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Analysis of 2021 critical wildfire events in the Mediterranean region

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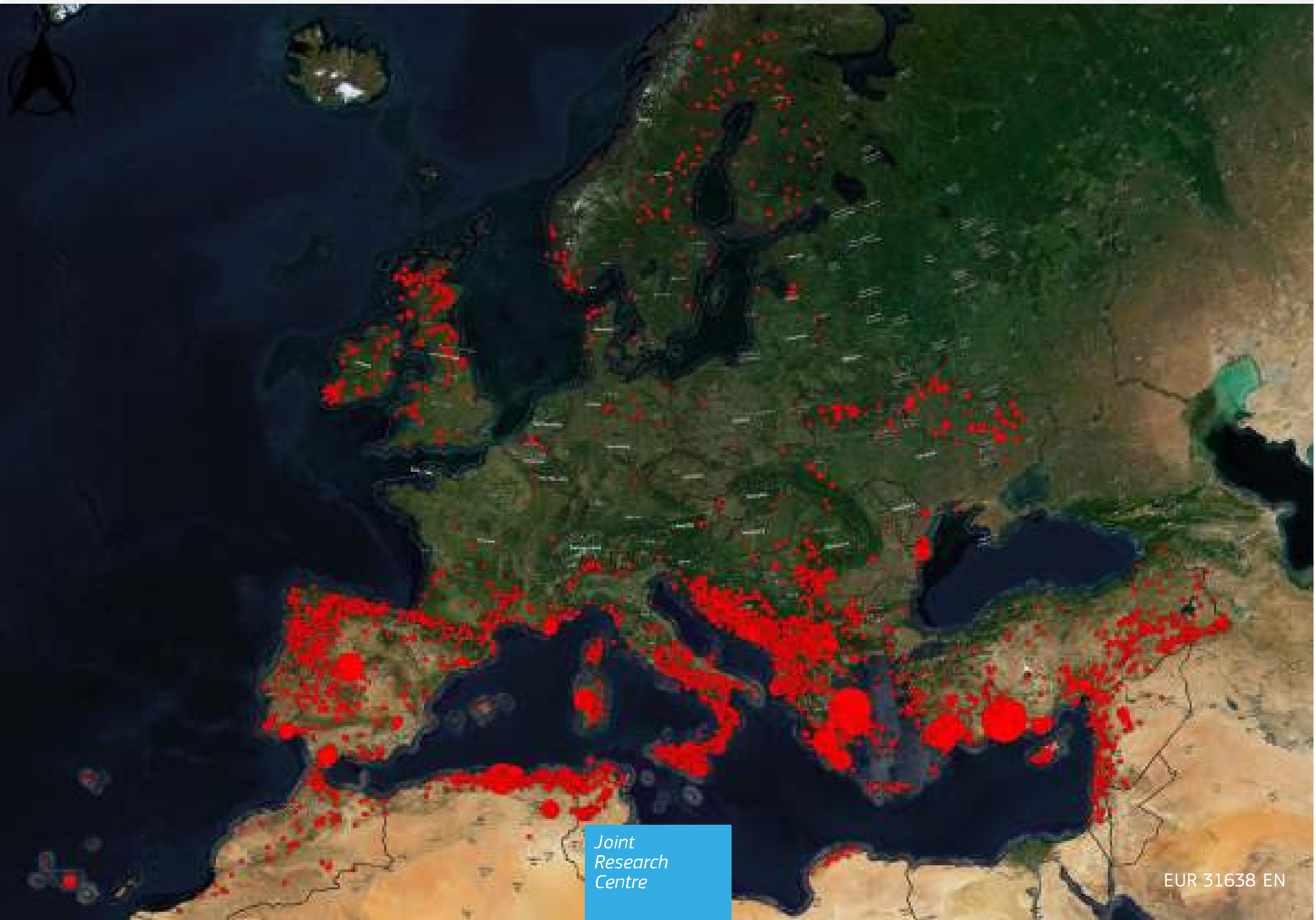

Joint Research Centre

EUR 31638 EN

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

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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

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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/fcLgxESfAxg, 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)

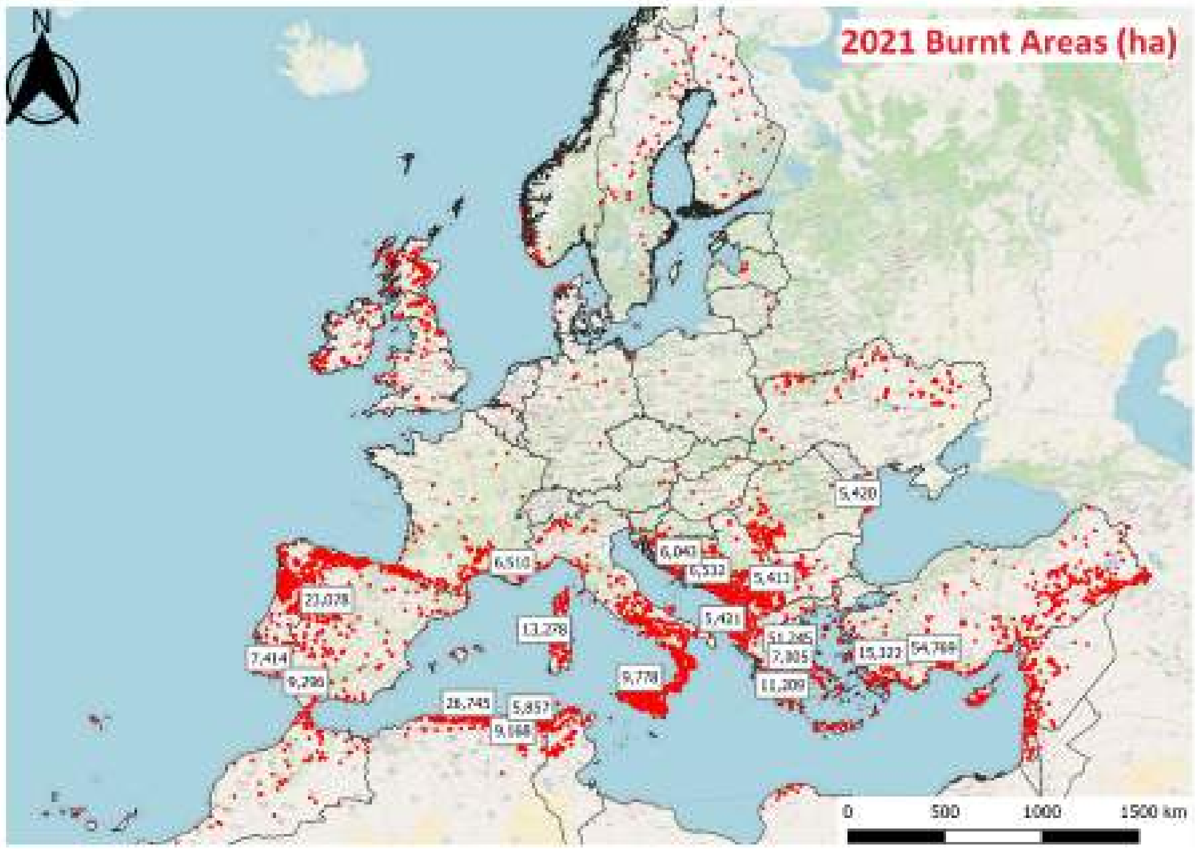


Figure 1. Burnt areas mapped during the 2021 fire season. Largest fires are indicated in ha.

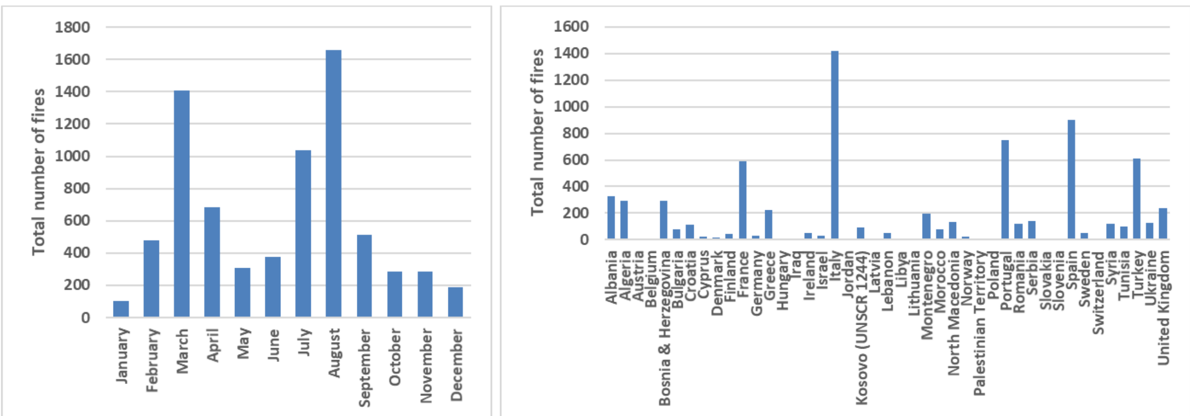


Figure 2. Total number of fires mapped by month and country in 2021.

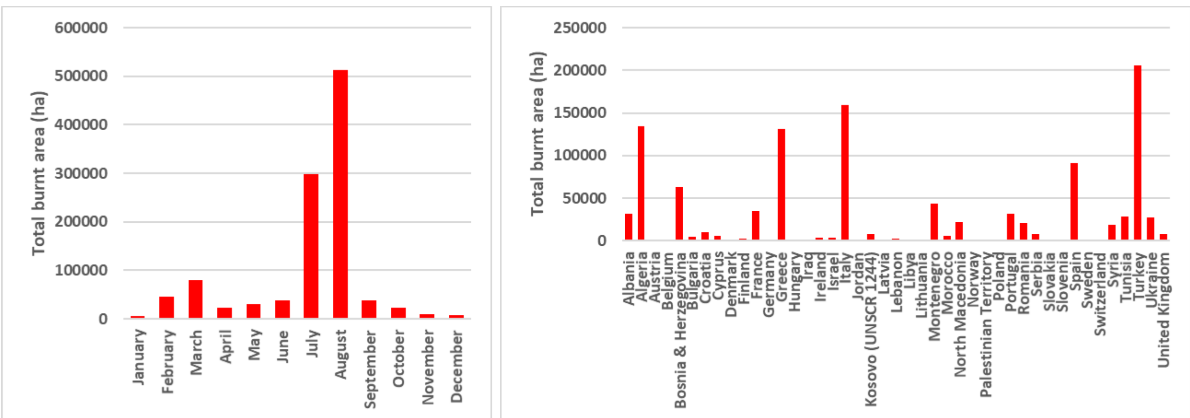


Figure 3. Total burnt area of fires mapped by month and country in 2021.

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**

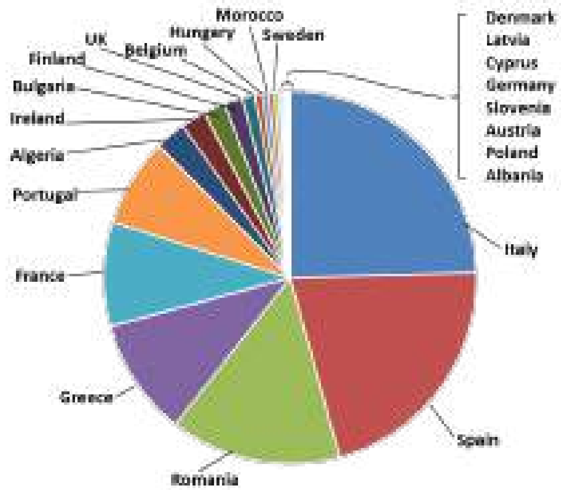


Figure 4. relative proportions of burnt area mapped in protected areas in 2021, ordered by size.

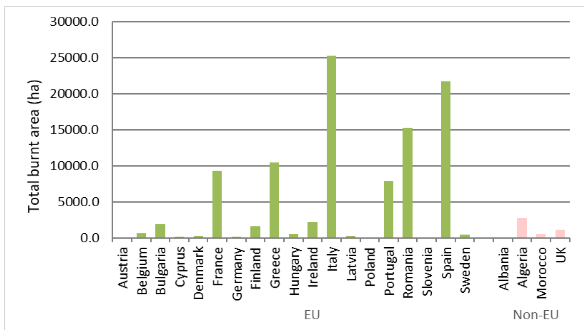


Figure 5. Burnt area in Natura2000 sites and other protected areas in 2021.

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.

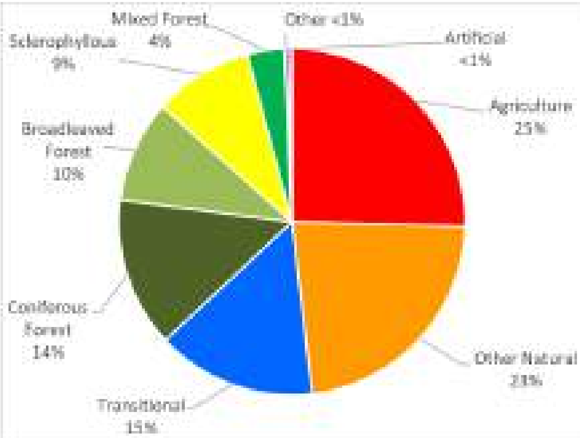


Figure 6. Proportions of land cover types affected in 2021 (all countries, ordered by total burnt area).

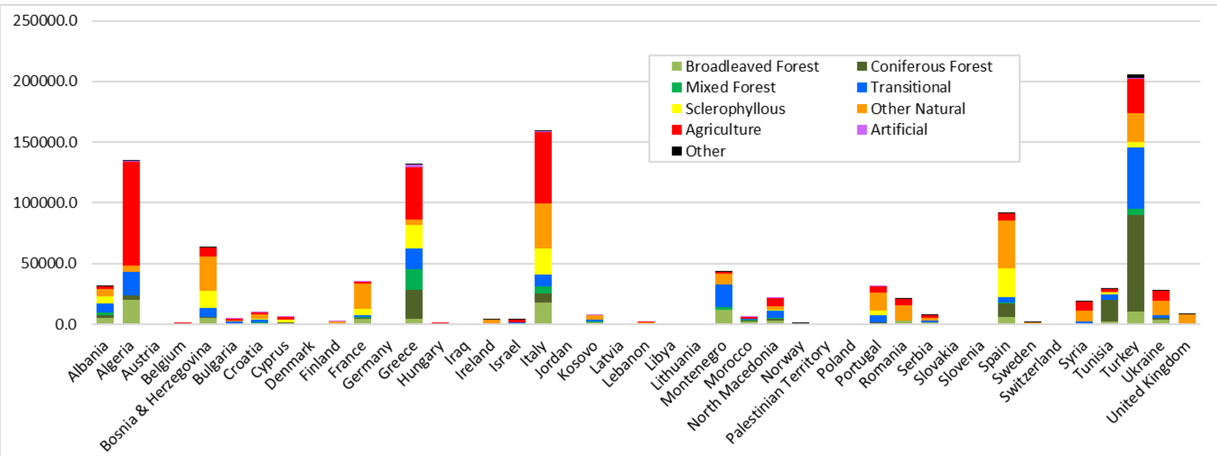


Figure 7. Burnt area in each country in 2021 by CORINE land class.

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.

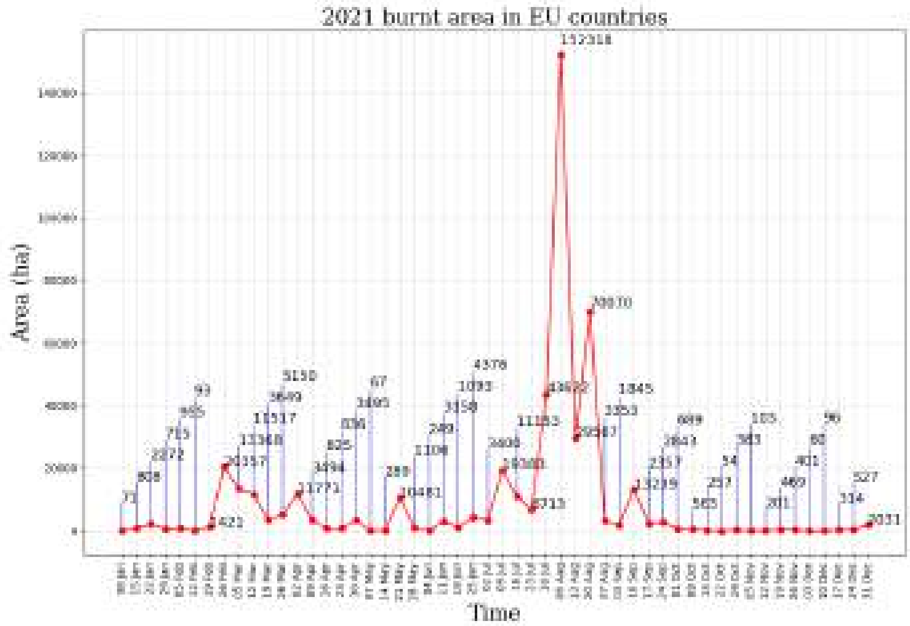


Figure 8. Burnt area weekly evolution in 2021 (European Union countries).

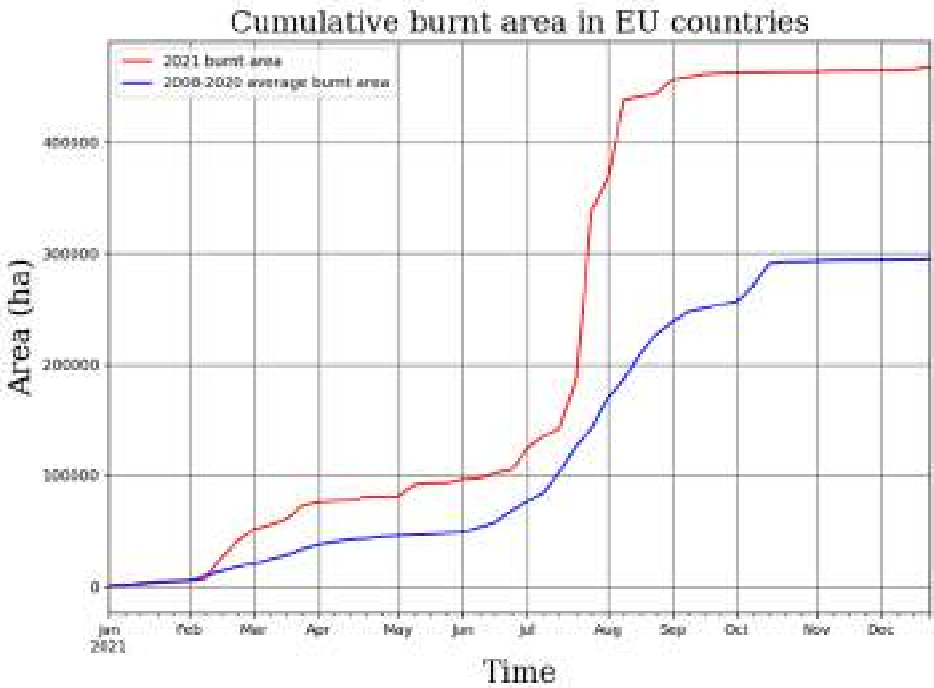


Figure 9. Cumulative burnt area in 2021 (European Union countries).

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.

(a) (b)

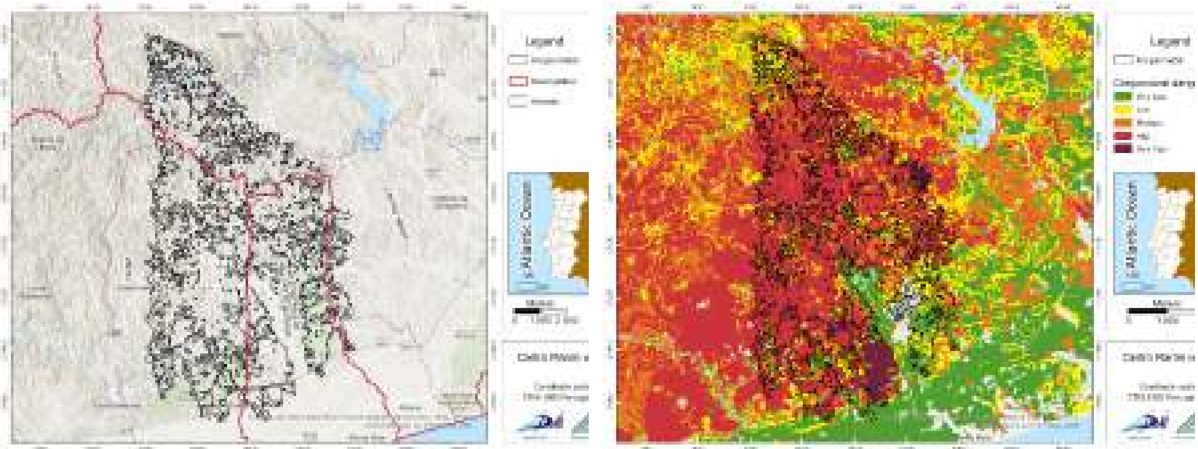


Figure 11 – a) Geographical setting of the Castro Marim Fire; b) Conjunctural danger for 2021 (Source: ICNF [1]).

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/km^{2}*	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.

(a) (b)

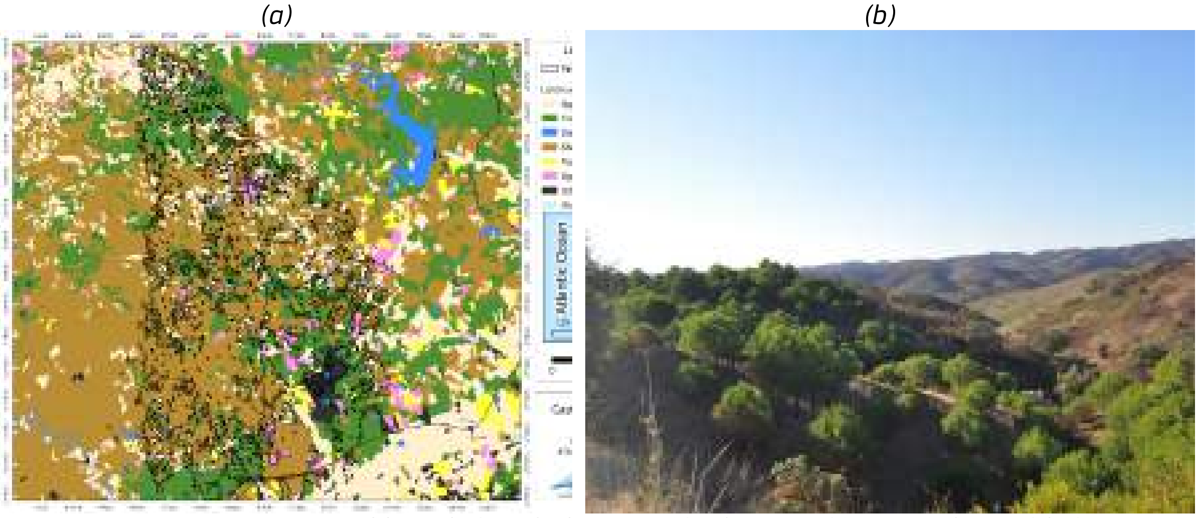


Figure 12 – Representation of forest fuels in the fire area: a) land use map; b) image with typical fuels.

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.

(a) (b) (c)

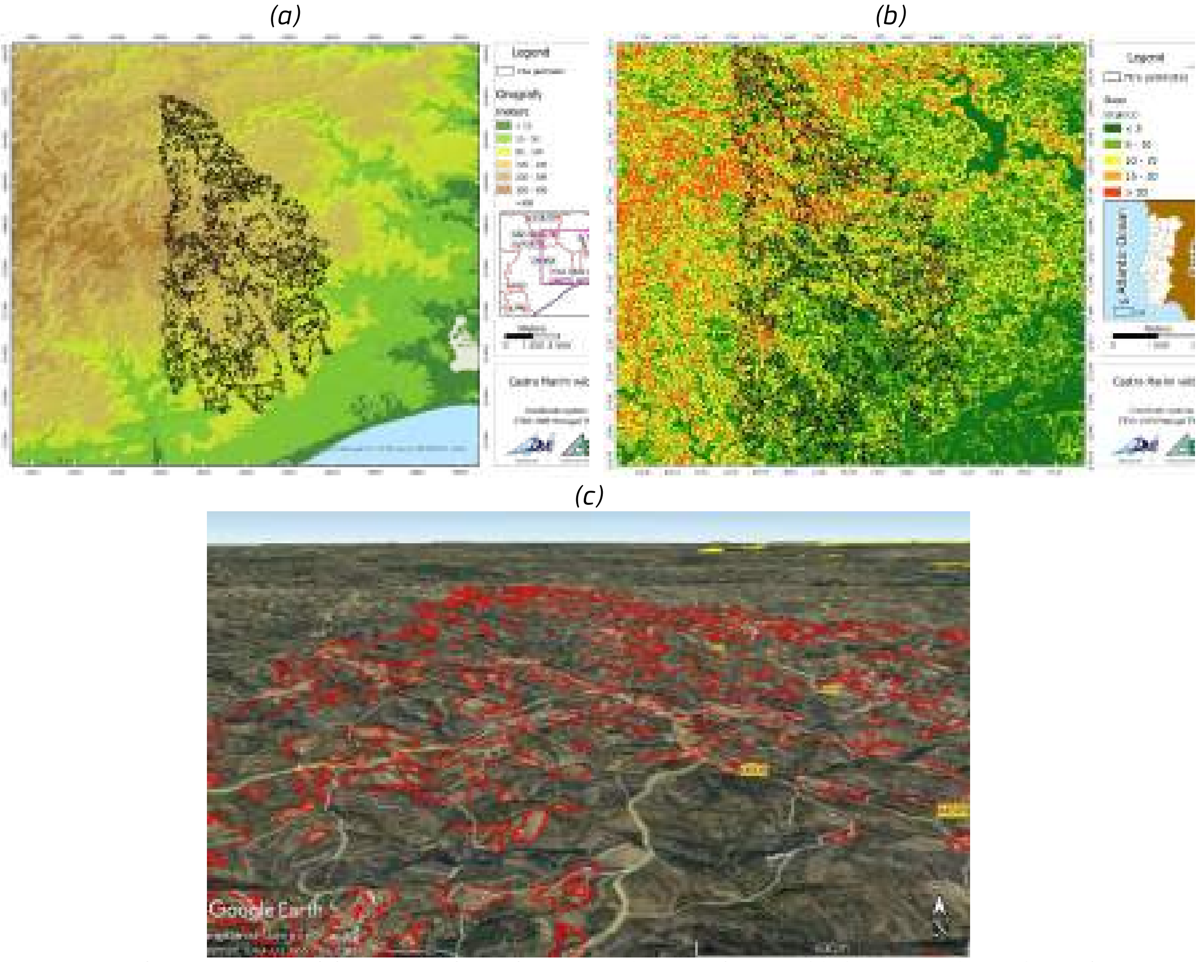


Figure 13 – Characterization of the topography in the region: a) orographic map; b) slope map; c) Google Earth image showing the typical orographic pattern.

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.

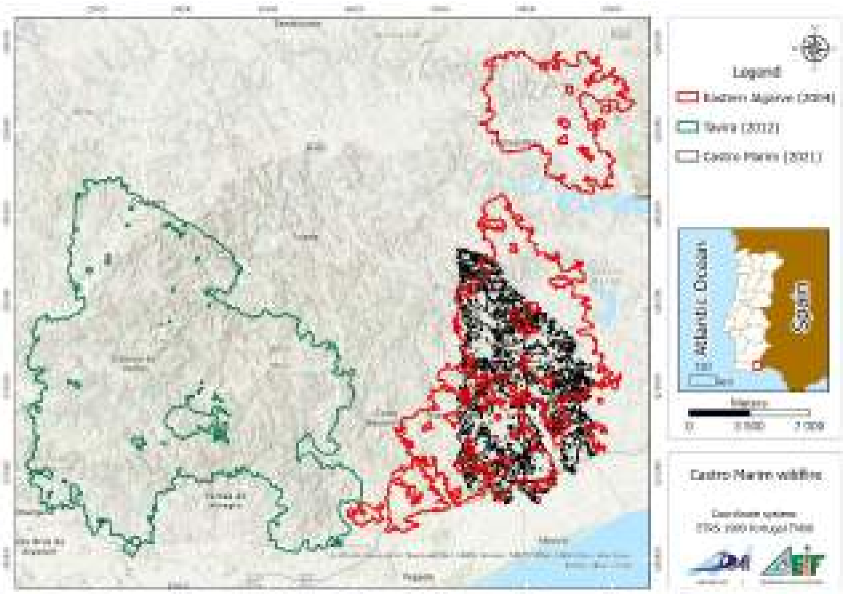


Figure 14 – Final perimeter of the largest fire events that occurred in the region since 2000.

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.

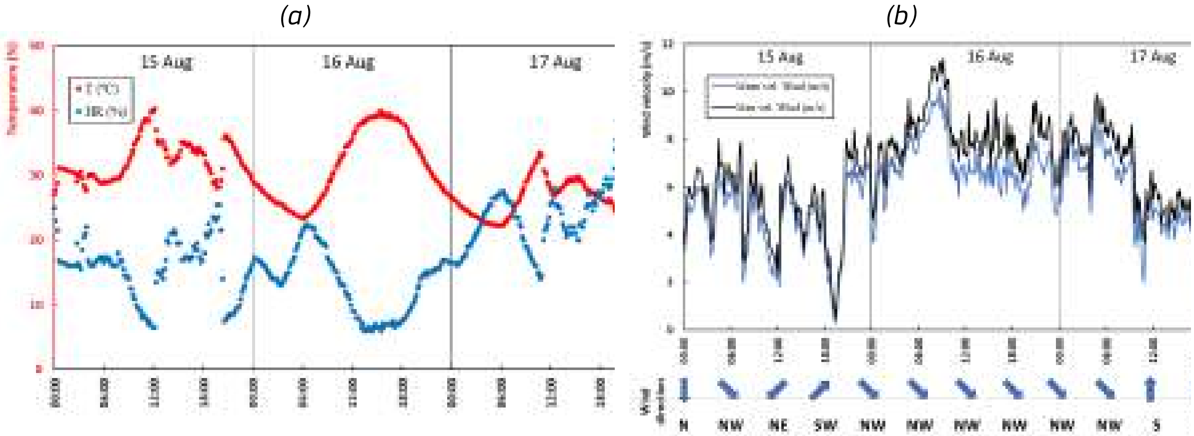


Figure 15 – Meteorological conditions registered by the Meteorological Station of Castro Marim between August 15th and 17th, 2021 (source: IPMA [6]): a) temperature and relative humidity variation; b) wind variation.

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.

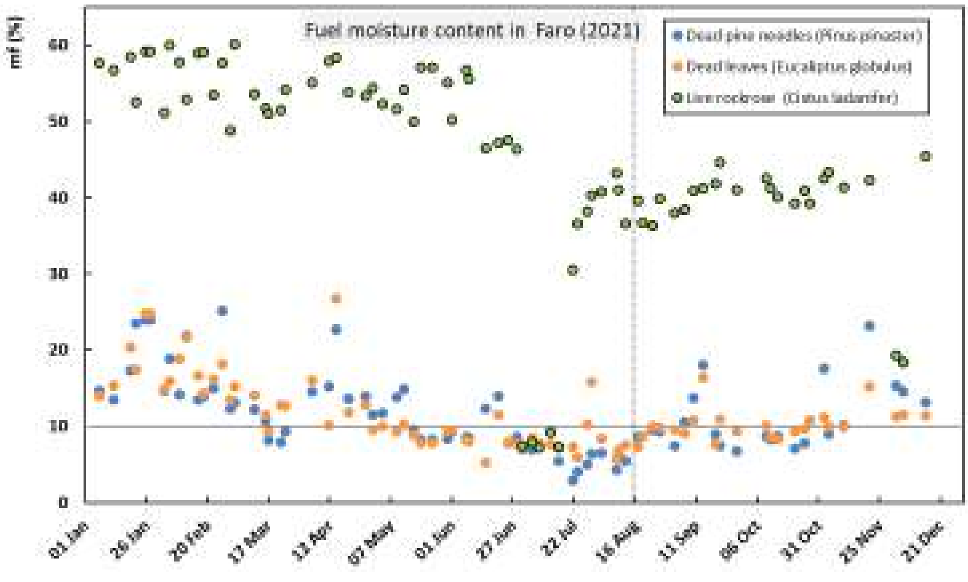


Figure 16 – a) Fuel moisture content (mf) for dead Pinus pinaster needles and dead Eucalyptus globulus leaves during 2021 in Faro (Algarve). Data source: MCFIRE/ Univ. Algarve).

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.

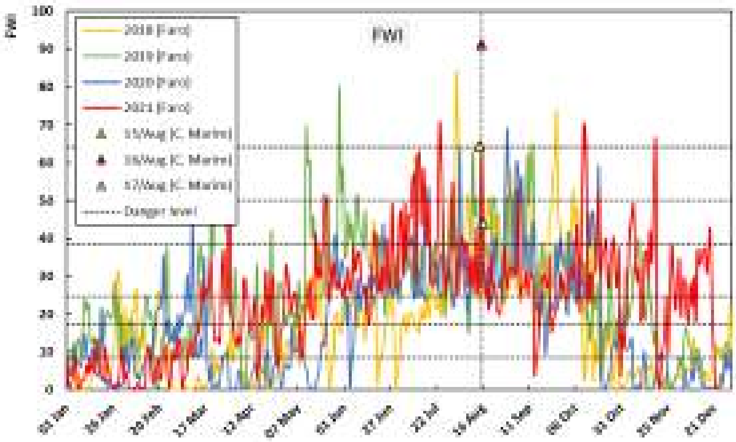


Figure 17 – a) Fire Weather Index (FWI) determined by the observed meteorological data from the weather station of Faro between 2018 and 2021 and the weather station of Castro Marim between August 15th and 17th (data source: IPMA).

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.

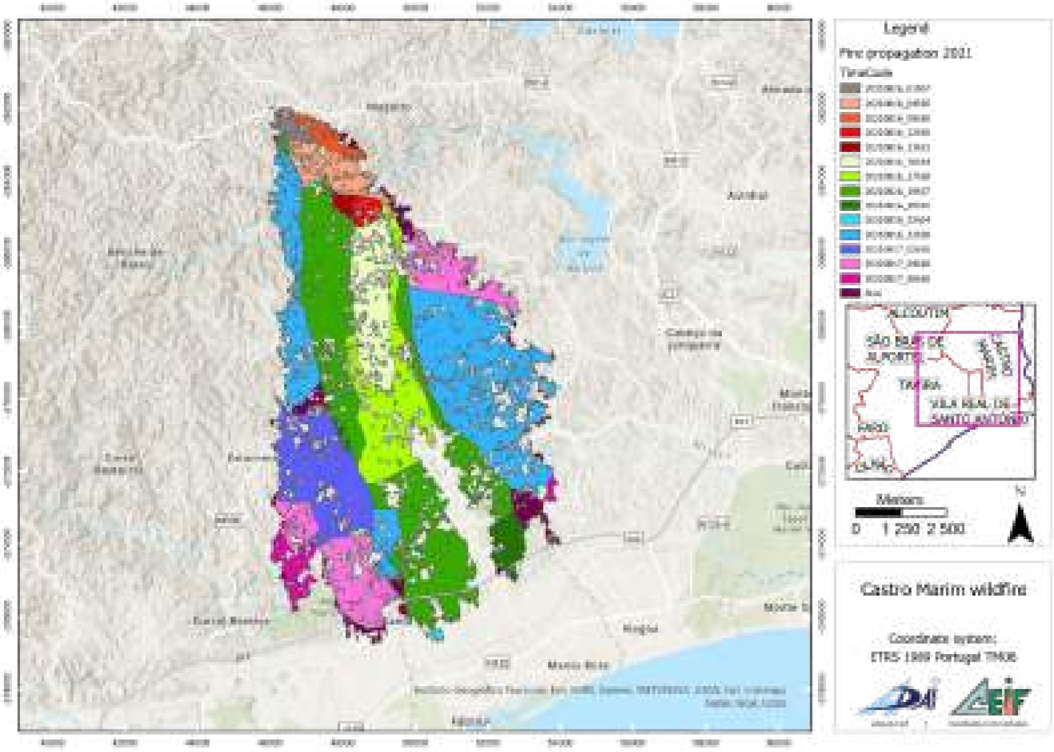


Figure 18 – Representation of the estimated fire behavior according to the indications from ANEPC.

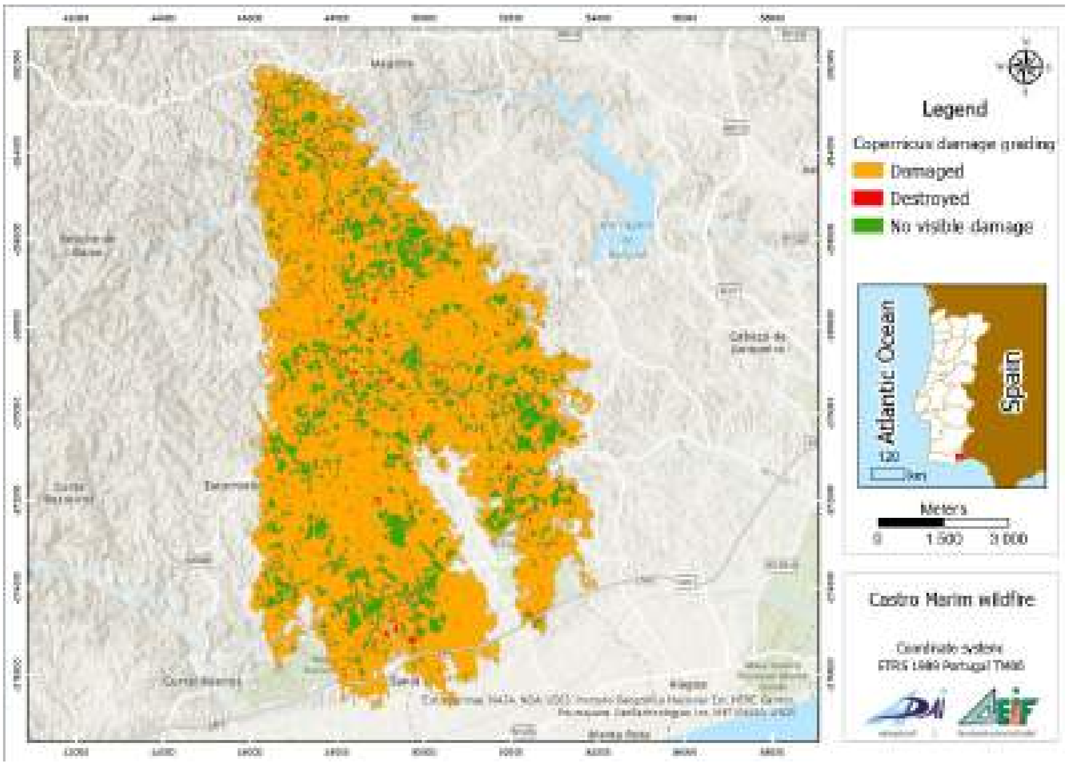


Figure 19 – Damage grading of the burned area (image adapted from Copernicus).

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.

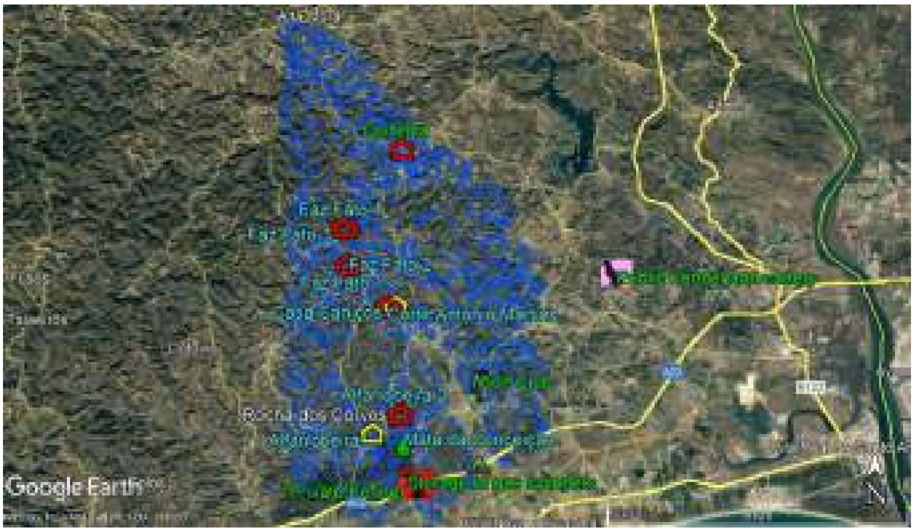


Figure 20 – Location of wildland-urban interface elements damaged or threatened by fire, considered to be of greatest interest for the study.

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.

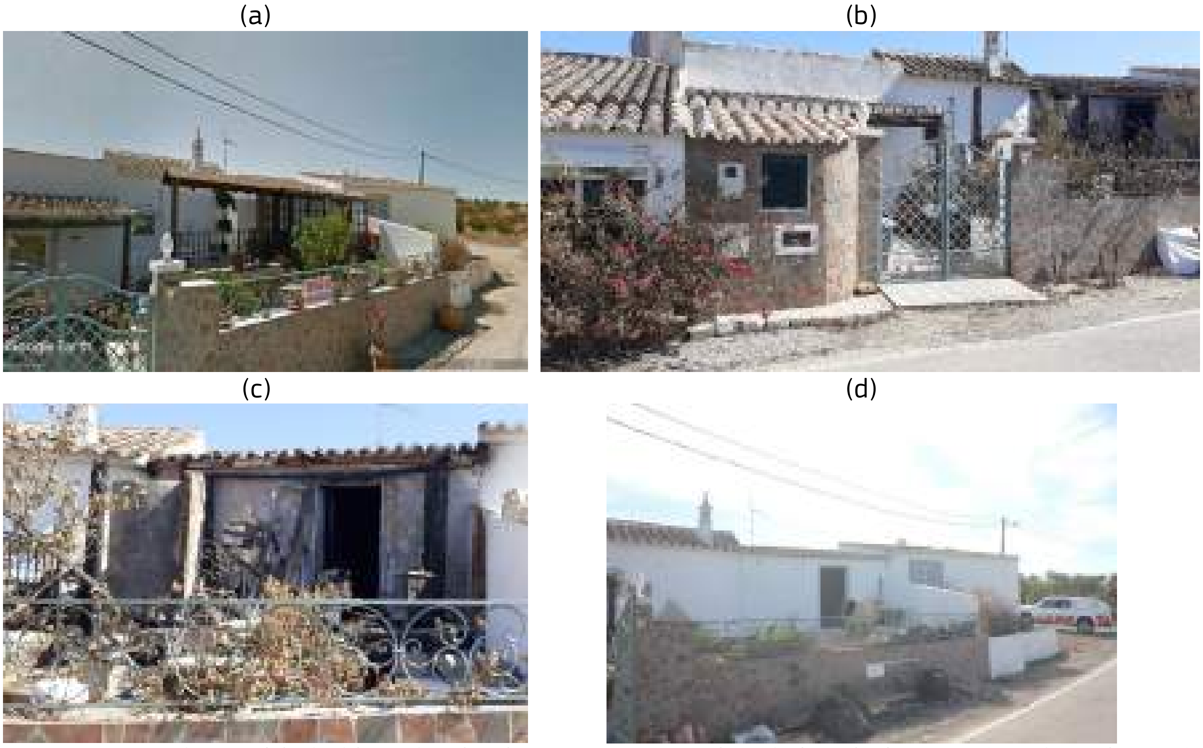


Figure 26 – General view of the building related to the "Faz Fato 2" episode: a) before the fire event (Google Earth image); b and c) after the fire event (photos courtesy of Tavira Câmara Municipal); and d) image of the house during its reconstruction.

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).

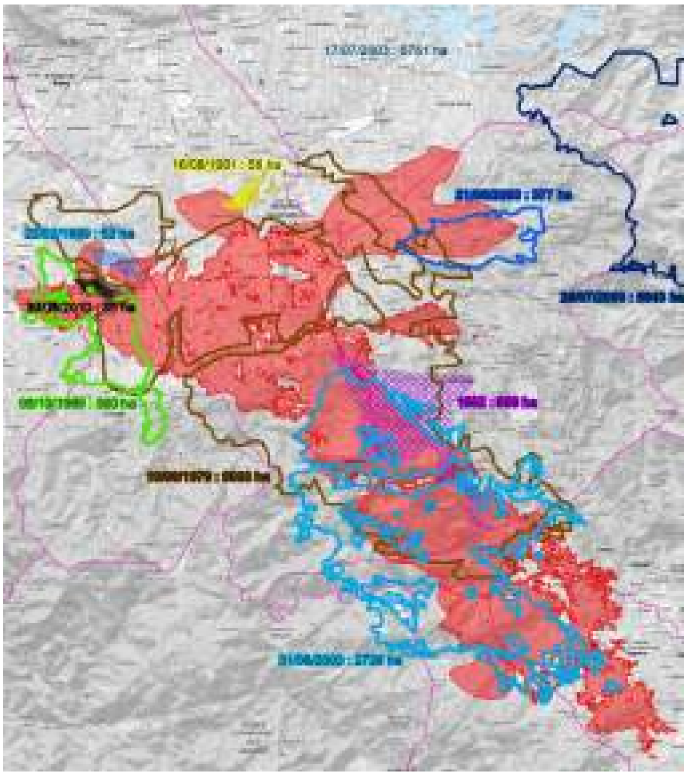


Figure 32 – Map of the history of fires on the impacted territory (source: National Forestry Office).

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.

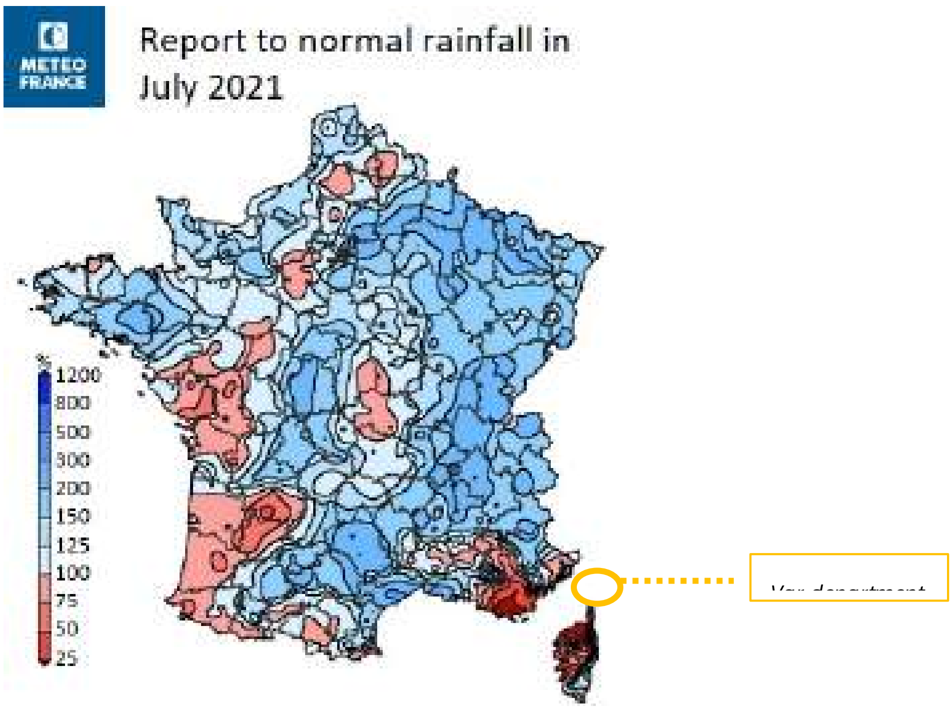


Figure 34 – Cumulative rainfall and ratio to normal in July 2021 (Source: Météo Villes & Météo France).

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 (270º/280º) 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".

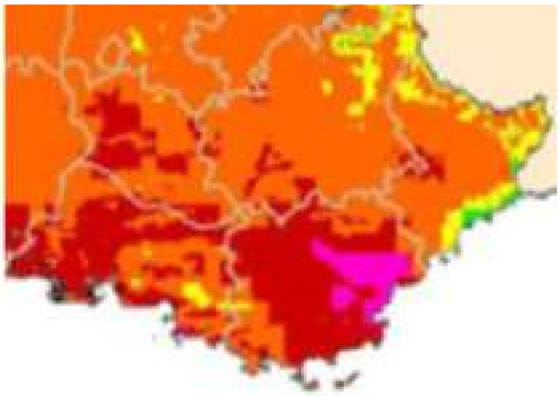


Figure 35 – Dead vegetation: IEP6x planned (purple) (Source: Departmental Fire and Rescue Service of the Var).

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.

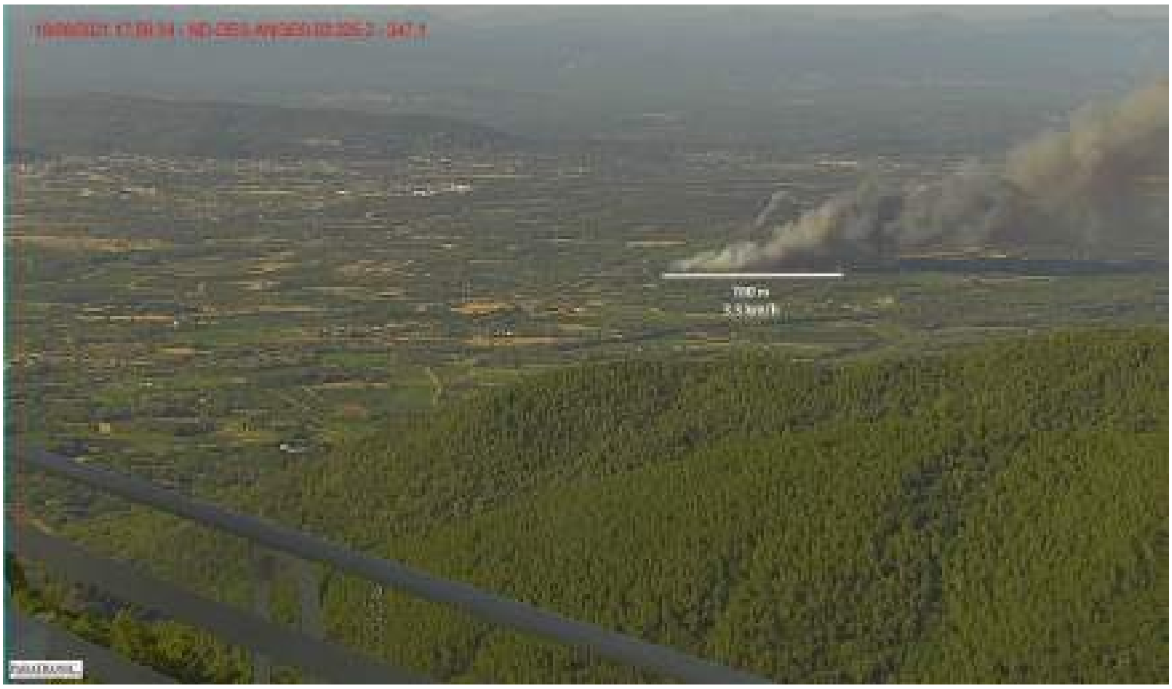


Figure 36 – Initial phase of the fire – photo taken at 5.59 p.m., 16 minutes after its ignition (Source: Departmental Fire and Rescue Service of the Var)

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)

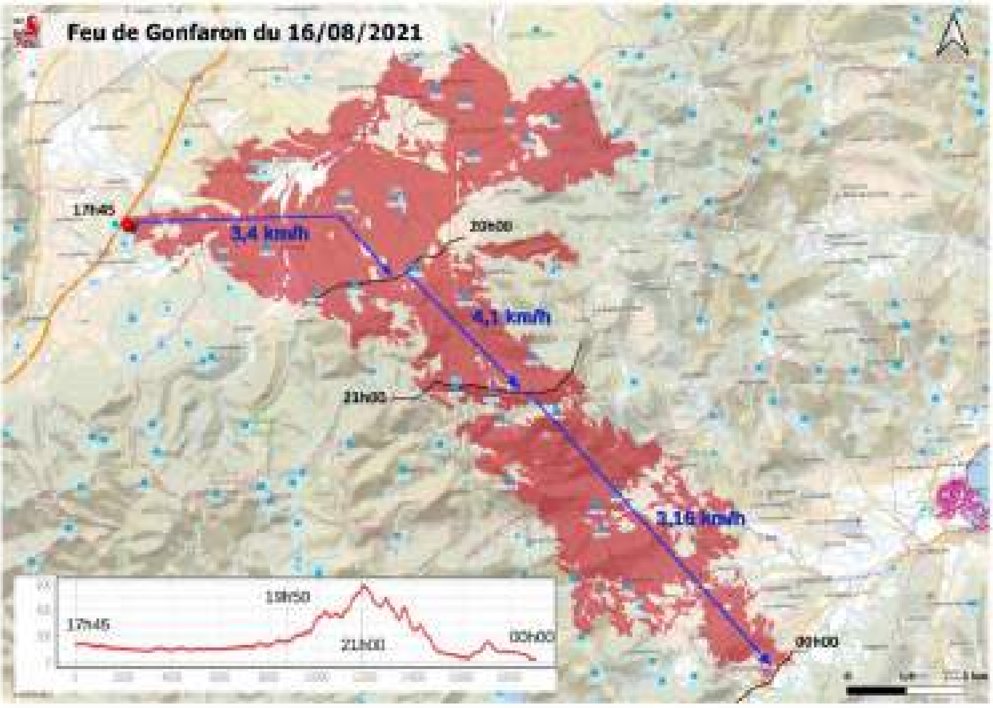


Figure 38 – Course of the fire between 05.45 p.m. and 12.00 p.m. of August 16th (Source: Departmental Fire and Rescue Service of the Var)

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.

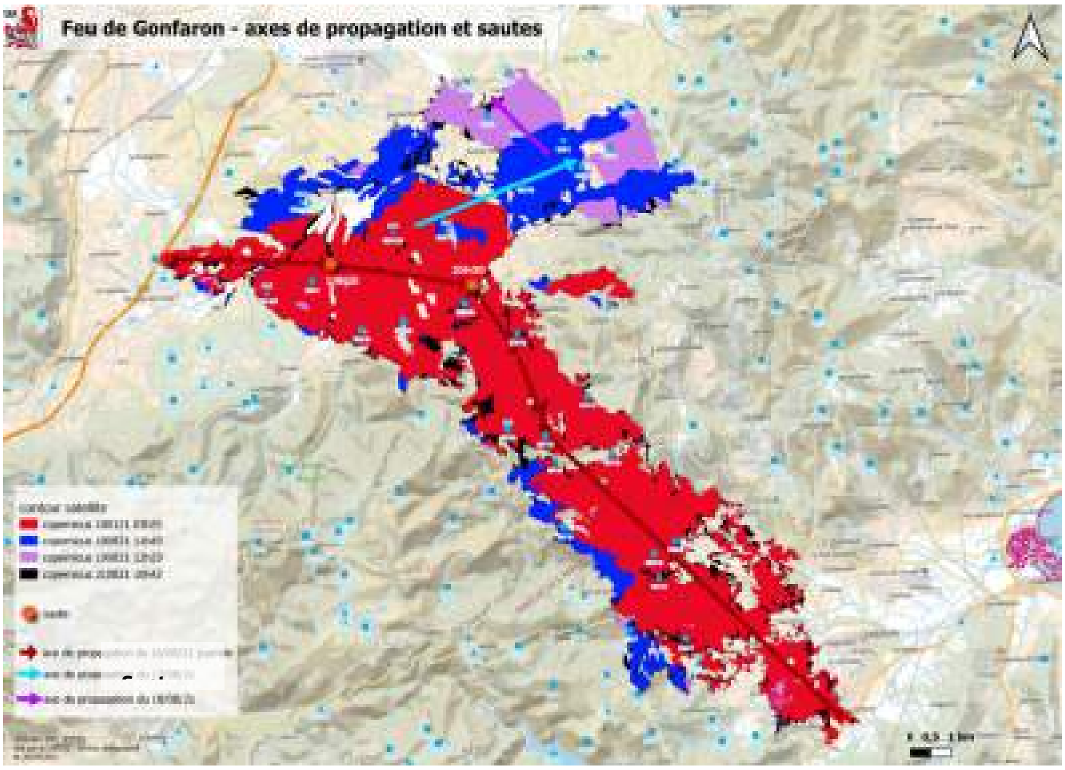


Figure 39 – Fire-covered area, indicating satellite contours, spot fires, and axes of propagation (Source: Departmental Fire and Rescue Service of the Var)

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.

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.

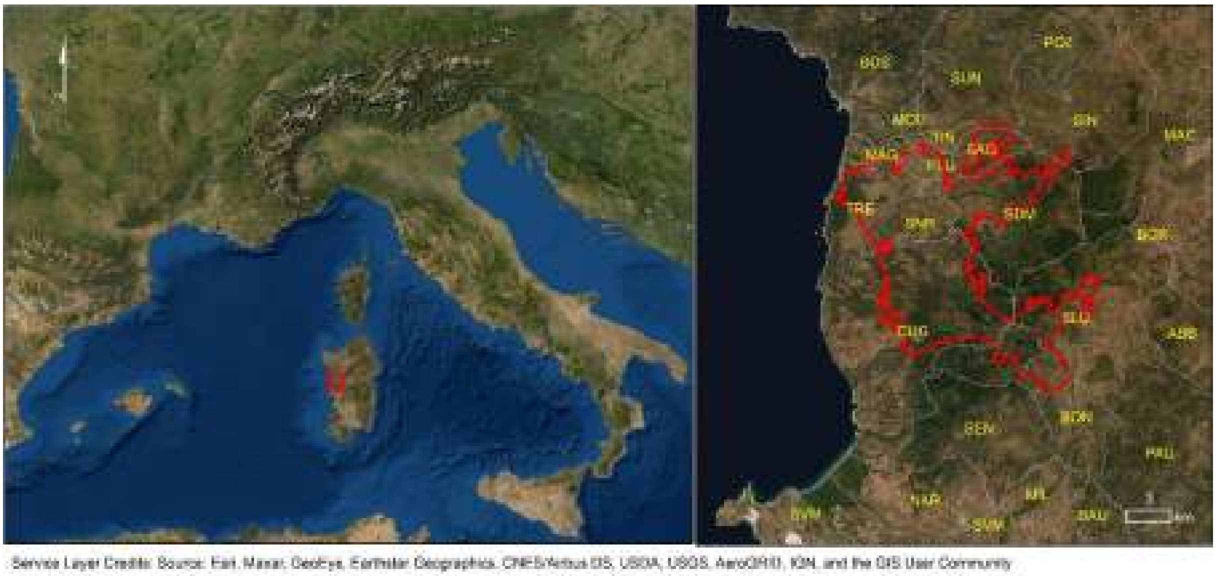


Figure 41 – General map of the Montiferru area, including the 2021 wildfire perimeter and the administrative municipal boundaries. ABB=Abbasanta; BAU=Bauladu; BON=Bonarcado; BOR=Borore; BOS=Bosa; CUG=Cuglieri; FLU=Flussio; MAC=Macomer; MAG=Magomadas; MIL=Milis; MOD=Modolo; NAR=Narbolia; PAU=Paulilatino; 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.

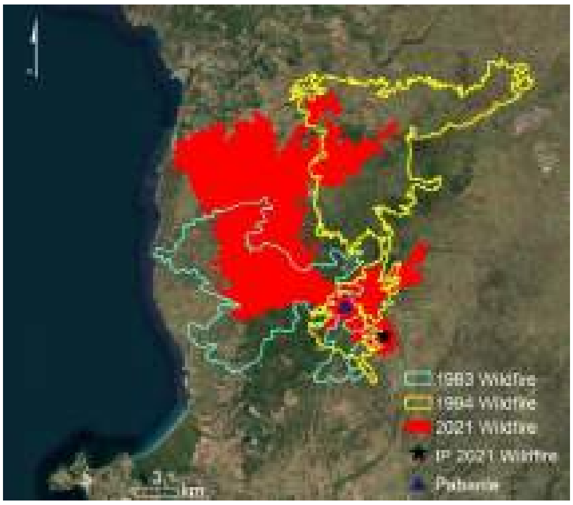


Figure 42 – Perimeters of the largest wildfire events that occurred in the Montiferru area in recent years.

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%).

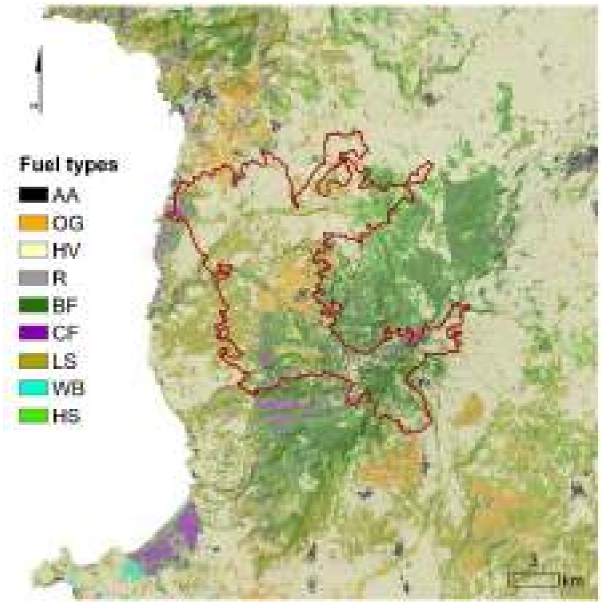


Figure 43 – Main fuel types of the area affected by the Montiferru wildfire. AA=anthropic areas; OG=olive groves; HV=herbaceous vegetation; R=rocks; BF=broadleaf forests; CF=conifer forests; LS=low shrubs; WB=water bodies; HS=high shrubs. On the right, some olive groves were affected by the wildfire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

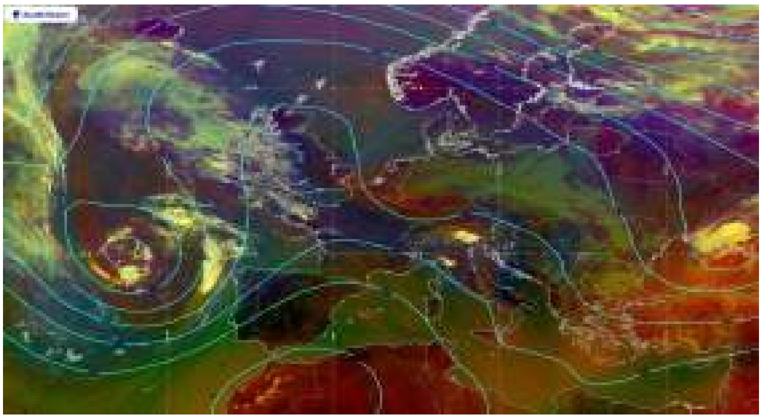


Figure 45 – MSG (Meteosat Second Generation) Air Mass RGB composition with ECMWF analysis of geopotential height (gpdam) and temperature (°C) respectively at 500 hPa and 850 hPa levels on 02.00 p.m. (12.00 UTC) of July 22nd.

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.

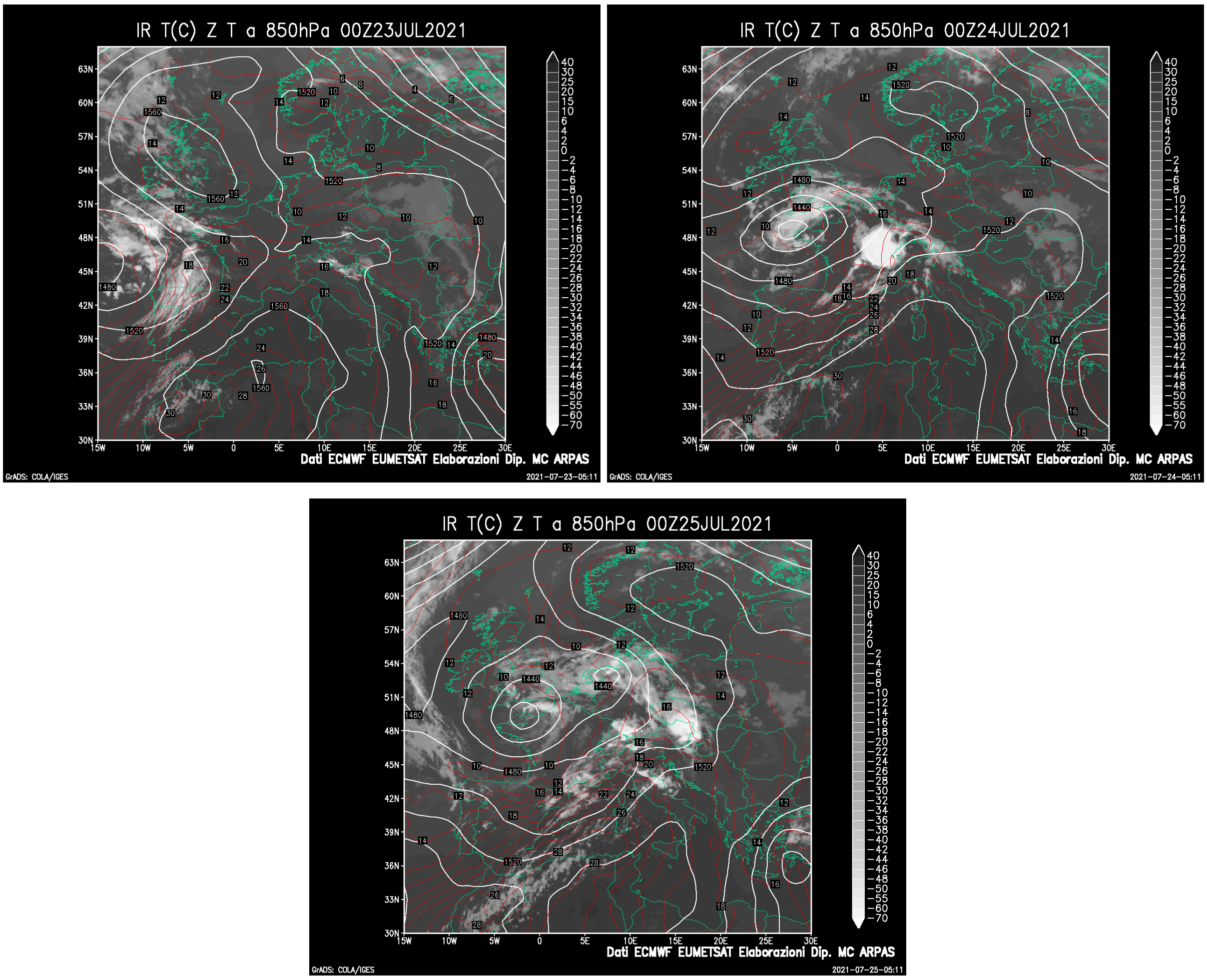


Figure 46 – Superimposed infrared MSG (Meteosat Second Generation) images and ECMWF analysis of geopotential height and temperature at 850hPa on 02.00 a.m. (00.00 UTC) of July 23rd, 24th, and 25th.

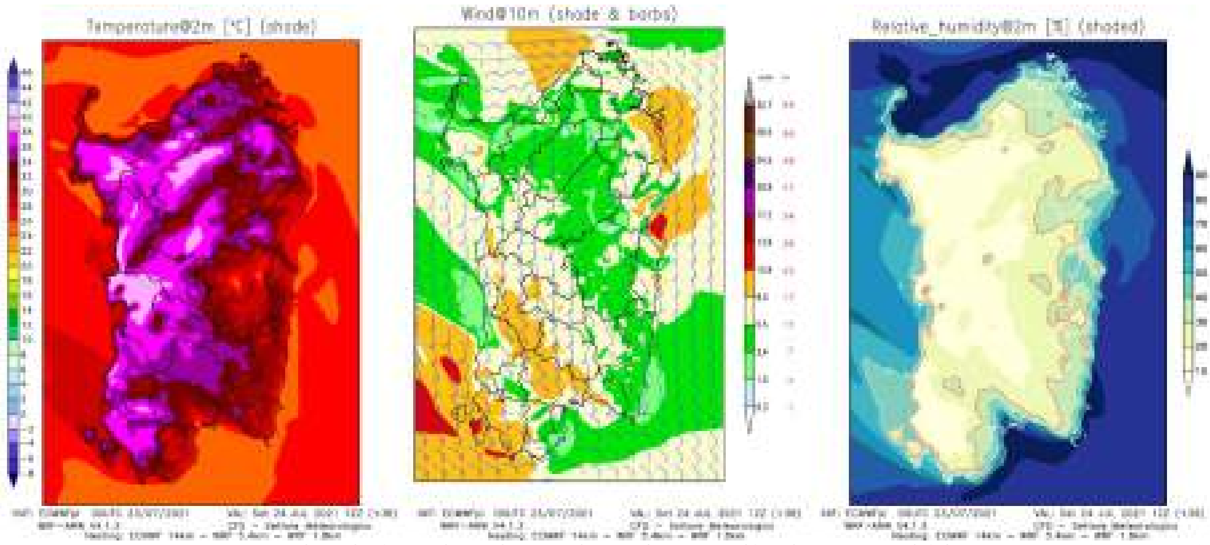


Figure 47 – Temperature, wind, and relative humidity conditions forecasted by the WRF model for 02.00 p.m. (12:00 UTC) of July 24th.

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.

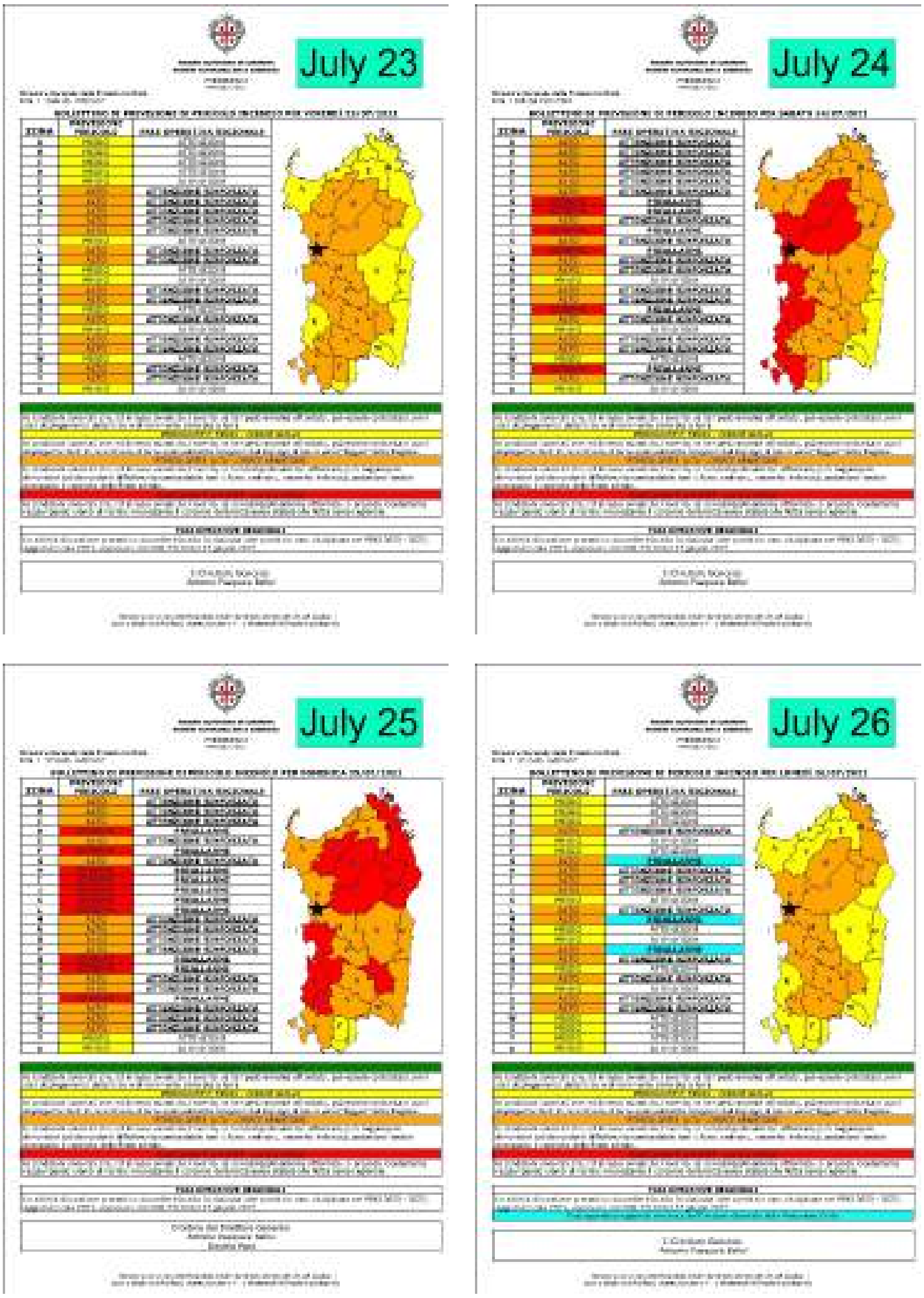


Figure 48 – Fire danger bulletins issued by the Sardinia Civil Protection for the period July 23rd to 26th. Sardinia is split into several homogeneous weather sectors (from A to Z). The black star indicates the Montiferru wildfire ignition.

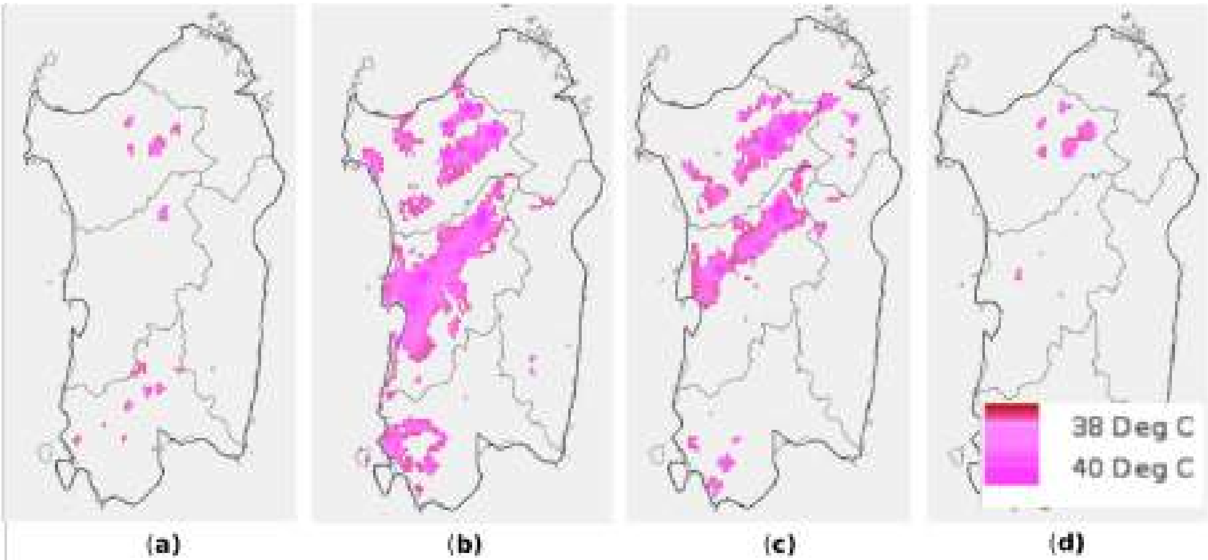


Figure 49 – Maximum temperature values above 37°C, as interpolated by the Dewetra integrated system of the Italian Civil Protection Department, from the data observed in the weather stations from July 23rd to 26th.

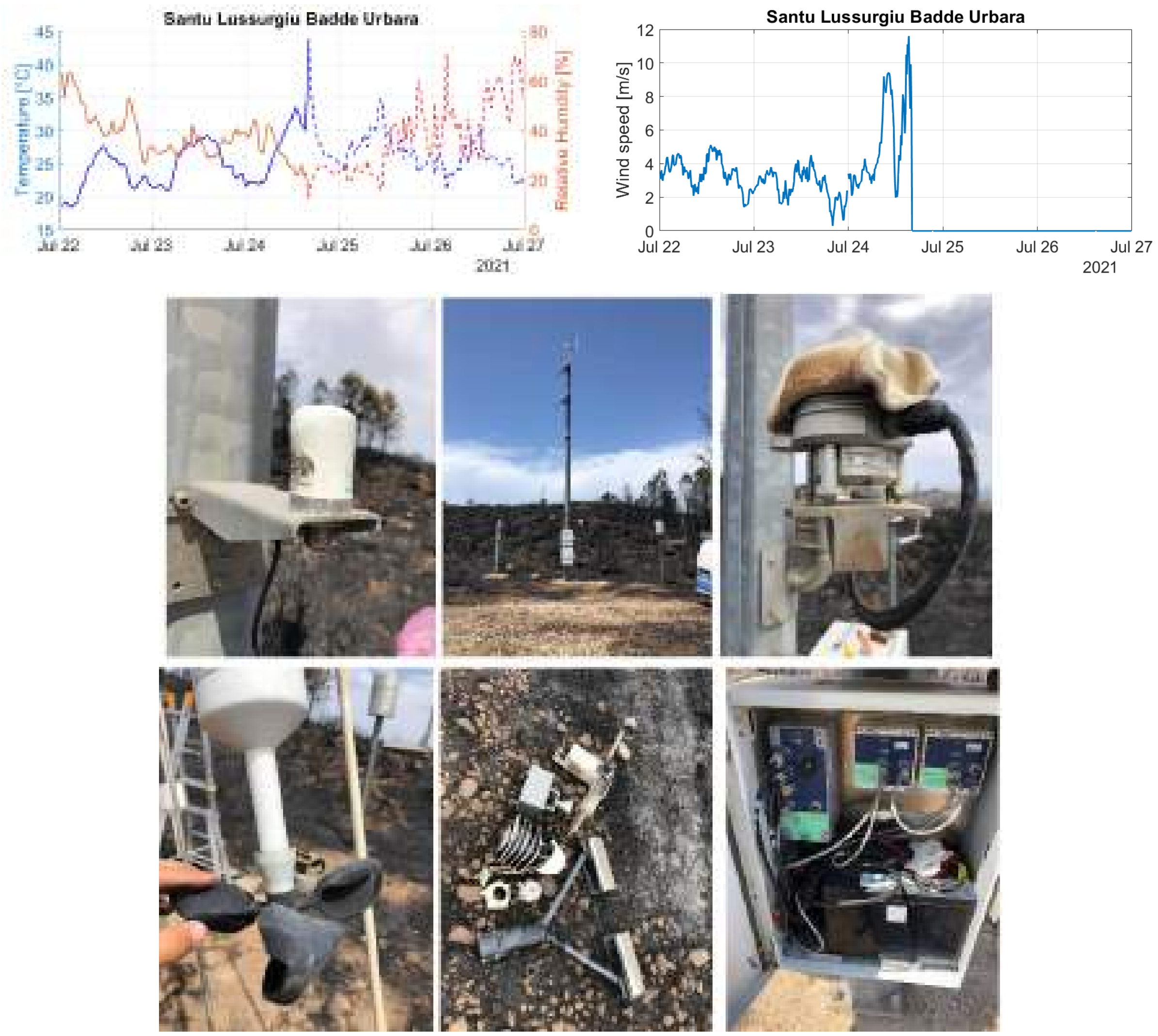


Figure 50 – Temperature and relative humidity, and wind intensity measured in the Badde Urbara (1,033m a.s.l.) weather station. The dotted line highlights when data of temperatures and humidity are not reliable as they refer to the period following the passage of the fire. The third image is evidence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

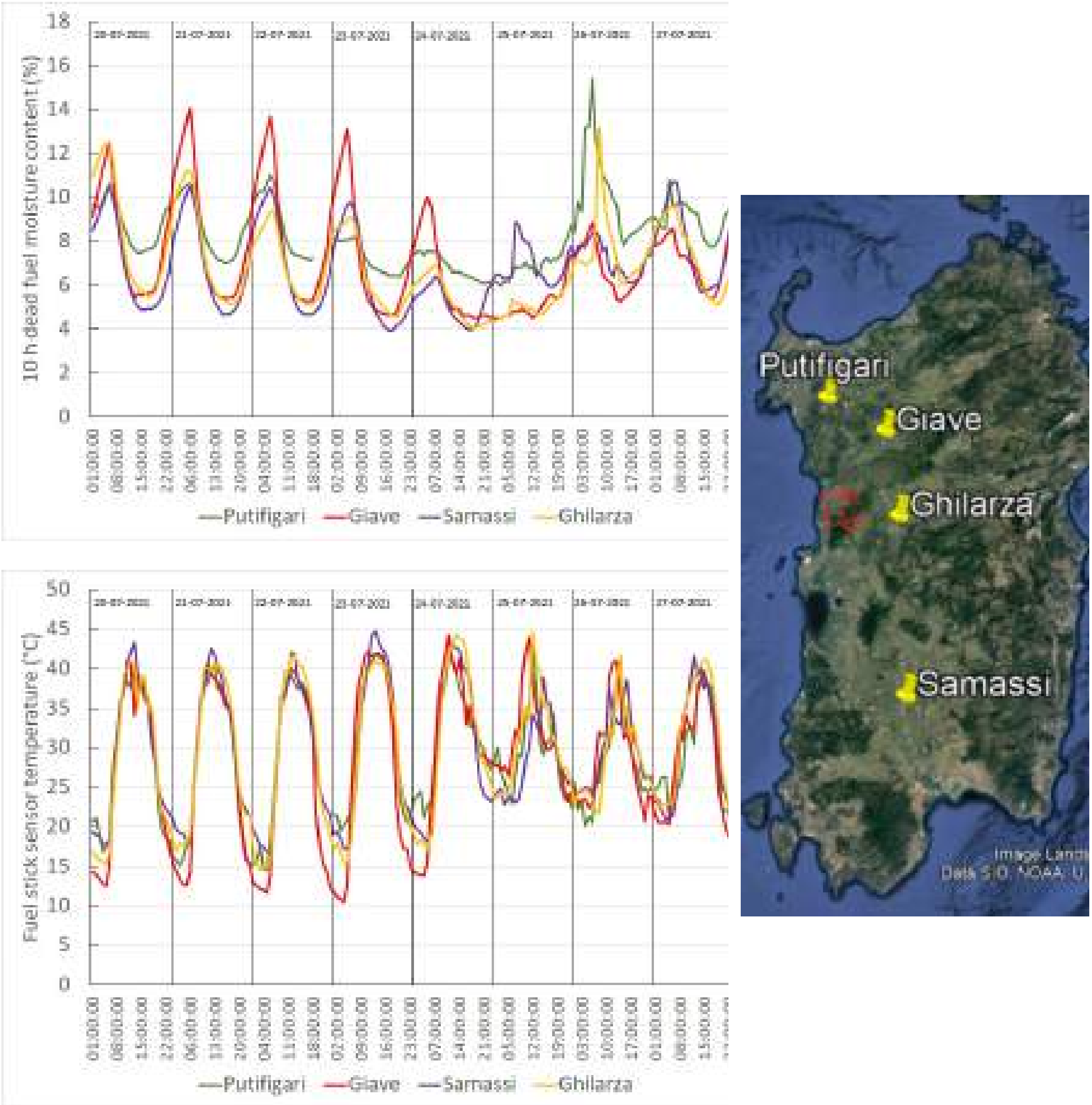


Figure 51 – 10h dead fuel moisture content and fuel stick sensor temperatures observed in four stations of monitoring, located in Putifigari, Giave, Ghilarza, and Samassi, from July 20th to 28th

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).

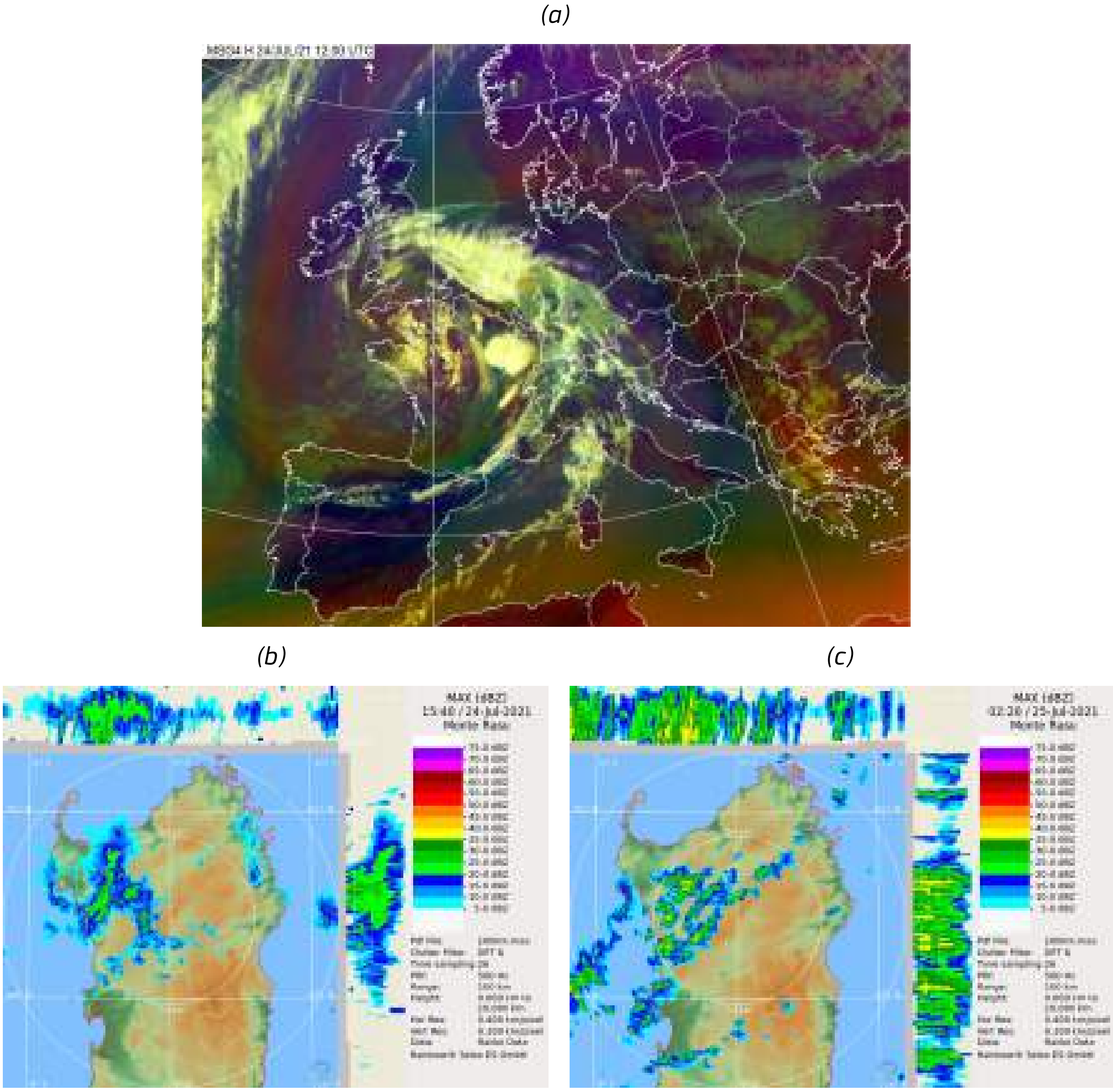


Figure 52 – Meteosat Second Generation (MSG) Air Mass RGB composition at 02.00 p.m. (12.00 UTC) of July 24th. Figures "b" and "c" present the vertical maximum reflectivity (dBZ) observed by the ARPAS weather radar (focus on two timeframes characterized by high wildfire growth rates).

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)*

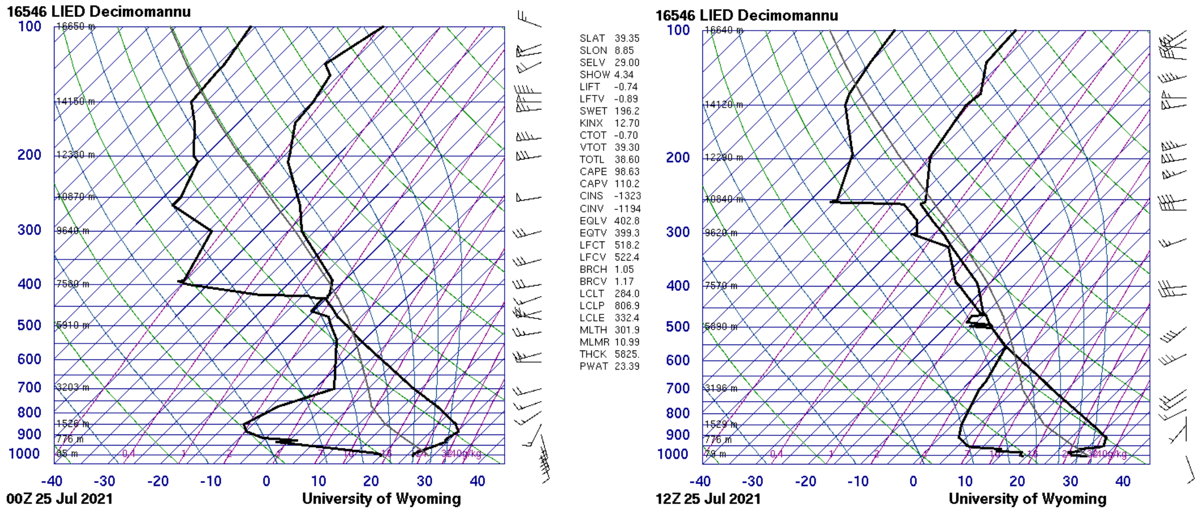


Figure 53 – Atmospheric radiosonde charts of Decimomannu (CA), 150km SE to the Montiferru, of July 25th, 00Z and 12Z.

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).

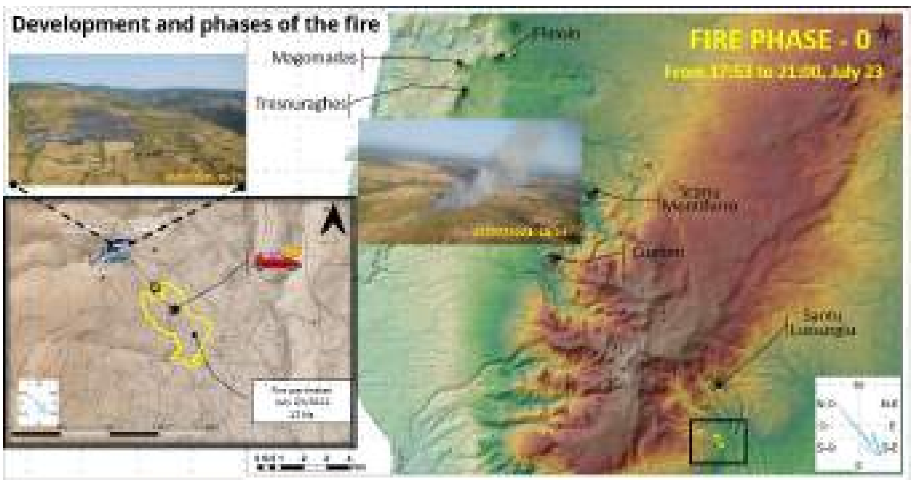


Figure 54 – Phase 0 of the Montiferru wildfire, July 23rd, from 05.53 p.m. to 09.00 p.m.

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.

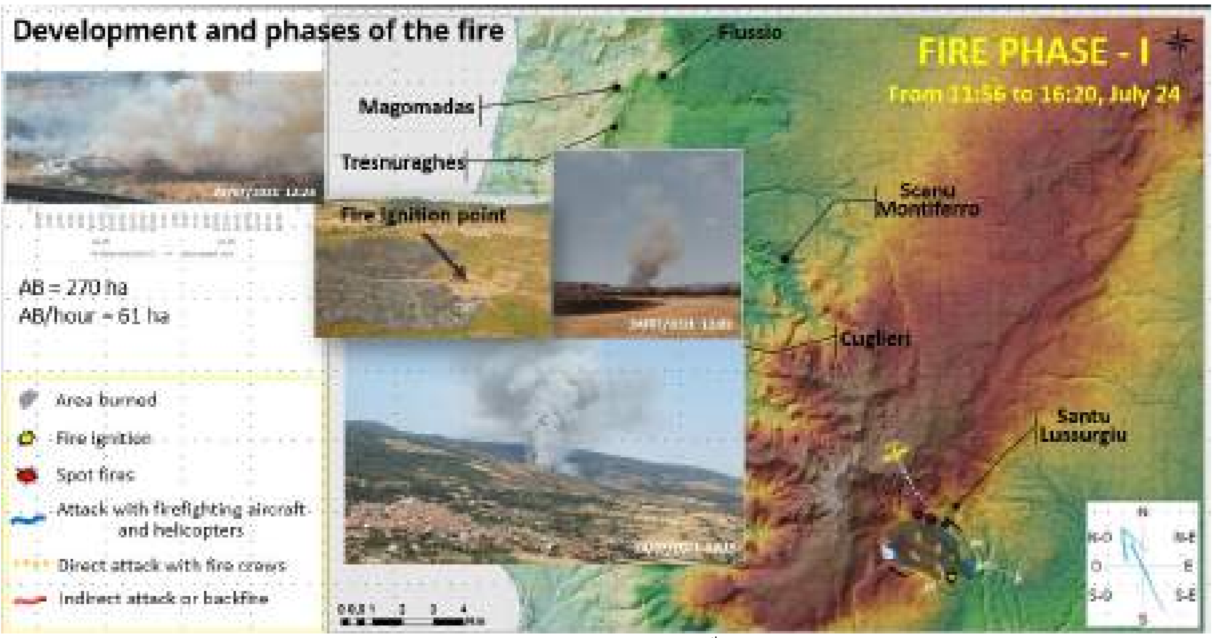


Figure 55 – Phase I of the Montiferru wildfire, July 24th, from 11.56 a.m. to 04.20 p.m.

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.

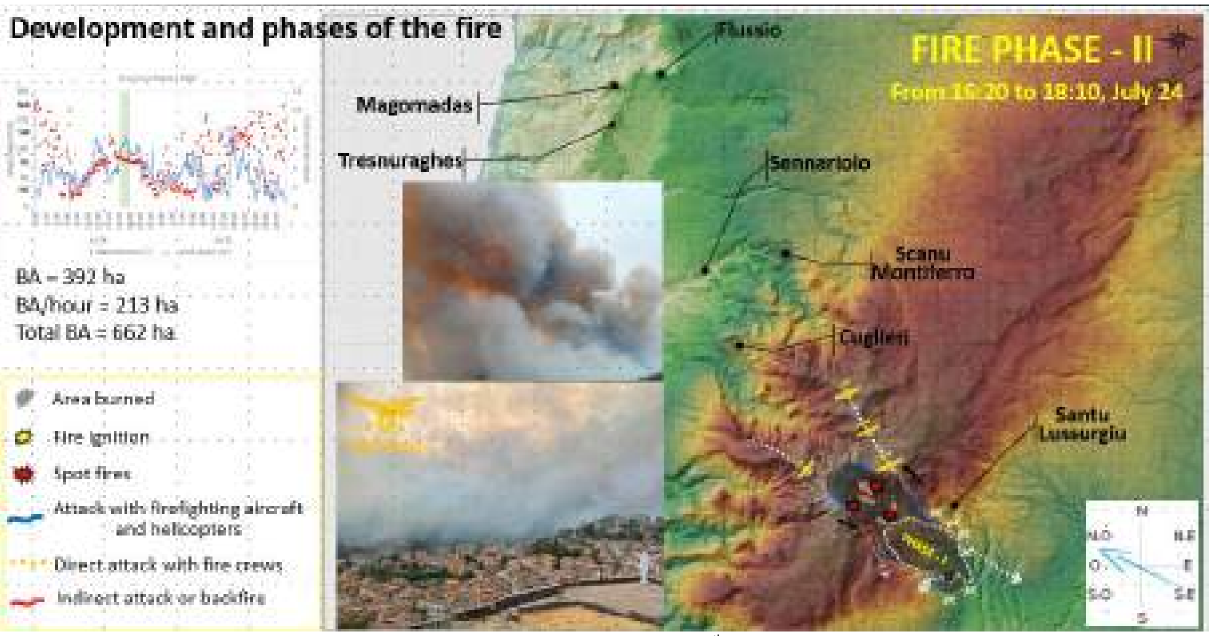


Figure 56 – Phase II of the Montiferru wildfire, July 24th, from 04.20 p.m. to 06.10 p.m.

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.

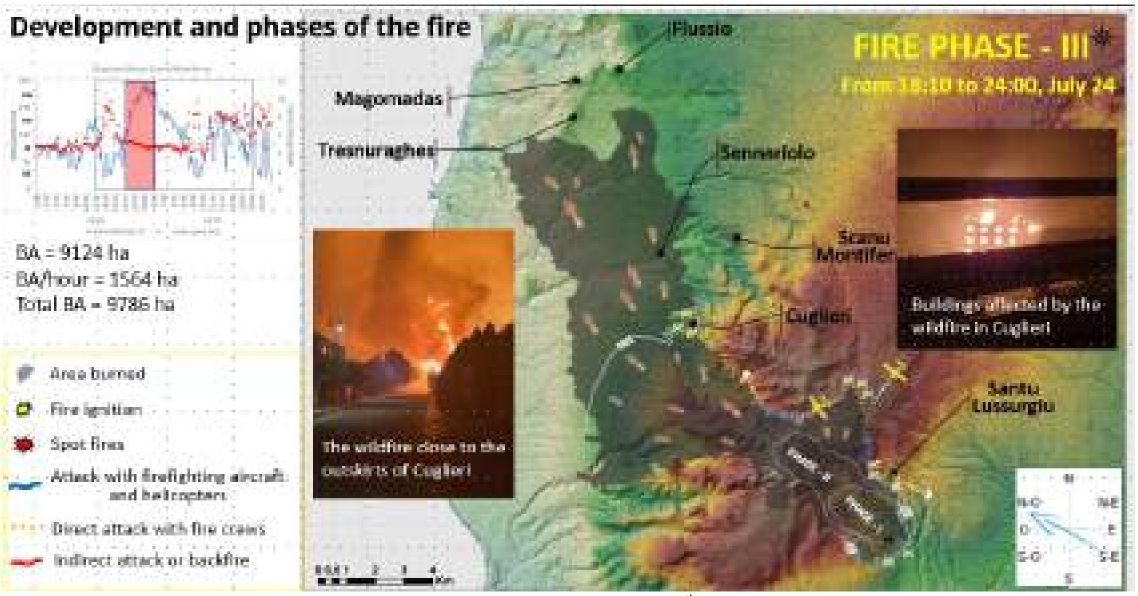


Figure 57 – Phase III of the Montiferru wildfire, July 24th, from 06.10 p.m. to midnight.

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.

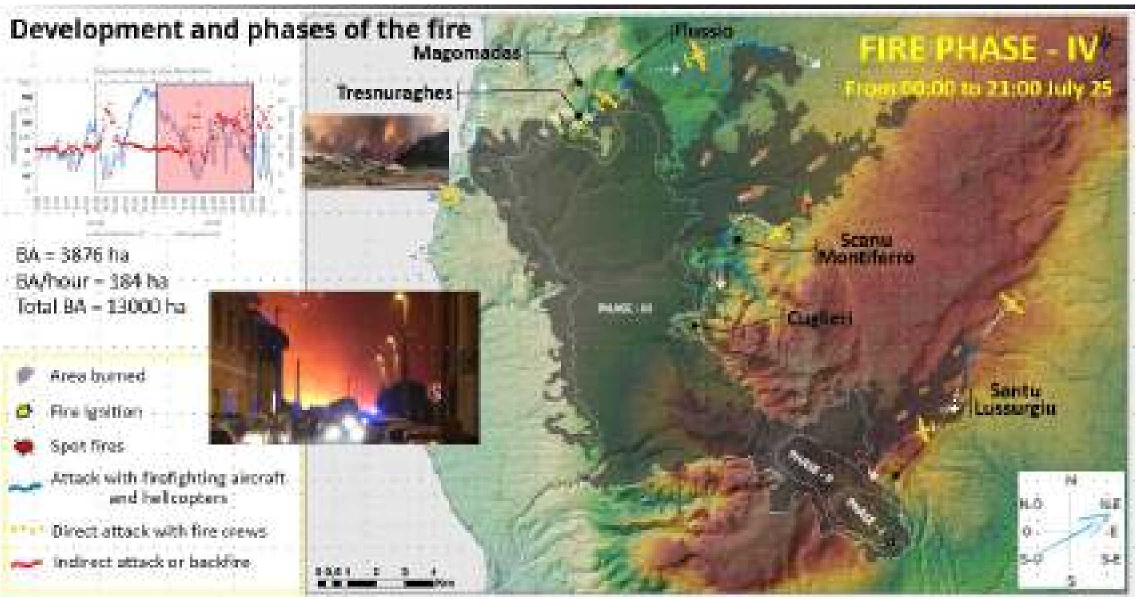


Figure 58 – Phase IV of the Montiferru wildfire, July 25th, from 00.00 to 09.00 p.m.

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).

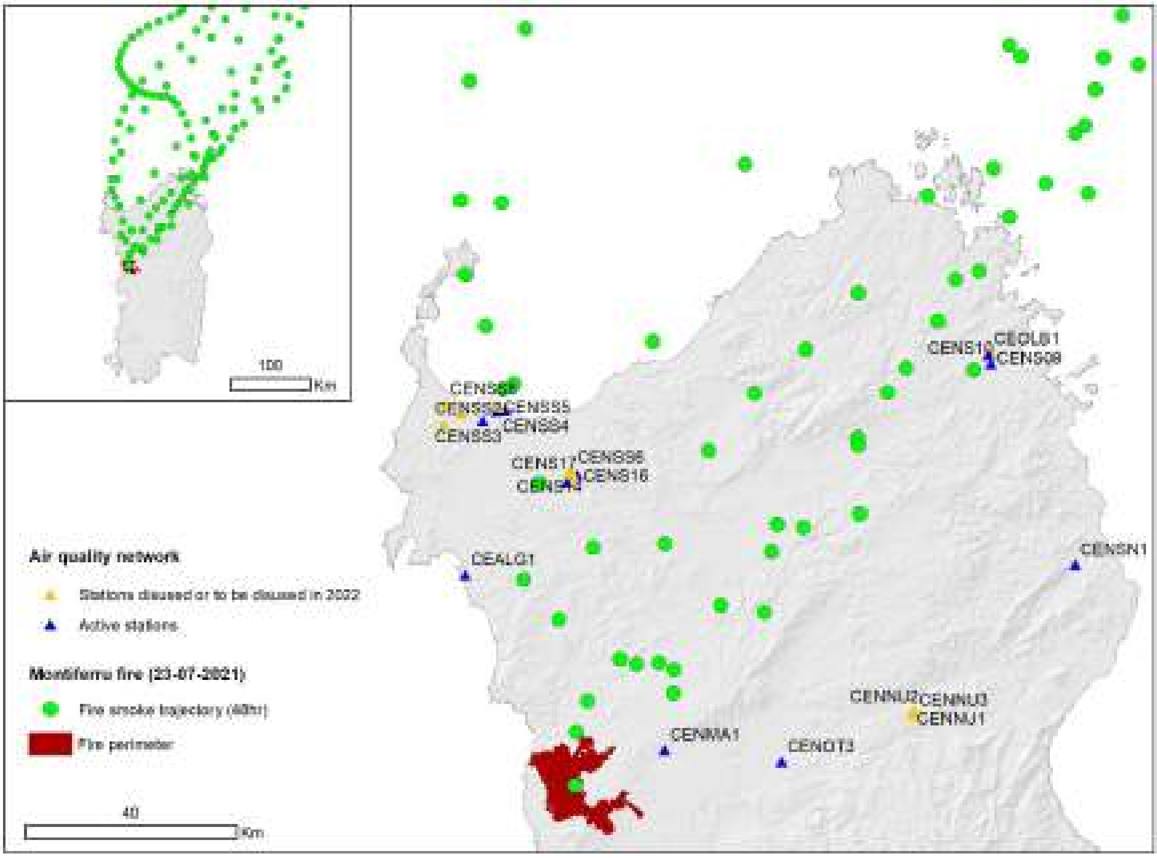


Figure 59 – Montiferru fire smoke plume trajectory at larger (a) and detailed (b) scale.

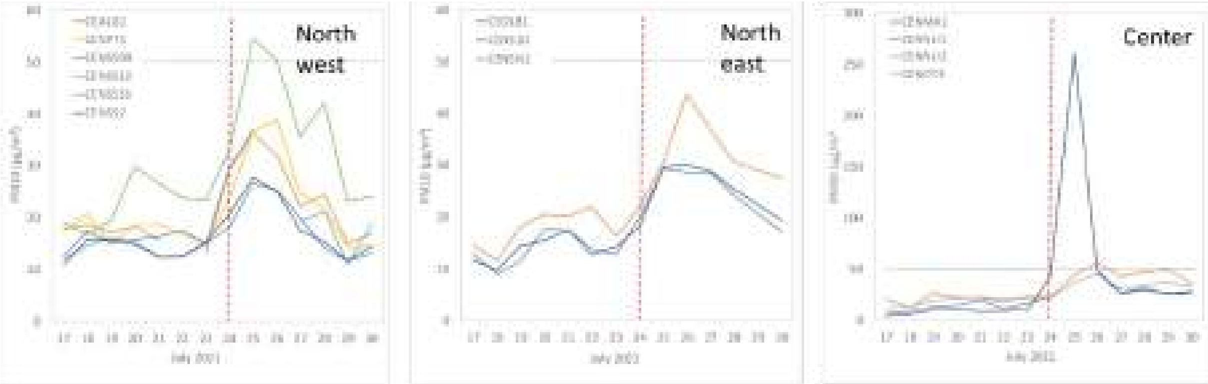


Figure 60 – Daily evolution trends for PM_{10} measured in ARPAS stations (Sassari, NW Sardinia; Olbia, NE Sardinia; and Nuoro, Central Sardinia), from July 17th to 30th.

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.

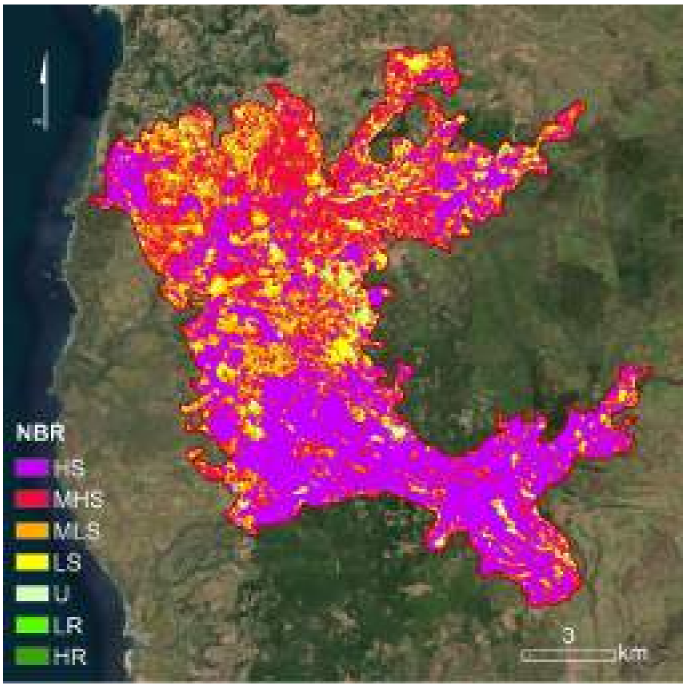


Figure 61 – Burn severity estimated for the Montiferru wildfire. This output was derived by rescaling the Normalized Burn Ratio index (NBR). HR=high regrowth; LR=low regrowth; U=unburned; LS=low severity; MLS=medium-low severity; MHS=medium-high severity; HS=high severity.

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

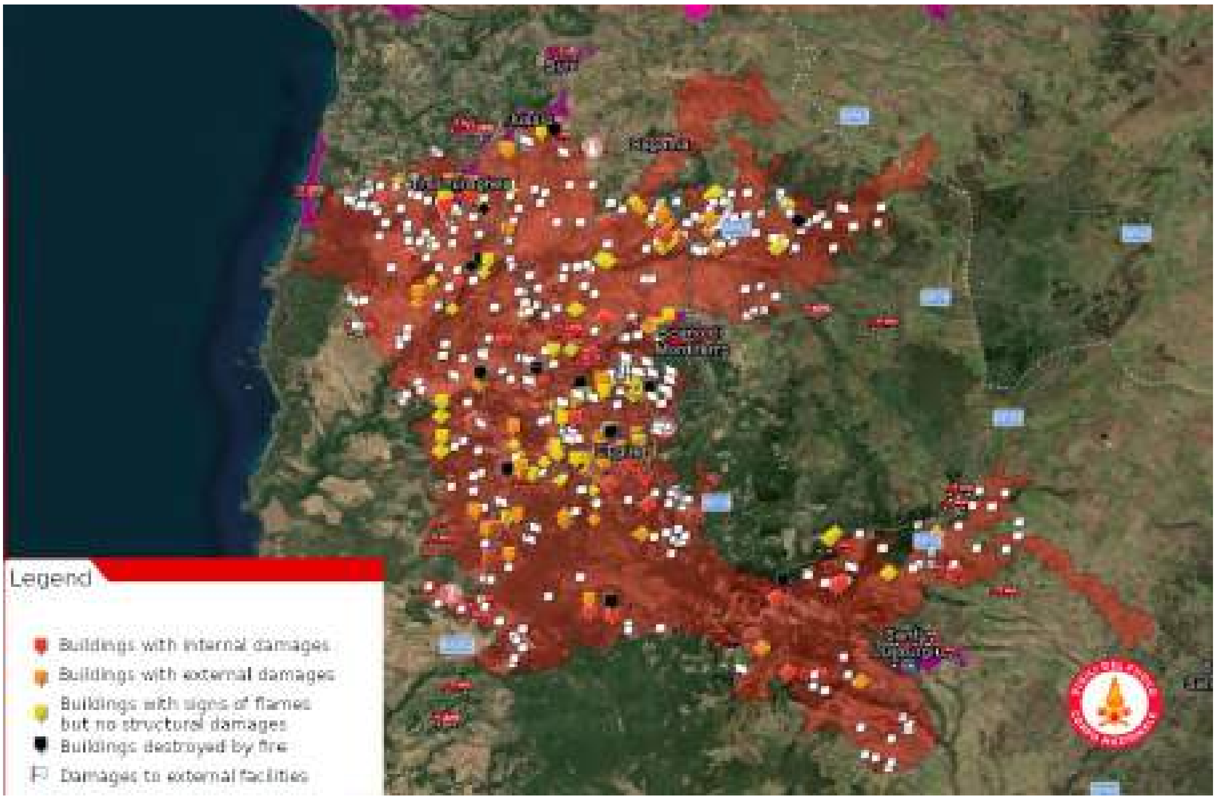


Figure 62 – Location of residential, agricultural, and other buildings partially or heavily damaged by the fire.

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**

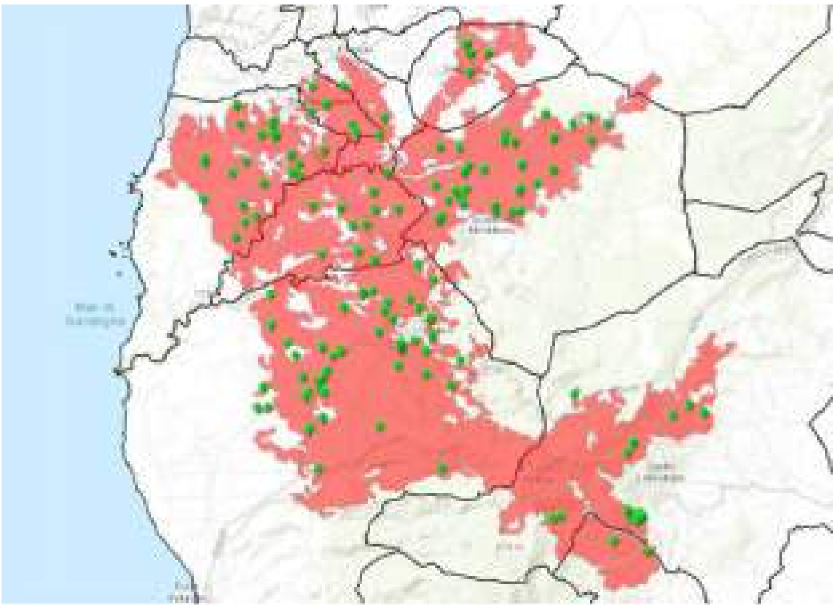


Figure 66 – Location of the livestock farms that were affected by the Montiferru wildfire. Source Protezione Civile.

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).

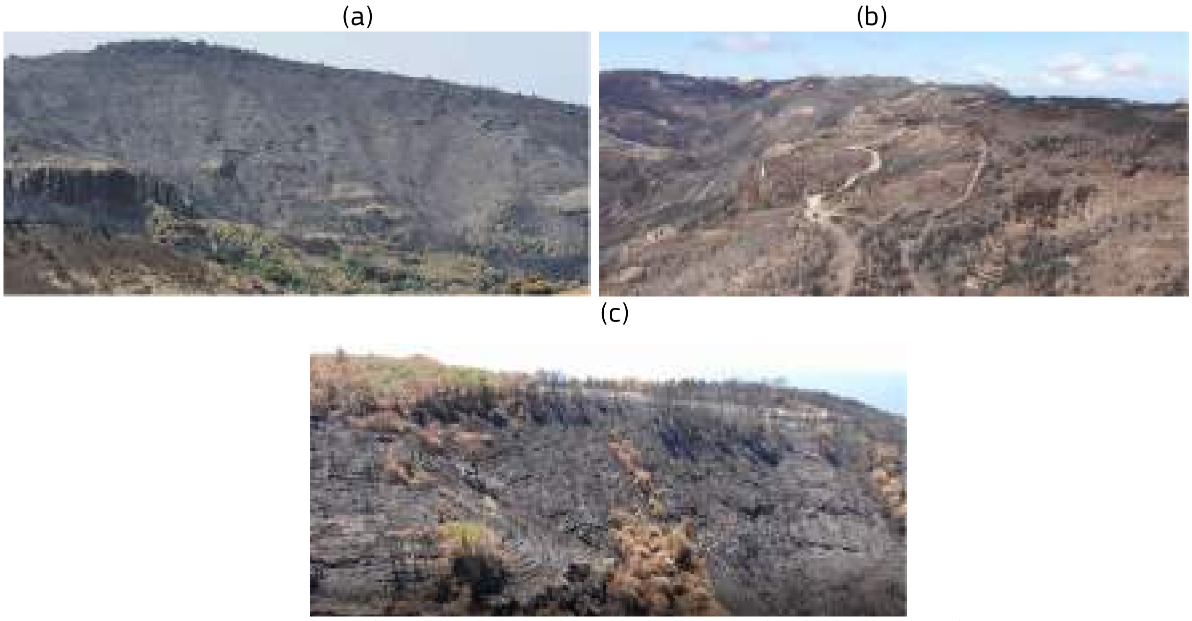


Figure 67 – Post-fire pictures in some areas characterized by high slope conditions:
(a) Cuglieri, (b)Santu Lussurgiu, and (c) Tresnuraghes.

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 42ºC, 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.

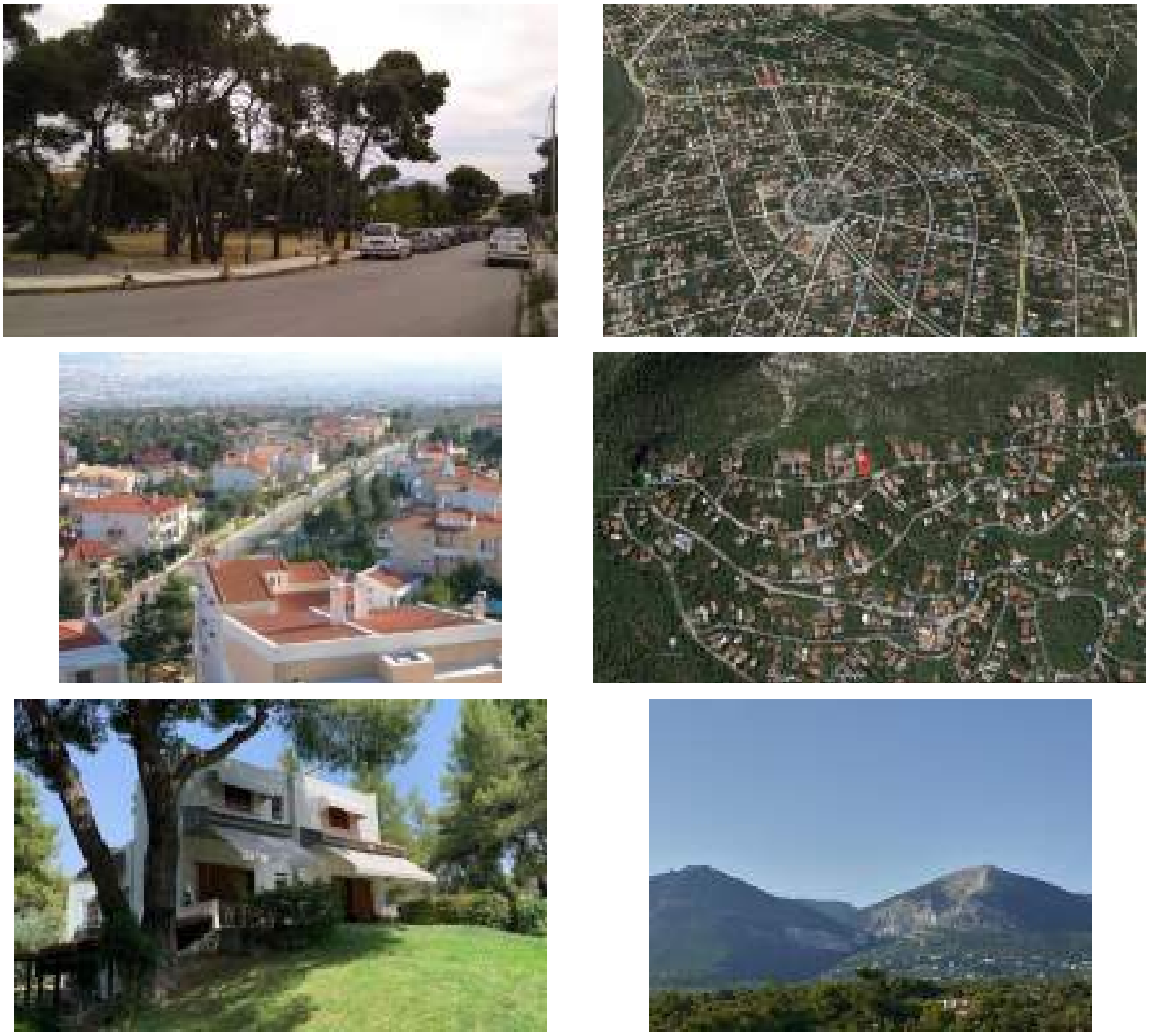


Figure 70 – Wildland urban interface in the wider area of the Varybobi 2021 fire.

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).

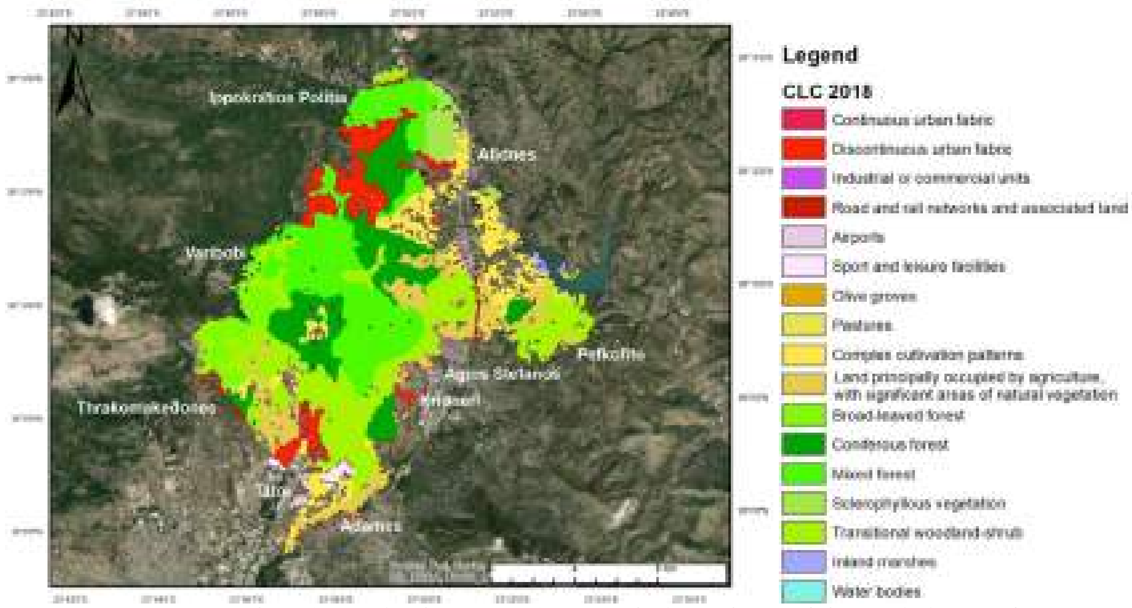


Figure 71 – Land use (Corine landcover 2018) map in the burned area of the Varybobi 2021 fire.

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)

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.

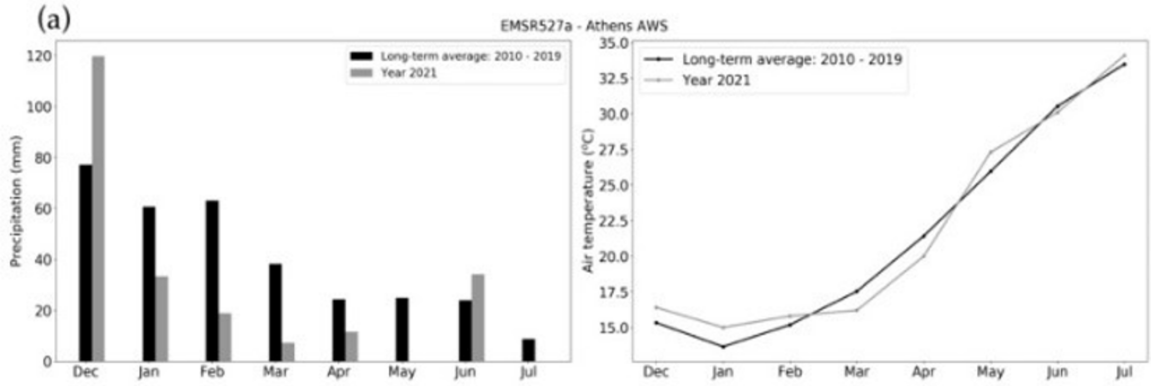


Figure 73 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527a).

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.

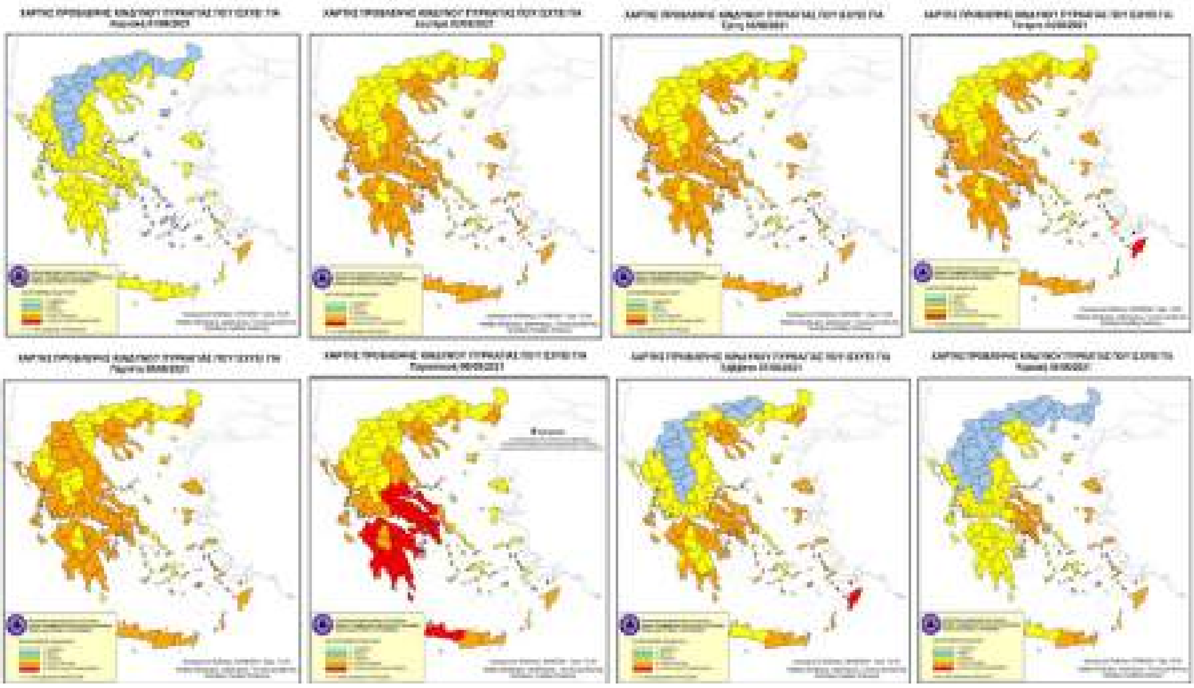


Figure 74 – Daily Fire Risk maps for 1-8 August 2021 issued by the General Secretariat of Civil Protection.

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)*

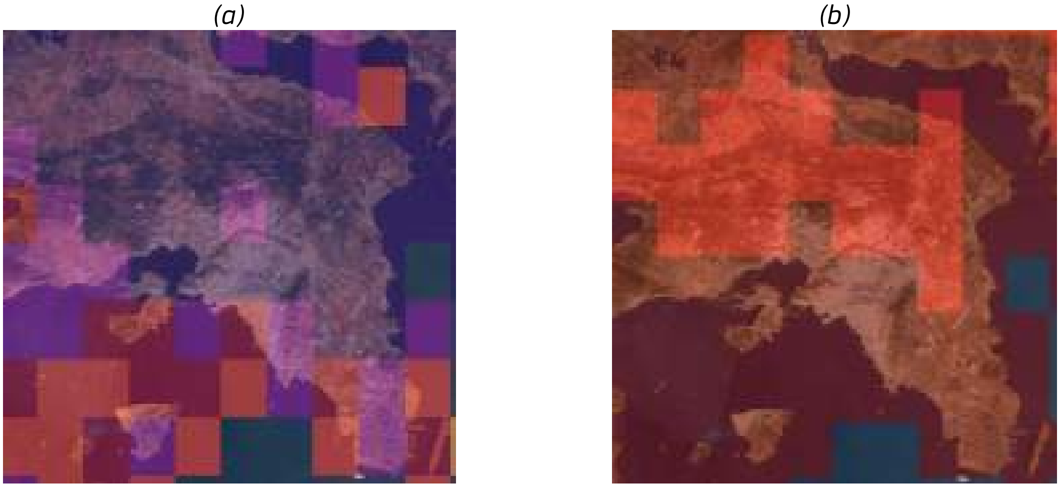


Figure 75 – Snapshot from the European Forest Fire Information System (EFFIS) showing the forecast of Fire Weather Index (a) and Drought Code (b) for the area of Varybobi on August 3rd.

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]).

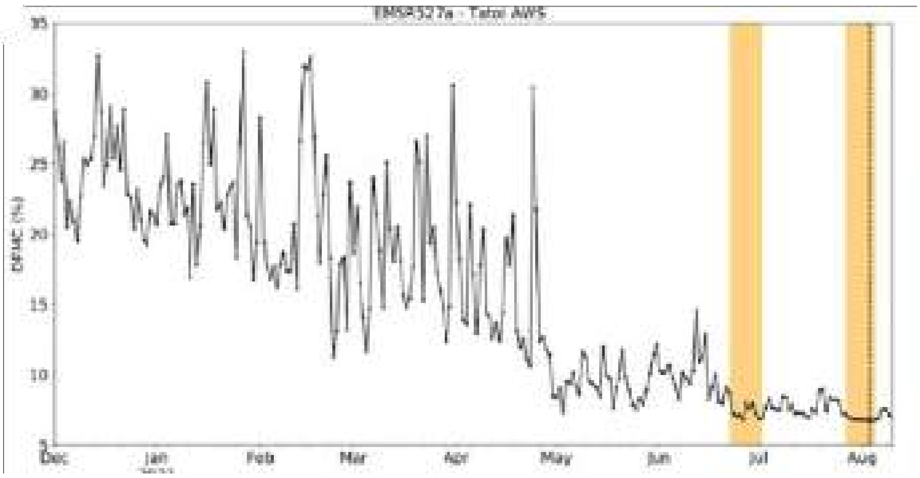


Figure 76 – Time series of the daily dead fuel moisture content (DFMC) for the period December 2020 and August 2021 [23].

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.

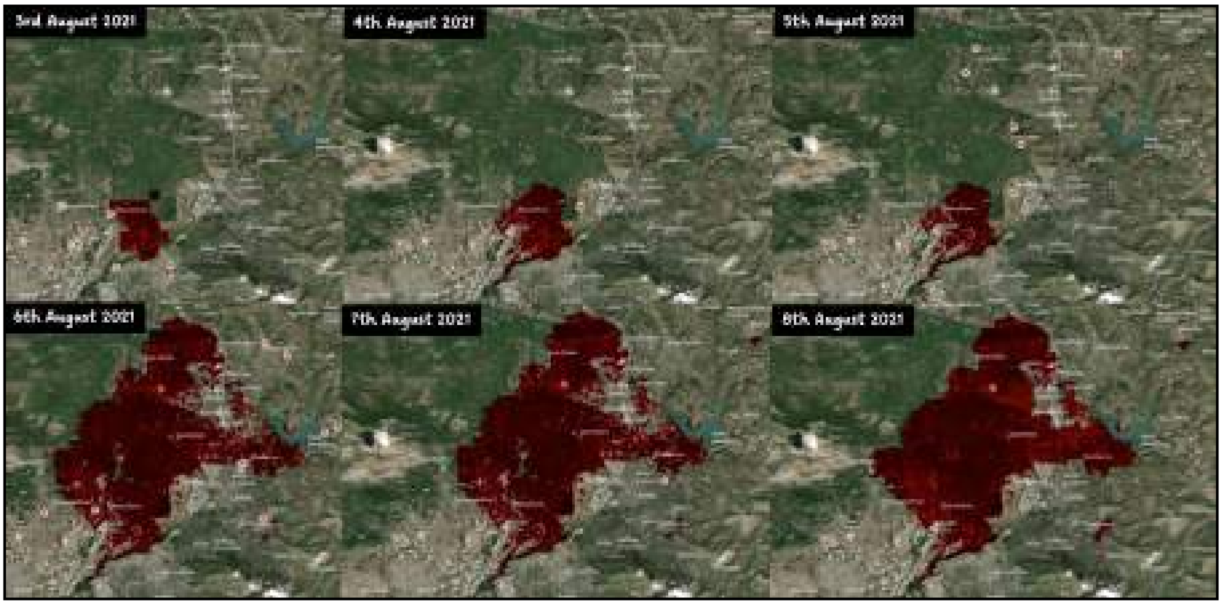


Figure 77 – Daily burned areas (Copernicus EMS) of the Varybobi fire between August 3rd and 8th (NKUA EDCM Newsletter, 2021 [24]).

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.

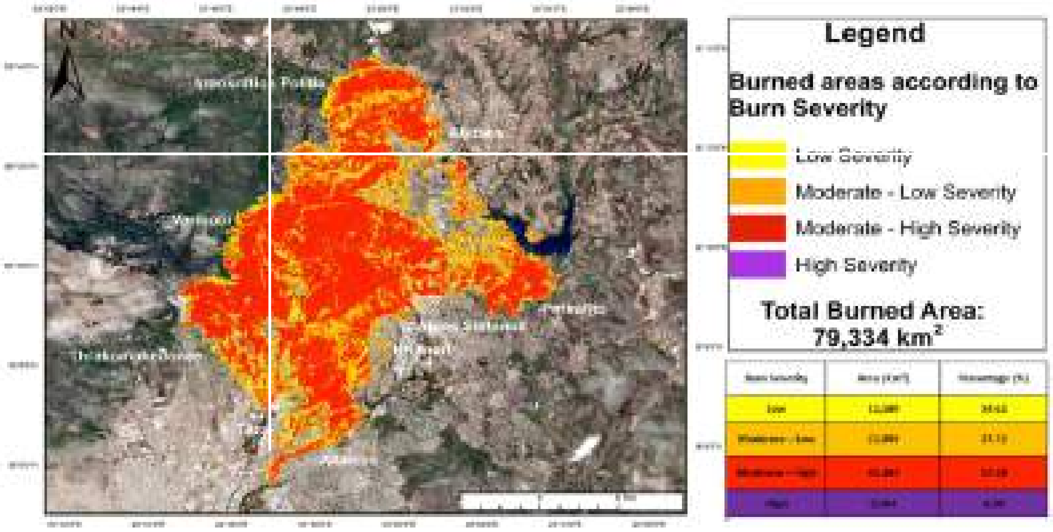


Figure 78 – Burned area mapping and classification according to Burn Severity using Sentinel-2B L2A images of July 29th and August 8th (Harokopeion University of Athens).

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).

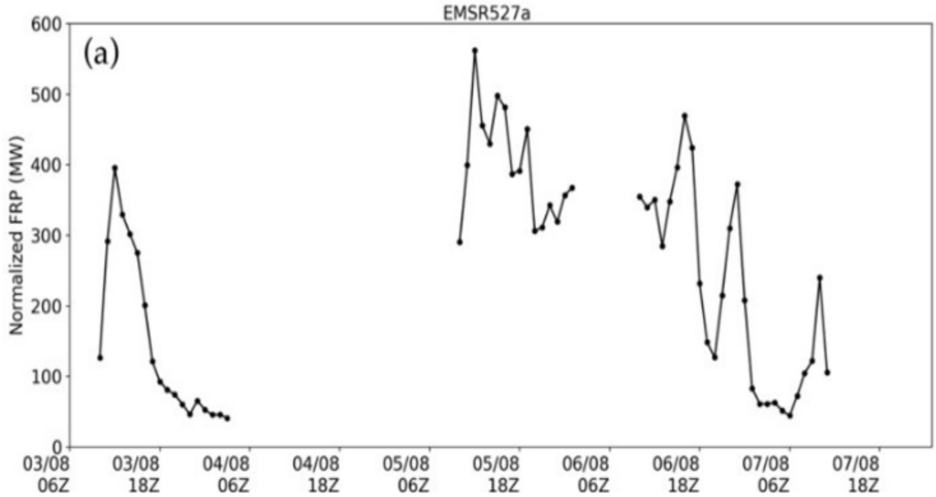


Figure 79 – Time series of hourly normalized FRP from SEVIRI/METEOSAT [23].

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).

(a)

(b)

(c)

(d)

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).

(a) *(b)*

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 PM2.5 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.

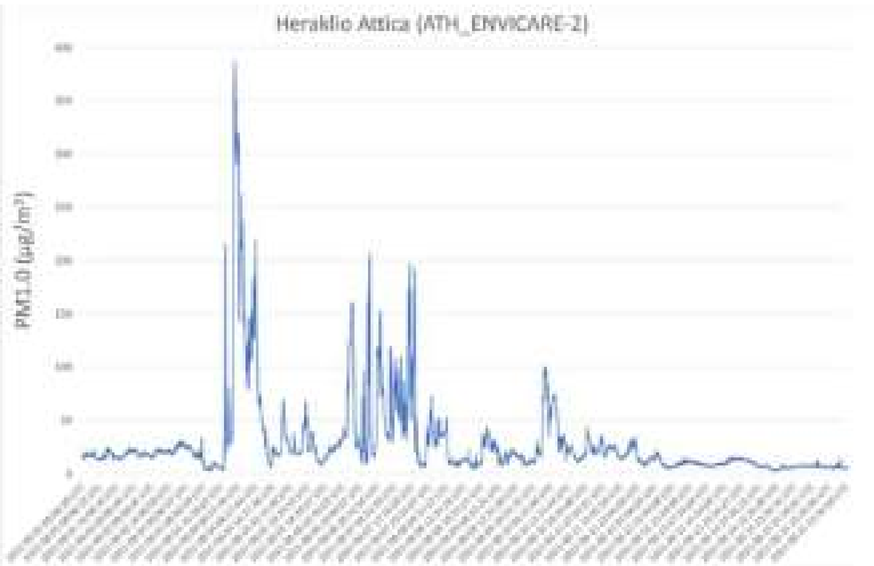


Figure 86 – Ambient particulate (PM1.0) pollution from the smoke of the Varybobi fire (Source: Project Envicare).

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).

(a) *(b)*

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.

(a) *(b)*

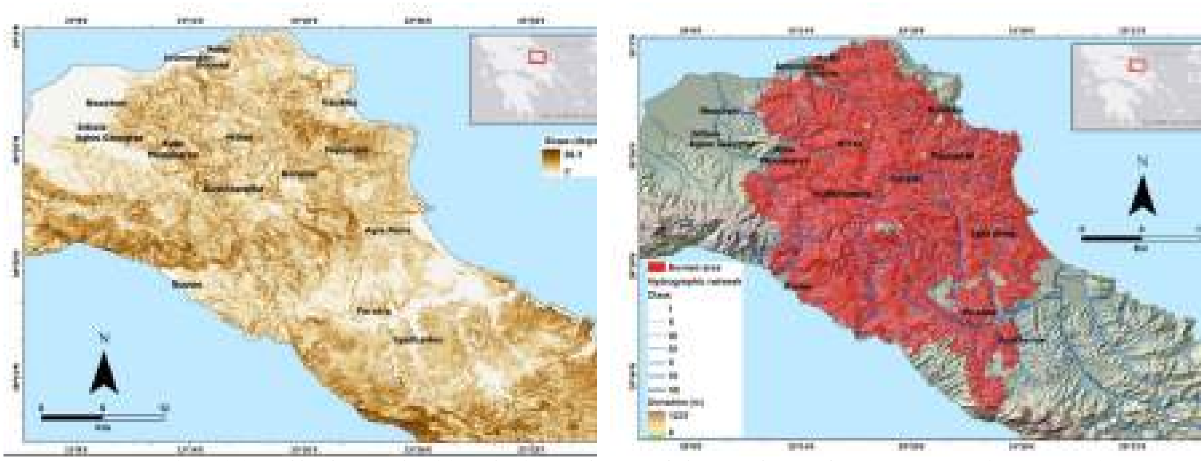


Figure 88 – Slope (a) and hydrography (b) in the burned area of the North Evia fire (NKUA Newsletter 2021)[24].

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).

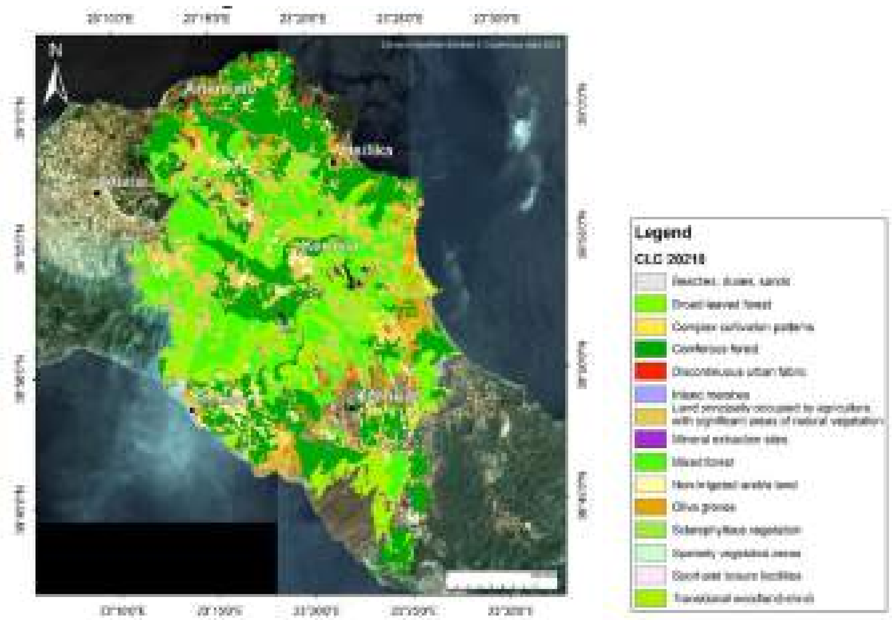


Figure 89 – Land use (CLC 2018) map in the burned area of North Evia 2021 fire (NKUA Newsletter) [24].

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.

(a) *(b)*

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).

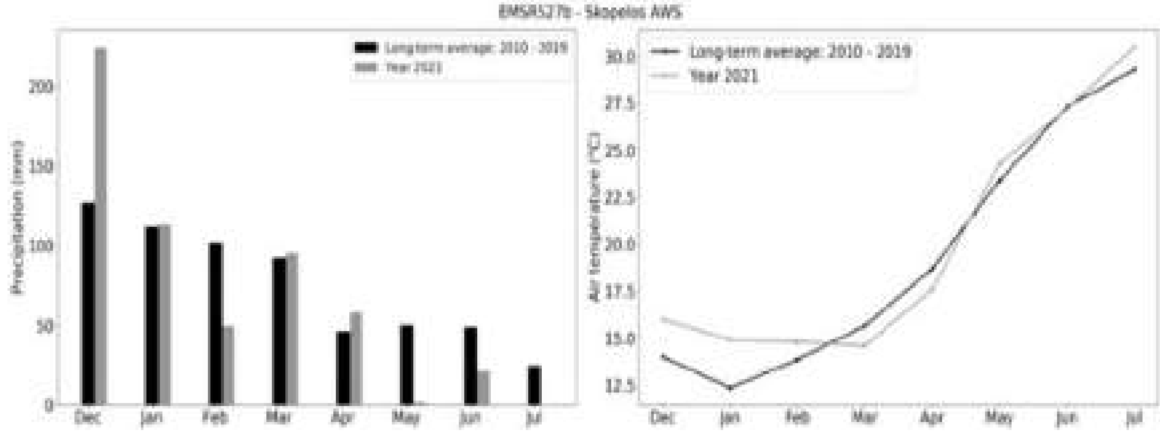


Figure 93 – Decline of mean monthly precipitation (left) and daily maximum air temperature for the period between December 2020 and July 2021 (Data source: Athens Weather Station EMSR527b).

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.

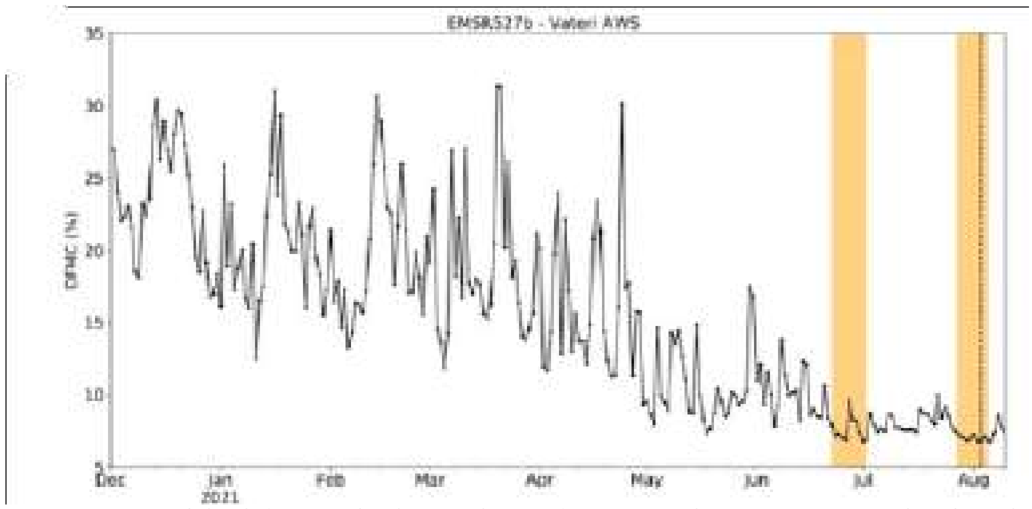


Figure 94 – Time series of the daily DFMC for the period December 2020 and August 2021 using data from the Vateri weather station [23].

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.

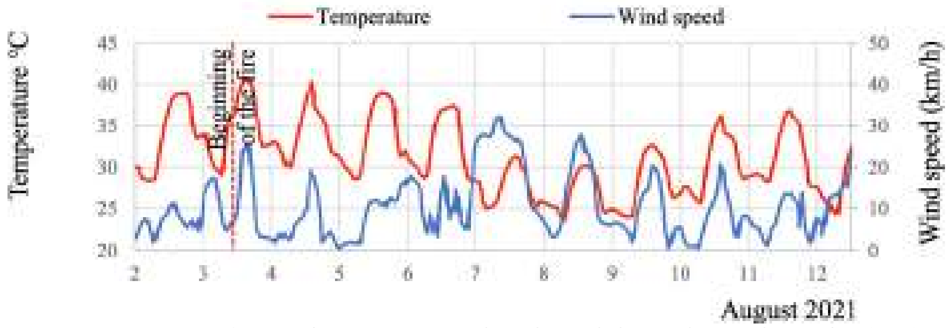


Figure 95 – Time evolution of temperature and wind speed during the North Evia fire ([27]).

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.

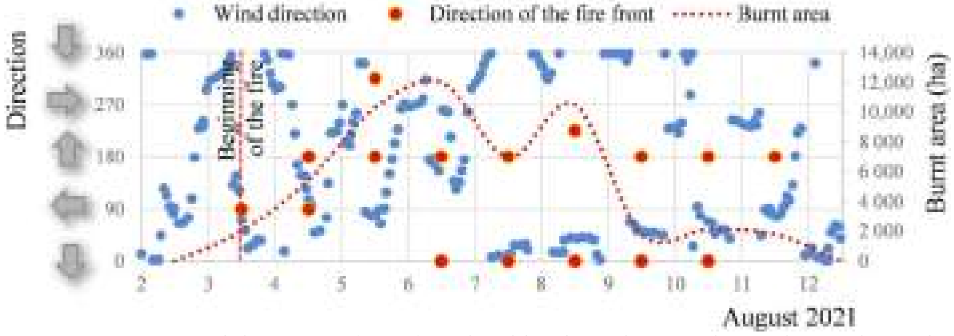


Figure 96 – Time variation of the meteorological wind and fire front direction during the North Evia fire ([27]).

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).

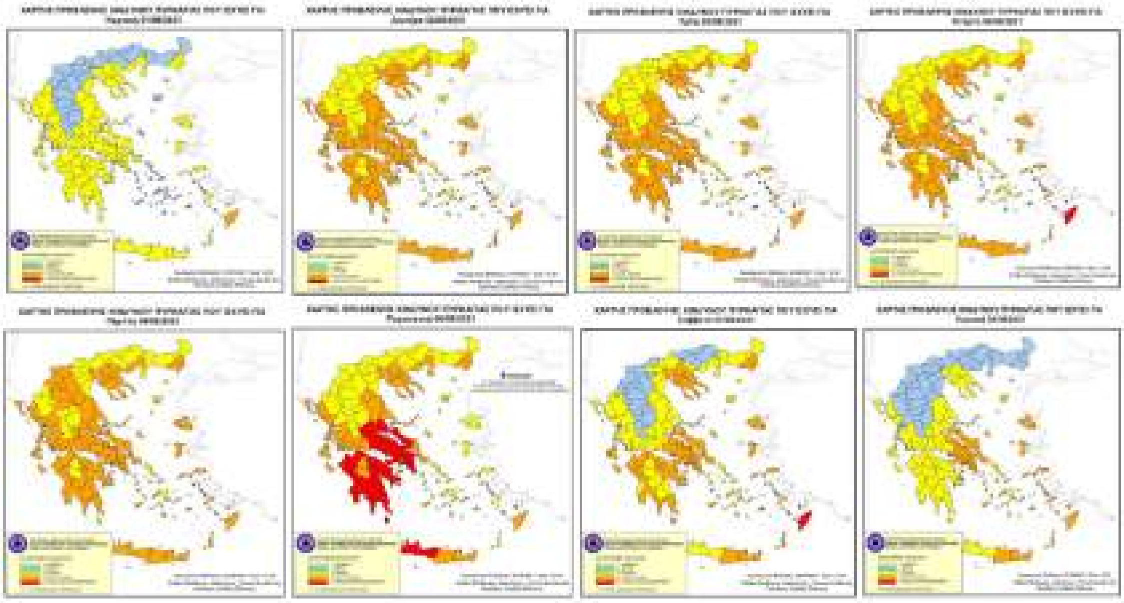


Figure 97 – Daily Fire Risk maps by the General Secretariat of Civil Protection for the period 1-8 August 2021 (Source: Greek General Secretariat of Civil Protection)

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).

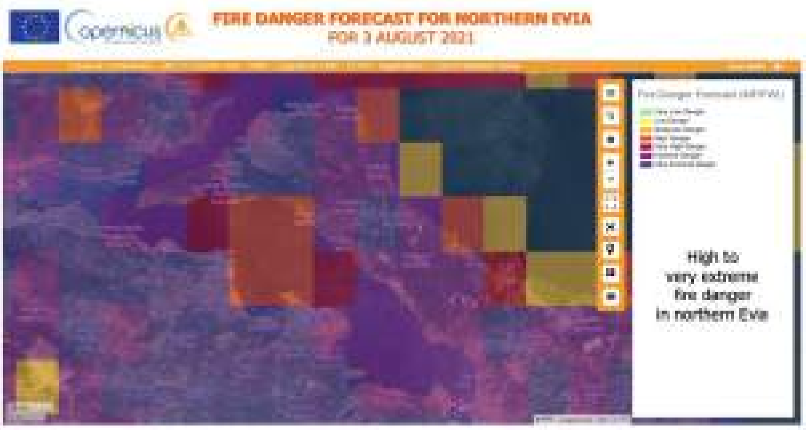


Figure 98 – Fire Danger Forecast based on the Fire Weather Index (FWI) computed from the MeteoFrance model (10km) Snapshot from the European Forest Fire Information System (EFFIS)
https://effis.jrc.ec.europa.eu/apps/effis_current_situation/

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].

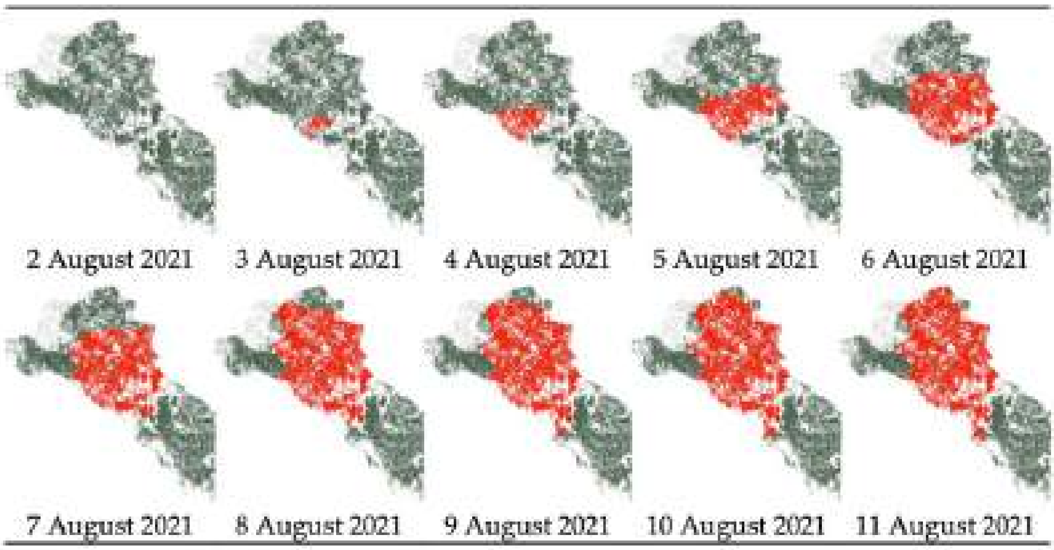
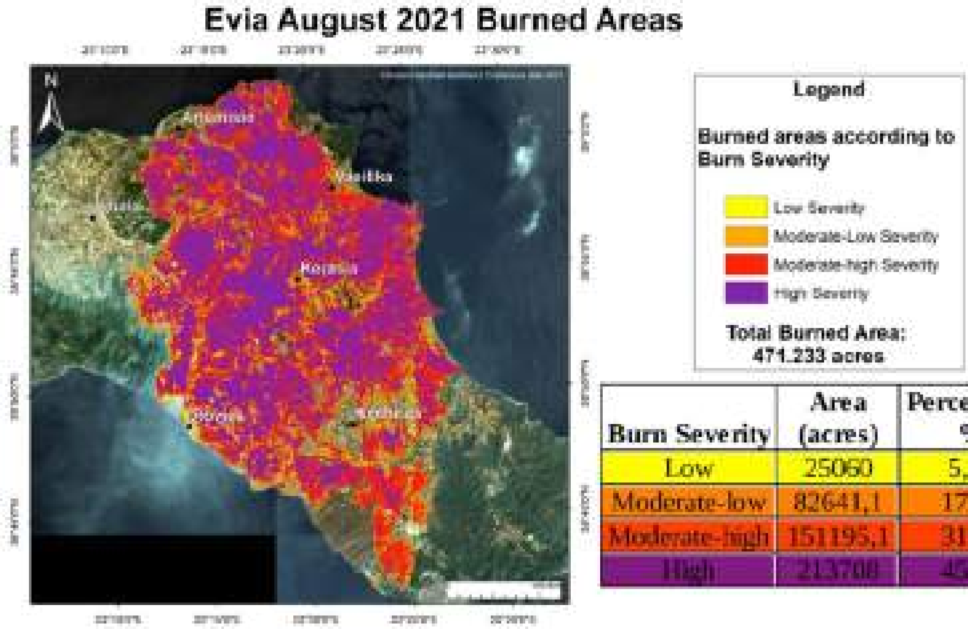


Figure 100 – The evolution of the fire in relation to forest continuity ([27]).

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).

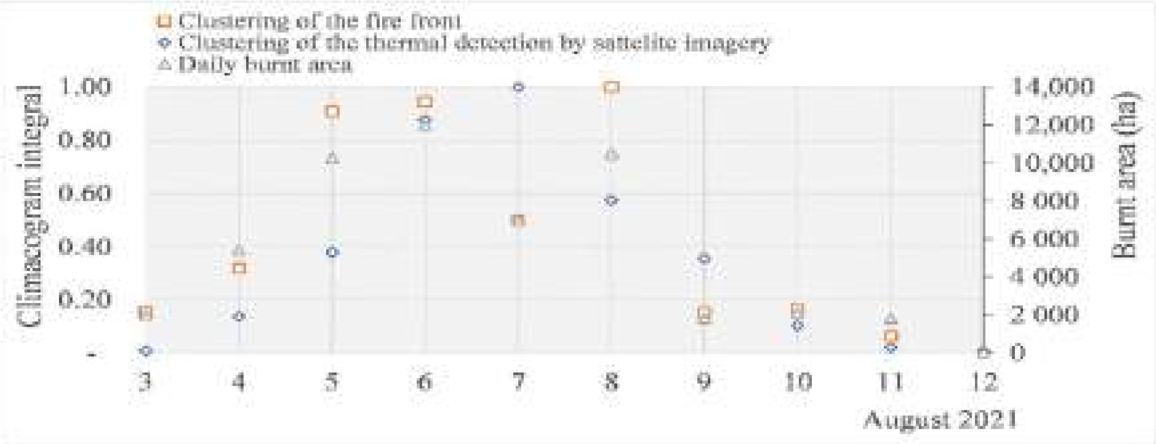


Figure 102 – Climacogram integral of the daily clustering of the fire front related to the respective burned area ([27].

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.

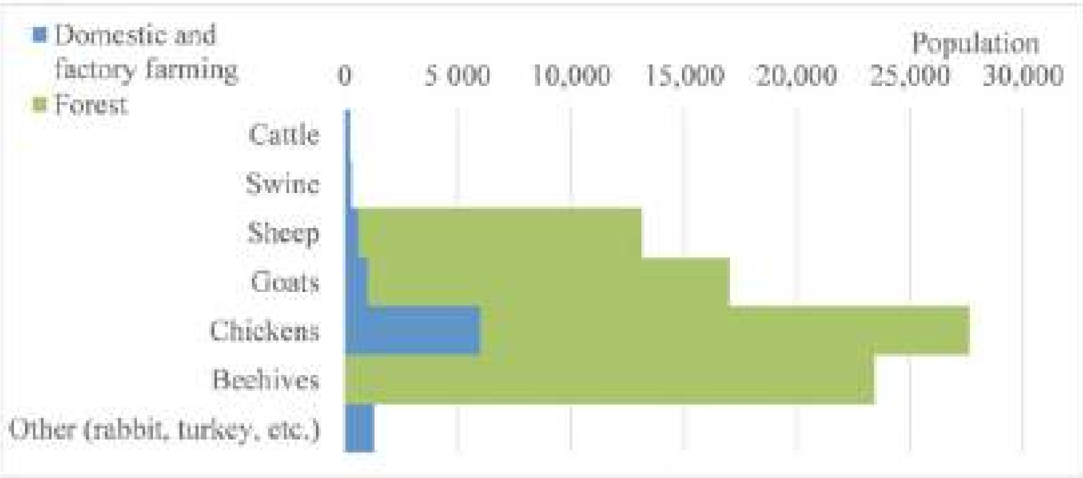


Figure 103 – The livestock and the beehives of the municipalities of Istiaia–Edipsos and Mandoudi–Agia Anna–Limni by the census 2019 ([27].

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).

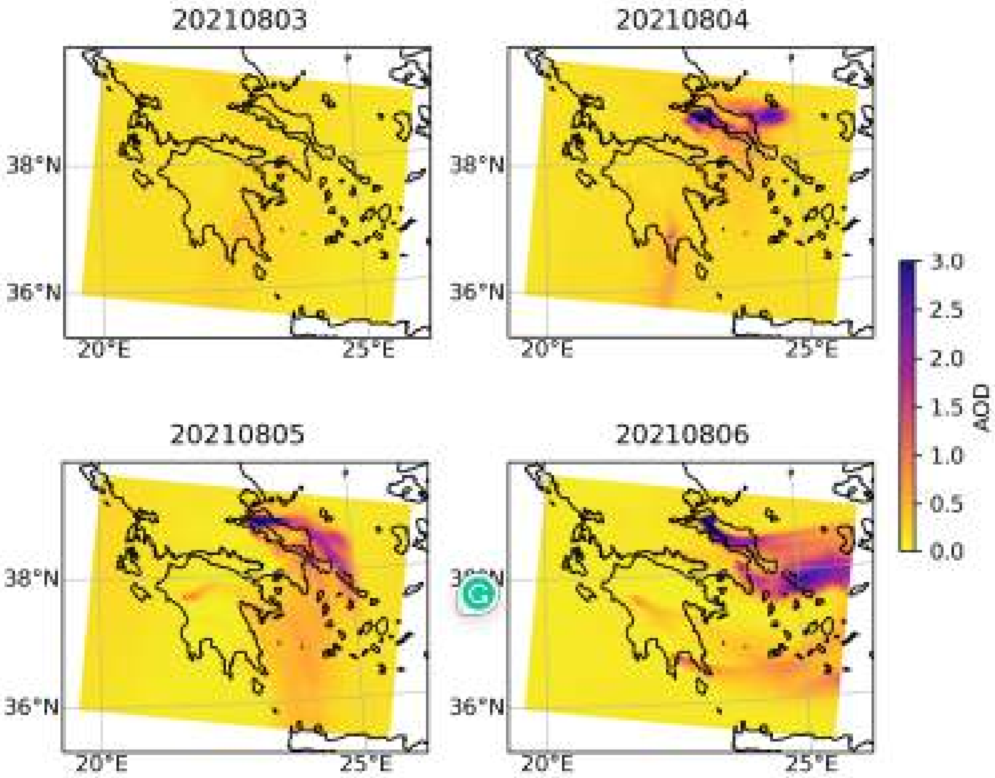


Figure 109 – Spatial distribution of aerosol optical depth (AOD) between August 3rd and 6th at 4.00 p.m., every day.

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].

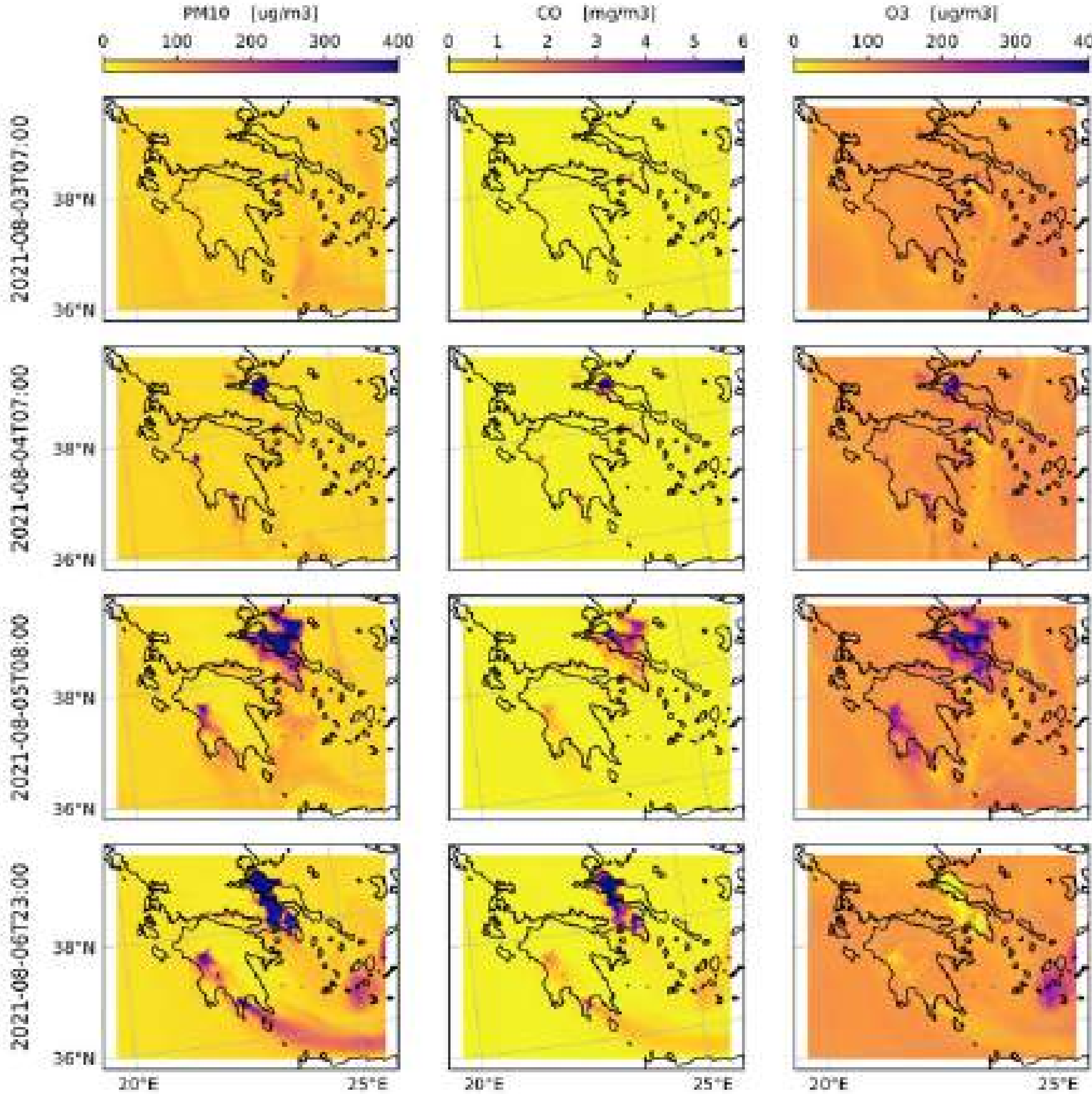


Figure 110 – Spatial distribution of the PM_{10}, CO and O_3 concentrations (μg/m^3) of simulated values at surface level

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.

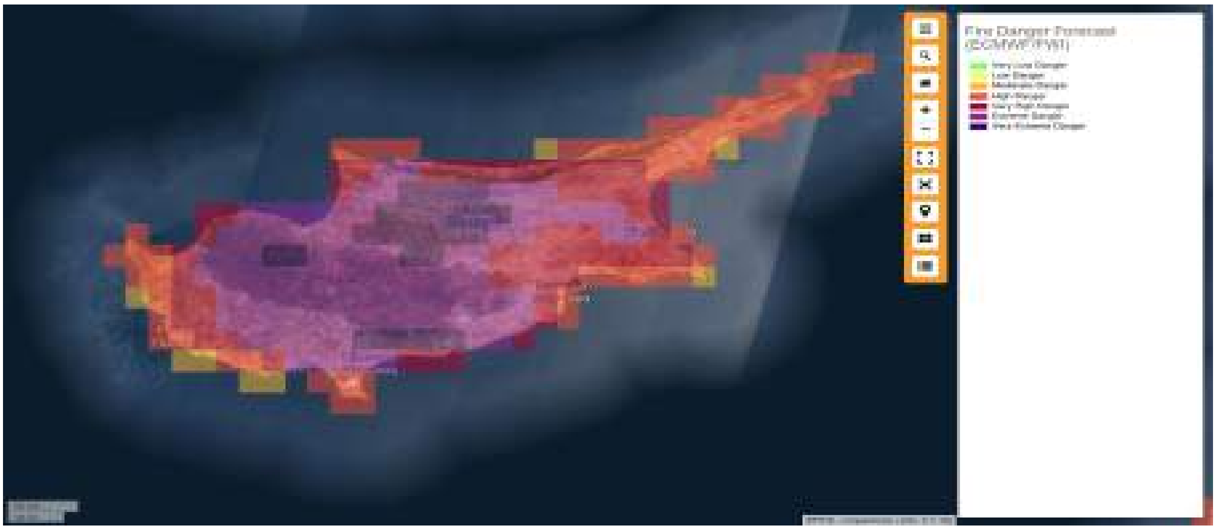


Figure 111 – EFFIS fire danger forecast for July 3rd(https://effis.jrc.ec.europa.eu/apps/effis_current_situation/ Accessed on 18.05.2022).

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.

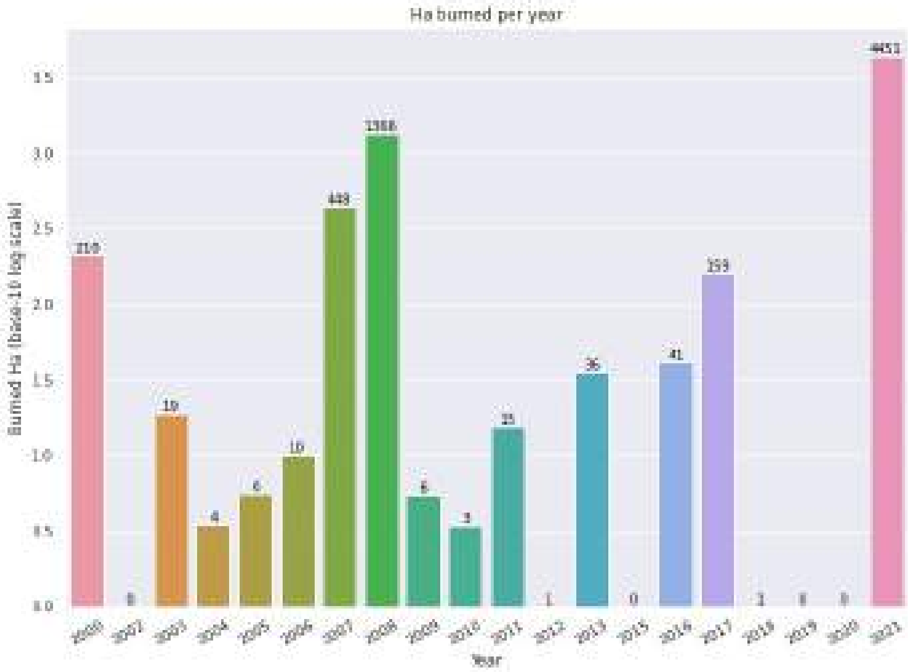


Figure 115 – Burned area in Ha per year in the Arakapas area (data provided by the Cypriot Department of Forests).

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.

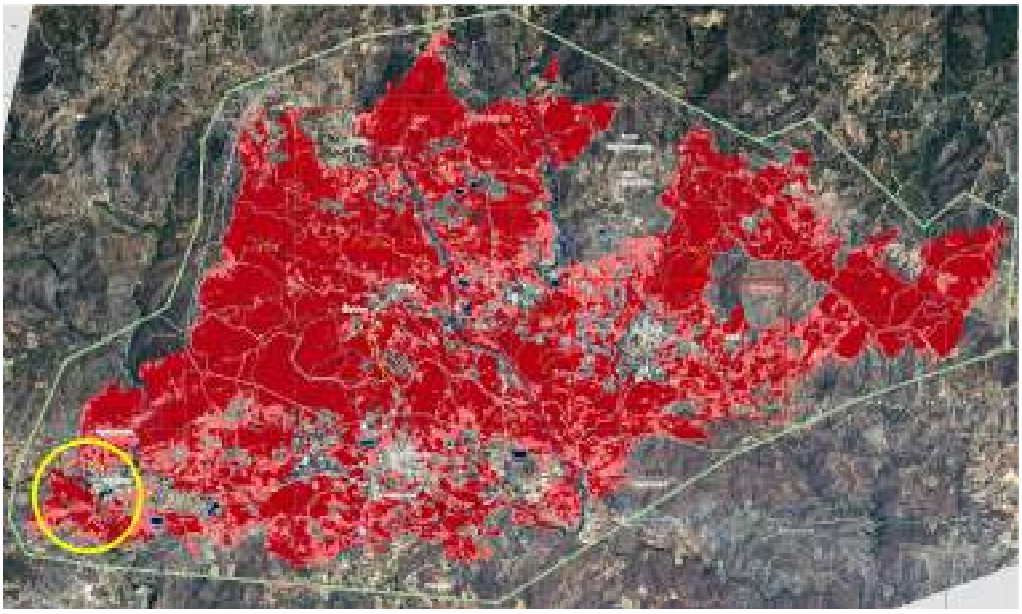


Figure 117 – Copernicus 2021-EMSR515 The map shows the damage grade assessment in Melini/Arakapas.

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

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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

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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

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