork, enhancing the accuracy and relevance of the thematic information. This fieldwork is essential for confirming the initial assessments and adapting the rehabilitation strategies to the specific needs and conditions of the affected areas.

The General Secretariat of Forests, under the aegis of the Ministry of Environment and Energy, has officially designated an expansive forested region encompassing 46,330,240 m^2 at the Dadia site in Evros for immediate reforestation. This decision comes in the wake of a catastrophic fire event that could have profound ecological ramifications.

The primary forest types impacted include Mediterranean pine forests with native species and oak woodlands with *Quercus cerris* and *Quercus petraea*, both exhibiting high resilience and regenerative capacity following fires. However, the fire also partially affected the priority habitat Pseudosteppe with grasses and annual Thero-Brachypodietea plants, thus requiring targeted restoration efforts.

Reforestation initiatives should be reserved for areas where the topography hinders natural regrowth or those previously affected by fires within the last ten years to avoid obstructing the ecosystem's intrinsic recovery mechanisms.

Figure 147. The 'feeding rock', a boulder in the heart of the national park where food is left for the area's endangered prey birds (a) and prey birds required care (b).

(a) *(b)*



Source: a) kathimerini.gr

Figure 148. Complete burning of the pine forest in the smaller of the two cores of the National Park.



Source: kathimerini.gr

Figure 149. Prey bird observatory (before & after fire).



Data source: kathimerini.gr

13.8 Cascading effects

The Dadia-Lefkimi-Soufli Forest National Park, a bastion of biodiversity in NE Greece, was engulfed by a catastrophic wildfire during the summer, scorching over 22,000 ha. Amidst the flames, vulture colonies faced dire threats during their breeding season, prompting swift conservation action. Months on, assessments unveil the breadth of ecological damage and implications for the vulture populations.

The park's international significance is underscored by its rich mosaic of species, providing sanctuary to a plethora of European and Asian wildlife, including endangered vulture species. The park's role as a vital haven for raptors, particularly the Cinereous Vulture, the Egyptian Vulture, and the Griffon Vulture, is critical. The Dadia colony is particularly noteworthy as the last natural breeding ground for Cinereous Vultures in the Balkans, making its preservation imperative.

During the blaze's peak, conservation efforts intensified to protect the vulture nests from the encroaching flames. The fire, striking at a critical juncture of the breeding cycle, posed an immediate risk to the nearly fledged vulture chicks. Remarkable coordination between governmental bodies, NGOs, and volunteers, including supplementary feeding and habitat protection strategies like new firebreaks, was instrumental in shielding the vulture habitats from destruction.

Despite the devastation surrounding them, all active Cinereous Vulture nests saw their chicks fledge, an outcome mirroring resilience amidst adversity. The immediate threat to vulture colonies was averted, but the path to recovery mandates vigilant monitoring and increased conservation efforts to mitigate the loss of nesting grounds for other key species.

13.9 Conclusions and lessons learned

The Dadia National Park wildfire has underscored the importance of robust fire management frameworks in protected areas. The post-fire scenario has emphasized the criticality of real-time monitoring, rapid

response systems, and the reinforcement of park infrastructure against future environmental challenges. The fire has also necessitated a revaluation of conservation strategies, focusing on restoration and prevention while highlighting the vital role of community engagement in preserving natural resources. Furthermore, the event has reaffirmed the ecological significance of the park as a sanctuary for diverse wildlife, and exceptionally various raptor species, thus necessitating focused conservation measures.

The Dadia wildfire experience has imparted key lessons in emergency management. Firstly, the indispensability of dynamic and adaptable management plans to effectively respond to crises. The collaborative efforts of local authorities, conservation groups, and volunteers have demonstrated the power of united action in crisis management. Moreover, integrating advanced technological tools for ecosystem monitoring and damage evaluation is pivotal. These lessons lay the groundwork for post-fire recovery and future strategies to fortify the park's resilience against similar events.

References

Aristotle University of Thessaloniki. (n.d.). ePADAP: Electronic Platform for Disaster Management. Retrieved from https://epadap.web.auth.gr/?lang=en

Natural Environment and Climate Change Agency -N.E.C.C.A (n.d.). The processing of satellite images of very high spatial resolution 3 meters from the Post-Fire Biodiversity Recovery Hub of O.FY.PE.K.A. after the destruction of the fire in Dadia National Park. Retrieved from https://necca.gov.gr/nea-anakoinoseis-deltia-typou/i-epexergasia-doryforikon-eikonon-poly-ypsilis-chorikis-analysis-3-metra-apo-to-post-fire-biodiversity-recovery-hub-tou-o-fy-pe-k-a-meta-tin-katasvesi-tis-pyrkagias-sto-ethniko-parko-dadias/

Vasilopoulos, G., & Survás, G. (2022, August 2). Preliminary Assessment of the Impact of the Fire in the Dadia-Lefkimi-Soufli Forest National Park. ForestPlan Environmental Consulting. Retrieved from https://dasarxeio.com/2022/08/02/115420/

Pleniou, M., (2022, August 12). Assessment of the Forest Fire in the Dadia-Lefkimi-Soufli Forest National Park. Institute of Forest Research (IFR). Retrieved from https://dasarxeio.com/2022/08/12/116119/

Copernicus Emergency Management Service. (n.d.). EMSR605: Activation EMSR605. Retrieved from https://emergency.copernicus.eu/mapping/list-of-components/EMSR605

URLs

https://www.esa.int/ESA_Multimedia/Images/2022/07/Wildfire_Threatens_Greece_s_Dadia_National_Park

https://www.meteo.gr/article_view.cfm?entryID=2352

https://www.facebook.com/flame.research.project/posts/pfbid02r4d1Q5oxNoc8YsLgAA3z4reW7JPqPBpXR647CsL3pRoZZeRvDmmQJ26czQCHNgbYl

https://emergency.copernicus.eu/mapping/list-of-components/EMSR605

https://4vultures.org/blog/how-did-the-massive-fire-in-dadia-greece-impact-key-vulture-colonies/

https://civilprotection.gov.gr/sites/default/files/emsr605_aoi01_gra_product_21000_rtp01_r1_v1.pdf

https://necca.gov.gr/nea-anakoinoseis-deltia-typou/i-epexergasia-doryforikon-eikonon-poly-ypsilis-chorikis-analysis-3-metra-apo-to-post-fire-biodiversity-recovery-hub-tou-o-fy-pe-k-a-meta-tin-katasvesi-tis-pyrkagias-sto-ethniko-parko-dadias/

https://genevasolutions.news/climate-environment/climate-change-is-driving-wildfires-can-we-tame-the-flames

https://www.wwf.gr/en/?uNewsID=7211916

https://www.facebook.com/Meteo.Gr/posts/pfbid09sRW5vVpzS2HxDtncUfrs16VXGMencZKLzDXq345nRiGnWzpy9kifbBnovuxpkPbl

14 Fires in Romania

Authors

Johan Sjöström	RISE
Marius Petrila	INCDS
Adrian Lorenţ	INCDS



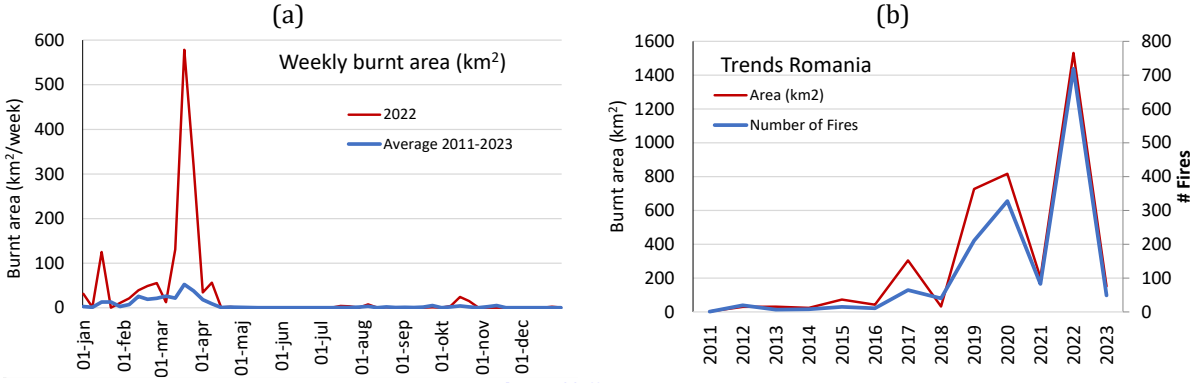
14.1 General Description

The fire 2022 season in Romania does not contain a few significantly large or notably high impact fires. Instead, it was characterized by a larger than normal numbers of fires which in combination burnt unusually large areas and brought consequences in terms of several lives lost and many injured together with record-high burnt area.

14.2 Second largest burnt vegetation area in Europe

While the 2022 fire season was very focused on large forest fires in France, Portugal and Spain, a quick glance at the numbers of burnt area in Europe put Romania in the spotlight. With 719 EFFIS-detected fires (the highest number in the EU) an area of over 150,000 ha was burnt, Romania appears just second after Spain among the worst hit European countries. Much of this affected open areas but also the closed canopy forests were affected with an area of >13,141 ha, the largest area of forest burned since 1965 (Popa, 2023e). For parts of the country (South-West), this followed the also exceptional 2021 with locally (but not nationally) large areas burnt (Lorenţ et al., 2022; Lorenţ et al., 2023). As for large parts of Europe, the 2022 season also stands out from the typical seasons since EFFIS started tracing fire areas in 2006 (although Romania is covered only since 2011). Clearly, the spring fires are completely dominating the tally and over 70% of the fires occurred in March (Figure 150). This is apparently the common seasonal trend in Romania where 85% of the area is burnt outside of the characteristic forest fire seasons for Europe (beginning of April to end of September) (Lorenţ et al., 2018; Mallinis et al., 2018). Although assessed over a very limited time-period, the total annual burnt area exhibits an increasing trend during the last decade.

Figure 150. a) Weekly burnt area in Romania for 2022 and the 2011 – 2023 average; b) The trend in number of EFFIS-detected fires and total burnt area in Romania since 2011.



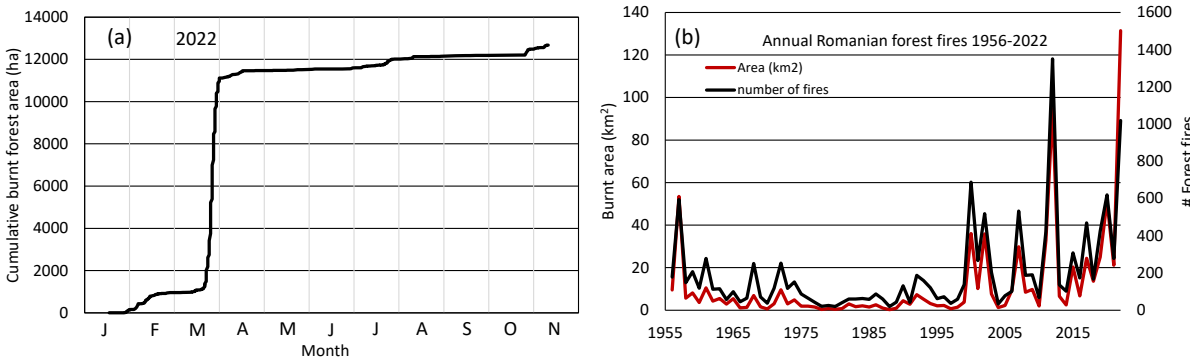
Source: https://effis.jrc.ec.europa.eu

14.3 Only a fraction of the area on forested land

Assessing the incident reports on forested land from Romanian Ministry of Environment, Water and Forests (MMAP, 2023) shows the same seasonal trend. Over 80% of all burnt forest areas was scorched in the second half of March but the total area for 2022 is less than 9% of that reported by EFFIS (Figure 151).

Figure 151. a) Cumulative burnt area on forested land during 2022 until November; b) Annual burnt area on forested land and the number of forest fires between 1956 and 2022.

(a) *(b)*



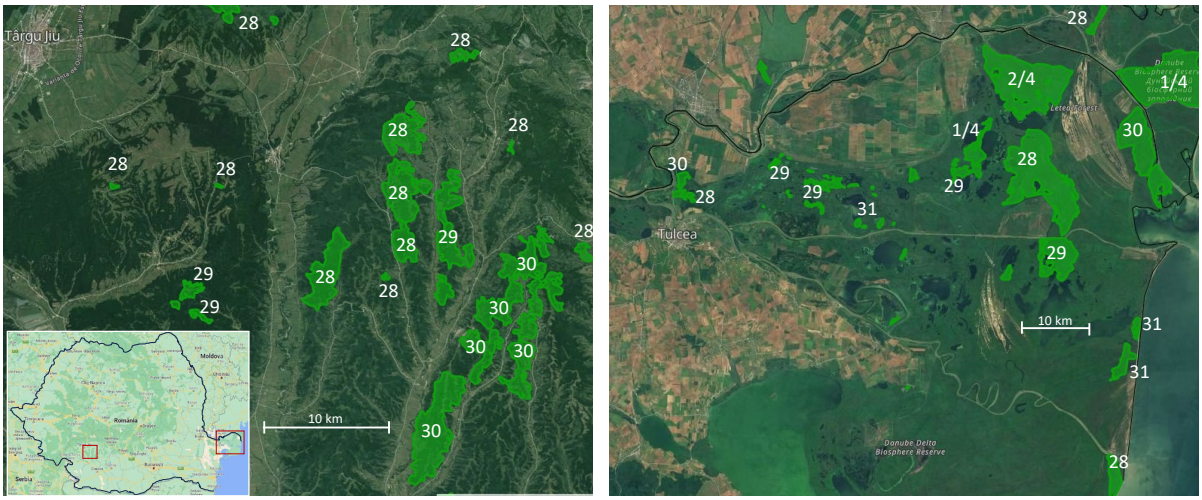
Source: a) MMAP, 2023; b) MMAP and RNP-ROMSILVA, 2023.

Thus, the main burnt area reported by EFFIS is not on forest fires but open area fires, mainly in the Danube Delta, the large wetland biosphere reserve at the mouth of the Danube into the Black Sea. It is an UNESCO world heritage site and comprises many Natura 2000 areas. On and along the many watercourses, vegetation is dominated by reed of many species such as the common reed (*Phragmites communis*) or cattail (*Typha latifolia*). The reed has been used for generations as construction material (such as roofing), for fuel pellets or food for livestock. Often, last season's litter is burnt during spring as soon as weather allows, which speeds up the succession of green vegetation and helps during harvesting, since old dead reed will be intermixed with the live material for at least a season or two. On solid ground within the landscape, grasses and reed are also burnt in spring enabling earlier possibility for grazing. Conflicts of access to and use of commercial areas for grazing, harvesting, and fishing lead to large areas being burnt also in the Danube Delta Biosphere Reserve. Agricultural burning is prohibited in Romania but not often considered a big problem by local authorities due to its long tradition (Popa, 2023a, 2023b). However, the legal aspect reduces the potential for large array of crews and planning a controlled event, thereby increasing the risks of uncontrolled spread.

Some of the fires during March became large. Examples include the burnt area polygons from MODIS in part of Gorj county and the Danube delta (where several fires are almost 1,000 ha) from the week March 28th to April 3rd (Figure 152). In the Gorj county, one can see how the fire perimeters boarder arable land and how the fires have climbed the forested hills between cultivated valleys, sometime covering several 100 ha. The Gorj fires shown here all occurred between March 28th to 30th.

Figure 152. MODIS polygons during March 28th to April 3rd in part of Gorj (a) and Tulcea (b) counties. The numbers indicate the date (in March if not stated otherwise) at which the fire was detected.

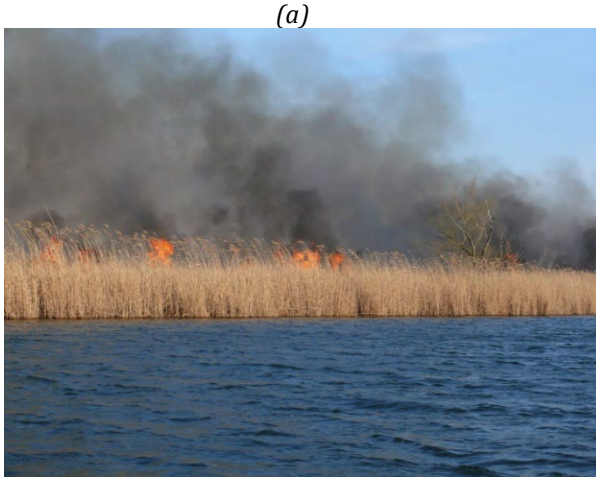
(a) (b)



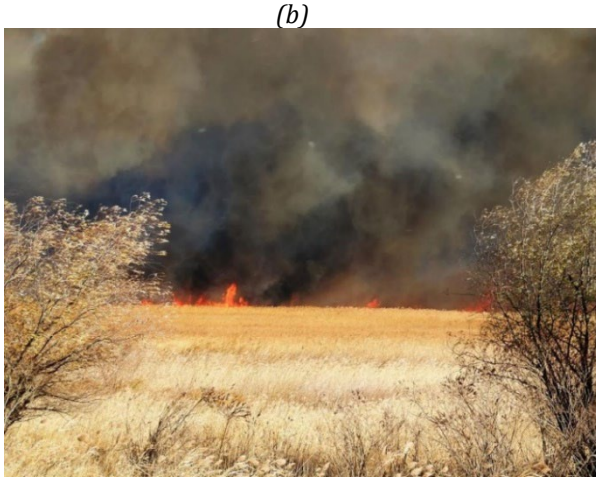
Source: Reuters

Figure 153. Photos with forest fires in Romania: a-b) Someșul Rece Forest District, Cluj, July 28th; c-d) Apuseni Natural Park, Cluj, July 21st.

(a)



(b)



(c)



(d)



Source: Photo credit: RNP-ROMSILVA

Figure 154. Photos with reed fires in the Danube Delta Biosphere Reserve.

(a) *(b)*

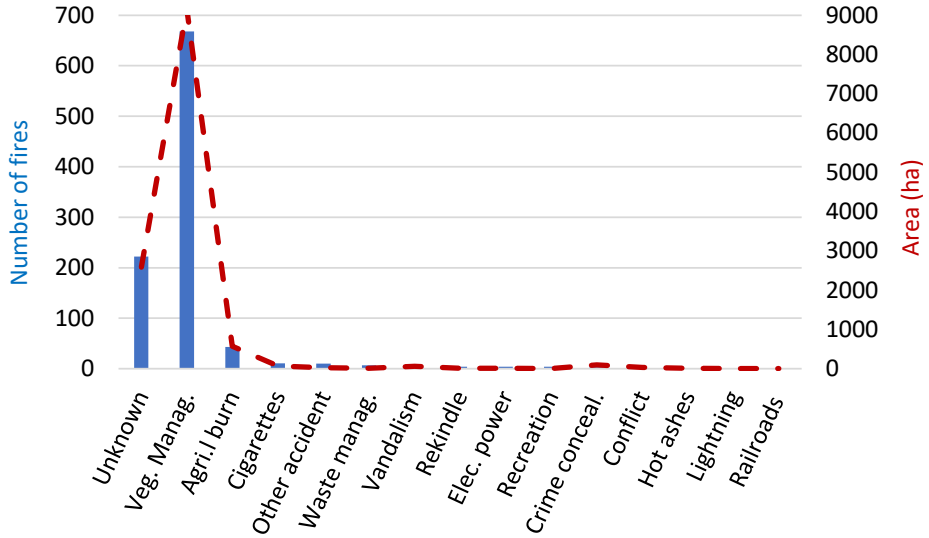


Source: Photo credit: Danube Delta National Research-Development Institute – INCDDD.

14.4 Vegetation management, the dominant ignition cause

Since the most of forested areas burn also in March, there is a strong indication that these too are connected to agricultural burning and management of debris from last season. The records of forest fire ignition causes from national authorities (MMAP, 2023; IGSU, 2023) also confirm that over 90 % of the fires in forests are caused by these activities (Figure 155).

Figure 155. Number of forest fires and burnt area broken down to cause of ignition (Data source MMAP, 2023).



Largest forested burnt areas and frequencies are in rural areas between the West and South-West Oltenia regions (counties of Gorj, Caraş-Severin, Mehedinți and Sibiu). The fires mostly originate in agricultural or grazing areas but can rapidly spread to adjacent forested regions, where they primarily consume readily available fuel such as litter, grass, and other lightweight dead vegetation from the previous growth season. Anecdotal examples of this can be seen from the photos (Figure 153).

The largest forest fire was just over 330 ha, but the area distribution is more uniform than for typical European countries. 20 fires burned almost 100 ha or more, these were all strictly surface fires, occurred in March and were either caused by vegetation management or had an unknown cause.

Reports on several deaths have also been found (IGSU, 2023; Popa, 2023b, 2023d). These occur in separate fires and involve mostly elderly people who have been burning the same land for many years (Popa, 2023d, 2023f). Just one single event caused two casualties, one death and one injured, all the other fire incidents having just one victim each. We find reports of 18 deaths in 18 different fires, 3 in forest fires and 15 in open

vegetation fires. These are high numbers for Romania, considering previous experience (0 cases in 2018, 1 case in 2019, 8 cases in 2020 and 5 cases in 2021). The number of injured people in 2022 is also higher, with 43 victims, more than the combined number for the preceding four years. The burnt area and estimated value of the damages are also the highest in the report for the year 2022 (IGSU, 2023).

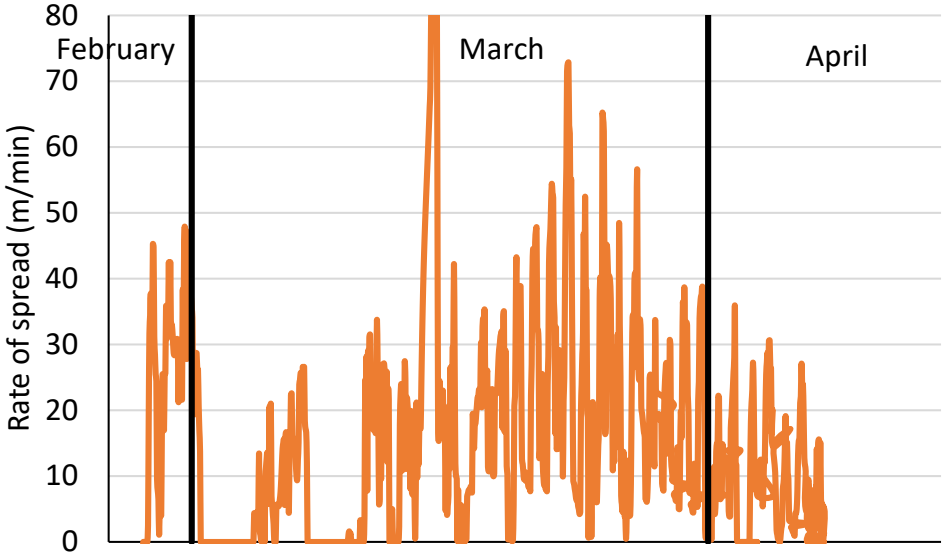
The apparent increase in burnt area shown above (Figure 150b and Figure 151) is not easily explained. High spread rates in the flammable vegetation in March will be determined by periods of dry air, sunlight and high wind gusts, even if the duration of these is only a day or two. An earlier snow melt will only shift the fire season to earlier in spring and not contribute to larger areas as it would for pure forest fires. The increase is likely much related to human behaviour, conflicts of land use and traditional ways of making a living from the land. Romania, like most parts of Europe, has seen an increase in urbanisation, leaving rural areas depreciated of young people and with and increasing portion of non-attended and uncultivated land (Mallinis et al., 2018).

14.5 Applying a grassland fire danger model to 2022

As March passes the new live light vegetation grows, which clearly hinders the fire spread propensity and intensity of fires (Sjöström & Granström, 2023). This is probably the reason the fire season almost came to a complete arrest during the summer months (Figure 151). For herbaceous dead fuels, only a few hours of low relative humidity can make fuel highly flammable and there is no need for long droughts, especially if exposed to wind and sunlight. Having said that, the winter of 2022 was unusually dry, which must facilitate the spread of fires from open into forested land.

We calculated the spread rates on a model grassland from the RING model (Rate of Spread in Northern Grasslands) used operationally for fire danger in grasslands in Sweden since 2021. This model accounts for the growth of new grass, the wind speed and the moisture of the fuel based on past hourly data of temperature, RH, precipitation, wind and solar irradiation. The danger indicator for grassland fires is related to spread rates and not to intensity as for forest fires. The weather data used here is hourly data from Bucharest and thus only represent one location of the country and not the danger indices for each fire. The Bucharest data however displays that danger indices were low first half of march, after which they peaked in the second half and thereafter decreased again (due to the continued growth of fresh grass) in April (Figure 156). This coincides well with the peak of fire occurrence although the model is not calibrated to Romanian conditions. The model predicts that grassland fire season is practically over by April 20th, coinciding well with what is seen from the forest fire record. It should however be noted that reed can probably burn later in the season due to its tall structure, but the model more resembles light fuels typical for borders between open and forested land.

Figure 156. Danger index (Rate of spread for a model grassland) based on the weather during spring 2022 in Bucharest and calculated according to [3] (Weather data source: https://www.visualcrossing.com/weather-history/bucharest, assessed 2023-10-12).



Source: https://www.visualcrossing.com/weather-history/bucharest (assessed 2023-10-12).

14.6 Summary

The very large wildfire areas reported for Romania 2022 were to over 90% dominated by fires on open land in the 2nd half of March. Vegetation management on reed areas in the Danube delta comprised an overwhelming majority of these fires. The tradition of burning past seasons light litter can be found all over Europe, especially in those of colder climate. However, even if concerning only fires in forests, this year also marked the most severe season known by records with 13,141 ha of forest in a total of 1,019 fire incidents. Also, the forest fires were mostly concentrated to March. They mostly show the same pattern of vegetation management fires escaping to surrounding forested land, burning mostly light litter from past season in low intensity, but sometimes rapidly spreading, fires. Many of these events had consequences and 18 people died in total, mainly older people igniting the initially controlled fire. The areas and numbers of spring fires appear to increase. The reason behind this increase is not fully investigated but is likely driven by human. For mitigation, a grassland fire warning model could be a helpful tool to focus public engagement during periods with highest likelihood of escaping fires.

References

IGSU (2023) Situation of Wildfires for the period 2018-2023, the Romanian General Inspectorate for Emergency Situation (IGSU), Bucharest, 2023.

Lorenț, A., Neagu, Ș., Petrila, M., Apostol, B., Gancz, V., Mitsopoulos, I. and Mallinis, G. (2018) Forest fire hazard assessment at territorial administrative unit level during 2006-2015 period - Evaluarea hazardului la incendii de pădure la nivel de unitate administrativ-teritorială în perioada 2006-2015. Revista Pădurilor nr. 4/2018, ISSN print 1583-7890, ISSN online: 2067-196. p. 37-58. https://revistapadurilor.com/wp-content/uploads/2017/09/art.-4.pdf

Lorenț, A., Gancz, V., Petrila, M., Apostol, B., Capalb, F., Marcu, C. and Badea, O. (2023). Detectarea și localizarea incendiilor de pădure și urmărirea evoluției acestora pe baza imaginilor satelitare de înaltă rezoluție temporală [Detection and localization of forest fires and tracking their evolution based on high temporal resolution satellite images], Revista de Silvicultură și Cinegetică, no. 52/2023, ISSN print: 1583-2112, ISSN online: 2284-7936, p. 63-69. http://progresulsilvic.ro/a-aparut-numarul-52-al-revistei-de-silvicultura-si-cinegetica-il-puteti-descarca-in-format-pdf (in Romanian)

Mallinis, G., Petrila, M., Mitsopoulos, I., Lorenț, A., Neagu, Ș., Apostol, B., Gancz, V., Popa, I. and Goldammer, J. G., (2019) 'Geospatial Patterns and Drivers of Forest Fire Occurrence in Romania', Applied Spatial Analysis and Policy, Vol. 12, pp. 773-795. https://doi.org/10.1007/s12061-018-9269-3

MMAP (2023) Forest Fires Record Situation for year 2022, the Romanian Ministry of Environment, Water and Forests (MMAP), Bucharest, 2023.

MMAP and RNP-ROMSILVA (2023) Forest Fires Record Situation for Romania for the 1956 – 2022 period, the Romanian Ministry of Environment, Water and Forests (MMAP) and the National Forests Administration (RNP-ROMSILVA), Bucharest, 2023.

Popa, L. (2023a). Romania burns: How the Danube Delta got on the fire map of Europe, https://www.europeandatajournalism.eu/cp_data_news/romania-burns-how-the-danube-delta-got-on-the-fire-map-of-europe, (accessed 2023-10-12)

Popa, L. (2023b). Romania burns: Vegetation fires claim victims, https://www.europeandatajournalism.eu/cp_data_news/romania-burns-vegetation-fires-claim-victims/ (assessed 2023-10-12)

Popa, L. (2023c). Despite a mild climate, forest fires are a serious problem in Romania, https://www.europeandatajournalism.eu/cp_data_news/despite-a-mild-climate-forest-fires-are-a-serious-problem-in-romania/ (assessed 2023-10-12)

Popa, L. (2023d). Rural depopulation is playing a major role in causing fires in Romania, https://www.europeandatajournalism.eu/cp_data_news/rural-depopulation-is-playing-a-major-role-in-causing-fires-in-romania/ (assessed 2023-10-12)

Sjöström, J. and Granström, A. (2023) A phenology-driven fire danger index for northern grasslands, International Journal of Wildland Fire Vol. 32, pp. 1332-1346. https://doi.org/10.1071/WF23013

15 Fire of Razdel (Bulgaria)

Authors

Nina Dobrinkova	IICT
Vassil Vasilev	IICT
Nadya Tsvetkova	IICT
Yanko Boyanov	FSPP - Yambol
Ilian Gospodinov	NIMH



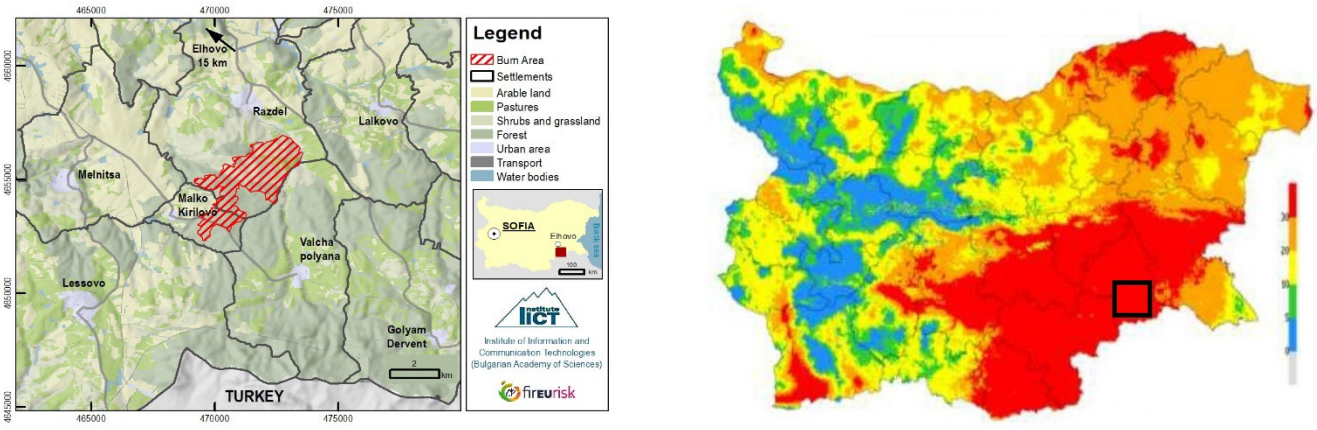
15.1 General Description

The Fire of Razdel started 2 km south-east of Razdel village, in the municipality of Elhovo, District of Yambol in the South-Eastern Region in Bulgaria. The ignition occurred on the morning of August 10th. The alert was given at 11:00 of the same day, and the fire was detected by the passage of the Terra MODIS at 11:26. Final total burned area was 797 ha, where 560 ha were forest areas, and 237 ha were grasslands and pastures. The size of the burned forest territory makes that fire the largest forest fire in Bulgaria in the year 2022 (another fire with 1,023 ha total burned area was also recorded during 2022 in another part of the country, but with a smaller part of the affected forest zones - 460 ha). Although the fire of Razdel village did not have an impact on residential zones, it affected considerable areas of NATURA 2000 and there was the risk of the fire crossing the Bulgarian - Turkish border.

The Razdel Fire was active for five days, spreading in two villages: the village of Razdel (affected territory is 667 ha) and the village of Malko Kirilovo (affected territory is 130 ha). Both villages are located under the same municipal territory of Elhovo (Figure 157a). 95% of the burnt area was reached during the first 60 hours of the fire, approximately around 12:00 on August 12th. The monitoring of the burned area continued until August 14th, several days after the major fire perimeter was suppressed. Smaller fires were active on August 15th and 17th but were considered as separate events. The description of this report focuses mainly on the period between August 10th and 14th. As shown in Figure 157b, the area where the fire was propagating was evaluated as a maximum fire danger zone with a red code probability for fire occurrence at the fire ignition date. The red code is the highest degree of fire danger in Bulgaria calculated on a daily basis by the National Institute for Meteorology and Hydrology (NIMH).

Figure 157. a) Geographical representation of the Razdel Fire (IICT - BAS); b) Fire hazard for August 10th.

(a) (b)



Source: NIMH

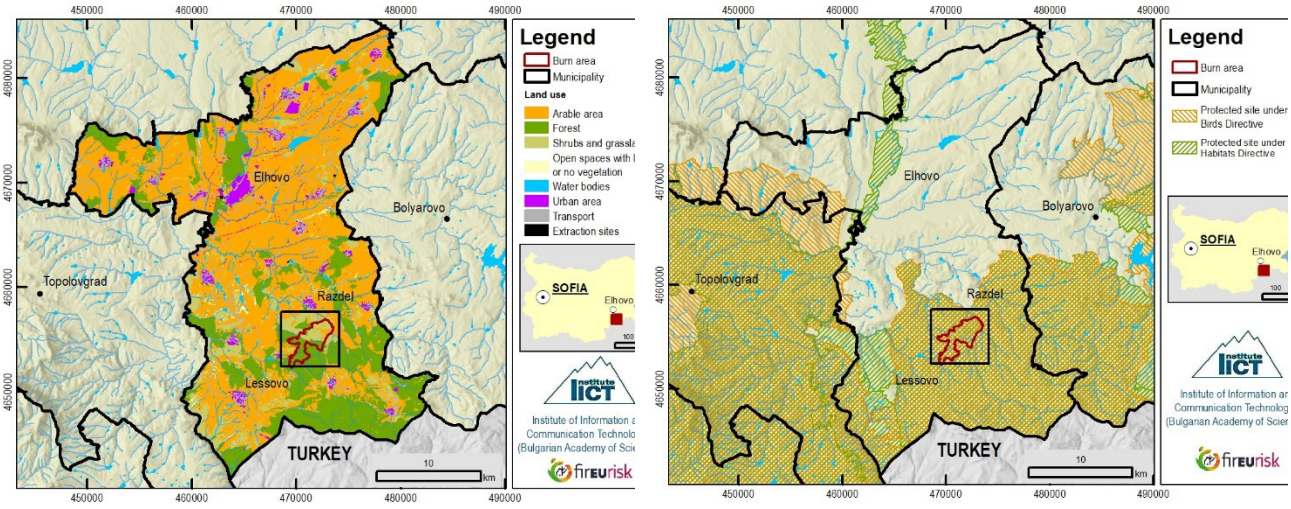
In March 2023, a team from the Institute of Information and Communication Technologies – Bulgarian Academy of Sciences (IICT-BAS) visited the area affected by the fire nearby Razdel village. The report is based on the collected data. The IICT-BAS team visited the locations described in the report and interviewed the local authorities, who took part in the suppression measures. Explanations were collected from both civil protection team members and foresters who were directly involved in the event suppression measures.

15.2 Characterization of the affected area

The Razdel Wildland Fire occurred within the municipality of Elhovo (LAU1), Yambol district (NUTS3), Bulgaria. The municipality is in the southeastern part of the country. This municipality is situated on the south end of the border between Bulgaria and Turkey. The burnt area covers the southern half of the municipality, on a territory characterized by a hilly relief with a predominance of forest and shrub vegetation. Agriculture is the main economic sector developed in the municipality (Figure 158a). The southern half of the municipality is entirely occupied by Natura 2000 protected sites under the Habitats Directive (BG0000218 Derventski vazvishenia 1) and the Birds Directive (BG0002026 Derventski vazvishenia) (Figure 158b). The existence of these two large protected zones is of high value to the biodiversity of the area. That is why specific rules for land management are applied in this municipality, which has an impact on fire response actions. This will be described in detail further in the report.

Figure 158. a) Land use map of Elhovo municipality (IICT - BAS); b) Natura 2000 protected sites under birds and habitats Directives.

(a) (b)



Source: IICT - BAS

The total population in Elhovo municipality is 16,219 people (NSI, 2021). 65% of them live in the municipal headquarter in the town of Elhovo. The remaining settlements are villages, with no additional towns, and the respective population there is less than 700 people in total. The villages in the southern half of the municipal area have a population of about 100 people, except for those in the western end, located along the main road No 7, which connects to the Bulgarian -Turkish border.

The population is characterized by a deteriorated age structure, except for the town of Elhovo and four other nearby settlements. For the rest of the villages in the municipality, the share of the population over 65 years is above 40%. The elderly population is predominantly found in the settlements in the southern part of the municipal territories. The population reduction is constant since 2011. The lack of young people puts at risk, not only the economic development of the area, but in addition in cases of natural hazards suppression measures are impossible to be maintained by the locals.

Regarding the migration of the population, the statistics are negative – since 2010. Based on the National Statistics Institute's (NSI) regular population reports from 2010 (-226), 2015 (-148), 2017 (-140), and 2021 (-70), the municipality of Elhovo has a constant decrease in its citizens.

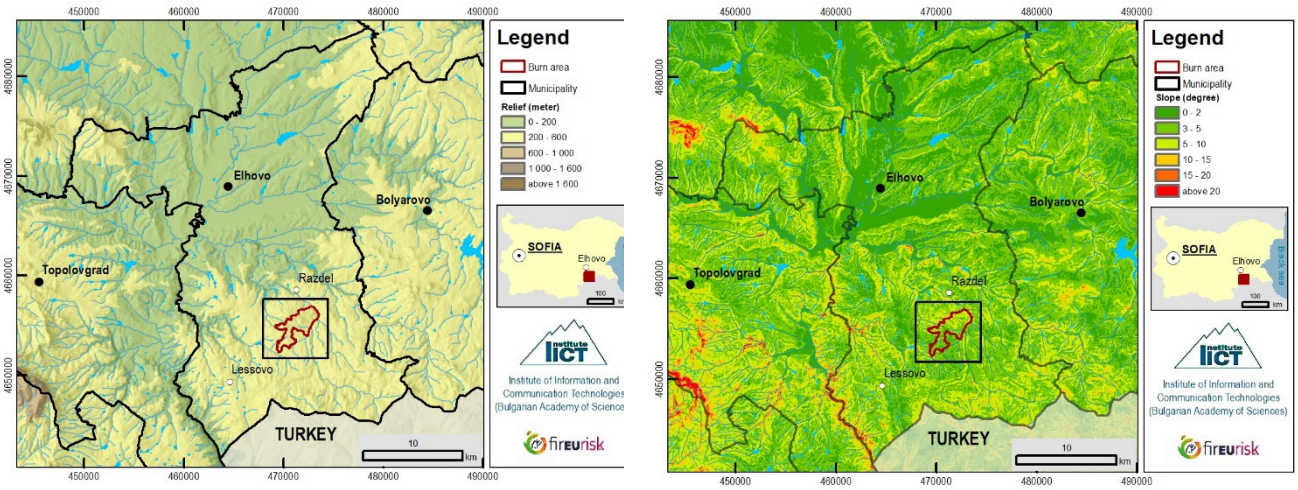
Unemployment in the municipality of Elhovo is 14.1%, significantly higher than the average for the country (5.2%). The number of people employed in agriculture in the Yambol district is low – 8,455 (18%), due to the predominance of cereal crops and the high degree of mechanization in the sector. In particular, for the municipality of Elhovo, permanent employees in the agriculture sector are 91%, and seasonal employees are 9% (*Census 2011, 2021; ** Census 2011 (NSI, Bulgaria).

Elhovo municipality is an agricultural territory (34,955 ha) (Agricultural Census 2020, Information system for agro-statistics). The largest share is arable land (71%), followed by permanent grassland (27%). Smaller areas are permanent crops (1%). The arable land is 24953 ha, where mostly cereals (48%) and industrial plants (39%) are farmed.

The terrain is lowland (in the northern half of the municipality) and hilly - in the southern part, where the fire occurred (Figure 159a). The average altitude in the north is about 160 m, but it increases to 295 m in the South. Hills in the South have a greater degree of roughness than the lowland (Figure 159b). The landscape is characterized by round-top hills cut by a relatively dense river network (Figure 160). Most of the rivers started from the Sakar Mountain and the Dervent Highlands located south of the border between Bulgaria and Turkey. The rivers have a small flow rate, which decreases further during the hot half of the year. There are a few dams located in the northern part of the Elhovo municipality. There are almost none in the South. This, combined with the higher degree of terrain roughness, is a prerequisite for the difficulties in finding water for firefighting needs. The main river is the Tundzha River, located west along the municipal end border. Although it is one of the biggest rivers in the country (the area of the Tundzha River watershed before entering the municipality is about 540,000 ha), there have been cases of fires that have crossed it and spread to the other side.

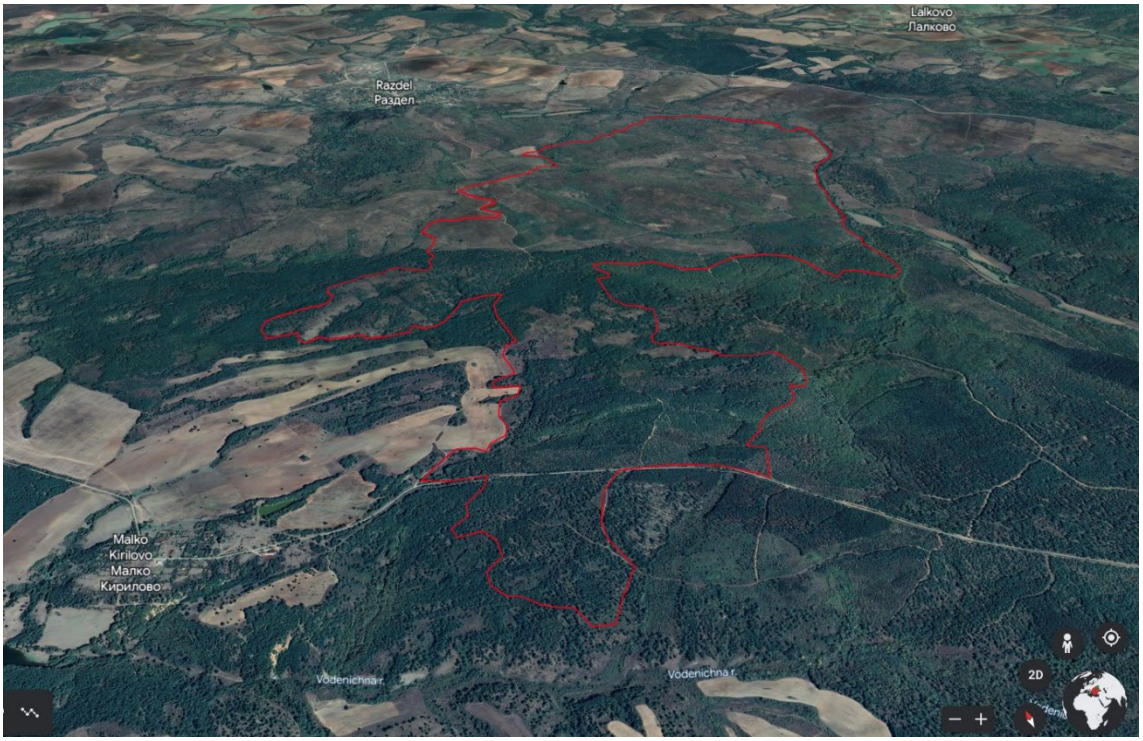
Figure 159. Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern.

(a) *(b)*



Data source: IICT-BAS (Aero-orthophoto base map).

Figure 160. Google Earth image showing the typical orographic pattern.

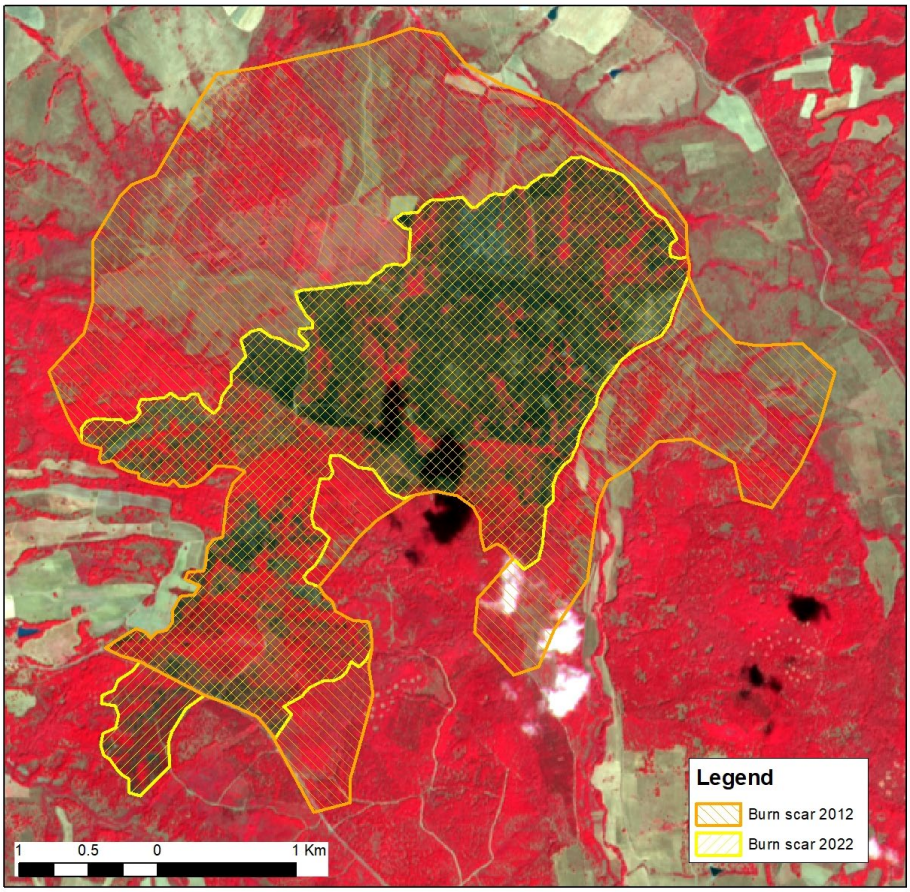


Data source: IICT-BAS (Aero-orthophoto base map).

The area of Elhovo municipality is affected regularly by small or large wildland fires. Since 2000, more than 35 wildland fires have been recorded within the municipal territory, which led to 5,640 ha burned area in total throughout the years. The three villages that were affected by the fire of 2022 had seven other wildland fires, in the period from 2000 to 2021, with a total burned area in the past of 2,200 ha.

Figure 161 shows the final perimeters of the two largest fires that occurred in this region for the last 10 years. Fire behaviour in the larger and smaller fires follows the same behaviour pattern from North to South. In the Southern parts, there are differences in the distribution, because the fire suppression measures can be done easily due to the existence of the asphalt road between the villages Malko Kirilovo and Valcha Polyana. The surrounding area along the asphalt road is regularly maintained with clear-cut techniques that helped a lot during the suppression measures of the Razdel fire in 2022, by stopping the fire propagation at that location.

Figure 161. Burned scars of the two largest fires in the area in the last 10 years, 2012 and 2022.



Data source: Copernicus EU, Sentinel 2.

15.3 Fire conditions

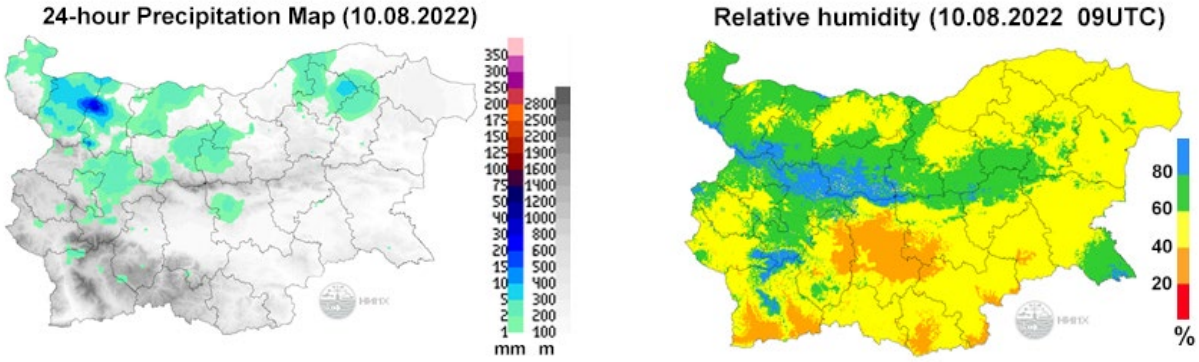
Typically, in Bulgaria, the hottest month of the year is August. This is especially true for the southeast regions of the country. During August 2022, 92 fires were registered in the country which is almost ¼ of all the fires in Bulgaria for that year. The total area burned in this month was more than 50% of the total area burned in 2022. 65% of the area burned in August was in the Southeast Region of Bulgaria in 2022.

15.3.1 Meteorological data

The forecast for August 10th, provided by the National Institute for Meteorology and Hydrology (NIMH), was for sunny weather with a clear sky Figure 162, and Figure 163, accompanied by strong winds from north-northeast with a speed of 6 to 9 m/s reaching up to 15 m/s. The forecast for the daily max temperatures was 32ºC to 34ºC for the region, where the Razdel Fire occurred.

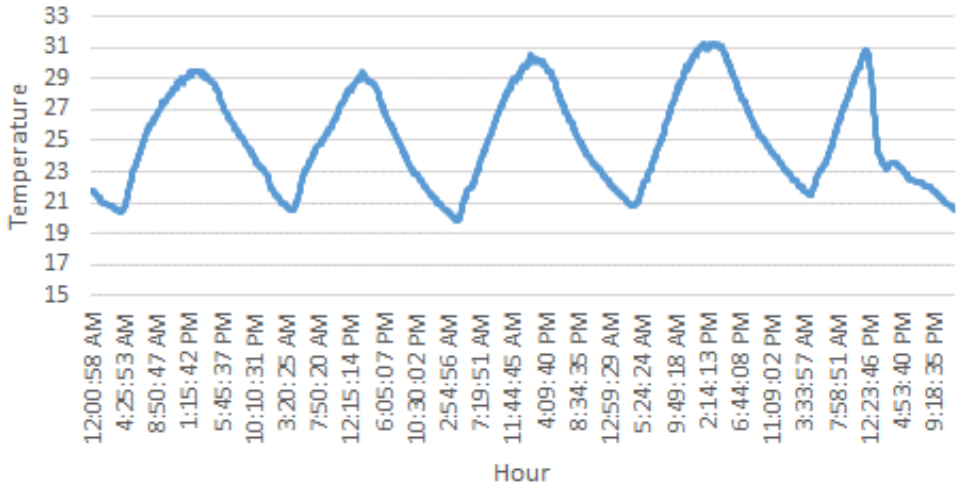
Figure 162. Meteorological parameters for August 10th, 2022: (a) 24-hour precipitation (mm); (b) Relative humidity (%), data from NIMH.

(a) (b)



Data source: NIMH.

Figure 163. Hourly meteorological conditions (temperature in ºC) registered by the meter. ac from August 10th to 14th in a station located in Elhovo.

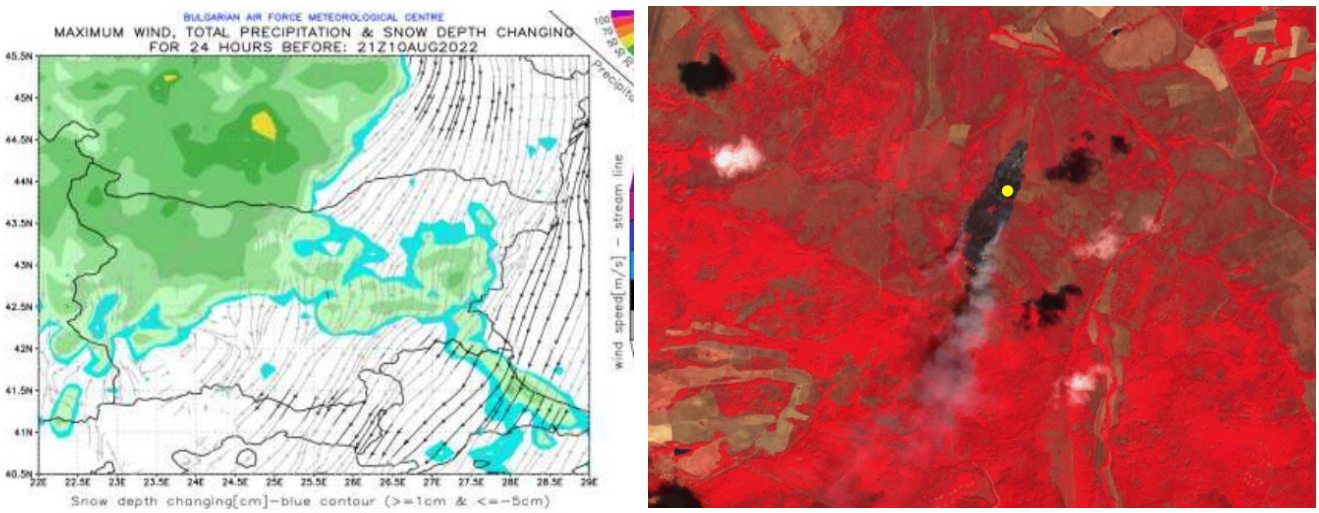


Data source: NIMH.

The wind had an important role in the fast fire perimeter spread of the Razdel Fire. As shown in Figure 164a, on August 10th, the wind was expected to be from the northwest reaching in the afternoon 10-15 m/s. This led to the fast spread of the fire in the southwest direction, but stopping the fire after reaching the top of the hill where it turns to the north (close to the village of Razdel). This could be seen in Figure 164b, where is the satellite image from Sentinel 2 from 10:55 on August 10th, taken just a few minutes after the fire started.

Figure 164. Wind influence on fire on August 10th: (a) Wind forecast for August 10th from NIMH; (b) Fire distribution on August 10th at 10:55, with a yellow dot, is presented the assumed start of the fire and the smoke shows the direction of the wind.

(a) (b)



Source: (a) Copernicus EU.

15.3.2 Fuel Moisture Content of dead fine fuels

The fuel moisture content of dead fine fuels in Bulgaria has no specific measurements performed. Bulgarian territory monitoring models are not developed for fuel moisture content estimations. The only regular data sets which are provided are the outcomes from the fire danger forecast from the NIMH system, which is based on a simplified Canadian Fire Weather Index (FWI). The Bulgarian FWI has three sub-indices that indicate the "dryness" of different "fuel" types. Each of these sub-indices is a complex function of the weather elements, but land cover datasets are not taken into consideration.

Each day, the system of NIMH generates FWI forecasts for the current day and the next 48 hours (a daily fire danger map of NIMH used by the Bulgarian fire brigades). The system outcomes are maps of the country giving information on fuels classified as follows:

- dry compact fuel;
- loose fuel (herbaceous vegetation);
- fine fuel (leaf litter).

The system is working every year, since April 2008, in the period from April until October (usually this corresponds to the Bulgarian Fire Season). The Bulgarian simplified FWI model uses the typical parameters for FWI calculation: precipitation for the previous 24 hours; and air temperature, relative air humidity, and wind speed at noon; added by the presence of snow cover and duration of the day. The colours used in the NIMH maps are presented in Table 29.

Table 29. Fire danger classes according to NIMH and used in the Bulgarian FWI.

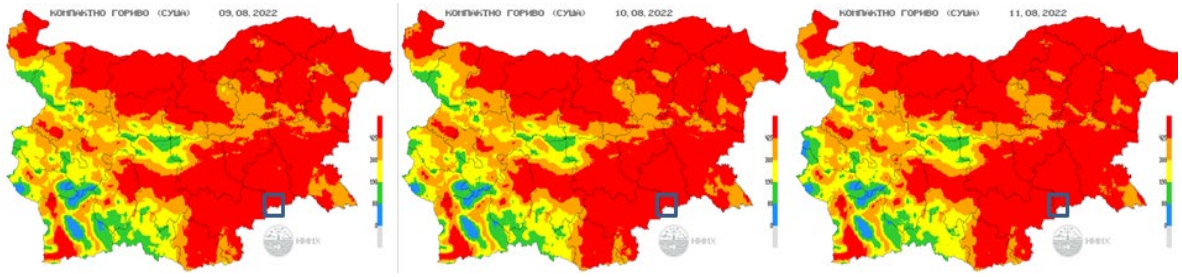
Degree of risk	Description
Low	Existing fires are self-extinguishing and new ones are unlikely to start. Live fires are possible only as smouldering in deep dry layers.
Moderate	Light and slow-growing fires are possible. Existing fires are easily extinguished by ground crews with pumps and hand tools.
High	Moderate to severe fires with entrainment of tree crowns are possible only locally. Fires are difficult for ground crews to control. It is often necessary to use heavy equipment to control fires (bulldozers, tanker trucks, airplanes).
Very high	Very strong fires with partial or complete involvement of tree crowns are possible. The front lines of the fires are impossible to contain by ground crews. Air attacks with a retardant are required to successfully attack the front lines of the fires.

Extreme	Fast-spreading, very intense fires with the involvement of tree crowns are possible. Fires are difficult to control. Extinguishing operations are limited to the flanks of the fire only. Only indirect actions directed against the front lines of the fires are possible.
Not calculated (snow)	No calculations are performed for this area. (Availability of snow cover).

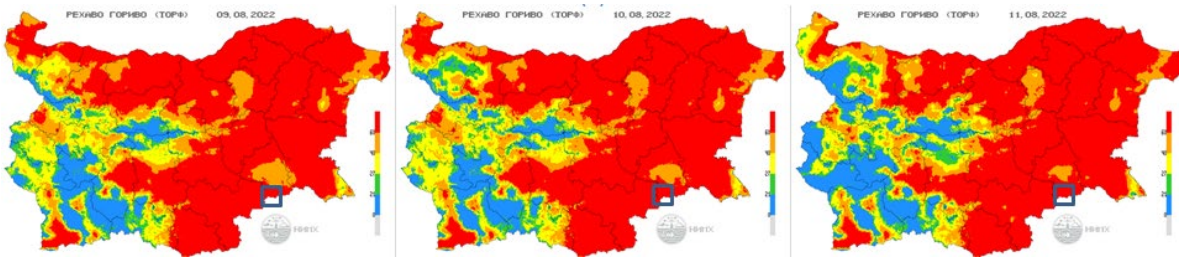
The fuel condition maps calculated by NIMH for the day before, during, and after the Razdel Fire was for extremely dry weather (Figure 165a-c). The dry conditions were constant status for the area of Razdel Fire (red colour) since the beginning of August 2022, based on the NIMH archive maps. The dryness decreases for the fine fuels and herbaceous fuel after August 15th when rain started in the area. On August 15th, the fire was already under control, and only isolated outbreaks were left to be monitored and responded to (the last blazes were declared completely suppressed on August 17th).

Figure 165. Maps of the fuel conditions for August 9th, 10th, and 11th provided by NIMH a) Dry compact fuel, b) loose fuel (herbaceous vegetation), c) fine fuel (leaf litter).

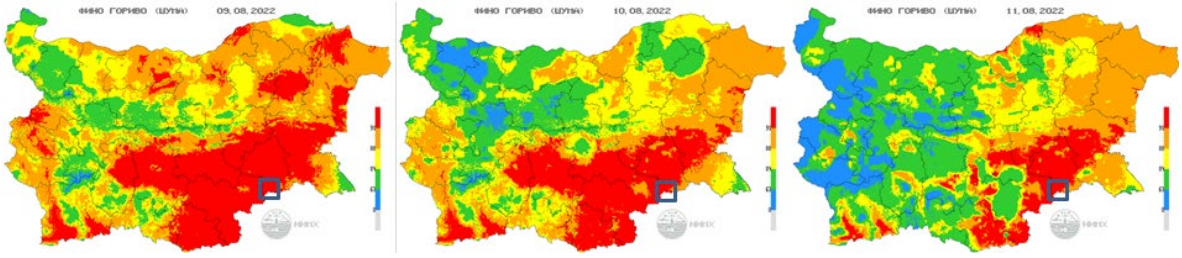
(a)



(b)



(c)



Very wet	*Wet*	*Dry*	*Very dry*	*Dangerously dry*	*Not calculated (snow cover)*

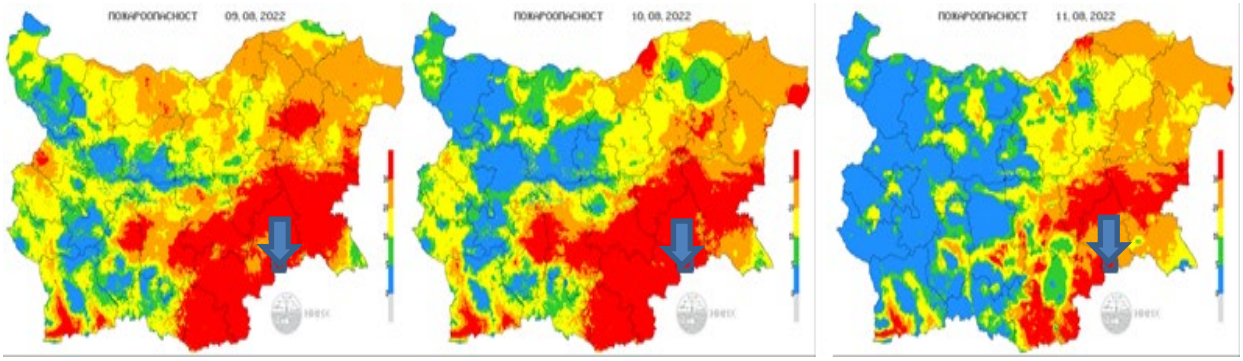
Data source: NIMH.

15.3.3 Fire danger

An analysis of the FWI shows that, for the day before, the day after, as well as on the day of the fire, the territory of the region was in an extreme degree of fire danger (Figure 166). The fire danger bulletin as color maps, together with additional meteorological data sets are sent regularly from NIMH to the corresponding firefighting administrations, alerting them to plan preparedness actions. On August 9th, the Governor of Haskovo District (neighboring the Razdel fire area), announced an emergency. During emergency conditions, actions on cutting grass in pastures are prohibited by Bulgarian legislation. The reason was the

high fire danger alert issued by the daily bulletin of NIMH. On August 9th three large wildfires started 30 km to 50 km Southwest of the Razdel Fire ignition zone.

Figure 166. Fire danger maps from NIMH for August 9th, 10th, and 11th (the burned area is represented with a dark rectangle).

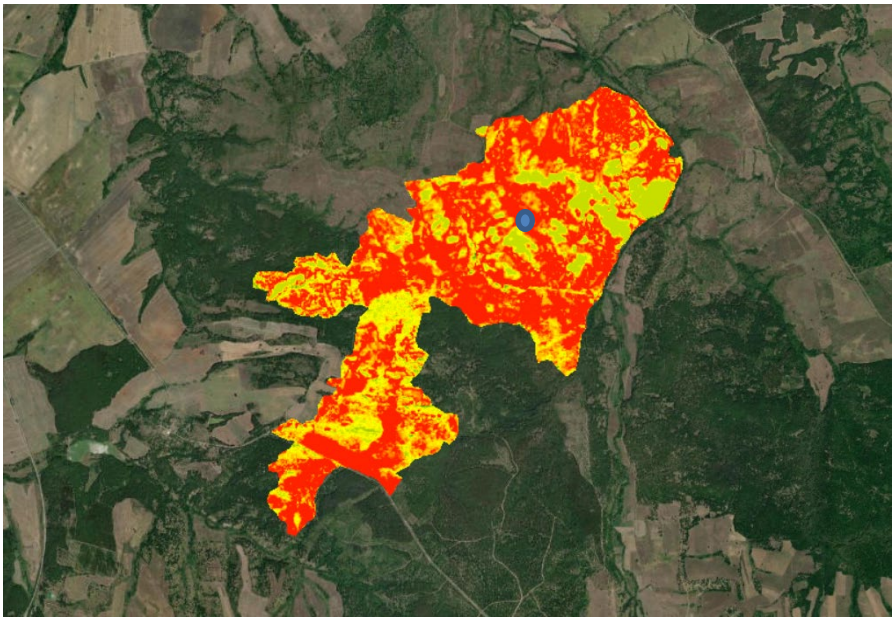


Data source: NIMH.

15.3.4 Fire Behaviour

In Bulgaria, fire evolution is not regularly monitored, because several datasets are missing to perform such analysis. In Figure 167, the level of destruction, calculated using the NBR-RAW (Normalized Burn Ratio), is presented. It was calculated by the IICT-BAS team for report visualization purposes. A detailed analysis of some relevant periods will be presented further in this report.

Figure 167. Degree of damage of the burned area difference between NBR-RAW (Normalized Burn Ratio) of the pre- and post-fire images / blue dot is approx. the ignition point of the Razdel Fire.



Data source: IICT-BAS (Burn severity map: red - high, green - low severity).

15.3.5 Resources allocation

The fire started close to the Razdel village, in a remote area 2.5 km from the settlement (coordinates: 42.054700°, 26.662987°). The closest firefighting station and professionals on duty are in the town of Elhovo, about 18 km from the ignition point. This station sent the first firefighting brigade to arrive by truck at the event scene, which happened shortly after the alert of the ignition was received. When the first brigade arrived, it was estimated that the fire perimeter was covering a 20 ha area. 50 minutes after the alert, two more fire trucks were sent from Elhovo and Yambol – located 56 km away from the fire. On the

same day (August 10th) teams from the State Forestry Service, from Elhovo, as well as two more fire trucks from the Regional Fire Directorate and Citizen's Protection, from Yambol, were also sent to fight the fire.

Until the evening of August 10th, the fire covered an approximate area of 80 ha, spreading in a south-southeast (SSE) direction pushed by the predominant wind. The fire stopped its propagation to the North. This was possible because the blazes reached the top of the hill where the fire started. The spread was only 800 m in this direction. During the evening, one fire truck remained on duty at the scene of the Razdel fire, following the regulations for wildland fire suppression of the Bulgarian disaster risks legislative framework.

On August 11th, the active firefighting operations continued. The western and eastern fronts of the fire were extinguished, leaving active only the Southern front of the fire (Arapliyska River was used as a natural barrier to stop the fire propagation at this zone). On the satellite images is confirmed that the East fire front stops when reaching the river. Due to the rise in temperatures and the appearance of strong wind in the afternoon hours, at 23:00 on August 11th, the burned area reached about 400 ha, increasing 50% from the previously burned area.

The forces engaged on August 11th were: 6 fire trucks from the Regional Fire Directorate and Citizen's Protection - Elhovo with 14 firefighters; 1 fire truck from the Regional Fire Directorate and Citizen's Protection - Yambol with 2 firefighters; State Forestry-Elhovo – 15 foresters and 1 fire truck.

On August 12th, the fire spread mainly in a southern direction towards the road from the national network III-7902. In the afternoon, at around 15:00, the fire crossed the road in one place. By order No: RD-518/12.08.2022 of the Mayor of Elhovo municipality, the municipal disaster protection plan was activated.

By 17:00 on August 12th, a firefighting helicopter from Airbase Krumovo was activated to support the ground firefighting in the suppression activities. The helicopter was used for suppression measures for the crown fires that were active in some areas and air support in surface fire spread. In general, the helicopter was not evaluated as effective as was thought when it was called on duty, because it was only one and could not help with vegetation cover as the Razdel Fire had. By the evening of August 12th, the fire in the south sector of road III-7902 was extinguished.

On August 13th the fire commander together with the local authority representatives decided to involve heavy chain machinery to participate in the suppression measures. The risk that day for the fire to continue South, approaching the Bulgarian – Turkish border, located less than 5 km, was very probable. On this day, the fire spread mainly in the southeast (SE) direction from Malko Kirilovo village to Valcha Polyana, where road III-7902 was used as a fire barrier (Figure 168).

Figure 168. Razdel Fire spread direction from the village of Malko Kirilovo to the village of Valcha Polyana, where road III-7902 was used as a fire barrier.



Data source: Google Earth Pro.

The help of heavy chain equipment to cut fuel breaks through the dense vegetation was used parallel to the road (on its northern side). In addition, a clearcut was performed perpendicular to the road in the North direction next to the existing forest road. Extra fuel management strips were performed on the South side of the road, in the section where the fire crossed the road the day before (these were protective measures for prevention of fire reoccurrence). The created strips of clear cuts and the backfire used in this zone were enough to stop the fire propagation.

The fire was surrounded by firefighters and heavy machinery, with no option to continue spreading, at 17:00 on August 13th and announced as extinguished at 22:30 on August 13th.

In Razdel Fire suppression measures were used: 11 firefighting trucks and 28 firefighters from the "Specialized operational activities" sector of the Regional Fire Directorate and Citizen's Protection located nearby the Razdel village zone. One bulldozer from "Mini Maritsa-East" EAD (coal powerplant), an MI-17 helicopter from Airbase Krumovo, and one tow truck. 38 foresters with 10 offroad cars, participated from the State Forestry Elhovo and the neighbouring State Forestry Tundzha.

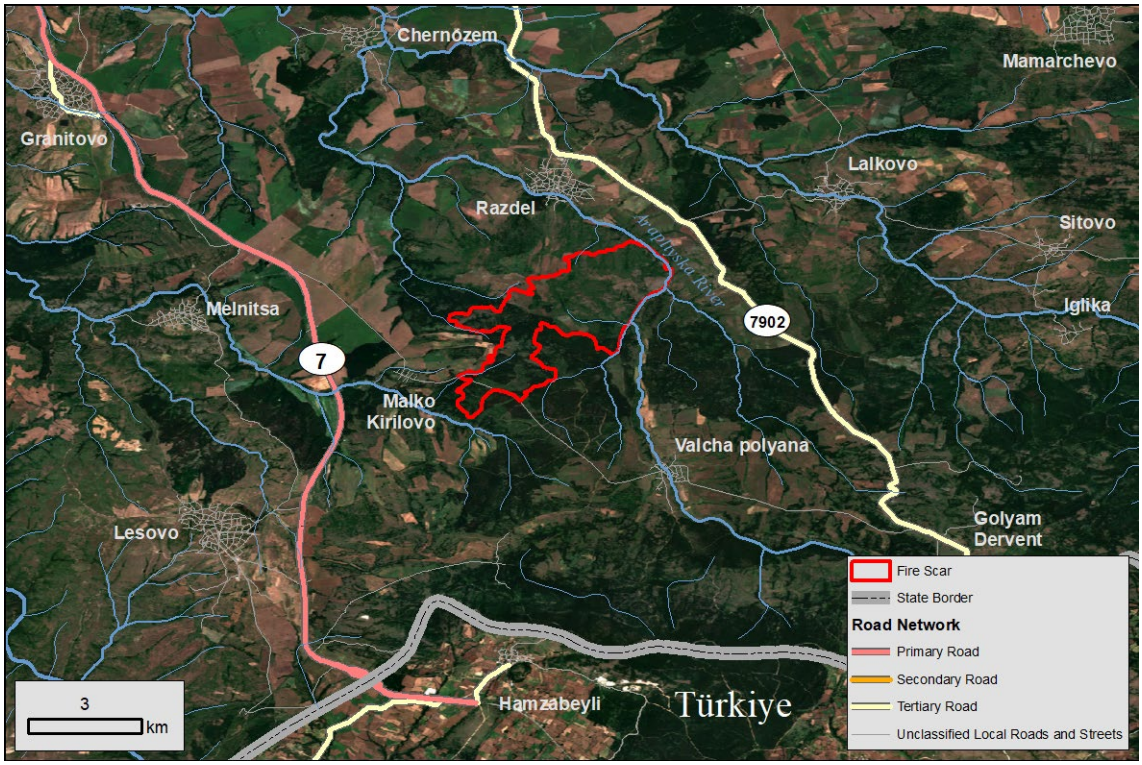
The estimations done by the firefighting brigades show that the fire covers a total area of over 797 ha. According to data from the State Forestry Elhovo 580 ha of forest territories were burned, divided as follows: 392 ha of deciduous forest (90 ha - crown fire and 302 ha surface fire), 4.3 ha of coniferous forest (surface fire) and 184 ha of areas not suitable for forestry. Young crops - 58.3 ha, up to 10 years old deciduous forests, artificially created were also burned.

To establish the causes of the fire, pre-trial investigations have been initiated. According to its findings and the Regional Office "Police" – Elhovo pieces of evidence collection, it was assumed that a spark released from a bush cutter during pasture cleaning was the most probable fire ignition cause.

15.4 Fire management at the WUI

The Razdel Fire occurred and spread mostly in a rural area, with only 3 villages in close vicinity (Figure 169) – Razdel, Malko Kirilovo, and Valcha Polyana. The main impact of the fire propagation was on forests, as the firefighting brigades were focused on the fire not reaching the road from the national network III-7902 leading to the Bulgarian – Turkish border (the road was only 2.5 km away from the fire perimeter). The other main concern of the local authorities was not reaching the Turkish territory – only 5 km in the South. During the field trip of the IICT-BAS team, together with the chief inspector from the Regional Directorate "Regional Fire Directorate and Citizen's Protection''- Yambol, were visited the main points where specific actions to stop the fire spread were performed. All the forest types affected during the fire spread were also registered.

Figure 169. Location of the Razdel Fire burned scar and vicinity to urban, and road infrastructure.



Data source: IICT-BAS.

15.4.1 Damage to buildings and other infrastructures

Three villages – Razdel, Malko Kirilovo, and Valcha Polyana – were directly affected by the fire. The number of inhabitants of the villages is Razdel (161), Malko Kirilovo (5), and Valcha Polyana (14). Casualties from Razdel Fire were not registered.

The two closest villages to the Razdel Fire were Razdel village and Malko Kirilovo village. Razdel village is located north of the fire. Due to the wind coming from the northeast, this community was in no direct danger for its infrastructure and population. The fire spread 800 m during the first hour, reaching the top of the hill in the north direction due to the local topography and wind. The efforts of the firefighters stopped the fire front propagation before heading to the village of Razdel.

On the second day (August 11th), the fire reached 1.5 km from Malko Kirilovo village. The existing secondary road on the west boundary of the fire was enlarged. This together with the fact that the western part of the fire perimeter was agricultural fields, stopped the fire progression in this direction, and it continued towards South, reaching the asphalt road between Malko Kirilovo and Valcha Polyana. This was one of the firefighting opportunities which was used by the firefighters to stop the fire spread in the South.

The only infrastructure damaged was part of a secondary road caused by a heavy bulldozer brought to this location to build a fuel break (Figure 170). The bulldozer broke an electric supply line and stopped the electricity to the nearby villages.

Figure 170. The road which was used as a border to stop the fire going south direction between Malko Kirilovo and Valcha Polyana and fire prevention measures next to the road before the pine forest.



The strategy used by the firefighters to protect the Valcha Polyana village from the Razdel Fire blazes was efficient. The road presence gave the fire brigades a useful fuel break that was enough to stop the fire from reaching Valcha Polyana village. The local authorities face regular wildland fires in this area, thus prevention measures such as buffer zones along the villages can be a good solution for future events. Clearcuts around the villages preventing future fire events from approaching houses, could be another good preventive measure for human and infrastructure safety.

15.5 Cascading effects

The main damages in the Razdel Fire were in the forest areas. The area is a mix of pastures (some of them unmanaged), shrub areas (almost exclusively from *Paliurus spina-christi*), artificially planted coniferous forests, and broadleaf coppice forests. As the area is in NATURA 2000 protected zone all three vegetation has understory and undergrowth, which is a big disadvantage in fire suppression measures.

15.5.1 Fire ignition area (shrubland - Area 01 and Area 02)

The starting point of the fire was in a pasture with the presence of *Paliurus spina-christi*. According to the investigation carried out, the most probable ignition cause is a mowing pasture work to remove Paliurus which produced a spark in a dry vegetation, igniting the Razdel Fire. The bushes of Paliurus are distributed 1 km south of the starting point of the fire which causes the spreading of the fire at a very high speed combined with the wind coming from north. A total area of 1.5 km^2 was burned after 2.5 hours. A landscape view of the most probable ignition point of the Razdel Fire is presented in Figure 171.

Figure 171. Area 01 and 02. The pasture (a) of the ignition area with the neighbouring hill with burned bushes from Paliurus (b).

(a) *(b)*



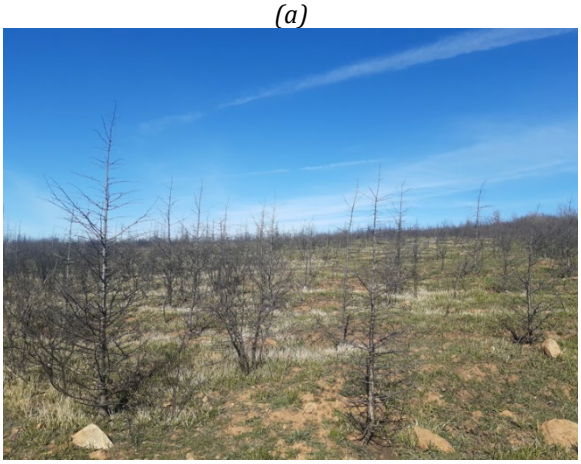


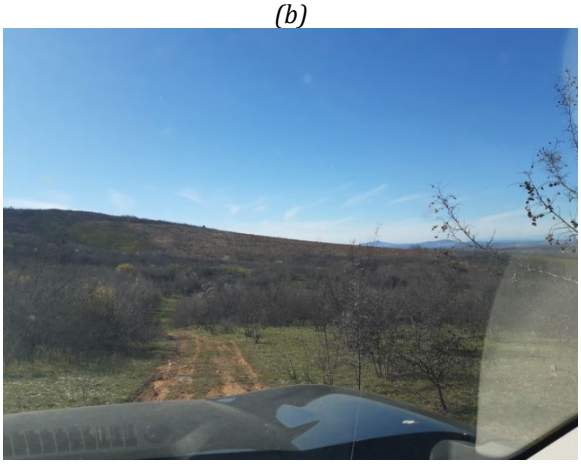
15.5.2 Area 03 Young coniferous forest

On the west and southwest of the shrubs of Area 02, young plantations of *Pinus sylvestris, Pinus nigra,* and cedar are located. Some of them were separated by the shrub area with a forest secondary road which acted as a fuel break, thus the fire did not spread there. Most of the fire brigade forces were focused on the south side of the perimeter and consequently, the fire spread towards the west causing a complete burning of a small area of *Pinus sylvestris*. After that zone, the fire did not continue to the west. Figure 172 represents a landscape view of the fire break, the forest secondary road.

Figure 172. Area 03 Burned young coniferous forest: cedar (a) and pine (b).

(a) *(b)*





15.5.3 Area 04 and 05 – Acacia area and pasture before the deciduous forest

When the fire reached the top of the hill with Paliurus, due to the wind and because it was difficult to protect this area (relief specificity, strong wind), the fire continued south and reached young (~5 years) acacia forest Figure 173a. This forest burned completely very fast as it was quite dense. The secondary forest road in the direction of the east-west was not enough to stop the fire due to its high intensity. So, it spread on the pasture (with small bushes Figure 173b) just close to the deciduous forest with *Quercus Cerris* and *Quercus frainetto*.

Figure 173. Area 04 and 05 Forest with acacia (a) and pastures with bushes (b) between the hill and the deciduous forest.

(a) *(b)*



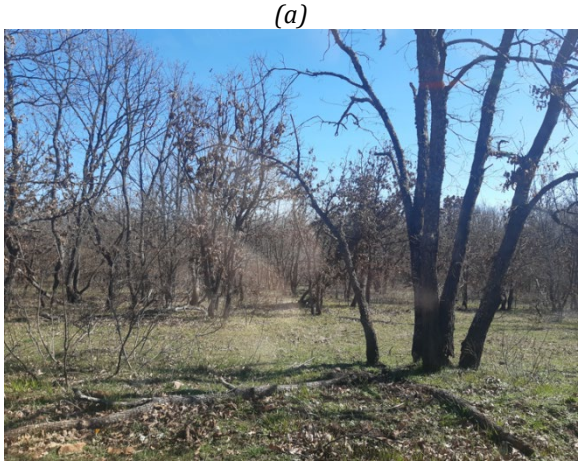


15.5.4 Area 06 and 07 – Mixed Forest of *Quercus Cerris* and *Quercus Frainetto*

Areas 06 and 07 are mixed forests of *Quercus Cerris* and *Quercus Frainetto*. The forest is around 50 years old with moderate crown density and understory. Here the fire spread was a surface fire and the main firefighting resources were focused on the road passing in the west border of the forest, preventing the fire to cross it and reach the neighbouring hill. Unfortunately, in one stretch of the road, the fire crossed and continued west. The interviewed firefighters mentioned that about 1 km west, another second fire started. This new ignition was unlikely to result from spotting caused by the main Razdel Fire front. The most probable assumption was that a fire camp of refugees passing in that area was the reason for the second fire occurrence. The spreading in the west was stopped and the fire continued only in the south direction as surface fire. Figure 174a represents the Quercus Forest, and Figure 174b represents the fire break that helped the firefighters to stop the fire spread.

Figure 174. Area 06 and 07. The Quercus Forest (a) and the road on the west (b) used as a fire break.

(a) *(b)*





15.5.5 Area 08 and 09 - Mixed Forest of *Pinus Nigra* and *Pinus Sylvestris* with deciduous species

The area between the forest of *Quercus Cerris* and the asphalt road between Malko Kirilovo and Valcha Polyana is covered with various types of mixed forest - mixed deciduous forest, and mixed coniferous (Figure 175) with deciduous species. The firefighting was focused mainly in the areas around the existing roads – the asphalt road on the south (which was assumed as a final opportunity where the fire should be stopped), and the secondary forestry road enlarged with the heavy machinery to stop the spreading of the fire in east direction. Coniferous trees affected during the Razdel Fire were cut later in the autumn of 2022.

The fire in this area spread as surface fire mostly, as can be seen in Figure 175b. The three trunks were severely damaged, but the crowns were intact.

Figure 175. Area 08 and 09 Mixed forests of *Pinus Sylvestris* (a) and *Pinus Nigra* (b) with deciduous species.

(a) *(b)*



15.5.6 Area 10 - Area with young *Quercus Cerris* and mixed forest

The forest before the asphalt road between Malko Kirilovo and Valcha Polyana is a mixed forest with a predominance of *Quercus Cerris*, *Quercus Frainetto,* and *Pinus Sylvestris* (Figure 176). It is a mixed forest of 25 to 45 years old trees. All the trees were not taller than 3-5 m, especially in the area with a predominance of coniferous forest. The active crown fire was present in this zone of the Razdel Fire.

The area between Malko Kirilovo and Valcha Polyana villages was the zone where helicopter and all extra firefighting forces were called on duty to stop the fire propagation in the south direction. That was crucial because the Bulgarian-Turkish border was only 5 km away and the weather conditions were favourable for the fire to spread in North Turkey if not stopped in this zone in Bulgaria.

Figure 176. a) Area 10 mixed deciduous forest b) just before the asphalt road between Malko Kirilovo and Valcha Polyana.

(a) *(b)*



15.5.7 Area 11 and 12 - Area south of the road and artificial clearing to stop the fire

Despite all the firefighting efforts, the fire crossed the asphalt road in one place and continued in the south direction. Here the forest was denser with a heavy understory (more than the forest in the north). The last big fire that consumed the fuels in this zone was in 2012. Secondary forest roads were built to separate

deciduous from the coniferous forest and were enlarged with heavy machinery to stop the fire in the eastern direction.

Since the international Bulgarian - Turkish border was only 5 km away from this location, it was decided to use a specialized and more efficient bulldozer from the coal mines "Mini Maritsa-East" EAD which made a new wide clear cut around the fire from the south. This measure stopped the fire spread which was extinguished in the following couple of days.

Figure 177. Area 11 Mixed deciduous forest with understory.

(a) *(b)*



Figure 178. The secondary forest road west of Area 11 (a) and the new extended one (b).

(a) *(b)*



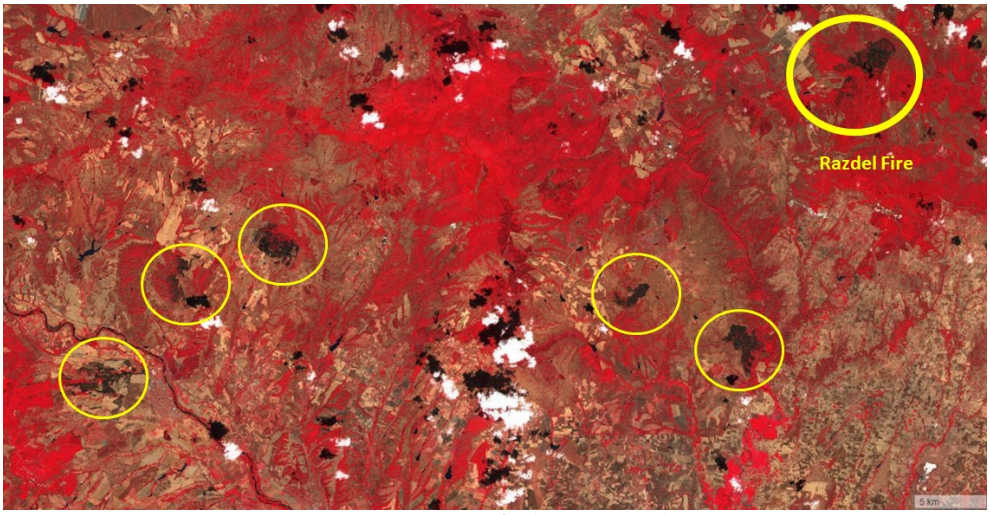
15.6 Conclusions and Lessons Learned

The Radel Fire started at a relatively close distance to the firefighting brigades and the first response was within an hour. The dry vegetation in the area – small bushes and a forest with an understory was the main reason for the difficulties in fire extinguishing.

The affected area is protected by the NATURA 2000 sites. According to the national legislation in such areas the mowing of meadows and pastures is forbidden until July 1st. Farmers can clean their pastures from that date onward and receive national support for agricultural work. The mowing is done with mulchers mounted on tractors. When the mulcher passes through stone or rock sparks are produced, which may cause an ignition in the surrounding dry vegetation. Probably, this was the ignition cause of the Razdel Fire - two tractors burned by the fire were found on the closest road after the fire was extinguished and local authorities did their first evaluations on the fire perimeter. An investigation into the fire causes is still being conducted by 31st July 2023, when this report is finalized, but this is the most probable reason for the Razdel fire start. Other similar wildland fire events were activated during the mowing of meadows in previous

years. It is common also for farmers from this zone to burn pastures eliminating bushes, even if it is illegal based on the Bulgarian law for prescribed burning and open fires. Yambol District, together with Haskovo District are the two administrative units with the highest number of fires and pasture burns in Bulgaria. The characteristics of vegetation along with very favourable weather conditions during summer and agricultural maintenance of pastures after July 1st make the southeast part of Bulgaria the most fire-prone zone in the country. Just the day before the fire (August 9th, 2022), several other small fires started in the closest municipalities (Copernicus image of parallel smaller fires Figure 179).

Figure 179. Burnt area in July-August 2022 in the vicinity of Razdel fire.



Data source: Sentinel 2 (Copernicus EU).

Although the local governor announced an emergency for August 9th, 2022, it was violated by the local farmers. A year after this event there are still fires that happen due to the same reason – pasture burns or pasture mulching. Local authorities are looking for a sustainable solution for the years to come trying to prevent more fires of such size.

Another lesson learned by the local authorities was, that the decisions to deal with wildland fires require expensive measures and timely activities, which cannot be taken by the local fire commanders. Decisions can be made, by legislation, at the regional or national level for fires above a certain size and fire spread rate. The waiting time is the time during which the fire is growing and putting at risk all suppression measures. For vulnerable areas close to the national borders the suppression measures should be more time efficient, and recommendations were sent to the Bulgarian Ministry of Interior for improvements in the response algorithms.

The territory of the Razdel fire is located at the foot of the westernmost low slopes of Strandzha Mountain. The rivers passing through it are small and dry up in the summer. The larger dams that can be used to fill the firefighting trucks with water are located to the north but are far away from the hazard area. Small dams which were near the fire location, were used from the helicopter and smaller cars to bring water for the fire suppression measures. The roads used by the cars were secondary small forestry roads. A lesson learned from the Razdel Fire is that in the zones regularly affected by wildland fires, there must be well-maintained secondary forest roads for both fuel/fire break and water supply measures. Due to logging, heavy trucks are damaging these secondary forest roads making them useless for smaller cars or firefighting trucks to pass in cases of emergency. Regular maintenance of such roads was accepted to be performed by the local authorities.

Finally, the Razdel fire zone has a large presence of refugees. The Bulgarian - Turkish border is only 10 km away. These people use the forest areas to cross the border unnoticed and move into the inner parts of the country. During the site visit, clothes, backpacks, and other belongings of refugees were observed throughout the area. Very often the refugees light a fire to keep warm or for other reasons that can lead to a fire. On the national level is decided that a more active solution for refugee control must be taken and such open fires to be eliminated.

References

Census 2011, 2021; ** Census 2011 (NSI, Bulgaria)

Agricultural Census 2020, Information system for agro statistics

Daily fire danger map of NIMH is available at: https://weather.bg/0index.php?koiFail=modelsFire&lng=0

NATIONAL SECURITY DEFENSE SYSTEM MANAGEMENT AND OPERATIONAL RESPONSE (in force since 01.11.2015): https://lex.bg/en/laws/ldoc/2136588572

URL:

http://www.weather.bg/pojaroopasnostPlus/index.php A daily fire danger map of Bulgaria provided as online service in NIMH. Link accessed on 15 July 2023

16 Conclusions

In this document, several of the major wildfires that occurred in Europe in the year 2022 across various countries have been presented and described. The situation of wildfires in Ukraine was also analysed, particularly in relation to the wartime situation experienced during this period. The primary objective of this study is centred around learning lessons, both for national benefit and for the improvement of the European civil protection system. It is crucial to emphasize that this study does not seek to assign responsibilities or evaluate decisions, assuming beforehand that all civil protection stakeholders aimed to do their best in situations where decisions must be made rapidly, with attention dispersed across various aspects and dynamic information. Nevertheless, the survey and analysis of events enable the enhancement of the wildfire management system by continuing or reinforcing positive aspects and eliminating or modifying decisions or actions that performed adversely. This improvement aims to enhance the fire management efficiency in future situations with similar conditions.

As reported, the year 2022 experienced highly conducive meteorological conditions for the occurrence of wildfires. Countries and regions with a limited history of wildfires faced some of the worst fires in their records. While the size and intensity of these fires are common in Mediterranean countries, the lesser responsiveness of countries less susceptible to fires made these incidents exceptional, sometimes requiring support from other nations. The European territory exhibits two distinct realities regarding the susceptibility and preparedness of countries or regions to face wildfires. It is crucial for countries and regions with a limited history in these matters to prepare for more frequent and severe wildfires, through allocating more resources for prevention and response, as well as establishing plans for support from other regions or countries, coordinated with the Union Civil Protection Mechanism (rescEU).

This report also describes wildfires that crossed borders, becoming international events within the European space. The relations between civil protection entities on both sides of the border were found to be good, but differences in working methodologies and the tendency to look at own countries individually led to less integrated cooperation in events that should be seen in an integrated perspective. Occasionally, even with shared information, the management of these incidents is divided along the transboundary line, creating two (semi)independent fire scenes. Given that fire knows no borders, it is essential for increased response efficiency that these events be treated in a harmonized manner, involving shared data, strategies, methods, and cooperative operations, considering the incident as a single fire scene.

Additionally, this document analyses aftermath events caused by wildfires, known as cascade effects. The higher intensity of wildfires increases the likelihood of these subsequent occurrences, sometimes with impacts greater than those directly caused by the fire itself. Cascade effects have different characteristics and importance depending on severity, period, or location. A greater knowledge and preparation for cascade effects are necessary, as these mechanisms do not always receive the anticipated attention they should have had.

Considering the insights gained from the study of past wildfires and to maintain a historical record of these events, it is important for the European Union to adopt the practice of regularly documenting the main fire events that have affected its territory. The authors of this report believe that this study has made a good contribution in that direction.

List of abbreviations and definitions

ADAI	Associação para o Desenvolvimento da Aerodinâmica Industrial [Association for the Development of Industrial Aerodynamics]
AEMet	Spanish Meteorological Agency [Portuguese Civil Protection Authority]
ANEPC	Autoridade Nacional de Emergência e Proteção Civil
AUTH	Aritotle University of Thessaloniki
BUI	Buildup Index
CMA	Air Resources Center
DNP	Dadia National Park (full name is Dadia-Lefkimi-Soufli National Pak)
EFFIS	European Forest Fire Information System
EMAK	Hellenic Fire Service's Special Disaster Response Unit
EMS	(Copernicus) Emergency Management Services
EPADAP	National Observatory of Forest Fire information (Greek initials)
FWI	Fire Weather Index
GeoCBI	Composite Burn Index
GFMC	Global Fire Monitoring Centre, Freiburg, Germany
GSCP	General Secretariat of Civil Protection
ICS	Command System
INCDS	The National Institute for Research and Development in Forestry
IPMA	Instituto Português do Mar e da Atmosfera [Portuguese Institute for Sea and Atmosphere]
ISI	Initial Spread Index
MMAP	Romanian Ministry of Environment, Water and Forests
NCSRD	National Centre for Scientific Research Demokritos
NECCA/OFYPECA	Natural Environment & Climate Change Agency
NOA	National Observatory of Athens
NOFFi	National Observatory of Forest Fire information
RCM	Conjunctural and Meteorological Risk
REEFMC	Regional Eastern Europe Fire Monitoring Center, Kyiv, Ukraine
RH	Relative humidity
RISE	Research institutes of Sweden
RNP-Romsilva	Regia Națională a Pădurilor Romsilva
SENP	Serra da Estrela Natural Park
SGIF	Forest Fire Information Management System
SIRESP	Integrated System for Portugal's Security and Emergency Networks
SPEI	Standardized Precipitation-Evapotranspiration Index
T	Temperature
TUD	Technische Universität Dresden [Dresden University of Technology]
U	Wind velocity
UAH	Universidad de Alcalá [University of Alcalá]

UIAR NUBiP	Ukrainian Institute of Agriculture Radiology of the National University of Life and Environmental Sciences of Ukraine, Chabany, Ukraine
URIFFM	Ukrainian Research Institute of Forestry and Forest Melioration, Kharkiv, Ukraine
VCI	Forest Fire Fighting Vehicle
VTT	Tactical Tank Vehicle
VTGC	Large Capacity Tank Vehicle
WIU	Wildland Urban Interface
WWF	World Wide Fund for Nature
ZCAP	Concentration Zone to Population Support

List of figures

Figure 1. Fire events addressed in the study. 7

Figure 2. Percentile of the mean-summer near-surface temperature (at 2m above ground) in 2022. The rank 20 (dark red) means that 2022 was the hottest year since 2003 in this grid cell. Conversely, rank 1 (dark blue) denotes the grid cells where 2022 had the coldest summer since 2003. 8

Figure 3. Percentile of the total precipitation amount during summer season 2022. The rank 1 (dark red) means that 2022 was the driest year in the corresponding grid cell. Conversely, dark blue (rank 20) denotes the grid cells where 2022 was wettest year out of 2003-2022 period. 9

Figure 4. Mean surface concentration of fire-induced fine particles ($PM_{2.5}$) in 2022, normalized with the mean 2003-2022 level [relative unit]. Dark red denotes 10-fold higher annual concentration, whereas dark blue shows the 10-fold lower level. 10

Figure 5. Annual average Fire Weather Index dynamic in Ukraine 1988-2022. 18

Figure 6. Spatial distribution of wildfires during the 2022 fire season and relation to land cover. 19

Figure 7. Spatial distribution of wildfires during the 2022 fire season and relation to the war zone 19

Figure 8. Representation of fires in the CEZ during 2022. Fires that occurred during the occupation are highlighted in red, while those following the territory's liberation are highlighted in yellow. 20

Figure 9. Sentinel-2 satellite images illustrating the situation during the largest wildfire in the CEZ, near Dytiatky village, on May 19th 22

Figure 10. Direct military operations causing extensive damage to forests (Luhansk oblast). 24

Figure 11. a) Map of the burned area in the municipalities affected; b) Map of the population density in the municipalities affected. 30

Figure 12. a) Map of relevant previous fires (2010 and 2016); b) Map of fire recurrence between 1975-2021. 31

Figure 13. a) Map of the orography in the region of Alberaria-a-Velha fire; b) The topography map in the region of Alberaria-a-Velha fire 31

Figure 14. Maps of the region of Albergaria-a-Velha fire characterizing the fuels available: a) Land use; b) Previous fires and respective periods; c) and d) pictures taken during the fire; e) Representative image of big piles of dead hood in the fire scene. 32

Figure 15. *Loca*tion of Aveiro's weather station when compared to fire burnt area *(ID: 702).* 34

Figure 16: Meteorological conditions between July 11th and July 17th, registered at Aveiro's weather station (ID. 702.): a) Temperature average (T_mean) and relative air humidity average (HR_mean); b) Windspeed average and gust maximum windspeed 34

Figure 17. Average hourly values temperature (T_mean) and relative air humidity (RH_mean) on July 13th, recorded at Aveiro's weather station (ID: 702). Being the dashed line indicative of the alert hour. 35

Figure 18. a) Average and maximum wind velocity (U_mean e U_max); b) Wind direction on July 13th, registered at Aveiro's weather station (ID: 702). The dashed line indicates the alert hour. 36

Figure 19. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Aveiro (ID:702) according to Lopes (2013); and mf of *Pinus pinaster* and mf *Eucalyptus globulus* measured in Lousã. Data from July 11th to July 16th. The dashed vertical line indicates the hour of the alert for Albergaria-a-Velha. 36

Figure 20. Operational means deployed in Albergaria-a-Velha fire: a) Human resources; b) Ground and aerial means. 39

Figure 21. Operational means deployed in Albergaria-a-Velha fire during the first 24 hours: a) Human resources; b) Ground and aerial means. 39

Figure 22. Images of the ignition area: a) local of ignition; b) Drone images collected after the fire focusing the area of the ignition; c) Image of the first aerial mean arriving to the fire; d) Image taken from the COS of the fire when arriving to the fire; e) Image taken from the helicopter showing spot fires near the electric grid. 40

Figure 23. Images taken when the fire was reaching the industrial zone: a) Infrared image taken at 19:35 showing several spot fires; b) Image taken at 20:17 showing great fire intensity and windy conditions. ... 42

Figure 24. Map of the key propagation phases during Albergaria-a-Velha fire. ... 43

Figure 25. Network of transmission of very-high voltage electricity in the area: a) Map of the lines in the affected area; b) Drone images showing the dimension and fuel management of the grid; c) Image showing the strawberry trees planted under the grid. ... 44

Figure 26. Picture taken by a TSF journalist traveling through A1 motorway. ... 46

Figure 27. Map of burned areas in the Ourém and Leiria fire complex. ... 50

Figure 28. Hypsometric fire map of Freixianda and Caranguejeira. ... 51

Figure 29. Slope terrain fire map of Freixianda and Caranguejeira. ... 52

Figure 30. Years since last fire map of Freixianda and Caranguejeira with statistics from 1975 to 2021. ... 52

Figure 31. Average hourly temperature values recorded at IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). ... 53

Figure 32. Hourly values of average speed and daily wind gusts recorded in the IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th: a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). ... 53

Figure 33. Hourly values of wind direction recorded at weather stations of the IPMA in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID:716). b) Leiria weather station (ID: 718). ... 53

Figure 34. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from 6th July to 14th July. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). ... 54

Figure 35. The aerial images presented here were provided by ANEPC and taken on July 7th during the fire through air way to support the analysis of the fire OSCAR02. a) Image of fire by 18:24 where can be seen a fire with an elongated elliptical configuration, configuration typical of a wind driven fire. b) Image of the fire at 19:14 that can be seen a spot fire on the left flank of the fire. ... 58

Figure 36. The aerial images presented here were provided by ANEPC and obtained on July 8th during the fire through OSCAR02 at a) 15:41 and b) 15:50. The figures show the beginning of the various reactivations during the period described above. ... 59

Figure 37. The aerial images presented here were provided by ANEPC and taken on the July 12th during the fire by OSCAR03. a) Image of the fire at 18:03 where one can see a fire with an elongated elliptical configuration, typical configuration of fire dominated by the wind and, in parallel, the columns also with a connecting power. b) IR image of the fire at 18:05 where the great depth of flames can be seen, making suppression operations difficult. ... 61

Figure 38. General view of the fire perimeter of the Garrocho wildfire (in black) and the representation of the six municipalities of Serra da Estrela affected by the fire (Celorico da Beira, Covilhã, Gouveia, Guarda, Manteigas, and Belmonte). ... 67

Figure 39. Fire recurrence of the region between 1975 and 2022. ... 68

Figure 40. Orography map of Garrocho / Serra da Estrela. ... 69

Figure 41. Slope map of Garrocho / Serra da Estrela ... 70

Figure 42. Meteorological parameters registered by the meteorological station of Covilhã (ID:687) during between August 5th and 17th: a) temperature (T) and relative humidity (RH) variation; b) windspeed (U) and wind direction. ... 71

Figure 43. Fine dead fuel moisture (mf): modelled variation using the meteorological data from the weather station of Covilhã according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. 71

Figure 44. Evolution of the resources in the fireground of Garrocho: a) human resources, b) ground and aerial resources. 73

Figure 45. Evolution of the Serra da Estrela fire divided in five phases. 74

Figure 46. Evolution of the Serra da Estrela Fire until 12:00 of August 6th. 75

Figure 47. Evolution of the Serra da Estrela Fire until 17:00 of August 8th. 76

Figure 48. MODIS satellite image of the fire situation at 11:08 of August 8th. It is possible to see the most active fire perimeter at the entrance of the Beijames Valley, NE of the burnt area. 76

Figure 49. Sequence of frames from two laboratory tests in a canyon (water line slope: 15º; versant slopes: 30º) with the same fuel conditions: top row - two fire fronts; bottom row – two fire fronts and a fire ignition. 77

Figure 50. Evolution of the Serra da Estrela Fire until 24:00 of August 9th. 78

Figure 51. Evolution of the Serra da Estrela Fire until 24:00 of August 12th. 78

Figure 52. Evolution of the Rekindling at Vale da Amoreira by the 15:47 of August 15th. Fire perimeter by the 24:00 of August 15th. 79

Figure 53. Evolution of the Serra da Estrela Fire – approximate final perimeter by the 24:00 of August 18th. 80

Figure 54. Image of the village of Sameiro (Manteigas) when threatened by a fire front (a) and after the passage of the fire (b). The effect of fuel management can be observed, as it delimited the burned area, ultimately saving the village (photos cordially provided by Manteigas City Council). 82

Figure 55. Orographic framing of the Bosque das Faias (Beech Forest), the Manteigas sub-basin and the Sameiro sub-basin. 83

Figure 56. Images showing the flash flood impacts in Sameiro. September 13th (a) and October 17th (b). 83

Figure 57. Images showing some direct impacts of the Fire of Garrocho on tourism infrastructures. 83

Figure 58. The final perimeter of the Murça fire from the 17th of July to the 21st, with a total area of 7185.78 ha. The two ignition points are marked in the map. The yellow cross indicates the location of the two fatalities and the vehicle symbol marks the location of the incident with a fire truck that was destroyed by the fire. In the inset map the location of Murça in the Northeast of Portugal is shown. 86

Figure 59. Fire recurrence in the region affected by the wildfire of Murça between 1975 and 2021. 87

Figure 60. Number of years since the last wildfire in Murça in 2022 (statistics from 1975-2021). 88

Figure 61. Orography in the area of the wildfire of Murça. 89

Figure 62. Slopes in the area of the wildfire of Murça. 89

Figure 63. Land use in the area of the wildfire of Murça 90

Figure 64. Temperature of the air (T) and Relative Humidity (RH) registered by the meteorological station of Vila Real (ID:567) between the 3rd and 22nd July. 91

Figure 65. Wind data registered by the meteorological station of Vila Real (ID:567) between 16th and 22nd July: a) Wind speed (U) in km/h, and b) Wind direction in degrees (º). 91

Figure 66. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from July 17th to July 22nd. 92

Figure 67. Evolution of the fire perimeter since the ignition on the July 17th till the extinction of the fire on the July 21st. 94

Figure 68. View of the location of the East ignition point, close to the electrical post shown in the photo near the road N212. 95

Figure 69. Location of the two ignition points and the perimeter of the fire in the SW section of the fire perimeter. 96

Figure 70. IR and video images from the fire of Murça obtained by the observation plane *Óscar 2*, around 17:26 on July 17th. 96

Figure 71. Level of damage grading provided by *Copernicus* satellite. 97

Figure 72. Evolution of the resources in the fire of Murça: a) human resources, b) ground and aerial resources. 98

Figure 73. Map of Penabeice, with the road (CM1176), that goes up from the village to the road ER314, that gives access to Murça. The yellow dot indicates the place where the car went out of the road to its left side falling in the ravine. 100

Figure 74. a) A view of the house where the couple lived; b) A view of the place where the vehicle fell… 101

Figure 75. Location of Sierra de la Culebra Fires (Riofrio de Aliste Fire in red and Losacio Fire in yellow). 104

Figure 76. Sentinel 2 images acquired before the fires occurred on May 26th, after the Riofrío de Aliste Fire on June 28th, and after the Losacio Fire on July 30th. The colour composite used (SWIR-NIR-RED) shows the vegetation in green tones, with light greens for growing crops and darker greens for forested areas; the burned areas are shown in magenta tones, areas with sparse or no vegetation are shown in light pink colour. The bottom right image shows the fire perimeters of both fires with the estimated burned area from satellite images. 104

Figure 77. Land covers affected by the Sierra de la Culebra fires (Riofrio de Aliste and Losacio) 106

Figure 78. Meteorology station of Villardeciervos – 2775X, at 850 m above sea level. A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB). Sources: AEMet and Castilla y León Forestry Department. 107

Figure 79. Geopotential pressure at 500hPa at 00z from July 12th to 15th and dominant synoptic situations during the week of June 13th to 19th. 107

Figure 80. Fuel moisture content of dead fine fuel from June 12th to 15th. 107

Figure 81. Standardized Precipitation-Evapotranspiration Index (SPEI) in Zamora during the six months prior to the Riofrio de Aliste and Losacio fires occurrence. 108

Figure 82. The map shows the lightnings strikes occurred in the region on June 15th in yellow and the lightning strikes which turned into active fires in red. Source: Report of the Forest Firefighting Service of JCyL. 109

Figure 83. Fire growth and dynamic on June 16th. Red stars mark the location of the ignition, blue arrows indicate the direction of the wind, and the red polygon indicates the size of the affected area. 110

Figure 84. Fire growth and dynamic on June 17th: a) Shows the fire growth at 3:00, b) the fire growth at 5:00, and c) shows the fire growth at 8:00. 110

Figure 85. Fire growth and dynamic on June 18th. Blue arrows indicate the direction of the wind, and the red polygons mark the extension of the burned area. 112

Figure 86. Fire growth and dynamic on June 19th. Blue arrow indicates the direction of the wind, red and orange arrows mark the fire spread. 112

Figure 87. Fuel moisture content of dead fine fuel from July 17th to 20th. Source: METEOSIG. 113

Figure 88. Meteorology station of Alcañices – 2966D, at 840 m above sea level (Right), during the previous days to the Losacio Fire (started on July 17th). A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB). 114

Figure 89. Fire growth of the Losacio fire following aerial photography and field reports. Yellow line: July 17th at 03:00; Light Blue line: July 18th at 08:00; Green line: July 18th at 13:30; Brown line: July 18th at 17:30; Dark Blue line: July 18th at 19:00; Magenta line: July 18th at 22:00; Discontinuous yellow line: July 19th at 05:00; Discontinuous green line: July 19th at 15:00; Discontinuous red line: July 20th at 15:00. 115

Figure 90. a) Post-fire situation in the central valley of the Riofrío de Aliste fire showing intense severity; b) Post-fire situation in the Southern mild slopes of the Riofrío de Aliste fire showing medium fire severity. (photos taken by Emilio Chuvieco in November 2022)..... 117

Figure 91. a) Post-fire situation in the north of Losacio fire showing intense severity; b) Post-fire situation in the North East of Losacio fire showing medium fire severity. (photos taken by Patricia Oliva in June 2023)..... 117

Figure 92. Burn severity estimation based on the difference in NBR for the Riofrío de Aliste fire (left) and Losacio fire (right), based on Sentinel-2 images. The Riofrio de Aliste estimation was computed by the difference between the NBR in the prefire date of May 26th and the postfire date of June 28th. The Losacio burn severity estimation was computed by the difference between the pre-fire image of June 28th and the postfire image of July 30th..... 118

Figure 93. Affected chestnuts plantations in the Riofrío de Aliste fire were already resprouting in November 2022 on the right. (photos taken by Patricia Oliva in November 2022)..... 119

Figure 94. General map of the Karst area, including the 2022 wildfire perimeter and the administrative municipal boundaries. DDL = Doberdò del Lago, FDI = Farra d'Isonzo, MON = Monfalcone, RDL = Ronchi dei Legionari, SAG = Sagrado, SDI = Savogna d'Isonzo, STA = Staranzano, DUA = Duino Aurisina, SGO = Sgonico, SEM = Šempeter- Vrtojba, REN = Renče- Vogrsko, KOM = Komen, MIK = Miren – Kostanjevica, NOV = Nova Gorica..... 123

Figure 95. a) Digital elevation model of the Karst area. b) Main fuel types of the area affected by the Karst wildfire. AA = anthropic areas; CA = cultivated areas; PC = permanent crops; BF = broadleaf forests; CF = conifer forests; SH = shrub vegetation; SV = sclerophyllous vegetation; W = wetlands; R= rocks. The map is derived from the Land Use Map of Europe 2017..... 124

Figure 96. Hourly values of air temperature and air relative humidity provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st..... 127

Figure 97. Hourly values of wind intensity and direction provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st..... 127

Figure 98. Hourly values of air temperature and air relative humidity measured by the weather station of Gradisca from July 15th to 31st..... 128

Figure 99. Hourly values of wind intensity and direction measured by the weather station of Gradisca from July 15th to 31st..... 128

Figure 100. Map of the three main steps of propagation of the Miren fire (in red). The ignition points of the different steps are showed, together with the main directions of propagation. The final perimeter of the Karst wildfire is also showed (in blue)..... 130

Figure 101. Map of the three main steps of propagation of Renče fire (in red). The ignition point of the fire, together with the main directions of propagation, is also included. The final perimeter of the Karst wildfire is showed in blue..... 131

Figure 102. Map of the burned area by the Monfalcone fire on July 20th (in orange) and on Juli 21st (in red). The ignition point, indicating the area where most of the fire ignitions near the railway line were observed, is also showed, together with the main directions of propagation and the Italian-Slovenian border. The final perimeter of the Karst wildfire is showed in blue..... 132

Figure 103. Map of the burned area by the Brestovec fire (left polygon, in red). The ignition point is also showed, together with the main direction of propagation. On the right, the western side of the Miren fire. 135

Figure 104. Pictures of the fires: (a) Initial propagation phase of the Miren wildfire (July 15th); (b) The wildland urban interface threatened by the Miren fire (July 20th); (c) View from north of the initial propagation of the Renče wildfire (July 17th). The are of ignition is located on the left; (d) View from north-east of the initial propagation phase of the Monfalcone fire (July 19th)..... 135

Figure 105. PM_{10} ($\mu g/m^3$) hourly data collected from the four air quality stations in Trieste (July 20th-25th). 141

Figure 106. PM_{10} ($\mu g/m^3$) hourly data collected from the Udine (via S. Daniele and S. Osvaldo) and S. Giovanni al Natisone air quality stations (July 27th-30th). 142

Figure 107. Location of the burned area in the two national parks on the border between Germany and the Czech Republic. 147

Figure 108. The Richterschlucht, a popular walking trail through the Saxon Switzerland National Park. 149

Figure 109. Dead standing and lying Norway Spruce (*Picea abies*). 149

Figure 110. Bark beetle affected areas in the two national parks with overlay of burned area. 150

Figure 111. Fire warning levels Saxon Switzerland National Park (according to the German Waldbrandindex) from July 1st to August 31st, i.e., before, during and after the fire. The red column indicates the date of the ignition and the orange box the period of the main fire spread. 151

Figure 112. Daily maximum temperature (a) and maximum speed of wind gusts (b) before, during and after the fire. 151

Figure 113. Fuel moisture and precipitation at the fire site. This station was destroyed by the fire on July 26th. 152

Figure 114. Conditions before and after the fire as captured by camera trap (images courtesy of Saxon Switzerland National Park). 153

Figure 115. Fire radiative power (FRP) over the burned area as observed by VIIRS satellite sensors between July 24th and 29th. (a) Highest fire energy emissions occurred at forest stands previously affected by bark beetle infestations and in some beech forests; b) FRP over the burned area – July 24th to 29th; c) FRP from July 24th to 29th. 153

Figure 116. Sandstone affected by high temperatures. 154

Figure 117. House destroyed by fire in the centre of Mezná. The house was not located close to the main burned area. The burning was likely caused by flying embers that ignited the coniferous garden hedges (right side). 155

Figure 118. Fires reached the village-forest interface in Mezná. This image was taken in early June 2023. One house to the left of the photograph was completely destroyed, neighbouring houses were untouched. 156

Figure 119. Regeneration of mosses 8 months after the fire. 157

Figure 120. Annual mapped burnt area of fires >=30 ha in Greece (a) and distribution of % total area burnt by land cover types in 2022 (b). 159

Figure 121. Total number of burnt areas (ha) for each of the country's thirteen region of Greece. 160

Figure 122. Examples of the received notifications to geotargeted population to evacuate as the fire approaches to residential areas. 161

Figure 123. Daily evolution of a) Fire weather index, b) initial spread index an c) drought code provided by EFFIS before and after the fire occurred in the burnt area of Penteli. 163

Figure 124. Spatial depiction of FWI index and Total burnt area by MODIS/SENTINEL2 (supervised) and MODIS & VIIRS NRT in the affected area (in green) of Mount Penteli. 164

Figure 125. Fire Risk Prediction Map for Tuesday, July 19th. The legend on the bottom left corner classifies by colour the fire risk in 5 categories, as (1.low, 2. moderate, 3. high, 4. very high and 5. alert situation). The black lines show the boundaries of local forest services). 164

Figure 126. First estimate product from the activation of emergency Copernicus focusing on Mount Penteli. 166

Figure 127. Fire delimitation in the area of Mount Penteli provided under Copernicus by the European Union and ESA 167

Figure 128. Fire delination in the area of Mount Penteli provided under Copernicus by the European Union and ESA. 168

Figure 129. Houses (a) and a car (b) are engulfed by flames during the Penteli Attica Fire – in Pallini, near Athens, Greece July 20th. REUTERS/Costas Baltas. 169

Figure 130 Copernicus EMS Mapping product depicting Dadia's 2022 fire extend and damage. 171

Figure 131. Dadia fire active hotspots – July 21st to 27th. 173
Figure 132. Daily progress of the Dadia fire – July 21st to 27th. 173
Figure 133 Daily burned areas in Dadia fire – July 21st to 27th. 174
Figure 134 Dadia National area and Park Zones with the daily burned areas during the 2022 fire. 177
Figure 135. Slope and elevation of the Dadia National Park area. 177
Figure 136. Recent fire history (a) in the area and fuel types (b). 178
Figure 137. Temperature anomaly over Europe at 1,500m – July 21st to 27th. 179
Figure 138. Temperature and wind speed data between July 21st and 27th. 179
Figure 139. Wind gusts graph in Dadia region between July 21st and 27th. 180
Figure 140. Fire risk map: a) July 21st; b) July 22nd, c) July 23rd, d) July 24th, e) July 25th,) July 26th. 180
Figure 141. Pyrometeorological index (hot-dry-windy) for July 28th. 181
Figure 142. Transient "shallow" pyroclouds over the induction column of the southwestern front of the forest fire in Dadia, Evros – July 26th. 182
Figure 143. Fuel types of Dadia area. 183
Figure 144. Patches of area burned during the seven days Dadia fire 184
Figure 145. Wind-driven smoke dispersion pattern of Dadia fire on July 23rd, 24th and 26th. 184
Figure 146. a) Map of the fire-affected area, encompassing 45,412 ha; b) Map detailing the fire's severity and impact on vegetation. 185
Figure 147. The 'feeding rock', a boulder in the heart of the national park where food is left for the area's endangered prey birds (a) and prey birds required care (b). 186
Figure 148. Complete burning of the pine forest in the smaller of the two cores of the National Park 187
Figure 149. Prey bird observatory (before & after fire). 187
Figure 150. a) Weekly burnt area in Romania for 2022 and the 2011 – 2023 average; b) The trend in number of EFFIS-detected fires and total burnt area in Romania since 2011. 189
Figure 151. a) Cumulative burnt area on forested land during 2022 until November; b) Annual burnt area on forested land and the number of forest fires between 1956 and 2022. 190
Figure 152. MODIS polygons during March 28th to April 3rd in part of Gorj (a) and Tulcea (b) counties. The numbers indicate the date (in March if not stated otherwise) at which the fire was detected. 190
Figure 153. Photos with forest fires in Romania: a-b) Someşul Rece Forest District, Cluj, July 28th; c-d) Apuseni Natural Park, Cluj, July 21st. 191
Figure 154. Photos with reed fires in the Danube Delta Biosphere Reserve. 192
Figure 155. Number of forest fires and burnt area broken down to cause of ignition (Data source MMAP, 2023). 192
Figure 156. Danger index (Rate of spread for a model grassland) based on the weather during spring 2022 in Bucharest and calculated according to [3] (Weather data source: https://www.visualcrossing.com/weather-history/bucharest, assessed 2023-10-12). 193
Figure 157. a) Geographical representation of the Razdel Fire (IICT - BAS); b) Fire hazard for August 10th. 195
Figure 158. a) Land use map of Elhovo municipality (IICT - BAS); b) Natura 2000 protected sites under birds and habitats Directives. 196
Figure 159. Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern. 197
Figure 160. Google Earth image showing the typical orographic pattern. 198
Figure 161. Burned scars of the two largest fires in the area in the last 10 years, 2012 and 2022. 199

Figure 162. Meteorological parameters for August 10th, 2022: (a) 24-hour precipitation (mm); (b) Relative humidity (%), data from NIMH. 199

Figure 163. Hourly meteorological conditions (temperature in ºC) registered by the meter. ac from August 10th to 14th in a station located in Elhovo. 200

Figure 164. Wind influence on fire on August 10th: (a) Wind forecast for August 10th from NIMH; (b) Fire distribution on August 10th at 10:55, with a yellow dot, is presented the assumed start of the fire and the smoke shows the direction of the wind. 200

Figure 165. Maps of the fuel conditions for August 9th, 10th, and 11th provided by NIMH a) Dry compact fuel, b) loose fuel (herbaceous vegetation), c) fine fuel (leaf litter). 202

Figure 166. Fire danger maps from NIMH for August 9th, 10th, and 11th (the burned area is represented with a dark rectangle) 203

Figure 167. Degree of damage of the burned area difference between NBR-RAW (Normalized Burn Ratio) of the pre-and post-fire images / blue dot is approx. the ignition point of the Razdel Fire. 203

Figure 168. Razdel Fire spread direction from the village of Malko Kirilovo to the village of Valcha Polyana, where road III-7902 was used as a fire barrier. 204

Figure 169. Location of the Razdel Fire burned scar and vicinity to urban, and road infrastructure. 206

Figure 170. The road which was used as a border to stop the fire going south direction between Malko Kirilovo and Valcha Polyana and fire prevention measures next to the road before the pine forest. 207

Figure 171. Area 01 and 02. The pasture (a) of the ignition area with the neighbouring hill with burned bushes from Paliurus (b). 207

Figure 172. Area 03 Burned young coniferous forest: cedar (a) and pine (b). 208

Figure 173. Area 04 and 05 Forest with acacia (a) and pastures with bushes (b) between the hill and the deciduous forest. 208

Figure 174. Area 06 and 07. The Quercus Forest (a) and the road on the west (b) used as a fire break. 209

Figure 175. Area 08 and 09 Mixed forests of *Pinus Sylvestris* (a) and *Pinus Nigra* (b) with deciduous species 210

Figure 176. a) Area 10 mixed deciduous forest b) just before the asphalt road between Malko Kirilovo and Valcha Polyana. 210

Figure 177. Area 11 Mixed deciduous forest with understory. 211

Figure 178. The secondary forest road west of Area 11 (a) and the new extended one (b). 211

Figure 179. Burnt area in July-August 2022 in the vicinity of Razdel fire. 212

Use the built-in function to generate a table of figures (References > Captions > Insert Table of Figures); or simply

use the example in the template and update it (click on table field, press F9) when the report is complete.

Note: Word does not distinguish between these tables; therefore when it asks if you want to replace the already inserted table (for boxes or tables), you answer No.

Figure 1. Fire events addressed in the study. 7

Figure 2. Percentile of the mean-summer near-surface temperature (at 2m above ground) in 2022. The rank 20 (dark red) means that 2022 was the hottest year since 2003 in this grid cell. Conversely, rank 1 (dark blue) denotes the grid cells where 2022 had the coldest summer since 2003. 8

Figure 3. Percentile of the total precipitation amount during summer season 2022. The rank 1 (dark red) means that 2022 was the driest year in the corresponding grid cell. Conversely, dark blue (rank 20) denotes the grid cells where 2022 was wettest year out of 2003-2022 period. 9

Figure 4. Mean surface concentration of fire-induced fine particles ($PM_{2.5}$) in 2022, normalized with the mean 2003-2022 level [relative unit]. Dark red denotes 10-fold higher annual concentration, whereas dark blue shows the 10-fold lower level. 10

Figure 5. Annual average Fire Weather Index dynamic in Ukraine 1988-2022. 18

Figure 6. Spatial distribution of wildfires during the 2022 fire season and relation to land cover. 19

Figure 7. Spatial distribution of wildfires during the 2022 fire season and relation to the war zone 19

Figure 8. Representation of fires in the CEZ during 2022. Fires that occurred during the occupation are highlighted in red, while those following the territory's liberation are highlighted in yellow. 20

Figure 9. Sentinel-2 satellite images illustrating the situation during the largest wildfire in the CEZ, near Dytiatky village, on May 19th 22

Figure 10. Direct military operations causing extensive damage to forests (Luhansk oblast). 24

Figure 11. a) Map of the burned area in the municipalities affected; b) Map of the population density in the municipalities affected. 30

Figure 12. a) Map of relevant previous fires (2010 and 2016); b) Map of fire recurrence between 1975-2021. 31

Figure 13. a) Map of the orography in the region of Alberaria-a-Velha fire; b) The topography map in the region of Alberaria-a-Velha fire 31

Figure 14. Maps of the region of Albergaria-a-Velha fire characterizing the fuels available: a) Land use; b) Previous fires and respective periods; c) and d) pictures taken during the fire; e) Representative image of big piles of dead hood in the fire scene. 32

Figure 15. *Loca*tion of Aveiro's weather station when compared to fire burnt area *(ID: 702).* 34

Figure 16: Meteorological conditions between July 11th and July 17th, registered at Aveiro's weather station (ID. 702.): a) Temperature average (T_mean) and relative air humidity average (HR_mean); b) Windspeed average and gust maximum windspeed 34

Data source: IPMA. 34

Figure 17. Average hourly values temperature (T_mean) and relative air humidity (RH_mean) on July 13th, recorded at Aveiro's weather station (ID: 702). Being the dashed line indicative of the alert hour. 35

Figure 18. a) Average and maximum wind velocity (U_mean e U_max); b) Wind direction on July 13th, registered at Aveiro's weather station (ID: 702). The dashed line indicates the alert hour. 36

Source: IPMA. 36

Figure 19. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Aveiro (ID:702) according to Lopes (2013); and mf of *Pinus pinaster* and mf *Eucalyptus globulus* measured in Lousã. Data from July 11th to July 16th. The dashed vertical line indicates the hour of the alert for Albergaria-a-Velha. 36

Source: IPMA. 37

Figure 20. Operational means deployed in Albergaria-a-Velha fire: a) Human resources; b) Ground and aerial means. 39

Figure 21. Operational means deployed in Albergaria-a-Velha fire during the first 24 hours: a) Human resources; b) Ground and aerial means. 39

Figure 22. Images of the ignition area: a) local of ignition; b) Drone images collected after the fire focusing the area of the ignition; c) Image of the first aerial mean arriving to the fire; d) Image taken from the COS of the fire when arriving to the fire; e) Image taken from the helicopter showing spot fires near the electric grid. 40

Figure 23. Images taken when the fire was reaching the industrial zone: a) Infrared image taken at 19:35 showing several spot fires; b) Image taken at 20:17 showing great fire intensity and windy conditions. 42

Figure 24. Map of the key propagation phases during Albergaria-a-Velha fire. 43

Figure 25. Network of transmission of very-high voltage electricity in the area: a) Map of the lines in the affected area; b) Drone images showing the dimension and fuel management of the grid; c) Image showing the strawberry trees planted under the grid. 44

Figure 26. Picture taken by a TSF journalist traveling through A1 motorway. 46

Figure 27. Map of burned areas in the Ourém and Leiria fire complex. 50

50

Figure 28. Hypsometric fire map of Freixianda and Caranguejeira. 51

Figure 29. Slope terrain fire map of Freixianda and Caranguejeira. 52

Figure 30. Years since last fire map of Freixianda and Caranguejeira with statistics from 1975 to 2021. 52

Figure 31. Average hourly temperature values recorded at IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). 53

Figure 32. Hourly values of average speed and daily wind gusts recorded in the IPMA meteorological stations in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th: a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). 53

Figure 33. Hourly values of wind direction recorded at weather stations of the IPMA in the period from July 6th to 14th. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID:716). b) Leiria weather station (ID: 718). 53

Figure 34. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from 6th July to 14th July. Shown in dashed lines are the start date of ignitions in Cumeada / Freixianda on July 7th and in Caranguejeira on July 12th. a) Ansião weather station (ID: 716). b) Leiria weather station (ID: 718). 54

Figure 35. The aerial images presented here were provided by ANEPC and taken on July 7th during the fire through air way to support the analysis of the fire OSCAR02. a) Image of fire by 18:24 where can be seen a fire with an elongated elliptical configuration, configuration typical of a wind driven fire. b) Image of the fire at 19:14 that can be seen a spot fire on the left flank of the fire. 58

Figure 36. The aerial images presented here were provided by ANEPC and obtained on July 8th during the fire through OSCAR02 at a) 15:41 and b) 15:50. The figures show the beginning of the various reactivations during the period described above. 59

Figure 37. The aerial images presented here were provided by ANEPC and taken on the July 12th during the fire by OSCAR03. a) Image of the fire at 18:03 where one can see a fire with an elongated elliptical configuration, typical configuration of fire dominated by the wind and, in parallel, the columns also with a connecting power. b) IR image of the fire at 18:05 where the great depth of flames can be seen, making suppression operations difficult. 61

Figure 38. General view of the fire perimeter of the Garrocho wildfire (in black) and the representation of the six municipalities of Serra da Estrela affected by the fire (Celorico da Beira, Covilhã, Gouveia, Guarda, Manteigas, and Belmonte). 67

Figure 39. Fire recurrence of the region between 1975 and 2022 68

Figure 40. Orography map of Garrocho / Serra da Estrela. 69

Figure 41. Slope map of Garrocho / Serra da Estrela 70

Figure 42. Meteorological parameters registered by the meteorological station of Covilhã (ID:687) during between August 5th and 17th: a) temperature (T) and relative humidity (RH) variation; b) windspeed (U) and wind direction. 71

Figure 43. Fine dead fuel moisture (mf): modelled variation using the meteorological data from the weather station of Covilhã according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. 71

Table 14. Classes of the Fire Weather Index (FWI) values according with: a) IPMA for the Portuguese territory and, b) Viegas et al. (2004) for the district of Guarda, and FWI description according with (IPMA, 2023b). 72

Figure 44. Evolution of the resources in the fireground of Garrocho: a) human resources, b) ground and aerial resources. 73

Figure 45. Evolution of the Serra da Estrela fire divided in five phases. 74

Figure 46. Evolution of the Serra da Estrela Fire until 12:00 of August 6th. 75

Figure 47. Evolution of the Serra da Estrela Fire until 17:00 of August 8th. 76

Figure 48. MODIS satellite image of the fire situation at 11:08 of August 8th. It is possible to see the most active fire perimeter at the entrance of the Beijames Valley, NE of the burnt area. 76

Figure 49. Sequence of frames from two laboratory tests in a canyon (water line slope: 15º; versant slopes: 30º) with the same fuel conditions: top row - two fire fronts; bottom row – two fire fronts and a fire ignition. 77

Figure 50. Evolution of the Serra da Estrela Fire until 24:00 of August 9th. 78

Figure 51. Evolution of the Serra da Estrela Fire until 24:00 of August 12th. 78

Figure 52. Evolution of the Rekindling at Vale da Amoreira by the 15:47 of August 15th. Fire perimeter by the 24:00 of August 15th 79

Figure 53. Evolution of the Serra da Estrela Fire – approximate final perimeter by the 24:00 of August 18th. 80

Figure 54. Image of the village of Sameiro (Manteigas) when threatened by a fire front (a) and after the passage of the fire (b). The effect of fuel management can be observed, as it delimited the burned area, ultimately saving the village (photos cordially provided by Manteigas City Council) 82

Figure 55. Orographic framing of the Bosque das Faias (Beech Forest), the Manteigas sub-basin and the Sameiro sub-basin. 83

Figure 56. Images showing the flash flood impacts in Sameiro. September 13th (a) and October 17th (b). 83

Figure 57. Images showing some direct impacts of the Fire of Garrocho on tourism infrastructures. 83

Figure 58. The final perimeter of the Murça fire from the 17th of July to the 21st, with a total area of 7185.78 ha. The two ignition points are marked in the map. The yellow cross indicates the location of the two fatalities and the vehicle symbol marks the location of the incident with a fire truck that was destroyed by the fire. In the inset map the location of Murça in the Northeast of Portugal is shown. 86

Figure 59. Fire recurrence in the region affected by the wildfire of Murça between 1975 and 2021. 87

Figure 60. Number of years since the last wildfire in Murça in 2022 (statistics from 1975-2021). 88

Figure 61. Orography in the area of the wildfire of Murça. 89

Figure 62. Slopes in the area of the wildfire of Murça. 89

Figure 63. Land use in the area of the wildfire of Murça 90

Figure 64. Temperature of the air (T) and Relative Humidity (RH) registered by the meteorological station of Vila Real (ID:567) between the 3rd and 22nd July. 91

Figure 65. Wind data registered by the meteorological station of Vila Real (ID:567) between 16th and 22nd July: a) Wind speed (U) in km/h, and b) Wind direction in degrees (º). 91

Figure 66. Fuel moisture content of dead fine fuels (mf): modelled variation using the meteorological data from the weather station of Vila Real (ID:567) according to Lopes (2013); and mf of *Pinus pinaster* and *Eucalyptus globulus* measured in Lousã. Data from July 17th to July 22nd. 92

Table 20. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Vila Real, and FWI description according with IPMA (2023). 93

Figure 67. Evolution of the fire perimeter since the ignition on the July 17th till the extinction of the fire on the July 21st. 94

Figure 68. View of the location of the East ignition point, close to the electrical post shown in the photo near the road N212. 95

Figure 69. Location of the two ignition points and the perimeter of the fire in the SW section of the fire perimeter. 96

Figure 70. IR and video images from the fire of Murça obtained by the observation plane *Óscar 2*, around 17:26 on July 17th. 96

Figure 71. Level of damage grading provided by *Copernicus* satellite. 97

Figure 72. Evolution of the resources in the fire of Murça: a) human resources, b) ground and aerial resources. 98

Figure 73. Map of Penabeice, with the road (CM1176), that goes up from the village to the road ER314, that gives access to Murça. The yellow dot indicates the place where the car went out of the road to its left side falling in the ravine. 100

Figure 74. a) A view of the house where the couple lived; b) A view of the place where the vehicle fell... 101

Figure 75. Location of Sierra de la Culebra Fires (Riofrio de Aliste Fire in red and Losacio Fire in yellow). 104

Figure 76. Sentinel 2 images acquired before the fires occurred on May 26th, after the Riofrío de Aliste Fire on June 28th, and after the Losacio Fire on July 30th. The colour composite used (SWIR-NIR-RED) shows the vegetation in green tones, with light greens for growing crops and darker greens for forested areas; the burned areas are shown in magenta tones, areas with sparse or no vegetation are shown in light pink colour. The bottom right image shows the fire perimeters of both fires with the estimated burned area from satellite images. 104

Figure 77. Land covers affected by the Sierra de la Culebra fires (Riofrio de Aliste and Losacio) 106

Figure 78. Meteorology station of Villardeciervos – 2775X, at 850 m above sea level. A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB). Sources: AEMet and Castilla y León Forestry Department. 107

Figure 79. Geopotential pressure at 500hPa at 00z from July 12th to 15th and dominant synoptic situations during the week of June 13th to 19th. 107

Figure 80. Fuel moisture content of dead fine fuel from June 12th to 15th. 107

Figure 81. Standardized Precipitation-Evapotranspiration Index (SPEI) in Zamora during the six months prior to the Riofrio de Aliste and Losacio fires occurrence. 108

Figure 82. The map shows the lightnings strikes occurred in the region on June 15th in yellow and the lightning strikes which turned into active fires in red. Source: Report of the Forest Firefighting Service of JCyL. 109

Figure 83. Fire growth and dynamic on June 16th. Red stars mark the location of the ignition, blue arrows indicate the direction of the wind, and the red polygon indicates the size of the affected area. 110

Figure 84. Fire growth and dynamic on June 17th: a) Shows the fire growth at 3:00, b) the fire growth at 5:00, and c) shows the fire growth at 8:00. 110

Figure 85. Fire growth and dynamic on June 18th. Blue arrows indicate the direction of the wind, and the red polygons mark the extension of the burned area. 112

Figure 86. Fire growth and dynamic on June 19th. Blue arrow indicates the direction of the wind, red and orange arrows mark the fire spread. 112

Figure 87. Fuel moisture content of dead fine fuel from July 17th to 20th. Source: METEOSIG. 113

Figure 88. Meteorology station of Alcañices – 2966D, at 840 m above sea level (Right), during the previous days to the Losacio Fire (started on July 17th). A) Wind speed, B) Temperature and relative humidity, C) Fine Fuel Moisture (FFM) and ignition probability (IG PROB). 114

Figure 89. Fire growth of the Losacio fire following aerial photography and field reports. Yellow line: July 17th at 03:00; Light Blue line: July 18th at 08:00; Green line: July 18th at 13:30; Brown line: July 18th at 17:30; Dark Blue line: July 18th at 19:00; Magenta line: July 18th at 22:00; Discontinuous yellow line: July 19th at 05:00; Discontinuous green line: July 19th at 15:00; Discontinuous red line: July 20th at 15:00. 115

Figure 90. a) Post-fire situation in the central valley of the Riofrío de Aliste fire showing intense severity; b) Post-fire situation in the Southern mild slopes of the Riofrío de Aliste fire showing medium fire severity. (photos taken by Emilio Chuvieco in November 2022)..... 117

Figure 91. a) Post-fire situation in the north of Losacio fire showing intense severity; b) Post-fire situation in the North East of Losacio fire showing medium fire severity. (photos taken by Patricia Oliva in June 2023). 117

Figure 92. Burn severity estimation based on the difference in NBR for the Riofrío de Aliste fire (left) and Losacio fire (right), based on Sentinel-2 images. The Riofrio de Aliste estimation was computed by the difference between the NBR in the prefire date of May 26th and the postfire date of June 28th. The Losacio burn severity estimation was computed by the difference between the pre-fire image of June 28th and the postfire image of July 30th. 118

Figure 93. Affected chestnuts plantations in the Riofrío de Aliste fire were already resprouting in November 2022 on the right. (photos taken by Patricia Oliva in November 2022). 119

Figure 20. Effect of the fire in architectonical heritage sites in Riofrio de Aliste fire..... 120

Figure 94. General map of the Karst area, including the 2022 wildfire perimeter and the administrative municipal boundaries. DDL = Doberdò del Lago, FDI = Farra d'Isonzo, MON = Monfalcone, RDL = Ronchi dei Legionari, SAG = Sagrado, SDI = Savogna d'Isonzo, STA = Staranzano, DUA = Duino Aurisina, SGO = Sgonico, SEM = Šempeter- Vrtojba, REN = Renče- Vogrsko, KOM = Komen, MIK = Miren – Kostanjevica, NOV = Nova Gorica. 123

Figure 95. a) Digital elevation model of the Karst area. b) Main fuel types of the area affected by the Karst wildfire. AA = anthropic areas; CA = cultivated areas; PC = permanent crops; BF = broadleaf forests; CF = conifer forests; SH = shrub vegetation; SV = sclerophyllous vegetation; W = wetlands; R= rocks. The map is derived from the Land Use Map of Europe 2017..... 124

Figure 96. Hourly values of air temperature and air relative humidity provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st..... 127

Figure 97. Hourly values of wind intensity and direction provided by the ERA5-LAND Reanalysis for the central sector of the Karst plateau from July 15th to 31st. 127

Figure 98. Hourly values of air temperature and air relative humidity measured by the weather station of Gradisca from July 15th to 31st..... 128

Figure 99. Hourly values of wind intensity and direction measured by the weather station of Gradisca from July 15th to 31st. 128

Figure 100. Map of the three main steps of propagation of the Miren fire (in red). The ignition points of the different steps are showed, together with the main directions of propagation. The final perimeter of the Karst wildfire is also showed (in blue). 130

Figure 101. Map of the three main steps of propagation of Renče fire (in red). The ignition point of the fire, together with the main directions of propagation, is also included. The final perimeter of the Karst wildfire is showed in blue..... 131

Figure 102. Map of the burned area by the Monfalcone fire on July 20th (in orange) and on Juli 21st (in red). The ignition point, indicating the area where most of the fire ignitions near the railway line were observed, is also showed, together with the main directions of propagation and the Italian-Slovenian border. The final perimeter of the Karst wildfire is showed in blue..... 132

Figure 103. Map of the burned area by the Brestovec fire (left polygon, in red). The ignition point is also showed, together with the main direction of propagation. On the right, the western side of the Miren fire. 135

Figure 104. Pictures of the fires: (a) Initial propagation phase of the Miren wildfire (July 15th); (b) The wildland urban interface threatened by the Miren fire (July 20th); (c) View from north of the initial

propagation of the Renče wildfire (July 17th). The are of ignition is located on the left; (d) View from north-east of the initial propagation phase of the Monfalcone fire (July 19th). 135

Figure 105. PM_{10} (μg/m^3) hourly data collected from the four air quality stations in Trieste (July 20th-25th). 141

Figure 106. PM_{10} (μg/m^3) hourly data collected from the Udine (via S. Daniele and S. Osvaldo) and S. Giovanni al Natisone air quality stations (July 27th-30th). 142

Figure 107. Location of the burned area in the two national parks on the border between Germany and the Czech Republic. 147

Figure 108. The Richterschlucht, a popular walking trail through the Saxon Switzerland National Park. 149

Figure 109. Dead standing and lying Norway Spruce (*Picea abies*). 149

Figure 110. Bark beetle affected areas in the two national parks with overlay of burned area. 150

Figure 111. Fire warning levels Saxon Switzerland National Park (according to the German Waldbrandindex) from July 1st to August 31st, i.e., before, during and after the fire. The red column indicates the date of the ignition and the orange box the period of the main fire spread. 151

Figure 112. Daily maximum temperature (a) and maximum speed of wind gusts (b) before, during and after the fire. 151

Figure 113. Fuel moisture and precipitation at the fire site. This station was destroyed by the fire on July 26th 152

Figure 114. Conditions before and after the fire as captured by camera trap (images courtesy of Saxon Switzerland National Park). 153

Figure 115. Fire radiative power (FRP) over the burned area as observed by VIIRS satellite sensors between July 24th and 29th. (a) Highest fire energy emissions occurred at forest stands previously affected by bark beetle infestations and in some beech forests; b) FRP over the burned area – July 24th to 29th; c) FRP from July 24th to 29th. 153

Figure 116. Sandstone affected by high temperatures. 154

Figure 117. House destroyed by fire in the centre of Mezná. The house was not located close to the main burned area. The burning was likely caused by flying embers that ignited the coniferous garden hedges (right side). 155

Figure 118. Fires reached the village-forest interface in Mezná. This image was taken in early June 2023. One house to the left of the photograph was completely destroyed, neighbouring houses were untouched. 156

Figure 119. Regeneration of mosses 8 months after the fire. 157

Figure 120. Annual mapped burnt area of fires >=30 ha in Greece (a) and distribution of % total area burnt by land cover types in 2022 (b) 159

Figure 121. Total number of burnt areas (ha) for each of the country's thirteen region of Greece. 160

Figure 122. Examples of the received notifications to geotargeted population to evacuate as the fire approaches to residential areas. 161

Figure 123. Daily evolution of a) Fire weather index, b) initial spread index an c) drought code provided by EFFIS before and after the fire occurred in the burnt area of Penteli. 163

Figure 124. Spatial depiction of FWI index and Total burnt area by MODIS/SENTINEL2 (supervised) and MODIS & VIIRS NRT in the affected area (in green) of Mount Penteli. 164

Figure 125. Fire Risk Prediction Map for Tuesday, July 19th. The legend on the bottom left corner classifies by colour the fire risk in 5 categories, as (1.low, 2. moderate, 3. high, 4. very high and 5. alert situation). The black lines show the boundaries of local forest services). 164

Figure 126. First estimate product from the activation of emergency Copernicus focusing on Mount Penteli. 166

Figure 127. Fire delimitation in the area of Mount Penteli provided under Copernicus by the European Union and ESA 167

Figure 128. Fire delination in the area of Mount Penteli provided under Copernicus by the European Union and ESA. 168

Figure 129. Houses (a) and a car (b) are engulfed by flames during the Penteli Attica Fire – in Pallini, near Athens, Greece July 20th. REUTERS/Costas Baltas. 169

Figure 130 Copernicus EMS Mapping product depicting Dadia's 2022 fire extend and damage. 171

Figure 131. Dadia fire active hotspots – July 21st to 27th. 173

Figure 132. Daily progress of the Dadia fire – July 21st to 27th. 173

Figure 133 Daily burned areas in Dadia fire – July 21st to 27th. 174

Figure 134 Dadia National area and Park Zones with the daily burned areas during the 2022 fire. 177

Figure 135. Slope and elevation of the Dadia National Park area. 177

Figure 136. Recent fire history (a) in the area and fuel types (b). 178

Figure 137. Temperature anomaly over Europe at 1,500m – July 21st to 27th. 179

Figure 138. Temperature and wind speed data between July 21st and 27th. 179

Figure 139. Wind gusts graph in Dadia region between July 21st and 27th. 180

Figure 140. Fire risk map: a) July 21st; b) July 22nd, c) July 23rd, d) July 24th, e) July 25th,) July 26th. 180

Figure 141. Pyrometeorological index (hot-dry-windy) for July 28th. 181

Figure 142. Transient "shallow" pyroclouds over the induction column of the southwestern front of the forest fire in Dadia, Evros – July 26th. 182

Figure 143. Fuel types of Dadia area. 183

Figure 144. Patches of area burned during the seven days Dadia fire. 184

Figure 146. a) Map of the fire-affected area, encompassing 45,412 ha; b) Map detailing the fire's severity and impact on vegetation. 185

Figure 147. The 'feeding rock', a boulder in the heart of the national park where food is left for the area's endangered prey birds (a) and prey birds required care (b). 186

Figure 148. Complete burning of the pine forest in the smaller of the two cores of the National Park. 187

Figure 150. a) Weekly burnt area in Romania for 2022 and the 2011 – 2023 average; b) The trend in number of EFFIS-detected fires and total burnt area in Romania since 2011. 189

Figure 151. a) Cumulative burnt area on forested land during 2022 until November; b) Annual burnt area on forested land and the number of forest fires between 1956 and 2022. 190

Figure 152. MODIS polygons during March 28th to April 3rd in part of Gorj (a) and Tulcea (b) counties. The numbers indicate the date (in March if not stated otherwise) at which the fire was detected. 190

Figure 154. Photos with reed fires in the Danube Delta Biosphere Reserve. 192

Figure 157. a) Geographical representation of the Razdel Fire (IICT - BAS); b) Fire hazard for August 10th. 195

Figure 158. a) Land use map of Elhovo municipality (IICT - BAS); b) Natura 2000 protected sites under birds and habitats Directives. 196

Figure 159. Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern. 197

Figure 160. Google Earth image showing the typical orographic pattern. 198

Figure 161. Burned scars of the two largest fires in the area in the last 10 years, 2012 and 2022. 199

Figure 162. Meteorological parameters for August 10th, 2022: (a) 24-hour precipitation (mm); (b) Relative humidity (%), data from NIMH. 199

Figure 163. Hourly meteorological conditions (temperature in ºC) registered by the meter. ac from August 10th to 14th in a station located in Elhovo..... 200

Figure 164. Wind influence on fire on August 10th: (a) Wind forecast for August 10th from NIMH; (b) Fire distribution on August 10th at 10:55, with a yellow dot, is presented the assumed start of the fire and the smoke shows the direction of the wind..... 200

Figure 166. Fire danger maps from NIMH for August 9th, 10th, and 11th (the burned area is represented with a dark rectangle)..... 203

Figure 167. Degree of damage of the burned area difference between NBR-RAW (Normalized Burn Ratio) of the pre-and post-fire images / blue dot is approx. the ignition point of the Razdel Fire..... 203

Figure 168. Razdel Fire spread direction from the village of Malko Kirilovo to the village of Valcha Polyana, where road III-7902 was used as a fire barrier..... 204

Figure 169. Location of the Razdel Fire burned scar and vicinity to urban, and road infrastructure..... 206

Figure 170. The road which was used as a border to stop the fire going south direction between Malko Kirilovo and Valcha Polyana and fire prevention measures next to the road before the pine forest..... 207

Figure 171. Area 01 and 02. The pasture (a) of the ignition area with the neighbouring hill with burned bushes from Paliurus (b)..... 207

Figure 172. Area 03 Burned young coniferous forest: cedar (a) and pine (b)..... 208

Figure 173. Area 04 and 05 Forest with acacia (a) and pastures with bushes (b) between the hill and the deciduous forest..... 208

Figure 174. Area 06 and 07. The Quercus Forest (a) and the road on the west (b) used as a fire break..... 209

Figure 175. Area 08 and 09 Mixed forests of *Pinus Sylvestris* (a) and *Pinus Nigra* (b) with deciduous species..... 210

Figure 176. a) Area 10 mixed deciduous forest b) just before the asphalt road between Malko Kirilovo and Valcha Polyana..... 210

Figure 177. Area 11 Mixed deciduous forest with understory..... 211

Figure 179. Burnt area in July-August 2022 in the vicinity of Razdel fire..... 212

List of tables

Table 1. Monthly distribution of fires by landscape type in Ukraine in 2022. 15

Table 2. Characteristics of large fires within the Chornobyl Exclusion Zone 21

Table 3. Breakdown of landscape fires in 2022 within the military engagement zone (30 km each side of front line), by land cover type and month, measured in hectares. 23

Table 4. List of largest landscape fires that occurred in Ukraine (whole country) during war period of February 24th and July 1st (note: LC = Land-use Classes). 24

Table 5. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Aveiro, and FWI description according with IPMA (2023). 37

Table 6. RCM and FWI observed and predicted on July 13th as well as the classification-related colours considering the level of danger for RCM. 38

Table 7. Selected fires of Complex Fires of Ourém 49

Table 8. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Leiria. FWI description according with IPMA (2023). 54

Table 9. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for July 7th and July 12th. The colours indicate the fire danger level (cf. Table 8). 55

Table 10. Information on rural fires to the municipality for the districts of Santarém and Leiria. 56

Table 11. The burnt areas of the Freixianda / Cumeada Fire by Municipality. 62

Table 12: The burnt areas of the Caranguejeira Fire by Municipality. 63

Table 13. Some socio-economic indicators of the most affected municipalities of the Garrocho Fire. 67

Table 14. Classes of the Fire Weather Index (FWI) values according with: a) IPMA for the Portuguese territory and, b) Viegas et al. (2004) for the district of Guarda, and FWI description according with (IPMA, 2023b). 72

Table 15. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for August 6th in Guarda weather station (ID: 683). The yellow colour in RCM indicates the Moderate (level 2) danger classification. 72

Table 16. a) Fire behaviour indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) in Guarda weather station (ID: 683) between August 5th and 7th; b) Danger scale for ISI, BUI and FWI. 73

Table 17. Damages registered in the municipalities affected by the Serra da Estrela Fire. 81

Table 18. Main actions of people management during the fire in Serra da Estrela. 81

Table 19. Percentage per class of land use in the area of the wildfire of Murça (ordered from the highest to the lowest value). 90

Table 20. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Vila Real, and FWI description according with IPMA (2023). 93

Table 21. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for July 17thin Vila Real. The red colour in RCM indicates the maximum danger classification. 94

Table 22. Summary of fire propagation parameters for the Riofrío de Aliste Fire. 112

Table 23. Summary of fire propagation parameters for the Losacio Fire. 114

Table 24. Burn severity classes derived from dNBR values obtained from Sentinel 2 data. 118

Table 25. Content of the 2006 Civil Protection MoU and 2022 Fire Brigades Agreement. 136

Table 26. Fire Danger classes for the FWI and its sub-components by EFFIS 162

Table 27. Fire Danger behaviour indicators. 162
Table 28. MODIS burnt area detailed layer information for Penteli Attica Fire. 165
Table 29. Fire danger classes according to NIMH and used in the Bulgarian FWI. 201

Use the built-in function to generate a table of figures (References > Captions > Insert Table of Figures); or simply use the example in the template and update it (click on table field, press F9, update entire table) when the report is complete.

Note: Word does not distinguish between these tables; therefore when it asks if you want to replace the already inserted table (for boxes or figures), you answer No.

Table 1. Monthly distribution of fires by landscape type in Ukraine in 2022. 15
Table 2. Characteristics of large fires within the Chornobyl Exclusion Zone 21
Table 3. Breakdown of landscape fires in 2022 within the military engagement zone (30 km each side of front line), by land cover type and month, measured in hectares. 23
Table 4. List of largest landscape fires that occurred in Ukraine (whole country) during war period of February 24th and July 1st (note: LC = Land-use Classes). 24
Table 5. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Aveiro, and FWI description according with IPMA (2023). 37

Table 6. RCM and FWI observed and predicted on July 13th as well as the classification-related colours considering the level of danger for RCM. 38

Table 7. Selected fires of Complex Fires of Ourém 49

Table 8. Classes of the Fire Weather Index (FWI) values according with: a) IPMA (2023) for the Portuguese territory and, b) Viegas et al. (2004) for the district of Leiria. FWI description according with IPMA (2023). 54

Table 9. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for July 7th and July 12th. The colours indicate the fire danger level (cf. Table 8). 55

Table 10. Information on rural fires to the municipality for the districts of Santarém and Leiria. 56

Table 11. The burnt areas of the Freixianda / Cumeada Fire by Municipality. 62

Table 12: The burnt areas of the Caranguejeira Fire by Municipality. 63

Table 13. Some socio-economic indicators of the most affected municipalities of the Garrocho Fire. 67

Table 15. Fire Weather Index (FWI) and Conjunctural and Meteorological Index (RCM) observed and predicted for August 6th in Guarda weather station (ID: 683). The yellow colour in RCM indicates the Moderate (level 2) danger classification. 72

Table 16. a) Fire behaviour indices (ISI – Initial Spread Index, Buildup Index – BUI, FWI – Fire Weather Index) in Guarda weather station (ID: 683) between August 5th and 7th; b) Danger scale for ISI, BUI and FWI. 73

Table 17. Damages registered in the municipalities affected by the Serra da Estrela Fire. 81

Table 18. Main actions of people management during the fire in Serra da Estrela. 81

Table 19. Percentage per class of land use in the area of the wildfire of Murça (ordered from the highest to the lowest value). 90

Table 22. Summary of fire propagation parameters for the Riofrío de Aliste Fire 112

Table 25. Content of the 2006 Civil Protection MoU and 2022 Fire Brigades Agreement. 136

Table 26. Fire Danger classes for the FWI and its sub-components by EFFIS 162

Table 27. Fire Danger behaviour indicators. 162

Table 28. MODIS burnt area detailed layer information for Penteli Attica Fire. 165

Table 29. Fire danger classes according to NIMH and used in the Bulgarian FWI. 201

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub
EU Science Hub - Joint Research Centre
EU Science, Research and Innovation
EU Science Hub
@eu_science

Appendix B: Wildfire Investigation Protocol

FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

Grant Agreement Number: 101003890 **Call identifier:** H2020-LC-CLA-2018-2019-2020	
Topic:	LC-CLA-15-2020 Forest Fires risk reduction: towards an integrated fire management approach in the E.U.
Instrument:	RIA

Wildfires Investigation Protocol

Deliverable Identifier:	N/A
Deliverable Due Date:	N/A
Deliverable Submission Date:	N/A
Deliverable Version:	Final
Lead partner:	ADAI
Authors:	Miguel Almeida (ADAI), Luís Mário Ribeiro (ADAI), Domingos Xavier Viegas (ADAI), David Caballero (MTG), Emilio Chuvieco (UAH), Patricia Oliva (UAH) and Mikhail Sofiev (FMI), Tiago Rodrigues (ADAI)
Work Package:	WP2 – Risk reduction to improve protection
Task:	Task 2.4 Reduce communities' vulnerability
Dissemination Level:	☒ CO: Confidential

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

Executive Summary

The FirEUrisk project, which brings together a very large consortium involving 38 institutions from 17 countries is an ambitious project addressing the problem of integrated wildfire management, particularly those occurring under extreme conditions that endanger human lives and expose assets to risk.

Among the various objectives of the FirEUrisk project, “Objective 8” stands out, which consists of " Gather, formalise, and organise in a functional way, the experience, facts, and lessons learned from previous extreme wildfires in the EU and worldwide. Develop protocols to collect and analyse impacts of extreme wildfires on people's health and property, critical infrastructures, as well as the effects of fire on soil, water, fauna, flora and air quality aiming to share knowledge, raise awareness and improve risk perception and preparedness among local populations, stakeholders and policymakers." In pursuit of this objective, Task "T2.4: Reduce communities’ vulnerability," from the FirEUrisk Project Working Document, integrates Activity "A2.4.1: Lessons learned from past cases," which envisages the analysis "feedback from five or more past large and high-impact wildfires, both in Europe and in partner countries of North America and Australia, with special focus on fire development in the WUI and impacts on the communities. This review will also consider aspects of land planning, community awareness, alert systems, social perception, and structural damages..." and the development of "protocols to collect data for future fire impact analysis."

This deliverable reports the work carried out in Activity A2.4.1, presenting the results of the analysis of 20 wildfires that occurred in Europe in the years 2021 and 2022, and presenting the study of several wildfires that occurred in the year 2023, including the wildfires in Canada where the European Union sent a common force to support Canadian authorities. Additionally, this document includes a protocol for the analysis of past wildfires, which benefited from the multidisciplinary of the project consortium and its experience, gained from analysing various wildfires within and outside the scope of FirEUrisk.

The results of A2.4.1 provide direct benefits for a better understanding of wildfires, as lessons are drawn from each analysed wildfire event, based on described facts, enabling learning, validation of other studies and statements, and a critical and constructive analysis of policies followed in the context of wildfire management. On the other hand, the activities of A4.2.1 integrate the flow of information among the various tasks of the FirEUrisk project. For example, the products developed in the tasks of WP1: “Risk Assessment” were relevant for presenting information and maps that helped frame and explain the analysed wildfires. The activities developed in WP1 also allowed the development of methodologies to obtain analysis data that were considered in the development of the protocol for the analysis of past wildfires, included in this deliverable. On the other hand, the lessons learned from past wildfires, following the analysis conducted, allowed the development or refinement of several guidelines developed in WP2: “Risk Reduction”. Unfortunately, the analysed year sequence - 2021-2023 - was not long enough to establish trends or support statistical studies that could be useful for WP3: “Risk Adaptation”. Thus, this methodical and systematic analysis of wildfires occurring in European territory, or outside it, continues, so that we can develop a consistent wildfire history, enabling society to better understand how to prepare for the future. We believe that this set of wildfire studies can be a good source of inspiration and information, and the suggested protocols can be a valuable ally for future studies.

Copyright © FirEUrisk Consortium. All rights reserved.

Disclaimer

The content of the publication herein is the sole responsibility of the publishers, and it does not necessarily represent the views expressed by the European Commission or its services.

While the information contained in the documents is believed to be accurate, the authors(s) or any other participant in the FirEUrisk consortium make no warranty of any kind with regard to this material including, but not limited to the implied warranties of merchantability and fitness for a particular purpose.

Neither the FirEurisk Consortium nor any of its members, their officers, employees or agents shall be responsible or liable in negligence or otherwise howsoever in respect of any inaccuracy or omission herein.

Without derogating from the generality of the foregoing neither the FirEurisk Consortium nor any of its members, their officers, employees or agents shall be liable for any direct or indirect or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

Copyright message

© FirEUrisk Consortium, 2021-2025. This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both. Reproduction is authorised provided the source is acknowledged.

Table of Contents

1 Introduction 6
2 Local data survey and intervenient interviews 9
3 Complementary data survey 33
4 Data mining, process and analysis 49
5 Conclusions 57
6 References 58

Copyright © FirEUrisk Consortium. All rights reserved.

List of Figures

Figure 1. Basic levels of building affectation: a) No appreciable damage; b) Moderate damage; c) Severe damage; and d) Complete destruction. 23
Figure 2. An example of territory segmentation into 12 sectors in the Mati-Kokkino Limanaki area during the Mati wildfire in July 2018. This segmentation was crucial for the systematic study of building impact. Where possible, the street and road network were used as boundaries between sectors, but it is also possible to use other administrative boundaries or landscape features (rivers, mountain ridges, etc.). 24
Figure 3. Example of labelling all buildings present in block M, segment 10 of the Mati-Kokkino Limanaki area, corresponding to the Fisiolatron zone. This labelling allowed for later comparison of on-site photos and orthophotos before and after the wildfire. 25
Figure 4. Example of on-site assessment of a building, based on its pre-fire condition as captured by Google Earth Street View. The labelling greatly aids in correlating potential factors with the observed degree of destruction. 26
Figure 5. Degree of damage of the 192 buildings in sector S08 of the Mati wildfire (Greece, 2018), according to on-site observations and subsequent review in the orthophoto. While cases 1 (No appreciable damage) and 4 (Complete destruction) are clear, the intermediate cases (2 Moderate damage and 3 Severe damage) are more difficult to classify accurately, as subjective damage assessment procedures are applied. 27
Figure 6. Spatialisation detail of the territorial impact based on the assessment of the degree of destruction of each of the houses (their identifier is shown). As seen, a score is assigned to each cell of a fine grid (1 m) and all values are summed in each cell of a coarse grid (30 m). 28
Figure 7. Example of correlating the level of impact with the continuity of vegetation around each building, as per (Caballero, 2019). 29
Figure 8. Schematic representation of a the difference between DSM and DTM, taken from Guth et al., (2021). 33
Figure 9. Example of a 5m DTM, custom built from level curves and elevation points, also shown on the image. 35
Figure 10. Example of 10 cm resolution products derived from Orto-photogrammetry applied to images captured with a drone: a) orthophoto, b) shaded relief of a DSM and c) 1 meter contour lines. 36
Figure 11. Example of LiDAR data in a power line: a) 3d point cloud; b) DSM; c) DTM. 37
Figure 12. Example of a spherical image taken during the Mati wildfire in 2018. An iPad and a panoramic stitching application were used for this purpose. The result was employed in the subsequent analysis by visualizing it with a VR headset. 50
Figure 13. Example of a wildfire reconstruction using numerical CFD models and its integration into Unreal Engine with the CESIUM plug-in, which provides access to Google tile services. The georeferencing has been precise in order to analyse the position and intensity of the fire at each point. 54

Copyright © FirEUrisk Consortium. All rights reserved.

1 Introduction

The documentation of real wildfire events is a crucial source of information and data that serves various purposes, such as supporting wildfire history, guiding wildfire management, aiding scientific research, facilitating legal or forensic procedures, and enhancing training efforts. While the specific requirements for each of these purposes may differ, they all share the common goal of conducting thorough investigations of each event, covering all relevant aspects and details as comprehensively as possible. To achieve this, it is essential to have and adhere to guidelines derived from experience in producing such reports.

The purpose of this document is to present a comprehensive set of guidelines for investigating wildfires. These guidelines are aimed at assisting researchers with varying levels of experience and proposing standardised procedures for producing wildfire reports in Europe, with potential to be used in other regions of the world.

Although the investigation of large wildfires is paramount, every outstanding wildfire events should ideally be documented. Even smaller wildfires should be documented if they offer new insights or lessons to be learned. Investigating incidents or accidents, particularly those resulting in loss of human life, is a vital aspect for wildfire investigation. These incidents should be investigated from a scientific perspective, although they may involve additional complexities and technique as will be addressed in the following chapters.

Although advocating for thorough investigations, it is essential to document and report wildfires even if only partial data exists, such as scattered testimonies, photos or media coverage. Such incomplete data may still offer valuable insights further investigation may uncover additional sources of data or different perspectives.

This report focuses on scientific investigation of wildfires and related events, including accidents or actions that incur in judicial, operational or legal responsibilities. Collaboration between various research initiatives is possible, but scientific research should maintain its independence and freedom to guide investigations and draw conclusions. Collaboration and complementarity between the various research initiatives is possible and desirable, but scientific research should maintain its independence and freedom to guide investigations and draw not influenced conclusions.

Wildfire investigation is more advanced in the USA, Canada, and Australia than compared to Europe. In the literature we can find many reports, sometimes published as scientific papers or books, documenting large wildfires and accidents. These reports serve as invaluable learning resources, offering insights into fire behaviour and human response, thereby influencing wildfire risk management practices and policies. In the USA every major wildfire, especially if there were fatal accidents involved, motivated the designation of an official multidisciplinary and multi-institutional committee to investigate and report on the case. In Australia the investigation of major wildfires, like for example the Canberra 2003 wildfires and the New South Wales 2009 wildfires, was coordinated by a Judicial Coroner, who resorted to a wide set of experts with different backgrounds to hear all involved, including the population, to gather the facts in support of policy and justice.

In Europe, there is less systematic documentation of wildfire investigation. While some major historical wildfires have been documented by the national authorities, there is no coordinated policies for such investigations at either national or European levels.

In Portugal, the ADAI Team acquired an extensive experience studying and analysis large wildfires and investigating accidents, sometimes on its own initiative but seldom by request of the official authorities, both in Portugal and abroad.

Copyright © FirEUrisk Consortium. All rights reserved.

These investigations aim to establish facts and extract lessons to improve wildfire safety. The knowledge gained from this research has been disseminated to operational agents though various means, including reports articles, books and lectures. The experience acquired, combined with the expertise and knowledge of the other coauthors, has significantly contributed to the preparation of this document. The reports on the 2021 and 2022 large European wildfire events and related accidents (Almeida, 2023 and Almeida, 2024) conducted within the context of the FirEUrisk project (www.fireurisk.eu), may serve as valuable references for investigation reports that can be visited to better understand the contents and explanations provided in this document. The next table resumes other publications from the authors where examples of other wildfire reports can be found – some of these publications are in the original language.

Title	Country	Year	Type of publication	Reference
Accident of Armamar [PT]	Portugal	1985	Book	Viegas, 2013
Accident of Agueda [PT]	Portugal	1986	Book	Viegas, 2017
Wildfire of Arganil (11kHa) [PT]	Portugal	1987	Internal report	Viegas et al., 1987[a]
Wildfire of Mira (2kHa) [PT]	Portugal	1987	Internal report	Viegas et al., 1987[b]
Wildfire of Arrábida [PT]	Portugal	1992	Internal report	Viegas et al., 1993
Accidents during the fires of 2003 [PT]	Portugal	2003	Book	Viegas, 2004
Accidents during the fires of 2003 [PT]	Portugal	2005	Book	Viegas, 2009
Accident of Guadalajara [ENG]	Spain	2005	Official report	Viegas and Caballero, 2009
Accident of Famalicão da Serra [PT]	Portugal	2006	Official report	Viegas et al., 2009
Accident of Kornati [ENG]	Croatia	2007	Official report	Stipanicev and Viegas, 2009
Wildfire of Tavira [PT]	Portugal	2012	Official report	Viegas et al.,
Fires and related accidents in 2013 [PT]	Portugal	2013	Official report	Viegas et al.,
Accidents occurred in Europe [ENG]	Europe	---	JRC Report	Viegas, 2009
Wildfire of Pedrógão Grande June 2017	Portugal	2017	Official report	Viegas et al., 2017
Wildfires of 15 October 2017 [PT]	Portugal	2017	Official report	Viegas et al, 2019
Extreme wildfires … around the world [ENG]	Global	2020	Book	Ribeiro et al., 2020
Wildfires of 2022 [PT]	Portugal	2022	Official report	Mendonça et al., 2023

This document offers a proposal for protocols that could serve as a reference for procedures in analysing wildfire events or wildfire episodes. It recognizes that wildfire analysis can utilize various methodologies, all ultimately aiming to gather data supporting analysis and conclusions. Information can be obtained through literature or internet research, on-site visits during or after the wildfire event, or by interviewing interveners or witnesses. While striving to be broadly inclusive with straightforward language, it does not delve deeply into certain topics that may warrant more detail. Nonetheless, this document can serve as a practical starting point for someone looking to initiate wildfire investigation work.

Interest in studying specific wildfire events is typically linked to their extent, impact, or associated episodes. However, regardless of the objectives, there are common elements in any study, including:

- Economic, social, and/or environmental characterization of the affected area.
- Susceptibility and historical context of the region regarding wildfires.

Copyright © FirEUrisk Consortium. All rights reserved.

- General description of the wildfire event – size, wildfire spread evolution, operational response, etc.
- Description of noteworthy episodes or those aligning with study objectives.
- Main impacts of the event.
- Potential subsequent consequences or cascading effects of the wildfire.

The suggestions presented in this document aim to facilitate the reporting of these typical components. Therefore, following this brief introduction, Chapter 2 focuses on obtaining central information for the report, with particular emphasis on field visits and interviews with key stakeholders involved in the wildfires or episodes being reported. Chapter 3 discusses methodologies and sources of complementary data essential for analysing results, such as socioeconomic data characterizing the affected population, meteorological and environmental information, orographic data, infrastructural characterization, and satellite image-derived data. Chapter 4 provides relevant information on methodologies and approaches to explore and present the obtained results. Finally, Chapter 5 compiles some of the main aspects as a conclusion to the document.

Copyright © FirEUrisk Consortium. All rights reserved.

2 Local data survey and intervenient interviews

Information gathering from wildfires or associated incidents can be conducted in various ways, depending on the study objectives and available resources. The methodologies for information gathering are diverse, including on-site evidence collection, testimonial interviews, and analysis of published information and news provided by the media.

The timing of information acquisition can vary greatly. Sometimes it is possible to visit the wildfire site while it is still ongoing. However, wildfires often need to be analysed afterwards, which has the main disadvantages of losing some field evidence, the inability to collect photographs and videos for specific purposes, and the loss of firsthand experience of the wildfire event, which allows for a more conscious and consistent analysis. On the other hand, studies conducted afterwards allow for more time to prepare field visits and interviews, consolidate objectives and methodologies, etc. Additionally, if the most relevant facts and episodes of the wildfire are already known, mission planning can be more objective and facilitated, making it more efficient. The collection of previously published information is usually less costly and provides various perspectives on events. However, it may not align with the specific study objectives and dilutes the personal authorship of the work. Overall, a fusion of various methodologies, involving field visits and testimonial interviews at different times, as well as analysis of existing publications integrating different perspectives and conclusions, allows for the completion of a comprehensive and consistent report.

Ethical considerations and respect for the suffering of others are fundamental in these studies. For example, in the analysis of serious or fatal accidents, interviews with those closest to the event or who witnessed it are extremely sensitive. Therefore, it makes sense not to conduct interviews immediately following the event, as individuals may be in a psychologically fragile state that could be exacerbated by the interview. However, some individuals may feel better discussing the case, expressing their emotions. Furthermore, it should be noted that over time, some people may construct narratives in their minds, creating distorted realities of the events, which naturally disturbs the study results. Therefore, there are more opportune moments for conducting interviews, with each case requiring a sensitive and experienced evaluation by the study conductor. The same applies to visiting certain locations where tragedies may have occurred, so the study author should always keep principles of ethics and rigorous reporting in mind when conducting the work. In short, analysing wildfires and their effects is a highly complex task, and the decisions made can have numerous implications. Ultimately, it falls to the authors of the study to make the final decisions because there are no one-size-fits-all solutions, and each case requires careful consideration that should result in very specific planning and decisions. The following suggestions aim to facilitate the structure the study planning and the decisions that authors will need to make regarding a wildfire study.

2.1 Data survey during the wildfire event

Visiting the wildfire scene area while the wildfire event is still ongoing allows for obtaining a lot of relevant information with a degree of reliability that is hardly achieved when information gathering is done afterward. In fact, although collecting data during the wildfire event presents challenges such as reduced safety, time constraints, or those related to the typica bustling environment of a wildfire scene, it is during this phase that the most unspoiled evidence is found, and firsthand and more reliable wildfire data can be obtained. Moreover, visiting the wildfire scene during the course

Copyright © FirEUrisk Consortium. All rights reserved.

of the wildfire allows for understanding the environment in which the event occurred, interacting with hands on stakeholders, both locals and operational and coordination teams involved in the operations. In short, it provides a much more faithful understanding of what is going on, which will surely result in a more authentic presentation or report of the events.

In this chapter, some of the main recommendations will be presented to be followed when someone decides to analyse a wildfire event during its course, aiming for better performance in achieving objectives and a safer performance that does not disrupt civil protection operations, which are a priority in these situations.

It is important to emphasize that wildfire scenes are areas with many dangers, not limited to the wildfire itself but also extending to other factors, such as roads with emergency vehicles travelling at speeds higher than usual, vehicles that due to their size occupy most of the often narrow roads, roads that may be obstructed by fallen trees, poles, or other materials, and the presence of psychologically disturbed or even panicked individuals, among various other dangerous situations that operational theatres present. Additionally, many people are present in a wildfire scene, such as locals residing there or having local interests, civil protection agents, and other individuals performing their professions (e.g., journalists). The more external individuals in the wildfire scene, the more complicated the wildfire management activities become. This implies that the decision to go to a wildfire scene to analyse a wildfire event should always be preceded by a reflection on the added value that this activity will represent, considering the aforementioned cons that it will surely affect the operations. Additionally, except for residents or other civilians who have no choice but to remain on the wildfire scene, all individuals in the wildfire scenes must have training and experience ensuring their performance safely and in perfect agreement with civil protection actions on the ground.

Visits to the wildfire scene during the wildfire are rarely sufficient to gather all the necessary information to meet the objectives. Therefore, it may be necessary to conduct additional visits and interviews with witnesses afterward, which will be addressed in section 2.2.

2.1.1 Before heading to the wildfire scene

Setting objectives

Typically, the interest in visiting a wildfire scene to analyse and report on it is motivated by some exceptional episode, such as a fatality, building destruction, community impact, or when the wildfire itself has reached a significant scale or assumed specific characteristics justifying its coverage. One of the most important aspects preceding a field study is precisely defining the mission's objectives. Going into the field without clearly defined objectives will likely result in a disjointed and unconnected set of information, hindering effective storytelling. Moreover, it's crucial to contain the ambition in defining objectives, as focusing on a single or a small set of objectives tends to yield better results. If the areas of interest for analysis are numerous, forming a team with diverse skills and distributed tasks might be the best solution. The myriad aspects of interest in a wildfire scene require clear, pre-defined objectives to prevent getting sidetracked during the visit and ending up with scattered information with superficial development.

Copyright © FirEUrisk Consortium. All rights reserved.

Ensuring access to the site of interest

In certain situations, access to the wildfire scene or to an incident scene may be limited to essential personnel. Therefore, it's advisable to ensure beforehand that our presence in the area for study is permitted, preventing wasted efforts. A phone call to coordinating authorities or someone already present in the area can help obtain this information; otherwise, it might be a gamble, relying on luck.

Contacting someone to accompany you in the mission

Whenever feasible, avoid visiting a wildfire scene alone. Given the various dangers and critical decisions associated with, activities are safer, more efficient, and enjoyable with more than one person. If possible, visiting the wildfire event with someone familiar with the region and its residents enhances the study's efficiency and increases the likelihood of obtaining more testimonials.

Compiling relevant information

Before embarking on the journey to the wildfire scene, compile all essential information to achieve the defined objectives. When a wildfire event or incident triggers mediatic interest warranting a study visit to the site, plenty of information surfaces on the internet and social media. It's crucial to discern which of this information is genuinely pertinent to the defined objectives and, within that group, which is reliable. Sometimes fake information spreads unintentionally online due to the heightened emotions or panic of those involved, skewing their perception of facts. The most reliable information is naturally that provided by official entities or documented in photographs or videos.
Among the various pieces of information that can be acquired beforehand, depending on its characteristics and the objectives of the work, the following information stands out as commonly of interest to all wildfire analysis activities:

- Information about the wildfire event: its size, particularly the wildfire perimeter, in the latest update; which villages were evacuated, affected by the wildfire, or threatened; and the hottest points, i.e., where fire fronts are most active and firefighting efforts are most intense.
- Information about the main recorded impacts: where, how, and when major events occurred, such as fatalities, building losses, or any accidents. This information may not only be important due to the interest the incident itself may raise but also to refine the sensibility on how these sites and the people living there should be approached, besides that these areas may be inaccessible.
- Operational information: the number of resources in the wildfire scene, the name of the operations commander, the location of the main command post or other critical operation centres, such as advanced command posts or traffic points, and the locations where people are taken during evacuation operations.
- Weather forecast: for the upcoming hours and for the period you intend to be at the wildfire scene, especially wind speed and direction, air temperature, air relative humidity, and likelihood of precipitation. Websites of the respective country's meteorological institutes or other websites with broader coverage (e.g., www.meteoblue.com , www.windy.com , etc.) can serve as sources of this information.

Copyright © FirEUrisk Consortium. All rights reserved.

- Information about area characteristics that may influence wildfire behaviour: if you're not familiar with the region, it's helpful to have an idea of the typical topography, areas with rugged terrain, land use distribution, or areas with higher fuel loads will help you to understand the wildfire's critical points. Google Earth is a useful tool for a quick analysis of this type of information.
- Personal logistical support areas: restaurants and other places where beverages and food can be found, fuel stations, and accommodation locations, if the mission involves spending one or more nights on-site, are typically the logistical information that may be most needed.

Analysing and organizing compiled information

Well-organized information facilitates its use when necessary. Therefore, it's advisable to arrange all information and, whenever possible, map it to provide the most integrated view possible. It's also important to print this information in more than one paper copy and upload it into digital format, making it available on a tablet, for example. Additionally, planning the route to follow is crucial. Naturally, unforeseen events may disrupt this plan, but it still proves useful for structuring the mission.

Developing data collection sheets

Based on the study's objectives, anticipate the information you intend to obtain in the field and consequently, the questions to ask the people you'll be speaking with. If conducting interviews, prepare a script with the most relevant questions. If conducting a photographic survey, prepare a list of details or perspectives to be photographed. Whatever the objective, it's important to plan in a way that allows you to obtain a set of harmonized answers that respond to your objectives. The collected information can be recorded in paper or digital format. Both formats can provide redundancy, which may be useful as a contingency measure. If the study motivating the visit to the wildfire scene is part of a broader program of missions with repetitive objectives, consider the possibility of creating a digital form that organizes the responses, such as Monkey Survey or other software freely available on the internet. Certainly, creating a script of questions or a form with fields to complete will allow for a comprehensive set of harmonized data, facilitating the elaboration of the mission report.

Preparing materials and equipment before departure

It's often said that "those who go to sea, prepare on land." Similarly, those heading to a wildfire scene should gather all materials and equipment they may need beforehand. Wildfire events usually occur in remote areas where it's not always easy to purchase materials or equipment at the last minute. Therefore, any oversight can greatly compromise or limit the mission. Below is a list of typical materials and equipment, which can be supplemented by others depending on the mission's characteristics:

- Wallet with basic documentation, emergency contact, blood type identification, and information about any eventual physical limitations (e.g., diabetes).

Copyright © FirEUrisk Consortium. All rights reserved.

- Mobile phone with a charged battery (sometimes smartphones have less communication capacity than older analogic phones).
- Camera and camcorder if the phone lacks this capability.
- Trackers if the phone lacks this function.
- GPS if the phone or vehicle lacks it.
- Power bank and mobile phone charger.
- Physical map of the area in case digital means fail.
- Data recording sheets and organized information dossier, as previously described.
- Tape measure or digital distance measurer.
- Portable weather station, preferably digital, with wind speed measurement.
- Intercoms (walkie-talkies) – if more than one team is on-site.
- Flashlight and whistle, which can be important for signalling your location.
- Notepad and pen/pencil.
- Voice recorder.
- Light first aid kit.
- Sunscreen and any medication you take regularly.
- Cash because digital payments may be compromised.
- Beverages (water, energy drinks, etc.) and non-perishable food (energy bars, etc.).
- Extra batteries and chargers for electronic equipment

Preparing appropriate clothing and footwear

The clothing and footwear you bring should be suitable for the various scenarios you will encounter. They should be sturdy and heat-resistant while also being comfortable. You'll likely have to walk several kilometres on rocky and rugged terrain, so wearing hiking socks and avoiding tight-fitting shoes is important to prevent blisters. Firefighters' operational uniforms provide a good reference for the type of clothing and footwear you should bring, with emphasis on boots, pants, and a jacket made of cotton or heat-resistant material with low thermal conductivity. The use of a hood or a respiratory protective mask, as well as a hat capable to protect the neck, are equally important. You should also consider the need for a visor, helmet, and fire shelter depending on your mission. Since you won't always be at the wildfire scene, it's also advisable to bring comfortable clothing and footwear for rest periods, as well as sunglasses and a common hat.

Copyright © FirEUrisk Consortium. All rights reserved.

If possible, wear clothes that identifies your affiliation or somehow indicates that you are on duty. If your uniform is properly identified, people will give you more credibility, and getting information will be facilitated.

Before departing, ensure thorough preparation.

Immediately before departure, ensure that the mission has been well-prepared and that nothing has been forgotten that could compromise the mission. It's important to focus because another phase of the mission is about to begin. Here are some recommendations to consider, which should naturally be adapted to the specifics of each mission:

- Check the materials, equipment, and procedures checklist mentioned earlier.
- Check the fuel, oil, and vehicle's condition, as well as the charge of electronic equipment.
- Inform family and friends, sharing the mission plan, especially the planned route.
- Review the safety recommendations described at the end of this chapter.

2.1.2 In the wildfire scene

The collection of data at the fire scene during the fire event is not always authorized by the authorities, so the interpretations of this section must take this potential limitation into account.
While there might be some excitement about going to the wildfire scene, it is important that the journey is conducted safely and carefully, considering that traffic, especially near the wildfire event affected area, may be busier and with more heavy vehicles than usual. When the mission is carried out by more than one person, the mission plan and safety precautions should be reviewed during the travel. As mentioned, the wildfire scene is a complex area with much movement and many potential dangers, so below are some of the main guidelines to be followed when entering the area affected by the wildfire event. Naturally, regulations or doctrines followed in certain countries may require adaptation of the following general guidelines. In any situation, safety procedures (see next section) and recommendations from authorities should be faithfully followed.

Check-in and Check-out at the Wildfire Scene Command Post

One of the first actions to be taken when entering the wildfire scene is to register your presence. Therefore, before starting any other task, you should go to the command post to report your entry to the site. You should also present the mission plan, request recommendations, and obtain authorization to access the areas you intend to visit. If necessary, depending on the practices followed in the region or country in question, you may request a document authorizing your access to the wildfire scene. You should also request a contact phone number to call if necessary – both for your safety and to report any situation of interest to the operations command. Additionally, leave your phone contact in case you need to be reached. Similarly, at the end of the mission, when you are about to leave the wildfire scene, you should inform the command post.

Interviewing witnesses

Copyright © FirEUrisk Consortium. All rights reserved.

Before approaching anyone, you should identify yourself and express your purposes to dispel any suspicion or misunderstanding that people may have upon initial contact. Whenever the information provided is of great relevance, you should try to obtain a telephone contact from the interviewee for possible future contacts. Likewise, you should leave your telephone contact. Authorization should be requested from the interviewees for audio or video recording, and their response should be recorded for the record. The intention of recording should be explained – for example, to be used as notes – opening the possibility that it may never be published, a commitment that should also be recorded. If the person does not agree to be recorded, their responses should be noted on paper.
Two types of interviewees are commonly the most relevant to approach during the course of the wildfire event:

- On-site agents/firefighters: you should primarily approach those personnel who are apparently not actively working, always avoiding disturbing operations or their eventual rest period as much as possible. The first person to be contacted should be the team or group leader in operations, informing them of your passage through the command post and the authorization given by the operations commander. It is important that the personnel know that they are not being evaluated but only contributing to a study. This contact should be as quick and objective as possible to avoid complicating the agents' activities.
- Citizens: You should seek to interview citizens who can provide information with insight because there are always many people who, affected by events, end up providing distorted or illogical information. The analysis of the information provided should also consider the possibility of some exaggeration in the testimonies. Sometimes, some citizens tend to provide excessive details or deviate from the desired information, so it is very important to moderate the response in order to follow the previously established script. It is natural for people to take the opportunity to express their distress and show their generosity in providing information, so the interviewer should listen to them calmly and respecting them feelings, always keeping in mind the mission objectives and the time available for its completion.

Recording video or photographic images

Recording images is usually an essential type of information, both for obtaining data and for reporting. It is very important that the images are georeferenced, both regarding their capture location and the location captured by the target image. The time and date when the photographs or videos were taken are equally very important. Whenever photographing individuals or specific property – i.e., not integrated into a general landscape – permission should be requested from those individuals or property owners.

Requesting specific information

Whenever your mission involves knowing the times when a certain incident occurred, when the wildfire passed through a certain location, or any other similar information, it should be noted that during a wildfire, people have a very distorted sense of time. It is very common for the hustle and bustle of the wildfire to disrupt people's routines (e.g., lunch), so the times witnessed are often deviated from reality. The photos or videos that people usually take with their mobile phones are usually time-stamped and sometimes georeferenced, so being a good ally to confirm

Copyright © FirEUrisk Consortium. All rights reserved.

the accuracy of the temporal information. Phone calls that people make during wildfires also help them situate themselves in time, so they can also be a good confirmation element. Some houses have video surveillance systems that can be a valuable source of information in reconstructing fire behaviour. It is a good procedure that temporal information is categorized according to its reliability.

The aforementioned elements, and others that may arise during the mission, can be fundamental for subsequent wildfire analysis studies. Thus, it may be requested that people provide these elements, ensuring that if presented in the report, authorship credits will be given to the owner(s). On the other hand, if people do not want these elements to be published, a commitment of honour to respect that decision should be assumed. It is very advantageous for these elements to be obtained on the spot because people often forget to send them later or lose interest in doing so. If they are not provided at that moment, you should keep the contact of the person who holds the elements of interest to eventually insist later on their sending.

Analysing regularly and on-site the information gathered

Rarely does analysing a wildfire involve staying in a unique place. Therefore, there are always several expeditions interrupted by stops to obtain information. It is important to periodically examine the information obtained so far to ensure that the data is being acquired correctly and that the information is being constructed coherently and according to the established plan. When two or more people are involved in the mission, favourable periods for examining the information gathered is during those expeditions between stopping points to save time and to consolidate the information gathered. The following list of procedures can be followed during those times of information examination and consolidation:

- Organize the information, forms, etc., proving self-explaining titles.
- Complete missing information in the forms while your memory of happenings and testimonies are fresh in your mind.
- If accompanied, discuss the perception of the wildfire event/episode and testimonies with your colleague(s).
- Summarize the main points and preliminary conclusions using a voice recorder of a video camera.
- Review the plan to redefine it or to determine if it is behind or ahead the previous strategy.

2.1.3 Safety procedures

For a mission to be truly successful, it is essential that it takes place safely. As mentioned, there is a wide variety of wildfire event related dangers of which we must be aware in order to prevent or respond effectively to.

- Everybody going to a wildfire scene must be aware of aspects related to fire behaviour and fire safety. Considering taking a course that provides this knowledge if your career involves visits to such areas is advisable. The dangers you will face in a wildfire scene are very similar to those faced by firefighters, except that unlike them, you do not have the protection of a specialized team and firefighting equipment behind. Therefore,

Copyright © FirEUrisk Consortium. All rights reserved.

aspects related to wildfire safety are of utmost importance. Following, some precautions to be considered in a wildfire scene mission are listed.

- Be aware of wildfire safety aspects, remembering that whenever you are at the wildfire scene, you should always be alert to what is happening around you: the fire behaviour at any moment, the manoeuvres of firefighters, the escape route you will take if the wildfire spreads eruptively, and a safe place you shall go if you need to take refuge. If accompanied, these decisions should be discussed among all.
- Although applied to firefighting operations, the LACES protocol – Lookouts, Anchoring points, Communication, Escape routes, and Safety zones – can be studied for adaptation to your mission. Safety such as the "Watch out situations" (NWCG, 2022) among many other publications are references on this matter as well.
- Always be accompanied, or if not possible, there should always be someone nearby who knows of your presence in the area.
- Avoid areas without the presence of other people.
- Avoid invading fenced areas unless you are allowed to do it.
- Do not enter in burned or damage buildings that can collapse, even if the fire was already extinguished.
- Be careful if you go inside previously burned forested areas specially if trees are fragile and likely to fall down – this precaution is even more relevant in boreal forests or forests with a very thick duff layer.
- Always be communicable – if for any reason you are in an area with poor mobile coverage, the need to be accompanied becomes even more important, as well as the need to inform others of your presence. The use of intercoms can also be a good safety procedure in these situations. Presence signalling systems such as whistles or light signals may work well if you need to be located.
- From time to time, inform you friends or relatives who are outside the wildfire scene of your location and plans so someone external to the mission follows-up the journey.
- Always wear appropriate clothing for your mission. Most accidents that occur at a wildfire scene are musculoskeletal injuries (sprains, fractures, etc.), so it is very important to wear good footwear and joint protection; as mentioned earlier, clothing and footwear should be comfortable while also protecting against heat.
- Take with you, personal protective equipment such as fire shelters, helmet, visors, hoods, and gloves, among others, according to you mission.
- Whenever possible, integrate or accompany civil protection teams in the field, which will allow you to obtain reliable information more easily, more interestingly, and more safely. Establishing a prior protocol in this regard could facilitate it.
- Be very careful when traveling to and from the wildfire scene. On the one hand, the excitement of the mission can lead you to drive faster and more recklessly. On the other hand, especially on the return trip, fatigue can limit some driving skills – in this case, you should rest before returning.

Copyright © FirEUrisk Consortium. All rights reserved.

2.2 Aftermath data survey

Analysis conducted after the wildfire occurrence can take place at any time, influencing the methodologies employed for information gathering. For example, immediate field visits following an event may offer abundant evidence but also various associated dangers, such as the potential fall of unstable trees. Conversely, analyses conducted months or years later may mitigate field visit dangers, but with diminishing human recollection and site remnants. Consequently, reliance on documented, photographic, or videographic records heightens in significance over time.
This section addresses key considerations when collecting post-wildfire information.

2.2.1 Acquisition of information directly related to the wildfire

When investigating and analysing directly wildfire related information, it is essential to consider the most relevant and trustworthy sources of information available. This activity should not be confused with the "Complementary Data Survey" in Chapter 3, which focuses on characterizing the conditions under which the fire developed (meteorology, topography, etc.) rather than the fire's development itself. The sources of information to better understand the wildfire facts and related events are varied, including the following main ones described below.

Satellite imagery

While satellite images may lack temporal resolution for precise fire front isochrone delineation, they hold value in reconstructing fire behaviour, particularly in defining final wildfire perimeter and burned areas. This method proves advantageous, especially in cases of fragmented perimeters or unburned patches within the fire boundary. Intermediate satellite imagery facilitates isochrone delineation validation and updates, contingent upon image quality regarding resolution and flame front detection. Section 3.5 will delve into "Earth observation imagery and derived products".

Elements obtained during the field visit to the wildfire scene during the occurrence of the wildfire event

Section 2.1 was entirely dedicated to obtaining data during the wildfire event. This is undoubtedly an activity that, although not always feasible, can provide a set of highly reliable information obtained firsthand by the author(s) on the field. Regardless of the primary objectives of this field visit, there would undoubtedly be field observations, photographs, videos, or narrative descriptions offering insights into fire front locations and the extent of burned areas, aiding in comprehensive wildfire analysis.

Data from on-site visits after the wildfire event

Despite the fire's extinguishment, conducting on-site visits remains crucial for consolidating information and validating accounts. If no visit occurred during the wildfire event, it's advisable to visit the site even before conducting interviews or gathering other information. This initial visit aids in filtering and interpreting received information effectively. Sometimes, information obtained from bibliographic sources, web references, or testimonies can be abstract, merely stating "the fuel load was high" or "the slope was steep." However, visiting the site provides tangible evidence to support such claims. These visits are even more beneficial when accompanied by individuals familiar with the terrain

Copyright © FirEUrisk Consortium. All rights reserved.

or involved in firefighting efforts. Additionally, conducting intermediate visits may help clarify any doubts arising during the investigations. Finally, a final visit, once all information has been compiled and the narrative outlined, serves to verify the coherence of the overall story.

Post-fire site visits offer numerous points of interest. The original ignition site often serves as the genesis of the entire story, providing insights into the initial attack and subsequent events. Accident sites or significant episodes should be explored to understand key facts, including fire behaviour, resource allocation, and interventions made. Locations where the fire exhibited extreme behaviour or where control was lost can offer valuable insights from academic, scientific, technical, and operational perspectives. Ultimately, there are many sites of interest that may warrant dedicated visits, depending on the objectives of the study.

Furthermore, post-fire site visits aid in reconstructing the fire's progression, particularly at critical locations like the origin site or accident spots. In addition to eyewitness testimonies, the terrain itself provides valuable information about the fire's direction and intensity. For instance, the extent of blackening or the depth of wood burning offers clues about the fire's severity. Notably charred surfaces on rocks, walls, or tree trunks indicate the fire's path. Being at the origin site and retracing the estimated fire path enables pinpointing the exact origin point and potentially assessing the fire's cause, although this typically falls under legal jurisdiction beyond the scope of this document.

As previously mentioned, visiting an area affected by a wildfire, even after it has been extinguished or closed off, poses several risks that escalate the closer the visit is to the time of the fire. In addition to the safety guidelines outlined in Section 2.1.3, there are specific considerations to keep in mind when conducting post-fire visits. The following recommendations are provided in this regard:

- Rekindling: It is essential to remain vigilant if the visited area still retains significant heat, as rekindling may occur, potentially trapping individuals who are unaware. Detecting rekindling in a smoky environment can be challenging.
- Falling trees and branches: In burned areas, particularly if there is wind, trees, branches, pinecones, and other fire-weakened materials may fall. The risk of tree falls is heightened in areas with a thick duff layer (e.g., boreal forest), which may have been consumed by the fire, exposing, and compromising the structural roots of trees. When visiting these areas, it is advisable to wear a helmet or other protective gear.
- Hot pockets: The burning of forest floor or tree roots can create pockets of hot air in the soil. Stepping on these pockets can cause them collapse, leading to musculoskeletal injuries or burns if the ground remains hot.
- Structure collapse: If a building or other infrastructure has been affected by fire, its structural integrity may be compromised. Therefore, entering these structures should be avoided, and photographs should be taken from a distance. If entry is unavoidable, all safety precautions must be observed, including the use of personal protective equipment, and authorization should be obtained from relevant authorities.
- Weakened terrain: Following a wildfire, the terrain structure becomes significantly fragile, increasing the risk of landslides or rockfalls. Special attention should be paid to these hazards.
- Disoriented animals: After a wildfire, wild animals may become disoriented and exhibit aggressive behaviour due to feeling threatened. If visiting an area where encounters with wildlife are possible, it is advisable to carry early warning systems (e.g., bells on shoes) or repellent sprays.
- Accompanied visit and communications: Given the aforementioned dangers, visits should be conducted by groups of at least two people, ensuring communication between them and with external support.

Copyright © FirEUrisk Consortium. All rights reserved.

Media news analysis

In cases where a wildfire captures media attention, a substantial number of journalists and image reporters typically converge on the wildfire scene. For the study, this presents a valuable and cost-effective source of information readily available to the public. It is recommended to scrutinize as many news reports as possible to gain a comprehensive understanding of the situation but minimizing to be influenced by external opinions.

Examining published videos or photographs enables identification of specific locations visited by reporters pertinent to the study. In such instances, it is advisable to reach out to the individual or entity holding the rights to these images, as they often possess additional unpublished material that could significantly contribute to the research. Professionally captured images typically include timestamps and location data, aiding in the reconstruction of fire behaviour. Naturally, proper credit must be given when utilizing any external imagery.

Use of digital tools

The guidance provided in the previous section also applies to digital social networks, where numerous photographs and videos of significant wildfires are often shared. In such cases, analysing these digital platforms could facilitate communication with individuals who were present during the event and may have captured noteworthy locations relevant to the study, thereby enabling requests for additional information or imagery.

If the available digital content pertaining to a wildfire or specific incident is insufficient for reconstructing the narrative, another option is to issue a public appeal for images or information via the internet. This entails creating a dedicated online space clearly explaining the purpose of the crowd-sourced request transparently.

Another valuable digital resource is Google Earth, particularly its Street View feature, which provides insights into the terrain or surroundings of a property prior to the wildfire occurrence, especially in less remote areas.

Interviews with citizens

Interviews with community members serve as a significant source of information, not only due to their direct involvement in the wildfire incident but also because they hold intimate knowledge of the affected area. Sometimes residents have also valuable photographs depicting houses or locations where accidents or other critical events occurred, which can be instrumental in analysing specific cases.

Approaching citizens for interviews should be done with sensitivity, considering potential periods of mourning and emotional distress they may be experiencing. Additionally, it's crucial to interpret the information provided with consideration for the emotional state of the interviewees, as emotions can inadvertently skew facts.

As previously mentioned, efforts should be made to supplement testimonial statements with tangible evidence such as photographs or videos. Mobile phone call recordings from citizens are particularly valuable for establishing the timing of specific events.

Interview preparation is essential for facilitating moderation, ensuring that the interviewee remains focused on relevant questions, and avoiding tangents. Throughout the interview process, it's imperative to maintain a demeanour of utmost politeness and empathy, recognizing the interviewee's need to express themselves while acknowledging that they are providing a favour by providing a statement.

Copyright © FirEUrisk Consortium. All rights reserved.

Recording the interview in audio or video format is often preferable to hastily taking notes, allowing for thorough review of the testimony later. However, it's essential to obtain consent from the interviewee before recording.

Interviews with responders

It is advisable to initially hold separate meetings with different agencies to avoid the formation of a unified narrative or the initiation of a blame game. If possible and necessary, a joint meeting involving multiple agencies may be beneficial to address any eventual discrepancies or contradictions.

Interviews with responders require authorization from their respective hierarchies and must be conducted with sensitivity, considering that some agents may have been affected by the wildfire or its consequences. If recording the meeting in audio or video format is intended, participants' permission should be obtained.

During interviews, it is convenient to have access to printed or digital maps of the terrain, as well as relevant o photos to aid in identifying and clarifying details.

These interviews can be structured with a standardized set of questions posed to all individual or groups involved, supplemented by specific inquiries as needed.

Interviews with authorities

Meetings with administrative authorities or the managers of operational agents, as well as representatives from other relevant institutions involved in the wildfire, such as motorway or electrical network managers, may be necessary to complement the information obtained from the ground operating personnel.

These meetings aim to acquire insights into the agency's overarching policies concerning planning and prevention measures. If incident reports are accessible, they should be requested and reviewed during these discussions.

These meetings aim to acquire insights into the agency's overarching policies concerning planning and prevention measures. If incident reports are available, they should be requested and reviewed during these discussions.

2.2.2 Actions for fire behaviour analysis

Analysing fire behaviour and defining fire front isochrones is a complex undertaking that relies on a variety of information gathered through multiple techniques, as outlined previously. The diverse nature of this information often leads to contradictions, complicating the interpretation of events. To mitigate this confusion, one approach is to categorize information based on its credibility. For instance, data sourced from images (such as satellites, photographs, and videos) with precise timestamps and locations can be considered highly reliable (level 1). Information found in reports or echoed by multiple sources or supported by additional evidence such as coincidental phone calls, can be classified as moderately reliable (level 2). Testimony from individuals or isolated sources generally falls into the lowest level of confidence (level 3), unless specific factors elevate its credibility.

Once information is categorized, the reconstruction of events typically begins with level 1 data, filling in gaps with less reliable information where necessary. Contradictory level 1 data or areas abundant with less credible information may

Copyright © FirEUrisk Consortium. All rights reserved.

necessitate additional efforts to gather data, such as conducting further site field visits, requiring additional interviews, or intensifying image acquisition efforts.

Supplementary information, described in Chapter 3, plays a vital role in understanding fire behaviour. Factors like wind direction and velocity, and digital terrain mapping are crucial for this understanding. However, in terrain with complex topography, dominant wind directions can be deceptive due to localized wind patterns. Utilizing computational fluid dynamics (CFD) wind simulation models, like the Canyon software developed by Lopes et al. (2019), can significantly aid in comprehending fire development by accounting for convective effects on airflow.

Another factor complicating the analysis of fire evolution is spotting, which can result in unexpected advancements of the fire front. Additionally, built-up areas, roads, rivers, fire breaks, and human interventions, such as firefighting tactics using water or controlled burns, further influence fire behaviour. Therefore, all information must be integrated and analysed comprehensively, irrespective of its source or type.

2.2.3 Actions for structural destruction analysis DC

In fire incidents affecting a large number of buildings, it is necessary to conduct a systematic analysis of the extent of the destruction of the homes and document it properly so that it can be compared later with the usual risk indices for WUI areas.

Assessing degrees of building affectation

Four levels of building damage are proposed to facilitate quick and simple visual assessment both at the scene and during subsequent review via the corresponding orthophoto. These levels are represented in Figure 1 and described as follows.



(a)



(b)

Copyright © FirEURisk Consortium. All rights reserved.



(c) (d)

Figure 1. Basic levels of building affectation: a) No appreciable damage; b) Moderate damage; c) Severe damage; and d) Complete destruction.

- No appreciable damage: The building shows no significant damage or only very minor effects, such as superficial blackening of paint or slight deformation of plastic elements (such as gutters or PVC profiles). Full functionality can be restored with minimal intervention.
- Minor to moderate damage: The building exhibits damage to exterior elements, with some rooms affected by fire, but the majority remaining undamaged. The structure remains intact. Restoration is possible with interior and exterior renovation work.
- Severe damage: The house has sustained significant exterior damage, with much of the interior affected, including many or all rooms being burned. However, the roof, floors, walls, and partitions remain standing without signs of structural damage. Restoration of functionality is achievable with extensive renovations and complete interior refurbishment.
- Complete destruction: The building has a collapsed roof and possibly some walls or partitions, with irreparable structural damage. Reuse is not feasible, and demolition is recommended.

Each of the levels is associated with a colour for easy interpretation on maps and tables. For levels 1 (no damage) or 4 (destroyed), visual assessment is relatively straightforward; however, this subjectivity sometimes limits the ability to distinguish between the intermediate classes, particularly between 2 (minor to moderate damage) and 3 (severe damage). A comprehensive analysis of the damage and an evaluation protocol can help mitigate some of this uncertainty arising from the subjectivity of a rapid visual inspection.
In order to assign a quantifiable value (K) to each dwelling, a scoring method based on the level of damage (A) has been proposed using the expression:

$$K = (A - 1)^2 \qquad \text{[Eq. 1]}$$

Thus, both the level of damage (A) and its quantification (K) are associated with each building and the land area they occupy. This resulting map will be taken as a reference for the proposed validation processes.

Copyright © FirEUrisk Consortium. All rights reserved.

Area segmentation (zones)

If the affected residential area is extensive, it is suggested to divide it into several territorial blocks that are significant and typically aligned with administrative boundaries. Subsequently, each block is divided into several sectors, which aid both in fieldwork systematization and in subsequent analysis in the office.



Figure 2. An example of territory segmentation into 12 sectors in the Mati-Kokkino Limanaki area during the Mati wildfire in July 2018. This segmentation was crucial for the systematic study of building impact. Where possible, the street and road network were used as boundaries between sectors, but it is also possible to use other administrative boundaries or landscape features (rivers, mountain ridges, etc.).

Structures' labelling

It is suggested to label each building with a number for identification purposes. For this, it is proposed to first use the block number, followed by the sector number, and then a house number within the corresponding sector, scanning the

Copyright © FirEURisk Consortium. All rights reserved.

territory from top to bottom and from right to left. This systematic labelling allows for easier identification of each building both in the orthophoto and in ground-level photos, both before and after the wildfire.

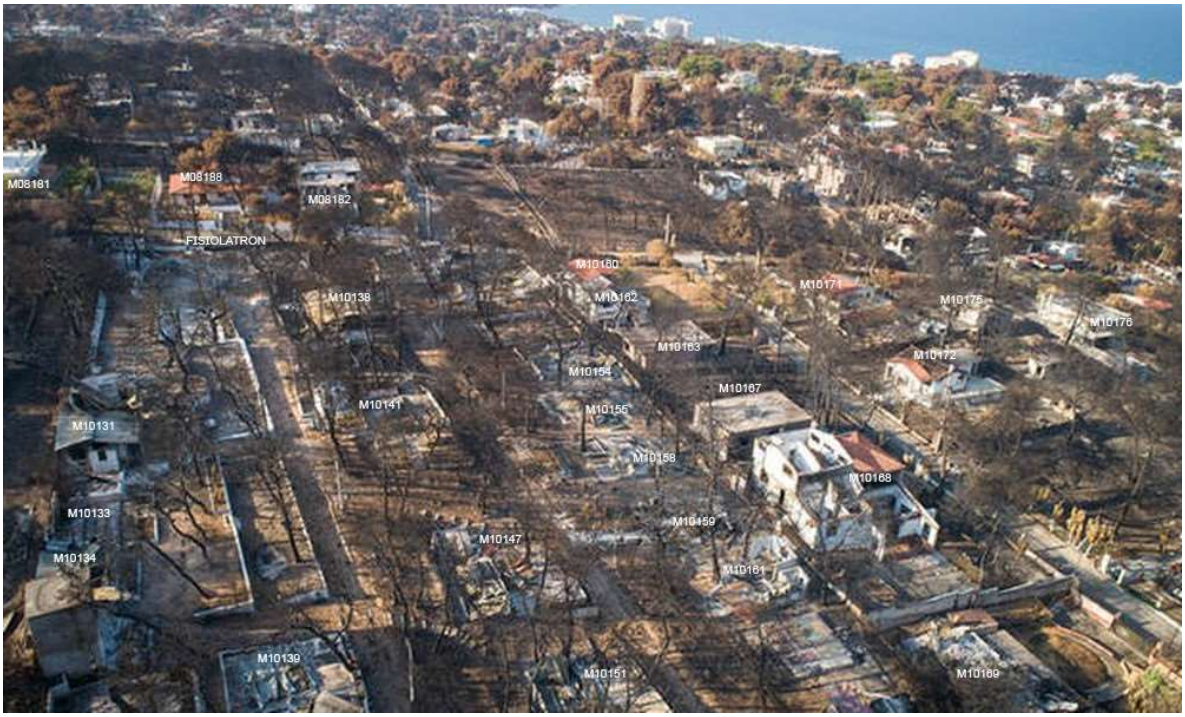


Figure 3. Example of labelling all buildings present in block M, segment 10 of the Mati-Kokkino Limanaki area, corresponding to the Fisiolatron zone. This labelling allowed for later comparison of on-site photos and orthophotos before and after the wildfire.

In situ assessment

A large portion of the buildings have partial damages that are difficult to identify from the orthophoto, requiring on-site assessment work, building by building. It is suggested to proceed systematically according to a work plan and to use the labels of each building to store information accurately. Additionally, it is possible and very useful to use a tablet with a GIS application that facilitates graphical data entry, for example, the level of destruction (color-coded) on a vector map of the buildings over an orthophoto. Furthermore, it is important to take georeferenced photographs of the buildings and refer them to the label of each structure.

Orthophoto/drone-based assessment

In wildfires where the destruction has been very severe, it is possible to identify the most affected buildings and those that remain intact, making it much more difficult to assess the degree of impact in intermediate situations. To perform this analysis, it is necessary to have an orthophoto taken after the wildfire, preferably as soon as possible, which is generally difficult unless a specific flight is scheduled for orthophoto mapping. In other cases where it is urgent to conduct such an assessment, it will be sufficient to schedule systematic drone flights to perform the same function, with the added benefit that, if a sufficient number of photos are taken and oblique shots are included in the

Copyright © FirEUrisk Consortium. All rights reserved.

programming, a 3D photogrammetric restitution of the scene can be made. As mentioned, the use of drones streamlines systematic data collection over large areas without the need for a costly airplane flight, which typically operates at higher altitudes.

Coupling existing photos with orthophotos and assessment

Thanks to the labelling of buildings, it is possible to do the same in all the photos that have been obtained, whether from reconnaissance activities, witnesses, or social media. Subsequently, in the office, it will be possible to integrate the analysis of images from before and after for each building, as well as for the orthophotos. The final assessment is completed with the data extracted on-site in the investigation of each property, in order to establish correlations between potential factors (proximity to vegetation, type of building, presence of flammable objects and materials, open windows or doors, type of roof, etc.).



Figure 4. Example of on-site assessment of a building, based on its pre-fire condition as captured by Google Earth Street View. The labelling greatly aids in correlating potential factors with the observed degree of destruction.

Insurance investigation assessment

In property damage research in wildfires, it's highly beneficial to establish collaborative agreements with insurance companies investigating their clients' property damage. Insurance companies may possess data relevant to scientific research and lessons learned extraction; reciprocally, the data we obtain and analyses we conduct can be valuable to insurance companies. Eventually, they may request technical reports and consultations from us to facilitate their client relations and compensation assessments.

Houses' mapping, degree of damage

Copyright © FirEURisk Consortium. All rights reserved.

It is proposed to create a map of the degree of destruction of dwellings using the cadastral vector layer representing the footprint of each building, to which we will assign the interpreted level of destruction, using the mentioned colour code.

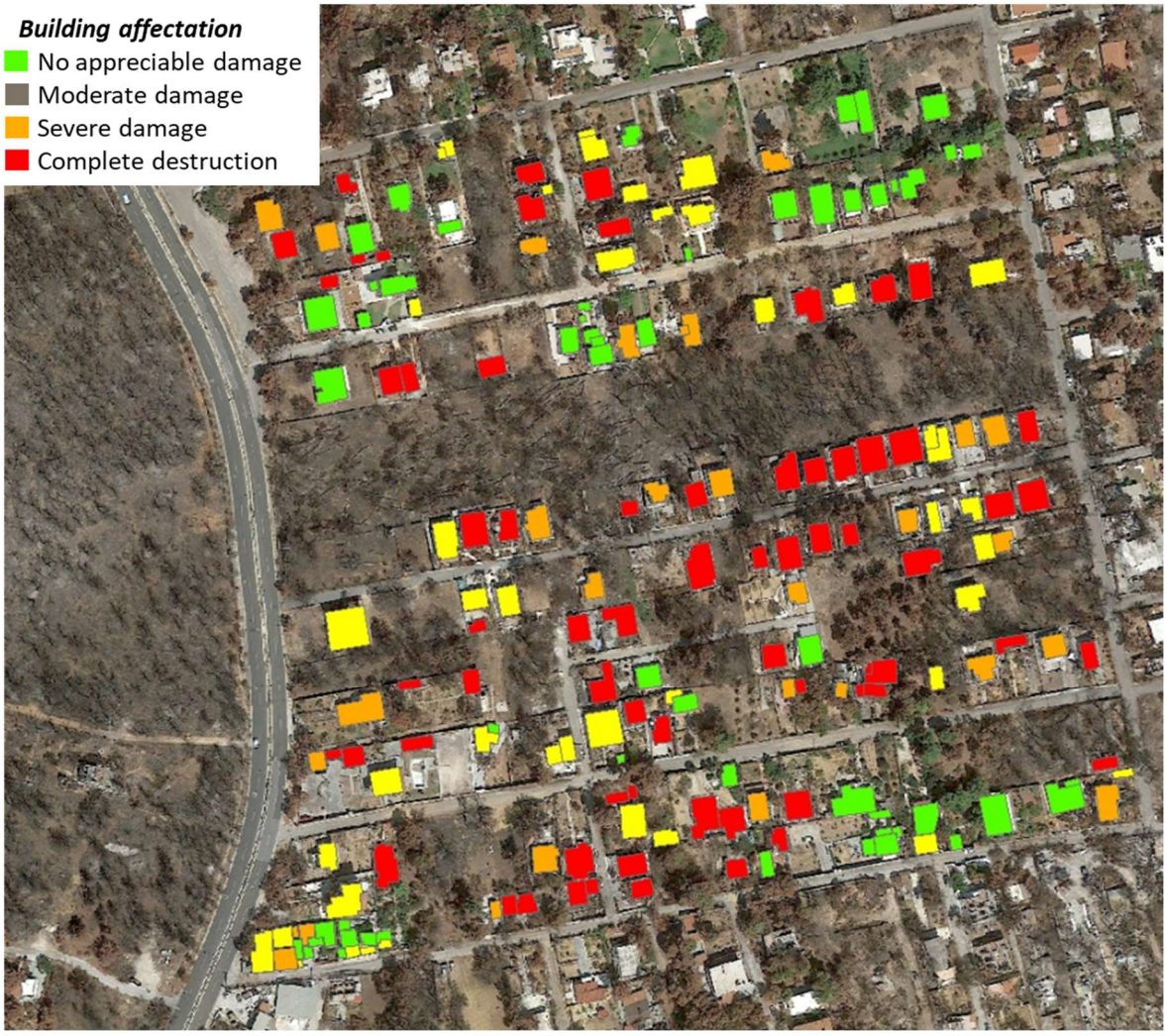


Figure 5. Degree of damage of the 192 buildings in sector S08 of the Mati wildfire (Greece, 2018), according to on-site observations and subsequent review in the orthophoto. While cases 1 (No appreciable damage) and 4 (Complete destruction) are clear, the intermediate cases (2 Moderate damage and 3 Severe damage) are more difficult to classify accurately, as subjective damage assessment procedures are applied.

Territorial damage (spatial interpolation)

It is proposed to use the quantification of the impact (*K*) associated with the geometry of each dwelling to obtain a territorial spatialisation of it.

For this purpose, the vector geometry of each building (footprint of the constructed surface) is first converted into raster cells corresponding to a finer resolution grid R_f, associating each one with the quantification K of its degree of impact. Then, for each cell of a territorial grid of coarser resolution cells R_g, all the k_i values corresponding to all the

Copyright © FirEURisk Consortium. All rights reserved.

cells of the fine grid that are buildings are aggregated, each one with its corresponding impact quantification. By operating in this manner, a total impact value is obtained in which the portions of the surfaces occupied by the buildings in each cell of the coarse grid are incorporated, each contributing with its level of impact. The obtained value is divided by the surface area of the cell of the coarse grid Sg to obtain a specific impact value K_o. Therefore,

$$K_g = \sum_{i=1}^{N^2} k_i \qquad \text{[Eq. 2]}$$

$$K_o = {K_g}/{S_g} \qquad \text{[Eq. 3]}$$

K_g: Impact value of the territory for each cell of the coarse grid (dimensionless)
k_i: Impact value in each cell of the fine grid that is a building (dimensionless)
N: Number of cells of the fine grid on each side of the coarse grid cell
K_o: Specific value of the territory's impact for each cell of the coarse grid (m^{-2})
S_g: Surface area of the cell of the coarse grid (m^2)

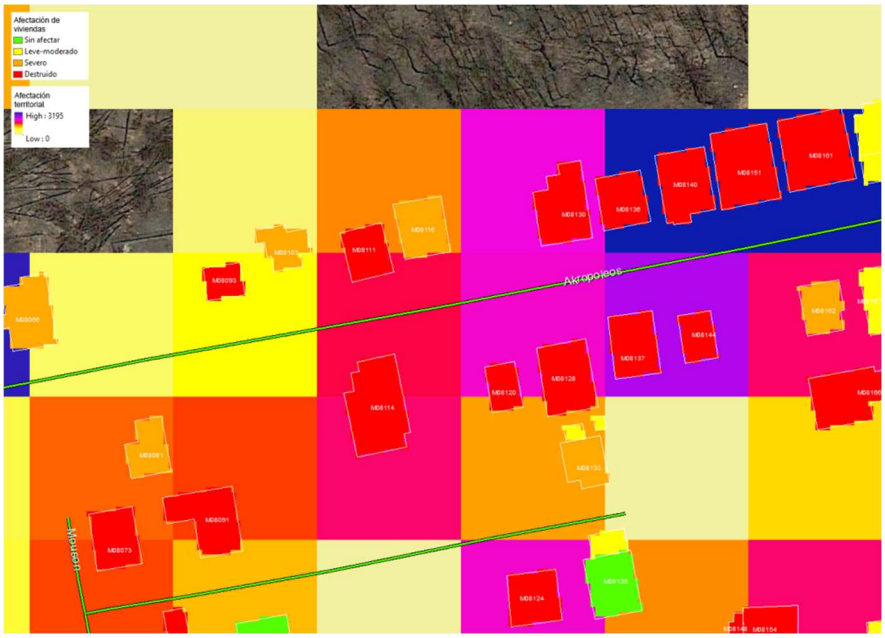


Figure 6. Spatialisation detail of the territorial impact based on the assessment of the degree of destruction of each of the houses (their identifier is shown). As seen, a score is assigned to each cell of a fine grid (1 m) and all values are summed in each cell of a coarse grid (30 m).

Correlation with fire behaviour, indexes

Once the spatialisation of the territorial impact degree is completed, it can be compared with the values and components associated with fire behaviour or risk indices calculated using indices such as WUIX (Caballero, 2019). From the analysis, conclusions can be drawn regarding the degree of involvement of each factor or process, such as the presence of vegetation around the houses or the degree of friction (contact) of the buildings with the vegetation itself.

Copyright © FirEURisk Consortium. All rights reserved.

This is possible because the degree of housing impact has been reinterpreted at a territorial level, with the same distribution and resolution of the cells used in the risk analysis.

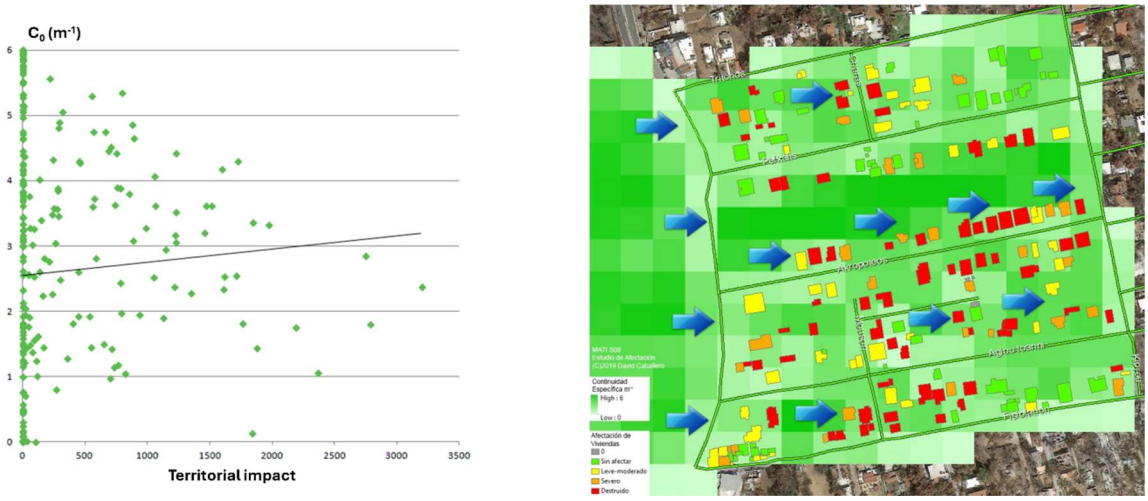


Figure 7. Example of correlating the level of impact with the continuity of vegetation around each building, as per (Caballero, 2019).

2.2.4 Actions for fatalities

When conducting a case study involving fatalities, it is crucial to take great precautions, as issues of judicial or criminal responsibility may arise, alongside concerns regarding personal data protection. Additionally, addressing delicate matters of interacting with relatives or friends of those affected is essential. Therefore, particular care must be taken in the investigation of such accidents.

While assessing the causes of the wildfire and any related incidents may not be the primary focus of the research, it remains important to assess the causes of the wildfire and any particular incidences related to the fatality.

After gathering relevant information about the individuals involved, including victims and others involved in the event or accident, it is essential to notify the authorities of the intention to conduct the investigation and obtain clearance to visit the site and interview operational personnel.

Visiting the accident site as soon as possible after its occurrence, accompanied by individuals familiar with the circumstances and ideally witnesses to the events, is crucial. During these visits, efforts should be made to gather as much information as possible through interviews with operational personnel, as well as members of the community such as neighbours, relatives and friends, who may offer insights into the event, the individuals involved, and their actions.

Photos, aerial images, sketches detailing wildfire displacement, weather conditions, fuel cover, and status reports, as well as statements regarding the actions of individuals entities involved, particularly regarding fire suppression efforts, if applicable, should be collected. This material will aid in constructing an initial overview and designing a first sketch of the wildfire and its related accident.

It is crucial to accurately reconstruct and describe the events leading up to the accident and determine whether the deaths were directly or indirectly caused by the wildfire or some external factor. Decisions taken by the victims or

Copyright © FirEUrisk Consortium. All rights reserved.

others that may have influenced the outcome must be documented. This task may be become challenging if there are multiple fatalities scattered over a wide area or if there are no witnesses.

The investigation of accidents involving fatalities share similarities with police investigations of crimes, even if no crime is suspected. As the investigation proceeds, new information may appear, requiring revisiting the site or re-interviewing individuals to refine the narrative until a coherent description emerges, free of contradictions or unresolved questions.

There should be no rush in conducting these investigations. It may be important, even essential, to interview relatives or friends of the victims or injured parties. However, such interactions should not occur immediately after the wildfire, and some days should be allowed before approaching families. Ideally, visits to their homes should be prioritized over summoning them to institutional offices.

Reports on the wildfire and accidents should be written with utmost care and discretion. If necessary, the identity of individuals involved, or at least part of them, must be withheld, using pseudonyms or numerical designations.

Although maintaining independence and responsibility for the report's contents and conclusions, it is prudent to consult other agencies before publishing it to ensure consistency and avoid discrepancies. If the investigation was ordered or requested by an entity, any decisions regarding the report's release, including potential embargoes should be respected, with clear rules established beforehand.

In investigations involving fatalities, handling media inquiries requires exceptional care, as tensions with authorities and families may arise regarding causality and accountability. It is very important to emphasize that scientific research is not looking for culprits or assigning blame, but rather to establish facts, enhance knowledge, and support authorities.

2.2.5 Actions for injured analysis

When individuals are injured in a wildfire, the procedures to adopt closely resemble those described above for cases involving fatalities. If the investigation is carried out shortly after the incident, it is important to note that the condition of some injured persons may not be definitive, as some may succumb to their injuries.

If there is a need to speak with or interview victims or their relatives, it is imperative to inform and obtain permission from the authorities, medical personnel and families. It must be acknowledged that besides the physical trauma inflicted by the wildfire, there may be psychological or emotional consequences that can prolong recovery and lead to unexpected reactions from the victims or their families.

Besides getting the testimony from the victims to reconstruct the events, accessing medical personnel or reports to objectively confirm the facts is beneficial.

Recording the circumstances of the accident, the actions taken by the victims, their protective reaction and procedures, the extent of injuries, timing and conditions of rescue by emergency services or by fellow citizens is very relevant. Moreover, the needs for long-term recovery, existence of incapacitation, or limitations on normal activities should be documented.

2.2.6 Actions for operations analysis

Gathering recordings and documents

Copyright © FirEURisk Consortium. All rights reserved.

The scientific investigation of the intervention of operational agents in wildfires is necessary for assessing their significance and roles, clarifying the cost-effectiveness of such actions, evaluating their efficacy under different conditions, refining guidelines, identifying best practices, and extracting lessons to enhance agents' training.
This information is valuable for scientific modelers working on realistic scenarios of cases in which specific actions were taken or ignored. For example, many fire spread simulations often overlook suppression actions or tactical fire usage. Therefore, knowledge of cases involving these actions can improve the realism of fire simulators by incorporating actual suppression activities.
It is worth noting that some of this information may involve issues of liability or responsibility attribution, potentially leading to difficulties in accessing certain data directly from authorities.
Field visits are always important, preferably accompanied by personnel involved in the operations, who can freely and knowledgeably describe the facts ideally having experienced them.
Supplementing field observations, data collection from authorities, should include:

- Operational reports detailing actions, locations, and timing of relevant events.
- Meteorological data and weather predictions that were available to the command post.
- Organization of the wildfire management system, including command post location(s), composition, roles of incident command system elements, and its evolution during the wildfire.
- Supporting data used in decision-taking process such as fire predictions and ground, aerial or satellite imagery depicting wildfire development in sectors.
- Issues related to logistics, such as timely food or accommodation, both for operational agents and for the displaced citizens in the evacuation processes.
- Evaluation of decision-making effectiveness and actions taken during each phase of the wildfire.
- Interaction with administrative authorities and the population, including decisions regarding evacuations or recommendations for people to stay onsite, with or without operational support.
- Status of fuel management procedures and their effectiveness.
- Reports on aerial intervention and their effectiveness.
- Reports on interventions by external forces, potentially from other regions or countries.

The availability of the aforementioned documents does not exclude the need of holding meetings or conducting interviews with relevant parties, which was already addressed in Section 2.2.2.

Timeline of operations

Establishing an accurate timeline of operations is paramount, particularly in cases involving accidents or significant damage. Typically, authorities have reports tracking the sequence of events and their timing. For example, in Portugal each wildfire event generates a dedicated electronic file known as the "fita do tempo" [time report]. In this report, all events, decisions, communications, and movements with timestamp are registered and recorded. It provides a comprehensive chronology of events throughout the operation, even if conducted by different agencies at various locations within the wildfire site. When available, access to this registry is very fruitful as many objective information

Copyright © FirEUrisk Consortium. All rights reserved.

can be extracted from it. To address any inaccuracies in the time report, it's essential to cross-reference and consult other data sources.
As previously described, nowadays, cellular phones equipped with high-quality cameras are extensively used by both operational agents and citizens to record wildfire-related events. The timestamps on these recordings are very reliable and can be used to validate other information.

One important piece of information derived from the time report is the sequence of firefighting resources dispatched to the wildfire, including their arrival times, intervention during operations and dismissal from the wildfire scene. These data allow for the estimation of the availability and deployment of agents, vehicles, aircrafts, and other resources at each stage of the fire's development.

Copyright © FirEUrisk Consortium. All rights reserved.

3 Complementary data survey

The exercise of understanding how a wildfire has spread in a particular set of conditions is a complex task, and usually involves several steps or phases. Most of these phases consist of extensive field work, as has been described before, either during or after the event, and sometimes before. But all these processes need to be supported on the physical description of the different conditions that may have an influence on fire behaviour.

It is widely known that fire spread depends on factors such as fuels (vegetation), topography and weather conditions, in what is commonly known as the fire environment triangle (Countryman, 1972), although wildfire creates its own dynamics over time, as a result of its interaction with the environment in which it develops (Viegas, 2004).

But a wildfire investigation doesn't only address fire propagation, it also needs to incorporate the social, environmental or structural characteristics, among others, of the affected area, as well as the fire management actions and means that are involved in fire suppression.

We must note that, although in some cases there are global services that provide data for all the world, most of the needed information needs to be obtained at a national, regional or local level, making it virtually impossible to identify here all those sources. Instead, in this section we try to identify and detail the previously mentioned information, as well as to provide guidance on how to obtain it, whenever possible.

3.1 Orography

The description of the terrain is a mandatory dataset to obtain, as even in the absence of all other parameters, to understand a wildfire evolution, the configuration of the terrain is essential. The descriptive parameters that are most important for the spread of fire are slope, orientation, shape and altitude.

The terrain is usually described using a Digital Elevation Model (DEM), which is a generic term, most commonly assuming a raster format. A DEM has elevation values over a topographic surface in a regular array of z-values, referenced to a common datum, either in decimal degrees or meters depending on the datum the surface is project on (Opie, 2020).

The elevation models (Figure 8) can refer to the bare ground - Digital Terrain Model (DTM), or the top of the elements above ground, which may include vegetation, buildings, etc - Digital Surface Model (DSM) (Guth et al., 2021).

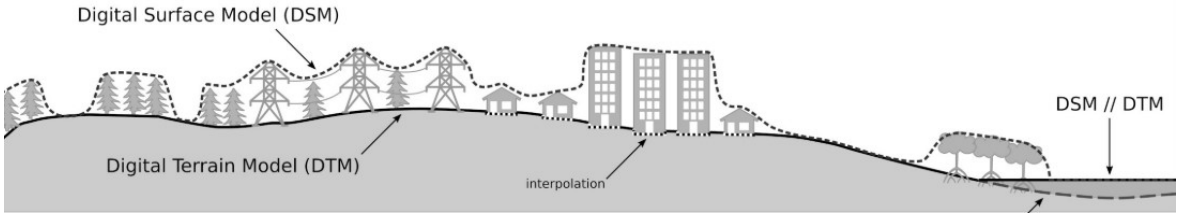


Figure 8. Schematic representation of a the difference between DSM and DTM, taken from Guth et al., (2021).

Elevation models are relatively easy to obtain, without cost, at a resolution of approximately 25 to 90 m, which is perfectly compatible with the goals of wildfire analysis. If finer resolutions are needed, then one should opt for

Copyright © FirEUrisk Consortium. All rights reserved.

commercial products, custom models or local or national datasets. We describe here some of the most known sources of DEMs.

3.1.1 Global datasets

Different agencies share in their repositories tiled global elevation models. These global models are built based on data acquired via satellite, and are based either on photogrammetry, radar or a combination of both. The most known and used datasets are:

- Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model V3 (ASTER GDEM), with an approximate resolution of 30 metres at the equator. The models were created using photogrammetry techniques from satellite images and can be obtained from NASA's Earth Data platform at: https://search.earthdata.nasa.gov/search (accessed on February 23, 2024).
- Shuttle Radar Topography Mission (SRTM-DEM), with an approximate resolution of 30 metres between latitudes 60S and 60N. The data can be obtained from NASA's Earth Data (https://search.earthdata.nasa.gov/search, accessed on February 23, 2024) or that of Japan Space Systems (https://gdemdl.aster.jspacesystems.or.jp/index_en.html, accessed on February 23, 2024).
- ALOS World 3D DEM, also obtained by photogrammetry with a resolution of 30 metres and available in the repository of Japan Aerospace Exploration Agency (JAXA) at https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm (accessed on February 23, 2024).
- Copernicus DEM, a Digital Surface Model (DSM) provided in 3 different instances: EEA-10 (European coverage, limited access), GLO-30 and GLO-90. The number after the acronym refers to the resolution in meters. Data were acquired through the TanDEM-X mission between 2011 and 2015, and made available for use in 2019 and can be obtained at https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model (accessed on February 23, 2024).

3.1.2 National or local datasets

National datasets are usually available, either for free or commercially. Each country may have different agencies or even private companies producing and offering elevation models. In commercial products the price is usually proportional to the resolution, i.e., finer resolutions are more expensive.
For instance, in Portugal, the General Directorate for the Territory (DGT) has different products, with different types of access and at different scales. Some examples are:

- DTM of mainland Portugal from 10 up to 200 meters metre spacing, built from the altimetry in vector format (paid). For example, the 25m version can be obtained at (https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/metadata/9c284004-d184-4192-9b70-bce501897b93, accessed on February 23, 2024).
- Digital Terrain and Surface Models with a spacing of 10 metres built from altimetric information of digital aerophotogrammetric.

Copyright © FirEUrisk Consortium. All rights reserved.

- 2-meter DTM of the coastal areas of mainland Portugal (https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/metadata/cc9ce53f-9f41-437b-89a4-80d02e023012, accessed on February 23, 2024), based on LiDAR and photogrammetry (free but with authorship attribution requested).
- Some municipalities offer 2-meter DTM's of their territory, but this is not generalized to all in the country.

Another provider for Portugal is the Army Geospatial Information Centre (https://www.igeoe.pt/, accessed on February 23, 2024), that sells DTM's at different resolutions, built based on vector altimetry.
Another example is the DTM and DSM made freely available by the Spanish Government at resolutions ranging from 2.5 and 200m, and that are based on LiDAR (https://pnoa.ign.es/pnoa-lidar/modelo-digital-del-terreno, accessed on February 23, 2024).

3.1.3 Custom data

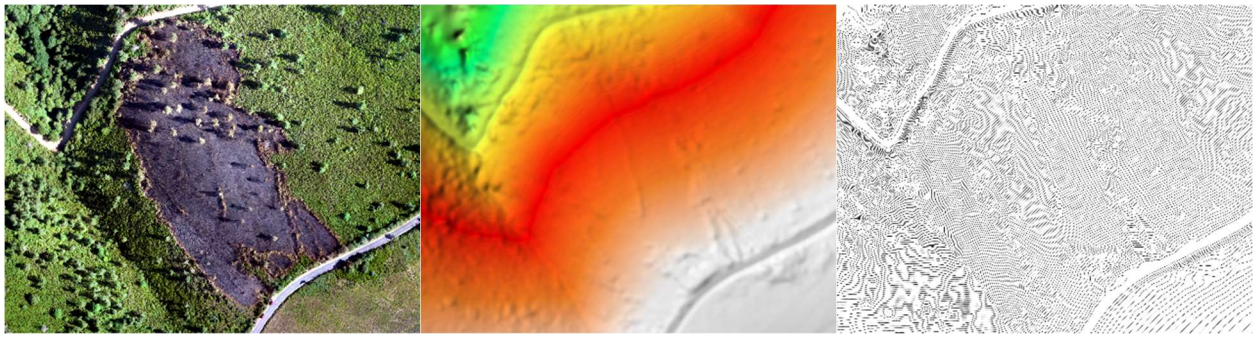
Custom DEMs can be produced with different techniques. One of the most accessible is the use of Digital Information Systems (e.g. ArcGIS, QGIS) to interpolate vector data, like level curves and elevation points, into raster data, producing a digital terrain model at the desired resolution, depending on the input data. Figure 9 depicts an example of a 5-meter resolution DTM custom built from contour levels and elevation points (also shown in the image, for reference), for a small region inside the Pilot Site in the Central Region of Portugal.



Figure 9. Example of a 5m DTM, custom built from level curves and elevation points, also shown on the image.

Copyright © FirEURisk Consortium. All rights reserved.

With the advance of technology, namely the availability of drones and different sensors, custom DTMs and DSMs are nowadays easier to obtain, although producing them at large scale may be a costly task, both in time and money. Even a basic drone that offers the possibility of performing planned flights with image acquisition can be used to, based on photogrammetric techniques, produce high resolution DSMs. Figure 10 shows an example of the usage of drones for the purpose of analysing the terrain in a wildfire propagation. The planned flight mission included capturing perpendicular photos at 1 meter interval, with an 85% overlap between photos in all directions. With post processing it is possible to create: Figure 10a) an orthophoto; Figure 10b) a DSM, here represented by a shaded relief image; and Figure 10c) the contour lines at desired spacing, in this case 1m. In both the DSM and the contour lines it is possible to identify the wildfire scar.

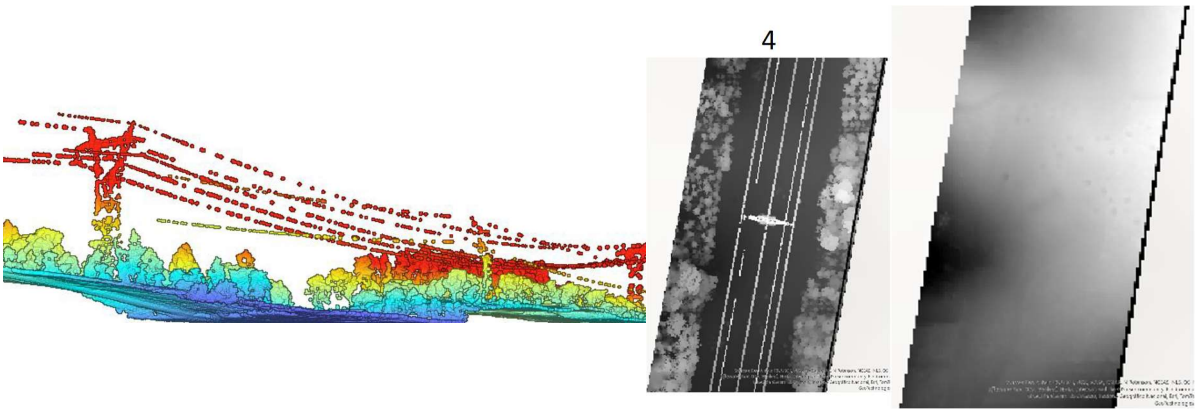


(a) (b) (c)

Figure 10. Example of 10 cm resolution products derived from Orto-photogrammetry applied to images captured with a drone: a) orthophoto, b) shaded relief of a DSM and c) 1 meter contour lines.

Using LiDAR based photogrammetry has the advantage of allowing a relatively fast and easy way of creating custom DSM models over small areas. The major disadvantages are that it is not possible to directly compute DTMs or to cover large areas in a reasonable amount of time. But, if LiDAR sensors are attached to the drones, the first disadvantage can be overcome, as laser pulses can penetrate vegetation and allow the identification of bare ground heights, thus also allowing the production of DTMs. Figure 11 shows an example of: a) 3D view of a LiDAR point cloud capturing a small part of a powerline and its surroundings; b) the DSM produced using the first return of the lidar laser pulses, where all the features are visible (trees, lines, poles) and c) the DTM, produced using the last return, where only the terrain is represented.

Copyright © FirEURisk Consortium. All rights reserved.



(a) (b) (c)

Figure 11. Example of LiDAR data in a power line: a) 3d point cloud; b) DSM; c) DTM.

3.2 Meteorological data

Meteorological information is relevant at all stages of the wildfire investigation: for predicting the conditions leading towards the fire, for choosing the right measures during the wildfire event, and for optimal post-fire restoration activities. The most-important climatic parameters are temperature, wind speed and direction, and precipitation amount. Secondary variables, such as ambient humidity, soil water content, thunderstorm activities, etc, should also be taken into account.

3.2.1 Primary climatic variables (temperature, precipitation, wind)

The accurate and fairly complete sets of primary meteorological variables can be obtained from several sources: in-situ observational network, satellite observations, and weather models. Each source has own strong and weak points, but output of modern meteorological models is arguably the most-appropriate choice in a general case. The meteorological forecasts incorporate in an optimal manner the observational information available for the region and the whole globe, thus practically including the other mentioned information sources, in an aggregated manner. They can also provide forecasting information, thus allowing for planning weeks in advance.

Meteorological forecasts for the whole world are available from several global centres, such as NOAA (https://www.noaa.gov/weather, accessed on February 23, 2024) in the US, JMA in Japan, and ECMWF (http://www.ecmwf.int, accessed on February 23, 2024) in Europe. Not all of them are open to the public. Thus, some ECMWF products are not freely available outside the European meteorological services. The spatial resolution of the global forecasts is, in most cases, sufficient for the general situation awareness. For instance, the ECMWF medium-range (15 days) forecast has ~9km spatial and 1-hour temporal resolution.

For retrospective analysis, several meteorological reanalyses are available, first of all, European reanalysis ERA5 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview, accessed on February 23, 2024), its surface-characteristic derivative ERA5-land (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview, accessed on February 23, 2024), and an American dataset MERRA (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/, accessed on February 23,

Copyright © FirEUrisk Consortium. All rights reserved.

2024). Their resolution (~22 km for ERA-5 and ~10 km for ERA5 Land, for instance), is again sufficient for the broadscale assessment of the situation and wildfire risk. In Japan, the Japan Meteorological Agency offers the JRA-55, with a global reanalysis of 55 years (https://jra.kishou.go.jp/JRA-55/index_en.html, accessed on February 23, 2024).

3.2.2 Supplementary meteorological variables

Apart from the primary meteorological variables, several other quantities can be useful at different stages of the wildfire assessment: ambient humidity, soil water content, probability and intensity of lightning associated with thunderstorms, etc. These variables are available from modern meteorological models described above but not always measured on a routine basis. This also means that the quality of these variables in the model output can be lower or more uncertain than in the case of the primary variables.

3.2.3 Local historical datasets

To assess wildfire propagation a detailed characterization of the wind speed and direction is often needed for the period in which the wildfire occurred. Usually, National Weather Services can be consulted to obtain such data. For example, the Portuguese Institute for Sea and Atmosphere (IPMA) offers different weather services, although most of them related to current and forecasted weather. For instance, on demand forecasts (https://mf2.ipma.pt/continent, accessed on February 23, 2024), online live automatic weather stations (https://www.ipma.pt/pt/otempo/obs.superficie, accessed on February 23, 2024), hourly weather observations (http://multisites.ipma.pt/anpc/observacao-superficie, accessed on February 23, 2024) and a set of API's to implement automatic weather fetching in web services (https://api.ipma.pt, accessed on February 23, 2024). But, more importantly, historical data records can be asked for specific regions, either of observed or predicted weather. Also in Portugal, the National Water Resources Information System (SNIRH) offers data from their hydrological and meteorological stations across the Country https://snirh.apambiente.pt/index.php?idMain=2&idItem=1, accessed on February 23, 2024).

On a different perspective, nowadays personal weather stations are broadly used by many people all around the world. Although the feasibility and accuracy may vary from station to station, there's a lot of data available in different webservices like, for example, the Wunderground website (https://www.wunderground.com/wundermap, accessed on February 23, 2024).

Environmental data

Environmental data comprises the different datasets that allow for the physical characterization of the landscape. This includes not only vegetation, but also all other characteristics that may have a direct or indirect influence in its development.

3.2.4 Land use/cover

One of the most important environmental datasets is related to the description of the vegetation, which, having described orography and meteorology, is the final component of the beforementioned wildfire environment triangle. There are currently several vegetation mapping projects at European or Global level, produced with different

Copyright © FirEURisk Consortium. All rights reserved.

techniques and methodologies, with greater or lesser accuracy and different classification schemes. This is not an exhaustive list of land use/land cover sources, but we refer here some of the most well-known and used, and that are freely available.

Global coverage

These are some initiatives attempting to produce worldwide coverage of land use/cover:

- Copernicus Global Land Cover, at a resolution of 100m, for the period 2015-2019 (https://land.copernicus.eu/global/products/lc, accessed on February 23, 2024). The product uses 23 classes according to the according to the Land Cover Classification System (LCCS) developed by the United Nations (UN) Food and Agriculture Organization (FAO)
- ESRI's Sentinel-2 10m land use/land cover time series of the world. Produced by Impact Observatory, Microsoft, and Esri. This product is composed of 11 classes distinguishing broad groups of land use. It doesn't distinguish species or types of forest, for instance. More information can be obtained at https://www.arcgis.com/home/item.html?id=cfcb7609de5f478eb7666240902d4d3d, (accessed on February 23, 2024). Access to individual 10-meter resolution GeoTIFF scenes, for each year from 2017-2021, can also be downloaded here: https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2 (accessed on February 23, 2024).
- ESA's Worldwide land cover mapping. The European Space Agency offers 2 products, at 10m resolution, both using Sentinel-1 and Sentinel-2 but made with different methodologies, for 2020 and 2021 World cover (https://esa-worldcover.org/en, accessed on February 23, 2024). These products provide 11 classes, defined using the UN-FAO LCCS (Kerchove et al., 2022).
- NASA's Global Land Cover Mapping and Estimation Yearly. This product covers the years 2001 to 2019 at 30 m resolution, derived from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI). More information can be found at https://lpdaac.usgs.gov/products/glance30v001/ (accessed on February 23, 2024).

European coverage

Europe has some of the most advanced and up-to-date datasets regarding land use/cover, some produced by the European Commission, and others from different authors, often in EU funded Projects. Here we describe 3 of them, relevant for the purpose of this document, but other variants exist.

CORINE Land Cover. This is probably the most widely used land cover dataset across Europe and has been available since 1990. The CORINE (COoRdination of INformation on the Environment) foi program was initiated in an attempt to "effort to develop a standardized methodology for producing continent-scale land cover, biotope, and air quality maps" (EEA, 2020). The datasets, at 100m resolution, are available at the Copernicus website, at https://land.copernicus.eu/en/products/corine-land-cover (accessed on February 23, 2024). CORINE has 44 classes (on level-3) in five main land use/cover groups: artificial surfaces, agriculture, forests and seminatural areas, wetlands and water, with a geometric detail of 25 hectares (minimum mapping unit) (EEA, 2020).

Copyright © FirEURisk Consortium. All rights reserved.

FirEUrisk fuel type map. This dataset is worth mentioning because it is one of the results of the project of the same name, under which this document is also produced. The methodology to create it is state-of-the-art and is well described in Aragoneses et al. (2023). The classification system is hierarchical and includes a total of 85 fuel types, grouped into six main fuel categories (forest, shrubland, grassland, cropland, wet and peat/semi-peat land, and urban), plus a nonfuel category. The major drawback, at the moment, of this dataset is that it is produced at 1km resolution, although some regions of Europe, namely the Pilot Sites of the project, have 100m maps. The European dataset is available at https://doi.org/10.21950/YABYCN (accessed on February 23, 2024).

Annual land use and land cover at 30 m (2000–2020), produced by the Open Environmental Data Cube Europe (https://stac.ecodatacube.eu/, accessed on February 23, 2024), combining information from different sources using Machine Learning. This dataset refers to "land use land cover classes for continental Europe based on Ensemble Machine Learning (EML), samples obtained from LUCAS (Land Use and Coverage Area frame Survey) and CLC (CORINE Land Cover) Maps, and several harmonized raster layers (e.g. GLAD Landsat ARD imagery and Continental EU DTM) (Witjes et al., 2022). The dataset, with a resolution of 30m, is available at https://stac.ecodatacube.eu/lcv_landcover.hcl_lucas.corine.eml/collection.json (accessed on February 23, 2024).

National Land use/Land Cover data

Despite the existence of Global or European datasets, most countries opt for also producing National maps, that are usually local adaptations of the former, often with more frequent updates and further refinement of the classes.

Again, using the Portuguese example, the General Directorate for the Territory (DGT), has produced CORINE versions for Portugal, the first one in 1990, with updates in 2000, 2006 and 2012 (Caetano & Marcelino, 2017). At the same time, DGT has been developing National Datasets that are compatible with the CORINE system, entitled "Carta de Uso e Ocupação do Solo (COS)", or Land Use and Cover Map (COS), with the last version being launched in 2018 (Direção Geral do Território, 2019). DGT started the COS production at the same time of the CORINE, in 1990, and updates in 1995, 2007, 2010, 2015 and finally the referred 2018. Nowadays it includes 83 classes in its most detailed level and can be accessed at https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/home (accessed on February 23, 2024). The minimum mapped unit is 1Ha.

In order to increase the frequency of updates, DGT nowadays produces a secondary product which is called "Conjunctural Land Cover Map (COSc)". Differently to COS, which is a vector product, COSc e a raster dataset, produced annually at with a 10m pixel and 15 thematic classes. (Direção Geral do Território, 2022). According to DGT, "Its production is based on spatial technologies and Artificial Intelligence with machine learning algorithms and expert rules to automatically classify multispectral and multitemporal series of Sentinel-2 satellite image data".

Fuel Maps

In order to analyse fire behaviour, more specifically, to simulate fire propagation, the vegetation needs to be quantified with physical parameters that serve as input to fire behaviour propagation models. This term is mostly associated with the Rothermel surface fire propagation model (Rothermel, 1972). There are two widely used sets of fuel models, both developed in the USA but adopted worldwide, either in its original form or adapted. These are the original set of 13 models, or NFFL models (Anderson, 1982) and the expanded set of 40 by Scott & Burgan (2005). Mapping fuel models is a very complex task, as it involves extensive field work to characterize the vertical composition of a fuel bed, although

Copyright © FirEUrisk Consortium. All rights reserved.

it may be facilitated by the photo guides that are included in the two publications mentioned. Usually, different techniques are used to try to reclassify land use/cover maps into fuel maps, with or without the use of other auxiliary data. In many cases, a set of rules is defined in order to allow the update of fuel maps whenever new versions of land use/cover are also produced.

The European Union, through the Joint Research Centre, offers a European Fuel Map in the European Forest Fire Information System (EFFIS) platform (https://effis.jrc.ec.europa.eu/about-effis/technical-background/fuels, accessed on February 23, 2024). This map was "derived in the context of JRC Contract Number 384347 on the "Development of a European Fuel Map." Although the original map contained 42 vegetation complexes, these were assigned to the 13 categories of the NFFL or fire behaviour models (Anderson, 1982). The last three categories of the NFFL models are not used in the European Fuel Map".

The before mentioned FirEUrisk fuel type map may also be reclassified into fuel models, using the crosswalk proposed by its authors, either for the 13 NFFL or the 40 Scott&Burgan models Aragoneses et al. (2023).

In many countries, in particular in the Mediterranean Basin, National or local fuel maps are produced, mostly also by reclassifying National or local land cover/use maps. In Portugal at the moment there is no official National fuel map, but the vast majority of the municipalities have local maps, produced under specific guidelines of ICNF (AFN, 2012). Sá et al. (2023) recently developed a methodology for producing a fuel map for Portugal, creating a tool called FUMOD that consists of a set of sub-models that run using ArcGis' ModelBuilder and allow the map to be updated whenever there is new input data. The methodology combines a series of maps and data with the knowledge of the researchers. The resolution is 100 metres and both the map, and the tool are available at https://github.com/anasa30/PT_FuelModels (accessed on February 23, 2024).

3.2.5 Lithology

The European Geological Data Infrastructure (EGDI) provides access to Pan-European and national geological datasets and services from the Geological Survey Organizations of Europe (https://www.europe-geology.eu/, accessed on February 23, 2024). EGDI hosts a large amount of geological information, that is mostly the outcome of different research projects on geoscientific themes. Compiling and deriving information from here, Hengl (2021) shared a "Continental Europe surface lithology based on EGDI / OneGeology map at 1:1M scale" at https://zenodo.org/records/4787632 (accessed on February 23, 2024).

The European Commission INSPIRE Geoportal also offers Geological data, for some of the member states, with different levels of detail at:

https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=themeOverview&theme=ge (accessed on February 23, 2024). Some States don't share data to download, but they share metadata and contacts for the information providers.

3.2.6 Hydrography

River and drainage networks can be derived from topographic products, with GIS techniques, albeit this process needs an accurate revision, as not all features that may have water do in fact have it. This is also a fairly easy dataset to obtain,

Copyright © FirEUrisk Consortium. All rights reserved.

as many services or institutions make it available. At a European level, Copernicus Land Monitoring Service offers a EU-Hydro River Network Database, based on "photo-interpreted river network, consistent of surface interpretation of water bodies (lakes and wide rivers), and a drainage model (also called Drainage Network), derived from EU-DEM, with catchments and drainage lines and nodes https://land.copernicus.eu/en/products/eu-hydro/eu-hydro-river-network-database, accessed on February 23, 2024). This dataset has a Minimum Mapping Unit (MMU) of 1 ha.
The INSPIRE Geoportal offers hydrography data at:
https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=themeOverview&theme=hy
(accessed on February 23, 2024). Some States don't share data to download, but they share metadata and contacts for the information providers.
The Food and Agriculture Organization (FAO) offers a dataset of the rivers of Europe based on GIS analysis, at:
https://data.apps.fao.org/catalog/iso/e0243940-e5d9-487c-8102-45180cf1a99f (accessed on February 23, 2024).

3.2.7 Protected natural areas

The best way to obtain spatial information related to sensitive areas, like National or Natural Parks, Protected Sites, and similar, is by searching the respective Countries' National Institutes or Organisms in charge of Nature Protection or Forest Management. For instance, in Portugal ICNF shares this information in their web geo-catalogue, at https://geocatalogo.icnf.pt/catalogo.html (accessed on February 23, 2024).
There are some EU level compilations of such information, like for instance the already mentioned INSPIRE Geoportal, where some countries share their repositories (https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=themeOverview&theme=ps accessed on February 23, 2024).
The EFFIS also has a downloadable layer entitled "Protected Areas Layer", available at:
https://effis.jrc.ec.europa.eu/applications/data-and-services (accessed on February 23, 2024).

3.2.8 Human settlements

The spatial arrangement of human settlements in the landscape is crucial to understand some aspects related to wildfire management actions in wildfire analysis. Most commonly firefighting teams need to be deployed wherever there is human presence to ensure their protection when the fire front passes. Also, any evacuation action that needs to be put in place depends on a well performed planning that needs not only the knowledge of the road network infrastructure, but also all the inhabited places.
This layer of information can be derived from the land use maps, using the urban areas classes, but their coverage degree will be determined by the scale at which land use/cover is produced.
The location of the populated places or human settlements is easy to visualize in any web map application like Google Maps, OpenStreetMap or Bing Maps, but it is useful to have a spatial layer to incorporate in GIS analysis. For that purpose, National or local datasets should be pursued in each Country's Institutions. In many cases there are layers of Built-up areas, that are composed of polygons of the constructed areas, but in others only a point shapefile, where each point represents a populated place. For example, in Portugal DGT offers both datasets: built-up areas (https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/metadata/4cb8ce5d-3231-4d42-bbac-b2447e936104,

Copyright © FirEURisk Consortium. All rights reserved.

accessed on February 23, 2024) and populated places at 1:200 000 scale (https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/metadata/57479cf3-df10-47a0-9860-f7e3157596b1, accessed on February 23, 2024).
EFFIS offers a "Human Settlement Layer", that is available at https://effis.jrc.ec.europa.eu/applications/data-and-services (accessed on February 23, 2024).

3.3 Infrastructure characterization data

Data related to infrastructures can be complex to obtain. Some information may be available freely, but other is in many cases sensitive data that is not made available to the general public. Some of the information is relevant for the analysis of fire progression but other may be relevant for the damage assessment phase. For instance, the road network or water source's location is useful for understanding firefighting displacement and strategies, fuel management to understand its relative impact on fire behaviour and structures characterization and maintenance assessment to understand how the wildfire impacted on communities. Regarding this last information, one possibility to obtain it is to have public participatory actions in the affected areas, using one of the multiple web tools available nowadays. For example, in a specific action of FirEUrisk, we developed a questionnaire aimed at analysing the impact of the major European fires of 2021 on infrastructures. For that we set up an ArCGIS web survey, which allows to easily georeferenced a place and connect it to a set of previously defined questions. The mentioned example can be viewed at https://arcg.is/1OCi1K (accessed on February 23, 2024).

3.3.1 Road network

Like the human settlements, this information can be viewed on any of the web map platforms identified earlier. Obtaining GIS layers may be achieved through the OpenStreetMap platform, using the Geofabrik download portal (https://download.geofabrik.de/, accessed on February 23, 2024).
To obtain more accurate data, especially including secondary roads, forest or mountain roads, and other that may not be found freely online, it may be necessary to contact different National or Regional Institutions. For instance, in Portugal one can contact ICNF, DGT or the Municipalities to ask for detailed data.
The INSPIRE Geoportal offers transportation network related data at:
https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=themeOverview&theme=tn
(accessed on February 23, 2024). Some States don't share data to download, but they share metadata and contacts for the information providers.

3.3.2 Fuel management network

Fuel management networks planning, execution and management, as well as the entities or organisms responsible for it, may vary from Country to Country. As far as we know, there are no European or Global datasets depicting the fuel management networks implemented, as this is a dynamic dataset. These layers need to be obtained at National, Regional or Local level. In Portugal fuel management has different levels of planning and management, being divided

Copyright © FirEUrisk Consortium. All rights reserved.

in primary, secondary and tertiary. The Portuguese Agency for Integrated Rural Fire Management (AGIF) makes the following distinction AGIF (2023):

- The primary is implemented at the landscape level and is composed of the larger strips of 125m, with the objective reducing the area covered by large wildfires, enabling and facilitating direct firefighting intervention and aiming to establish favourable firefighting conditions in strategic locations in rural areas. This dataset can be obtained at the ICFN Geocatalogue (https://geocatalogo.icnf.pt/catalogo.html accessed on February 23, 2024).
- The secondary network is composed of smaller strips, varying from 3 to 100m, depending on the feature. It serves the purpose of reducing the effects of wildfires, passively protecting communication routes, infrastructure and social facilities, built-up areas and forest and agricultural patches of special value. It also fulfils the function of isolating potential wildfire ignition points. This information is produced locally by the municipalities and under specific guidelines produced by AGIF (2023) and can be obtained at https://fogos.icnf.pt/infoPMDFCI/PMDFCI_PUBLICOlist.asp (accessed on February 23, 2024).
- The tertiary is of local implementation and design fulfilling the function of isolating potential sources of wildfire ignition and is made up of the road networks, divisions and other infrastructures of the local forestry or agroforestry management units.

3.3.3 Firefighting infrastructures

As in the previous point, and as far as we know, spatial data related to firefighting infrastructures is not publicly available at a European or Global level. National, Regional or Local datasets must be pursued when analysing wildfires. We provide here the Portuguese example, to serve as a guideline.

Water sources

Water sources are usually categorized in terrestrial, aerial or mixed, and subdivided in first and second order, if they are accessible both to terrestrial and aerial means or just terrestrial, respectively. The water sources network and the individual specifications of each one can be consulted freely in https://fogos.icnf.pt/sgif2010/PublicoInfraPontosAgualist.asp (accessed on February 23, 2024). Spatial datasets for GIS analysis can be downloaded at ICNF's Geo-catalogue (https://geocatalogo.icnf.pt/catalogo.html, accessed on February 23, 2024).

Firefighting resources

The location of terrestrial firefighting headquarters and aerial means bases is not available as a spatial data layer at a European or Global level. Nevertheless, this type of information is usually available at the National Civil Protection services. Taking again the example of Portugal, the location of firefighting operational infrastructures is not publicly available, but can be requested, if justifiable, to the Civil Protection authorities. This is valid for volunteer and professional firefighters. The Portuguese National Firefighters League (LBP) lists on their webpage the postal addresses of all their associates, which are basically all the volunteer firefighter associations of the Country. The National Republican Guard (GNR) is also involved in firefighting, especially in aerial and terrestrial first intervention, but being a

Copyright © FirEUrisk Consortium. All rights reserved.

military unit there may be some restrictions in sharing this kind of data. As for the Aerial Mean Centres (CMA), their geographic coordinates are available in the National Operational Directive no.2 - DECIR (Special Directive for Fighting Rural Fires) from the National Emergency and Civil Protection Authority (ANEPC) (https://prociv.gov.pt/media/xgnjpypf/don02_2023_final__.pdf, accessed on February 23, 2024).

3.4 Earth observation imagery and derived products

Satellite imagery is the basis for many of the landscape analysis performed in current days. There are specific wildfire related products and generic ones that allow for very detailed analysis and the computation of different indexes. We describe here some of them.

3.4.1 Copernicus Emergency Management Service

Copernicus is a European programme focussed on developing information based on satellite observations about the state of the environment on land, sea and in the atmosphere, to support climate change mitigation and adaptation strategies, the efficient management of emergency situations and the improvement of the security of every citizen.
Within the six Copernicus Services that offer free and open information to the Users, the Copernicus Emergency Management Service (EMS, https://emergency.copernicus.eu, accessed on February 23, 2024) provides a rapid mapping service in cases of natural disasters, human-made emergency situations and humanitarian crises throughout the world, such as, floods, landslides, wildfires or volcanic eruptions. Rapid Mapping provides geospatial information within hours or days from the activation following a disaster in support of emergency management activities. In the case of fires, standardised mapping products are provided to roughly identify and assess the most affected areas (first estimate product), assess the geographical extent of the event (delineation product) or to evaluate the severity of the damage resulting from the event (grading product).
The activation of the EMS can be triggered only by or through an authorised user. Authorised Users include National Focal Points (NFPs) in the EU Member States and countries participating in the Copernicus programme, as well as European Commission services and the European External Action Service (EEAS). Therefore, the EMS service doesn't cover all the wildfires occurred in the European region as they operate on-demand. However, the service offers detailed, free-of-charge information in a timely manner of the extreme wildfires occurred in Europe and internationally. For more information you can browse the list of activations here: https://emergency.copernicus.eu/mapping/list-of-activations-rapid (accessed on February 23, 2024).

3.4.2 Active wildfire detections from MODIS/VIIRS sensors

Active wildfire detections (hotspots) derived from satellite Earth Observations are a very common product used to monitor fire activity. The commonly used and easy to access active fire products freely available are the MODIS and VIIRS active fire products. Both products are available to download form the FIRMS service (https://firms.modaps.eosdis.nasa.gov/download/, accessed on February 23, 2024).

Copyright © FirEURisk Consortium. All rights reserved.

The MODIS active fire product has a spatial resolution of 1 km and offers a temporal coverage from November 2000 to present. However, the satellites carrying the MODIS sensor, Terra and Aqua, are currently over their lifetime which produced changes in the orbit on one hand and on the other hand the sensor is also degrading. The last reports from the NASA Science Team estimate the Terra and Aqua could offer quality observations until 2025. From that date the continuity of the product is uncertain.

The VIIRS active fire product offers two spatial resolutions, 750m and 375m (Schroeder et al., 2014). The product at 750 m follows the same algorithm as the MODIS active fire product, while the 375 m operates on an improved algorithm which enables an enhanced sensitivity to small wildfires. The VIIRS active fire product offers a temporal coverage from 2012 to present. The VIIRS sensor was first launched onboard the Suomi-NPP satellite in January 2012 as part of an exploratory mission to ensure the continuity of Earth Observations. The continuity of the active fire product is secured as the VIIRS sensor is also onboard the satellites NOAA-20 and NOAA-21 launched in January 2020 and 2024, respectively.

3.4.3 Sentinel data for burned area burn severity mapping

We recommend the use of Sentinel-2 data for a detail analysis of the extent and damage produced by the wildfires. The Sentinel-2 mission consists of two identical satellites, Sentinel-2A and Sentinel-2B, that were launched in 2015 and 2017 with an orbit phased 180° to ensure higher frequency of acquisitions over the same area (5-8 days) (Gascon et al., 2014). The MSI instrument onboard the Sentinel-2 satellites offer information at 10, 20 and 60 m of spatial resolution. The spectral bands used for burned area assessment operate at 20m resolution. The Sentinel-2 data can be downloaded free of charge from Copernicus browser (https://browser.dataspace.copernicus.eu/, accessed on February 23, 2024). The browser offers several options for image visualization and precalculated vegetation indices which are used for burned area identification.

To produce burn severity mapping we suggest calculating the difference Normalized Burn Ratio (*dNBR*). The *dNBR* has established as a standard procedure to compute burn severity from satellite data since its implementation by the *USGS* (Lutes et al., 2006). The *dNBR* is computed as the temporal difference of NBR from before (t_1) and after (t_2) the wildfire:

$$dNBR = NBR_{t_1} - NBR_{t_2} \qquad \text{[Eq. 4]}$$

The Normalized Burn Ratio (*NBR*), which is a spectral index closely related to post-fire effects is defined by:

$$NBR = \frac{\rho_{SWIR} - \rho_{NIR}}{\rho_{SWIR} + \rho_{NIR}} \qquad \text{[Eq. 5]}$$

Where *ρNIR* and *ρSWIR* refer to the reflectance values in the *NIR* and *SWIR* bands, respectively. When calculating the index from Sentinel-2 images we recommend using band 8A for the *NIR* band and band 11 as the *SWIR* band.

Once the difference was computed, the severity levels were classified using intervals based on the standard intervals applied by the *USGS* (Lutes et al., 2006) (Table 1).

Copyright © FirEURisk Consortium. All rights reserved.

Table 1. Burn severity classes derived from dNBR values obtained from Sentinel 2 data.

Severity level	*dNBR* range
Unburned	-0.1 - 0.99
Low severity	0.1 - 0.26
Moderate severity	0.27 - 0.469
High severity	0.47 - 0.66
Extreme severity	> 0.66

3.4.4 National or custom datasets

Currently, there are several sources that provide burned area (BA) perimeters. There are two types of burned area products: i) near-real time BA products that are available a few days after the fire is extinguished, and ii) processing BA products that are available a few months after the wildfire season finishes. The first type is produced by visual interpretation of high and medium resolution images and is useful for a rapid assessment of the damage produced by the wildfire. On the other hand, the second type is produced from the application of classification algorithms on remote sensing images of medium and coarse resolution. Those processed burned area products are indicated for a more detailed analysis of all the wildfires occurred in a region.

Regarding the first type, the main source of data comes from the Copernicus emergency management service, described in section 4.6.1, and the European Forest Fires Information system (EFFIS). In the last years, EFFIS has been providing information on Fire Danger Forecast, active wildfires and burned areas from MODIS and VIIRS satellite data. During the wildfire season they also offer near real-time burned area perimeters obtained from Sentinel-2 data at 20 m resolution (https://effis.jrc.ec.europa.eu/applications/data-and-services, accessed on February 23, 2024).

For the second type of burned area product the FireCCI burned area products offer a possibility to obtain the burned area perimeters at several spatial resolutions. The global products are FireCCI51 and FireCCIS311, with a coarser resolution product (FireCCILT11) also available (https://climate.esa.int/en/projects/fire/, accessed on February 23, 2024). There are also two burned area products, only for sub-Saharan Africa, available at a finer resolution. Table 2 shows the characteristics of each of these datasets.

Table 2. Characteristics of the FireCCI burned area products. SR: Surface Reflectance; HS: hotspots.

	FireCCI51	**FireCCIS311**	**FireCCILT11**	**FireCCISFD11**	**FireCCISFD20**
Coverage	**Global**			**Sub-Saharan Africa**	
Time series	2001-2021	2019-2022	1982-2018 (gap 1994)	2016	2019
Pixel resolution	250m	300m	0.05 deg.	20m	20m
Grid resolution	0.25 deg.	0.25 deg.	0.25 deg.	0.25 deg.	0.05 deg.
Input information	MODIS (SR & HS)	Sentinel-3 SYN (SR) + VIIRS (HS)	AVHRR LTDR (SR)	Sentinel-2A (SR) + MODIS (HS)	Sentinel-2A&B (SR) + VIIRS (HS)

Copyright © FirEUrisk Consortium. All rights reserved.

At National level, European countries operate in different ways. Portugal has a service which produces the burned area perimeters from satellite data and uploads them to an online catalogue (https://geocatalogo.icnf.pt/catalogo.html, accessed on February 23, 2024). However, the perimeters are produced at the end of the wildfire season and updated in spring of next year. So, they cannot be used for a real-near-time analysis of wildfire damage.

Similarly to Portugal, Greece also has a service at Nacional level that provides wildfire perimeters from satellite data at 20 m resolution. Although they are not freely available, they can be requested to the Greek Ministry of Environment and Energy.

In Spain, there isn't a service that provides wildfire perimeters at National level, the provinces are responsible for providing the wildfire report after the wildfire is controlled or extinguished. Part of those reports include the delimitation of the area affected by the wildfire. For the province of Catalunya, the reports can be found in https://interior.gencat.cat/ca/arees_dactuacio/bombers/foc-forestal/incendis_forestals/ (accessed on February 23, 2024). The Generalitat Valenciana also provides the wildfire reports in a timely manner (https://cjusticia.gva.es/va/web/prevencion-de-incendios/informes-post-incendio, accessed on February 23, 2024). Even though the information exits, the wildfire perimeters are not easily available for download.

3.5 Statistical data

Although general information on demographics, economy, or housing, among others, can be obtained at EU level searching Eurostat (https://ec.europa.eu/eurostat, accessed on February 23, 2024) it is usually easier to search for it at National level, as National Institutes will most certainly have more detailed census. Among other publicly available information, Eurostat has some geographical data available, for instance some basic statistics at https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data (accessed on February 23, 2024).

In Portugal, the National Statistics Institute (INE) offers data referring to the last 3 National census (1991, 2001 and 2021) both as tables and georeferenced information. This last one can be downloaded at https://mapas.ine.pt/download/index2011.phtml (accessed on February 23, 2024).

Copyright © FirEUrisk Consortium. All rights reserved.

4 Data mining, process and analysis

4.1 Useful tools

In a WUI post-fire scenario, it is necessary to capture reality as quickly and accurately as possible. The enormous amount of details and the complexity of the scene make the task of manually obtaining all relevant information for subsequent analysis practically impossible. Fortunately, technology developed in recent years can be of great assistance.

4.1.1 Spherical photography

Nowadays, the common use of 360° cameras that capture immersive photos and videos for VR applications is widespread. In this market, there are more affordable consumer alternatives (Insta360 X3, GoPro Max, Ricoh Theta X), an intermediate segment for multimedia and scientific applications (Xphase pro S2/X2, Z CAM S1 6K, Labpano Pilot Era 8K, Insta360 Pro 2, Kandao Obsidian R), and more professional and, of course, much more expensive versions (Insta360 Titan 11K, Kandao Obsidian Pro 12K). These cameras capture two or more hemispherical images that, with the help of specialized software, compose a single image in a spherical projection. These resulting images are viewed with specific applications that utilize VR headsets, providing the user with the sensation of being in the scene where they were taken.

An alternative method, simple yet highly useful, involves capturing a 360° mosaic of images using a regular camera or, more interestingly, a mobile phone or tablet. There are applications (such as Hugin, AutoStitch, Autopano Pro, GigaPan Stitch) that assemble this mosaic into a spherical panoramic image. While the two-dimensional interpretation may not convey much, when projected onto the interior of a 3D spherical object, it allows for the immersive recreation of the exact environment at the point of capture.

Some experiences conducted with this technology involve using these immersive images on the interior of large 3D spheres in immersive environments. This is relatively easy to implement on game development platforms like Unity or Unreal Engine, allowing subsequent placement of the observer inside and projecting the result onto virtual reality (VR headsets). For the development of these immersive experiences, it is crucial to know in advance the necessary resolution for each eye, providing a compelling immersive experience. This resolution is determined by the screens used in the VR headset, which, in the case of modern Meta Quest 3, is 2208 pixels per eye. Since this is the maximum native resolution of the hardware, it will also be the target resolution for capturing spherical images, considering the need to provide the same resolution to each eye. For example, for the mentioned Meta Quest 3, the resolution per eye is 2064 x 2208 pixels, requiring capturing a spherical photograph of 4128x4416 pixels. Nowadays, it is not necessary to have an expensive 8K or 12K spherical camera, as a regular camera, mobile phone, or tablet can construct a high-resolution image from a 360° mosaic, as mentioned earlier.

Copyright © FirEURisk Consortium. All rights reserved.

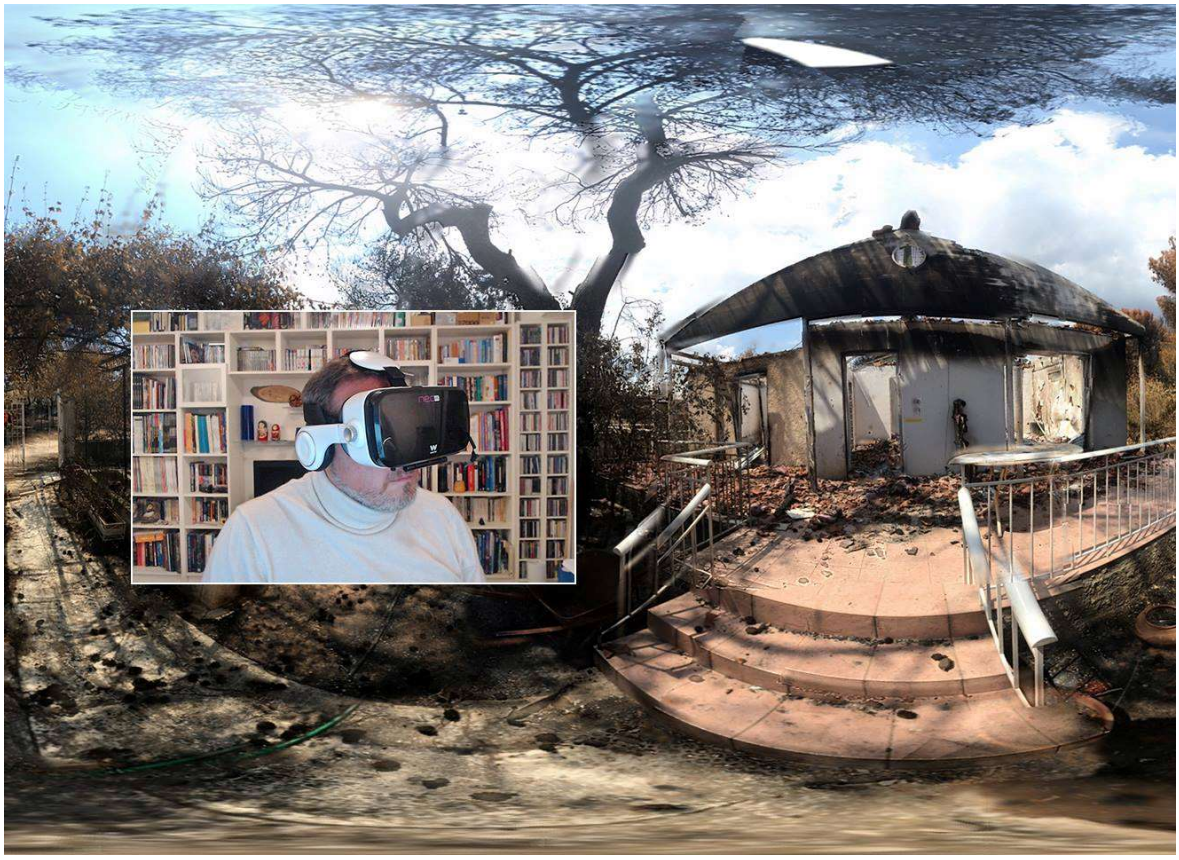


Figure 12. Example of a spherical image taken during the Mati wildfire in 2018. An iPad and a panoramic stitching application were used for this purpose. The result was employed in the subsequent analysis by visualizing it with a VR headset.

The benefits of this technology are undeniable for the forensic study of post-fire scenarios: they capture a very complex reality with great detail and in a very short time. This allows for capturing immersive photographs at many points in the affected area and later analysing it in detail in the laboratory. In some specific cases, capturing immersive videos is justified, but generally, using spherical photographs is more than sufficient in most instances. The portability of the equipment used is more important, for example, as it is necessary to move quickly through an unstable and dangerous scene. The use of a tripod is recommended but not strictly necessary.

4.1.2 Photogrammetry, NERF and Gaussian Splatting

On many occasions, it is also necessary to have precise measurements of the post-fire scene, including distances, volumes, shapes, relative positions, etc., which will be used in subsequent forensic analysis. For this, the use of three-dimensional restitution technology through photogrammetric methods is paramount. Essentially, photogrammetry involves identifying points in space from sets of images obtained from different perspectives. This collection of points can later be used to generate three-dimensional objects with their exact position, orientation, and scale.

Copyright © FirEUrisk Consortium. All rights reserved.

Today, photogrammetry applied to the analysis of WUI post-fire scenes can be performed using images taken with a mobile phone or a regular camera. However, the results obtained, while visually correct, do not allow for precise dimension analysis. For this, it is necessary to have some method of positioning the photographs, that is, knowing the exact location in space from where the photograph was taken, as well as the orientation of its optical axis. Another alternative is to include a reference in the scene whose position is known with precision, such as coded targets, to which all the photographs taken can be referred. However, it is necessary to remember that in the process of capturing information in a WUI post-fire scene, a high degree of mobility must be maintained, and, to the extent possible, avoid deploying devices that are cumbersome or complicated to use.

Recently, two new technologies have emerged in the field of volumetric capture and representation of reality, Neural Radiance Fields (Nerf), and Gaussian Splatting.

Neural radiance fields (Nerfs) employ AI models to produce new perspectives of a specific 3D scene. Unlike photogrammetry, Nerfs don't need an extensive array of images. Instead, they employ a neural network trained with a set of input images to predict the colour and visual attributes of the scene from various viewpoints. Nerfs prove beneficial in scenarios where capturing real-world scenes from different perspectives is difficult or time intensive. One significant advantage of Nerfs lies in their capacity to produce realistic and high-quality visualizations of scenes, especially in handling intricate lighting conditions and delivering precise colour representations. However, Nerfs come with limitations related to metric accuracy and the capability to capture scene context. Additionally, their training demands substantial computational resources, making them less accessible for those without expertise in the field.

Gaussian splatting is a rendering technique in real-time that employs point cloud data for generating a volumetric depiction of a scene. Unlike photogrammetry and Nerfs, Gaussian splatting doesn't necessitate a mesh model. Instead, it leverages the positions and attributes of individual points to visualize a scene. The Gaussian splatting process includes projecting points onto an image plane, where each point takes the form of a splat. The attributes of the points govern both the size and opacity of the resulting splats. These individual splats are then blended together to craft the final image. Gaussian splatting is widely utilized in real-time applications, notably in realms such as video games and virtual reality environments. This technique offers interactive and dynamic rendering capabilities, providing users with the ability to explore scenes from various vantage points. Beyond its real-time rendering prowess, Gaussian splatting plays a crucial role in preserving the spatial intricacies of point cloud data, enabling the accurate measurement and representation of complex scenes. The primary strength of Gaussian splatting lies in its capability for real-time rendering, making it well-suited for interactive applications. Additionally, it possesses the capacity to capture and depict expansive scenes with intricate geometry. Nevertheless, Gaussian splatting might not achieve the photorealistic aesthetics of photogrammetry or the innovative viewpoint generation seen in Nerfs. Efficient point cloud processing algorithms are also essential for maintaining smooth frame rates during implementation.

In the coming years, we will witness significant advancements in the implementation of these technologies, particularly their integration with mobile devices such as phones or tablets, thereby adding greater flexibility and versatility. Indeed, capturing post-wildfire WUI scenes on the ground or from drones can be done swiftly, allowing for subsequent detailed analysis in the lab from various perspectives. It's worth noting, however, that both Nerfs and Gaussian splatting do not provide three-dimensional objects, unlike photogrammetry; instead, they behave like highly detailed visual

Copyright © FirEUrisk Consortium. All rights reserved.

backgrounds. In essence, if a detailed reconstruction of three-dimensional objects is required, photogrammetry must be used; in other cases, generating volumetric representations with Nerfs or Gaussian splatting is sufficient.

4.1.3 Drones

Undoubtedly, drones are excellent allies for obtaining images of a post-fire scene, thanks to the advantageous perspective provided by aerial views. Indeed, oblique photographs help capture and understand the spatial relationship between objects, especially between vegetation and buildings. It also allows for a complete three-dimensional reconstruction of structures, vegetation, topography, and all objects and materials distributed in the plots. Similarly to what has been explained in the 360° photography section, it is possible to create immersive images from photographs taken by drones, although the upper hemisphere makes less sense as it corresponds to the sky.

In the protocol for collecting information in WUI post-fire scenarios, the restrictions, and regulations on drone use in the countries and regions where work is being conducted must be included. Indeed, each EU country has developed regulations for drone use based on their maximum take-off weight (MTOW) and in accordance with limitations imposed by airspace control in the area of interest. There are also regulations for drone use in disaster areas or specialized use in search and rescue operations or advisory roles in firefighting activities. It is also necessary to design information capture missions, conduct a security study, and communicate the plan to the local competent authority as well as air traffic controllers in the area of operation. Simultaneously, it is necessary to consult limitations and regulations regarding the use of personal data, particularly regarding photos and videos taken on private properties, sensitive infrastructures, and facilities. Exceptionally, the purpose of the missions can be argued, and restricted use can be agreed upon by the analysts conducting the forensic study.

In recent wildfire experiences, the versatility of using small drones (Type A1, weighing less than 250 grams MTOW), such as the Mavic Mini 3 Pro, has been proven. These drones exhibit excellent flight capabilities, great agility, and reasonable image quality for obtaining small-scale photogrammetric products. For more extensive tasks, such as surveying a large area affected by wildfires, it is necessary to use more sophisticated and heavier drones, like the DJI Matrice 300 with precision RTK positioning (9 kg MTOW). This drone allows for flight programming and capturing photos with positioning accuracies between 3 and 5 cm. However, the use of these devices requires detailed planning and a safety study, and often their use is restricted and must be carried out by qualified operators. In our experience, the use of such heavy drones also necessitates traffic control by local police, which can be an inconvenience for residents and should be taken into account.

4.2 Reconstruction of events

4.2.1 Visual simulation of the integrated events (wildfire, operations, victims, house destruction)

Using the 3D reconstructions of objects in WUI post-fire scenes, it is possible to create 3D visual simulations of the events based on testimonies, videos, photographs, and measurements. The first step to carry this out is to organize the events in a timeline grid to understand the relative timing and simultaneity of some of them. It is suggested that the temporal resolution of this grid be one minute.

Copyright © FirEUrisk Consortium. All rights reserved.

Likewise, it is necessary to record the position of each element with the utmost precision possible. The positions of static elements, such as buildings, infrastructure, installations, and landscape features, can be more easily reconstructed. The positions of all mobile or dynamic elements, such as the flame front, smoke, people, or vehicles, must be approximated from testimonies, photographs, or videos. Nowadays, the ubiquity of mobile phones, with geolocation based on multiple positioning networks (GPS, GLONASS, Galileo, etc.), facilitates photographs taken with these devices to record the moment and position with acceptable resolution. Therefore, collecting as many photographs as possible and inserting them into the timeline grid facilitates event identification. These tedious and repetitive tasks can be replaced by AI routines that perform the capture and analysis automatically.

Once the position and moment of each element in the scene are known, it is possible to perform 3D reconstructions in visualization and rendering programs (Blender, 3D Studio Max, Maya) or in 3D experience and game development tools (Unity, Unreal Engine, Cry Engine, Lumberjack, Godot), including lighting effects. In 3D reconstructions of wildfire scenarios, perhaps the most complex part is representing smoke and fire, as these are non-geometric elements. Various techniques exist for this, ranging from using billboards to volumetric simulation of smoke and flames based on CFD simulations and rendering using sophisticated ray marching techniques.

The resulting scenes can be projected onto VR devices, such as headsets or immersive CAVE installations, allowing multiple users to share and discuss the details of the scenario's evolution in the same experience.

4.3 Animated timeline

Since the moment and position of the elements present in the wildfire scenes are known, thanks to the reconstruction of events and their inclusion in a timeline grid, it is possible to animate the movements in a synchronized manner and thus understand the evolution of the scene.

For simulating the evolution of the flame front, it is necessary to have at least the isochrones of the fire evolution, interpolating between the obtained lines. This allows obtaining a continuous progress of the evolution that can be saved as frames and subsequently projected onto a digital terrain model.

The simulation of vehicle movement can be obtained from some known positions and moments, programmed as keyframes, and reproduce their displacement through interpolation. This was carried out, for example, in the reconstruction of the movements of the vehicles involved in the Guadalajara accident (Spain) in July 2005, which served as expert evidence in the instruction of the relevant trial.

4.4 Integration in immersive environments

In more sophisticated versions of visual simulation, it is also possible to replace 2D representations of flame front propagation with iconized 3D representations of flames, thus capturing the geometry, particularly the height and angle. Regarding smoke, capturing the position and density of smoke columns, as well as their evolution, is challenging. While some techniques are based on measurements from planes with dedicated sensors, it is more practical to attempt photogrammetric reconstruction from photographs taken at ground level and from the air. Alternatively, visual simulation of smoke production and dispersion from the flame front position at each moment is suggested. This can be achieved using dedicated applications that employ simplified CFD solvers but generate highly convincing iconizations

Copyright © FirEUrisk Consortium. All rights reserved.

of smoke columns. Ambient smoke can be simulated as volumetric exponential fog, as explored in some VR experiences.

The final rendering can be carried out in the form of videos on the mentioned visualization platforms, including lighting effects and special effects (ambient smoke). One of these platforms, commonly used for digital game development, is Unreal Engine (UE), which allows integrating all elements into scenarios that unfold over the timeline. In the domain of wildfires, the challenge is to reproduce flames and smoke as faithfully as possible, as well as special behaviours typically associated with extreme fire behaviour, and their georeferenced representation in the landscape. MeteoGRID has developed some advanced visual simulation techniques in Unreal Engine for wildfire reproduction, with appropriate parameterisation of the fluid dynamics models used to represent flame geometry and smoke production according to reality. The resulting models are georeferenced and integrated with the CESIUM service, which offers a digitized version of the world.



Figure 13. Example of a wildfire reconstruction using numerical CFD models and its integration into Unreal Engine with the CESIUM plug-in, which provides access to Google tile services. The georeferencing has been precise in order to analyse the position and intensity of the fire at each point.

4.4.1 Reconstruction of specific events (accidents, operations)

In wildfires, especially those affecting the WUI, significant events, accidents, or operations occur from which lessons can be learned. In these cases, it is necessary to dedicate one or more days to gathering information at the scene of the incident, preferably as soon as possible so that relevant evidence and traces do not disappear. In the case of accidents resulting in fatalities or serious injuries, it will be very important to collect testimonies, measurements, and visual material and insert it into a table that locates them in time and space. With this data, it will be easier to reconstruct accurately what happened, especially if 3D technologies, as mentioned, are used.

Copyright © FirEURisk Consortium. All rights reserved.

For example, Unreal Engine has been used for forensic reconstruction of accidents and events requiring visual reconstruction of facts in legal proceedings. Some companies have developed technologies and methods based on UE for event reconstruction, such as Intervoke Forensic Animation (www.intervoke.com).

4.5 General advices

From the experience gained in some of the most significant wildfires in Europe in recent years, some tips and tricks can be drawn that may be useful.

- Plan your routes in advance. If the scenario is very large, divide the area into subzones and apply a method to identify each zone (for example, a grid with numbers and letters).
- It is very useful to have the scenario analysed in advance using orthophotos from before the disaster, particularly identifying access routes (streets, paths, and roads), houses and plots, critical facilities, and places where special events occurred, such as entrapments.
- It is very important to be informed in advance about access restrictions and to take photographs or videos. Scenes of accidents, especially when there are victims, are often sealed off, and access to the interior is restricted. Inform yourself before going and obtain any necessary permits.
- Wait for the most appropriate date. It is important to go to the scene as soon as possible to capture as much fresh information as possible, but this cannot interfere with investigation, firefighting, rescue, or latent hazard stabilization efforts. Also, if you plan to fly a drone, ensure that the weather conditions are suitable, especially the wind.
- Schedule several days for the mission. It is better to go without haste, act systematically in all areas, and gather as much information as possible. When this is not possible, select the most relevant points in the event and focus on them.
- Do not interfere with the work of deployed agents. Try to be as unintrusive as possible. Keep in mind that there may be relatives of the victims who do not want to be photographed, or their properties. Always inform about the purpose of your work there and make yourself available to the authorities present.
- Request, if possible, to participate in a reconnaissance flight. Aerial photographs and videos offer a sufficiently detailed view from a very advantageous perspective. Speaking with the authorities and requesting to participate in some of the reconnaissance flights, especially by helicopter, can be very helpful. Remember to secure your camera in the helicopter, especially if you are taking photographs with the windows or doors open, as it is common for them to fall due to wind effects.
- Identify places and houses. It is very practical to identify the houses being photographed, for example, with codes within each zone or subzone. This will allow for analysis of before and after if photographs of the same places before the wildfire are obtained.
- Use the widest possible focal range. In a camera for this type of reporting, it is sufficient to have a short telephoto lens, for example, a 24-70, but the latest bridge-type cameras usually have a much wider focal range, of the order of 24-400, thus including very useful telephoto capabilities when access to certain areas is not possible or is denied.

Copyright © FirEURisk Consortium. All rights reserved.

- Take panoramas. Panoramas greatly assist in contextual analysis. Even creating a mosaic of photos across the visible sphere can later be used to create spherical photographs, as explained earlier.
- Don't run out of batteries! Bring extra batteries, power banks, and some devices for charging your devices in the car. Do not rely on there being electrical power; often the service is not available. Also, bring enough memory cards to store photos and videos.
- Take as many photos as possible. Nowadays, digital photography is very inexpensive, and there is no justification for not taking as many photos as necessary. If possible, use a flash; this will provide more information in shadow details, even in broad daylight.
- Use your mobile phone. Many people, especially in disaster scenarios, feel uncomfortable when they see a camera, but seem indifferent to a mobile phone. Nowadays, mobile phones incorporate cameras of very acceptable quality, so sometimes it will be the most used tool due to its versatility and its small size, which make them discreet.
- Ensure that privacy and image rights are respected. This is especially sensitive in the case of minors but applies to all people. It is important to communicate the purpose of the photographs and, if necessary, ask for permission.
- Do not post anything on social media! The visual material obtained in a reconnaissance activity in a disaster area should be used strictly for investigation purposes, never for posting on social media or disseminating it without the express consent of the authorities, especially if there is an ongoing investigation subject to judicial secrecy.

Copyright © FirEUrisk Consortium. All rights reserved.

5 Conclusions

The wildfire analysis protocol presented in this document aims to provide support for those intending to analyse a wildfire event or a specific wildfire episode, focusing on the behaviour exhibited by the wildfire, the conditions of wildfire development, operational response, and the main resulting impacts, among other potential lessons that can be extracted from a wildfire analysis.

Several suggestions for procedures to be taken were presented, considering potential field visits during the wildfire, a few days after its conclusion, or long after the wildfire has occurred, considering that methodologies for obtaining evidence and information, as well as safety methodologies and procedures, may differ. Various methodologies and digitally available sources of information were also presented, considering that this complementary information certainly will help to understand, describe, and report the wildfire events.

Naturally, each wildfire has different characteristics, and each study has particular objectives. Thus, this document does not intend to cover all possibilities of study but only to serve as a reference for procedures and activities that should be adapted for each case study.

Copyright © FirEUrisk Consortium. All rights reserved.

6 References

AFN. (2012). *Plano Municipal de Defesa da Floresta Contra Incêndios (PMDFCI). Guia Técnico*. Direção de Unidade de Defesa da Floresta. Autoridade Florestal Nacional. Ministério da Agricultura, do Desenvolvimento Rural e das Pescas. http://www.icnf.pt/portal/florestas/dfci/Resource/doc/Guia-Tecnico-PMDFCI-AFN-Abril2012-v1.pdf/at_download/file

AGIF. (2023). *Normas técnicas para elaboração da cartografia das redes de defesa*.

Anderson, H. E. (1982). Aids to determining fuel models for estimating fire behavior. In *USDA For. Serv. Gen. Tech. Rep. INT-122*. lntermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Aragoneses, E., García, M., Salis, M., Ribeiro, L. M., & Chuvieco, E. (2023). Classification and mapping of European fuels using a hierarchical, multipurpose fuel classification system. *Earth System Science Data*, *15*(3), 1287–1315. https://doi.org/10.5194/essd-15-1287-2023

Caballero, D. (2019) Utilización, interpretación y limitaciones del índice de interfaz WUIX. Serie Cuadernos Técnicos, auto publicado. Agosto.

Caetano, M., & Marcelino, F. (2017). CORINE Land Cover de Portugal Continental 1990- 2000-2006-2012. *Relatório Técnico. Direção-Geral Do Território (DGT)*.

Countryman, C. M. (1972). *The fire environment concept* (Issue PMS 433). USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Direção Geral do Território. (2019). *Especificações Técnicas da Carta de Uso e Ocupação do Solo (COS) de Portugal Continental para 2018. Relatório Técnico*. http://www.ghbook.ir/index.php?name=فرهنگ و رسانه های نوین&option=com_dbook&task=readonline&book_id=13650&page=73&chkhashk=ED9C9491B4&Itemid=218&lang=fa&tmpl=component

Direção Geral do Território. (2022). *COSc – Carta de Ocupação do Solo Conjuntural. Ficha Técnica*. Sistema de Monitorização da Ocupação do solo (SMOS). Direção Geral do Territoório (DGT).

EEA. (2020). *CORINE Land Cover Product User Manual (Version 1.0)*. European Union, Copernicus Land Monitoring Service 2021, European Environment Agency (EEA) All. https://land.copernicus.eu/en/products/corine-land-cover

Gascon, F., Cadau, E., Colin, O., Hoersch, B., Isola, C., López Fernández, B., & Martimort, P. (2014). Copernicus Sentinel-2 mission: products, algorithms and Cal/Val. In J. J. Butler, X. (Jack) Xiong, & X. Gu (Eds.), *Earth Observing Systems XIX* (Vol. 9218, p. 92181E). SPIE. https://doi.org/10.1117/12.2062260

Guth, P. L., Van Niekerk, A., Grohmann, C. H., Muller, J. P., Hawker, L., Florinsky, I. V., Gesch, D., Reuter, H. I., Herrera-Cruz, V., Riazanoff, S., López-Vázquez, C., Carabajal, C. C., Albinet, C., & Strobl, P. (2021). Digital elevation models: Terminology and definitions. *Remote Sensing*, *13*(18), 3581. https://doi.org/10.3390/rs13183581

Hengl, T. (2021). *Continental Europe surface lithology based on EGDI / OneGeology map at 1:1M scale (v1.0) [Data set]*. Zenodo. https://doi.org/doi.org/10.5281/zenodo.4787632

Kerchove, R. Van De, Zanaga, D., Xu, P., Tsendbazar, N., & Lesiv, M. (2022). *ESA WolrdCover Product User Manual V2.0*. European Space Agency.

Lopes, A. M. G., Ribeiro, L. M., Viegas, D. X., & Raposo, J. R. (2019). Simulation of forest fire spread using a two-way coupling algorithm and its application to a real wildfire. Journal of Wind Engineering and Industrial Aerodynamics, 193(July), 103967. https://doi.org/10.1016/j.jweia.2019.103967

Copyright © FirEUrisk Consortium. All rights reserved.

Lopes, A. M. G. G., Ribeiro, L. M., Viegas, D. X., & Raposo, J. R. (2017). Effect of two-way coupling on the calculation of forest fire spread: model development. International Journal of Wildland Fire, 26(9), 829. https://doi.org/10.1071/WF16045

Lutes, D. C., Keane, R. E., Caratti, J. F., Key, C. H., Benson, N. C., Sutherland, S., & Gangi, L. J. (2006). *FIREMON: Fire effects monitoring and inventory system*. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-164

Mendonça, J. M., Máguas, C., Pereira, J. M. C., Fernandes, P., Viegas, D. X., Tedim, F., Keizer. J., Silva, J. S., 2023. Relatório Final do Grupo de Peritos dos Incêndios Rurais. ISBN: 978-972-27-3159-1. 12 abril 2023.

NWCG (2022). NWCG Incident Response Pocket Guide (IRPG). National Wildfire Coordinating Group. https://www.nwcg.gov/sites/default/files/publications/pms461.pdf

Opie, K. (2020). Slope and Terrain. In *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires* (pp. 1–4). Springer International Publishing. https://doi.org/10.1007/978-3-319-51727-8_240-1

Ribeiro, L. M., Viegas, D. X., Almeida, M., McGee, T., Pereira, M. G., Parente, J., Xanthopoulos, G., Leone, V., Delogu, G. M., Hardin, H. (2020). Extreme wildfires and disasters around the world: lessons to be learned. In: Tedim F., Leone V., McGee T. (Eds.), 2020. Extreme Wildfire Events and Disasters. Root Causes and New Management Strategies. Elsevier. 284 pages, ISBN: 9780128157213. https://doi.org/10.1016/B978-0-12-815721-3.00002-3

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115*. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station.

Sá, A. C. L., Benali, A., Aparicio, B. A., Bruni, C., Mota, C., Pereira, J. M. C., & Fernandes, P. M. (2023). A method to produce a flexible and customized fuel models dataset. *MethodsX*, *10*, 102218. https://doi.org/10.1016/j.mex.2023.102218

Schroeder, W., Oliva, P., Giglio, L., & Csiszar, I. A. (2014). The New VIIRS 375 m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment*, *143*, 85–96. https://doi.org/10.1016/J.RSE.2013.12.008

Scott, J. H., & Burgan, R. E. (2005). Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. In *USDA Forest Service - General Technical Report RMRS-GTR: Vol. RMRS-GTR-1* (Issues 153 RMRS-GTR). https://doi.org/10.2737/RMRS-GTR-153

Stipanicev, D. and Viegas, D. X. (2009). The Accident of Kornati (Croatia). In D. X. Viegas (Ed.), Recent Forest Fire Related Accidents in Europe. European Commission, Joint Research Centre, Institute for Environment and Sustainability, pp. 26-53. ISBN 978-92-79-14604-6

Viegas, D. X., Lourenço, L., Neto, L. P., Monteiro, J. M., Pais, M. T., Ferreira, A., Machado, M. G. (1988). Analise do Incendio Florestal ocorrido em Arganil/Oliveira do Hospital de 13 a 20 Setembro de 1987. Rel. Tec. C.M.F.- I.F.- 8801, 15 de Abril de 1988.

Viegas, D. X., Lourenço, L., Neto, L. P. C., Pais, M. T., Reis, J. F., Ferreira, A. (1987). Analise do Incendio Florestal Ocorrido em Vagos/Mira em 27/29 de julho de 1987. Rel. Tec. C.M.F - I.F.- 8703, 01 Out 1987. 50p.

Viegas, D. X., Viegas, M. T., Neves, A., Olim, A. (1992). Análise do Incêndio Ocorrido na Serra da Arrábida de 16 a 20 de setembro 1991. Relatório Interno de 1992.

Viegas, D. X. (2004). Cercados pelo Fogo. Os Incêndios Florestais em Portugal em 2003 e os Acidentes Mortais com eles relacionados. Editorial Minerva, Coimbra, 283 pp. ISBN: 9789727981052.

Copyright © FirEUrisk Consortium. All rights reserved.

Viegas, D. X. (2004). A Mathematical Model for Forest Fires Blowup. *Combustion Science and Technology*, *177*(1), 27–51. https://doi.org/10.1080/00102200590883624

Viegas, D. X. (2009). Cercados pelo Fogo, Parte 2. Relato dos acidentes fatais ocorridos em Portugal nos incêndios florestais de 2005. Editorial Minerva, Coimbra, 351 pp. ISBN: 978927982677

Viegas, D. X., Pita L., Rossa, C. and Ribeiro, L. (2009). The Accident of Famalicão (Portugal). In D. X. Viegas (Ed.), Recent Forest Fire Related Accidents in Europe. European Commission, Joint Research Centre, Institute for Environment and Sustainability, pp. 18-25. ISBN 978-92-79-14604-6

Viegas, D. X. and Caballero D. (2009). The Accident of Guadalajara (Spain). In D. X. Viegas (Ed.), Recent Forest Fire Related Accidents in Europe. European Commission, Joint Research Centre, Institute for Environment and Sustainability, pp.10-17. ISBN 978-92-79-14604-6

Viegas, D. X. (Ed.) (2009). Recent Forest Fire Related Accidents in Europe. JRC Scientific and Technical Reports, Joint Research Centre, Institute for Environment and Sustainability, European Commission. JRC 56107, EUR 24121 EN, ISBN 978-92-79-14604-6, ISSN 1018-5593. 75p.

Viegas, D. X., Gabbert W., Figueiredo A.R., Almeida M.A., Reva V., Ribeiro L.M., Viegas M.T., Oliveira R., Raposo J.R., (2012). Relatório do Incêndio Florestal de Tavira/São Brás de Alportel, 18 a 22 de julho de 2012. Centro de Estudos sobre Incêndios Florestais, ADAI/LAETA, Universidade de Coimbra, Coimbra, setembro 2012.

Viegas, D. X. (2013). Cercados pelo Fogo em Armamar. O Acidente de Armamar em 8 de setembro de 1985. Ediliber, ISBN: 978-989-20-4068-4, 279 p.

Viegas, D. X. (2017). Cercados pelo Fogo em Águeda - Relato do acidente ocorrido em Águeda em 14 de junho de 1986. FIG – Indústrias Gráficas, SA. ISBN: 978-989-99080-7-9, 333pages.

Viegas, D. X., Ribeiro, L. M., Almeida, M. A., Oliveira, R., Viegas, M. T. P., Raposo, J. R., Reva, V., Figueiredo, A. R., Lopes, S. (2013). Os grandes incêndios florestais e os acidentes mortais ocorridos em 2013 - Parte 1. Centro de Estudos sobre Incêndios Florestais (CEI/ADAI/LAETA).

Viegas, D. X., Almeida, M. F., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Jorge, H., Rodrigues, A., Lucas, D., Lopes, S., Silva, L. F. (2017). O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017. Centro de Estudos sobre Incêndios Florestais (CEI/ADAI/LAETA)

Viegas, D. X., Almeida, M. A., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Rodrigues, A., Ribeiro, C., Lopes, S., Jorge, H., Viegas, C. X. (2019). Análise dos Incêndios Florestais Ocorridos a 15 de outubro de 2017. Relatório Centro de Estudos sobre Incêndios Florestais, ADAI/LAETA, Universidade de Coimbra. 388 páginas.

Witjes, M., Parente, L., van Diemen, C. J., Hengl, T., Landa, M., Brodský, L., Halounova, L., Križan, J., Antonić, L., Ilie, C. M., Craciunescu, V., Kilibarda, M., Antonijević, O., & Glušica, L. (2022). A spatiotemporal ensemble machine learning framework for generating land use/land cover time-series maps for Europe (2000–2019) based on LUCAS, CORINE and GLAD Landsat. *PeerJ*, *10*, e13573. https://doi.org/10.7717/peerj.13573

Copyright © FirEUrisk Consortium. All rights reserved.