Fire Behavior Analysis Reports

Short Term Scientific Missions held at the National Authority of Emergency and Civil Protection (Portugal, 2024)

Index

1. Context

The european Network on Extreme fiRe behaviOr (NERO) aims at bringing together wildfire researchers with practitioners to advance the current state of knowledge on wildfire behavior. In 2024, NERO supported and promoted several Short-Term Scientific Missions (STSMs) aimed at enhancing real-time wildfire analysis capabilities. These missions were conducted during the active fire season at the National Wildfire Decision Support Cell of the National Authority for Emergency and Civil Protection of Portugal (ANEPC). The STSMs fostered direct operational collaboration and knowledge transfer between researchers and national wildfire response agencies. The main objectives were:

- To understand the operational fire management decision-making.
- To explore fire and environmental monitoring data in real-time wildfire analysis and forecasting.
- To learn and apply fire analysis methodologies used within operational settings, with a focus on fire behavior prediction and strategic support.

In general terms, the grantees were integrated in the National Wildfire Decision Support Cell of ANEPC during active wildfire management. Their work primarily focused on supporting fire behavior prediction and contributing to strategic suppression planning. An analysis of the lessons learned was conducted to identify potential improvements in operational wildfire management practices. This process aimed to evaluate the effectiveness of scientific support during active incidents and to inform future integration strategies between research and emergency response operations.

The STSMs contributed to multiple NERO Working Groups (WGs):

- Supported WG1's activities by contributing to the application of a storytelling-formatted protocol for communicating the spread and behavior of past wildfire events (NERO Storytelling). This protocol includes structured sections detailing fire progression, fire behavior and environmental drivers, observed impacts, and lessons learned. The aim of the NERO storytelling template is to standardize the documentation and presentation of significant wildfire events across Europe, facilitating comparative analysis and enhancing the outreach and communication of extreme fire behavior dynamics.
- Strengthened the link between research and operations (WG2) by fostering knowledge exchange, promoting close collaboration with operational agencies, and supporting the co-design of methodologies for extreme wildfire analysis. These efforts contributed to the enhancement of predictive capabilities and the operational relevance of fire behavior assessments.

- Empowered WG4 by facilitating knowledge exchange and promoting dialogue between researchers and practitioners.

This document compiles several fire analysis reports produced by the STSM grantees (following the NERO Storytelling Template), each focused on wildfires that occurred in Portugal during the 2024 fire season. The reports reflect the independent views and interpretations of the respective grantees. All information was kindly provided by the National Authority for Emergency and Civil Protection of Portugal, whose support and hospitality during the missions are gratefully acknowledged.

2. Alcabideche (Cascais) fire

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Location	Alcabideche, municipality of Cascais, Portugal
Dates	21/07/2024
Duration	5hr 10min
Burned Area	88 ha

Context

The Alcabideche forest fire in Cascais began on July 21, 2024, at 12:20 pm, approximately 170 meters east of Rua dos Urumais. The fire spread rapidly, burning 88 hectares of land. After significant suppression efforts, the active fire front was contained by 5:30 pm, marking a duration of around 5 hours and 10 minutes.

The fire occurred in an area with elevations ranging from 35 to 190 meters, with low to gentle slopes (<5%) across most of the affected area. The dominant vegetation consisted of tall Atlantic shrubs with significant amounts of dead and fine fuels (83%) and medium-to-long needle pine litter with shrubby understory (13%).

Leading up to the event, weather conditions included moderate fire weather, in line with the IPMA fire danger indices. Relative humidity was high (>80%) in the morning, gradually dropping to 65-70% in the afternoon. Air temperatures ranged between 22°C and 24°C, with a northerly wind intensifying from 30 km/h in the morning to 40 km/h in the afternoon.

Historically, the Cascais area has experienced recurrent fires, especially located near the coast, over the years. Notably, the area burned by the 2024 fire overlapped with: (i) a larger fire occurred in 2000 (that surrounded the northern and western parts of Alcabideche village), (ii) a smaller fire in 1992 that occurred in the eastern section; and (iii) a fire of similar size that occurred in 1987.

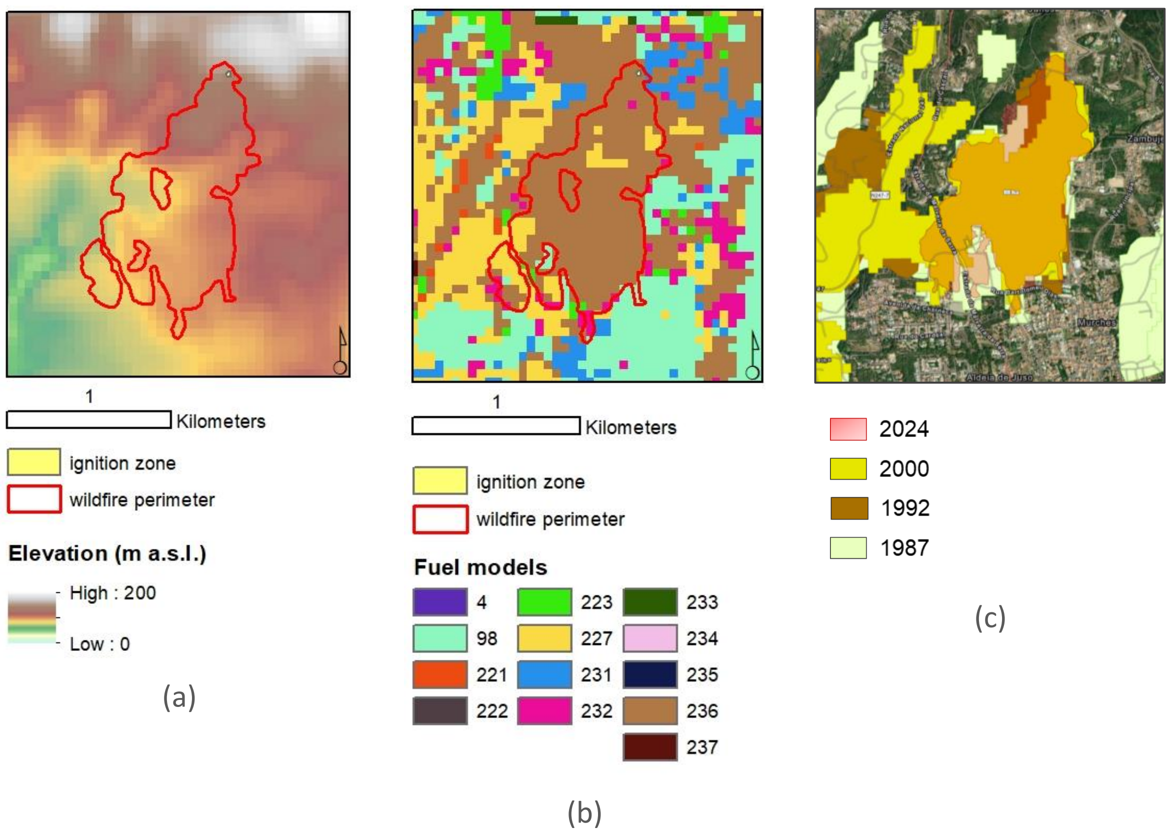


Figure 1 – Location of Alcabideche fire (Cascais) and (a) terrain elevation (m); (b) fuel models; (c) past event that affected the area. In red, the Alcabideche fire perimeter, in yellow the Alcabideche fire ignition zone. Fuel models: 4, Very tall bush with horizontal and vertical continuity; 98, No fuel; 221, Leafy deciduous hardwoods with shrubby understory; 222, Foliage of sclerophyllous hardwoods with shrubby understory; 223, Eucalyptus foliage with shrubby understory; 227, Medium to long needle pine litter with shrubby understory; 231, Tall grass; 232, Low grass; 233, Tall bush (>1 m) with a lot of dead and/or fine fuel; 234, Low grass (<1 m) with a lot of dead and/or fine fuel; 235, Low bush (< 1 m) and green, often discontinuous and with herbaceous plants; 236, Tall bush (>1 m) with little dead fuel and/or relatively thick foliage; 237, Low bush (<1 m), with little dead fuel and/or relatively coarse foliage.

Fire Progression

The progression of the fire is shown in **Figure 2**. The reconstruction of the event was done with data kindly provided by ANEPC, including data hosted in the FEB Monitoring platform.

According to confidential information provided by ANEPC, the ignition of "unknown" origin occurred about 170 m east of the Rua dos Urumais (Alcabideche, Cascais) at 12.20 pm. After investigation, information provided on the Forest Service website indicates that this fire started at 12:19 and was caused by negligent human behavior.

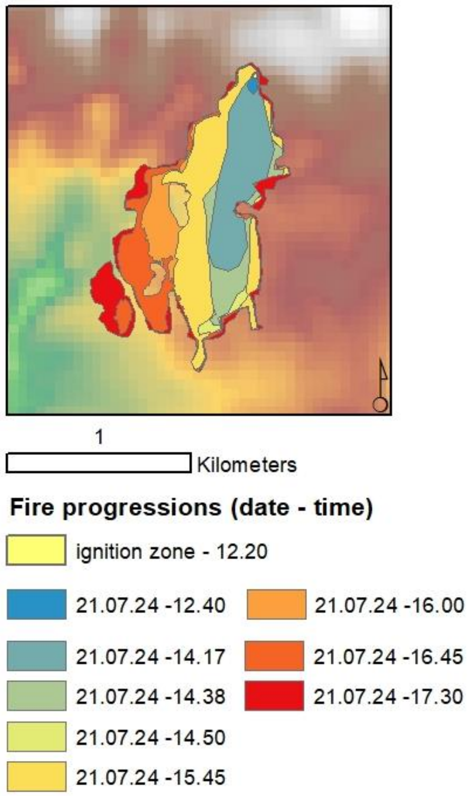


Figure 2: Progressions of the IF Alcabideche - Cascais. Information derived from data from ANEPC.

The fire's behavior varied across **four distinct phases:**

- **P1, from 12.20 to 12.40 pm**
- **P2, from 12:40 to 3.45 pm**
- **P3, from 3.45 to 4.00 pm**
- **P4, from 4.00 to 5.30 pm**

During P1 and P2, the fire moved downslope progressing rapidly due to strong northerly winds, towards Alcabideche village. In P3, fire enlarged the right flank and entered a valley area. Spot fires occurred. In P4, the fire was characterized by flanking propagation (mostly right flank). The fire was contained in the late afternoon, with the active spread effectively halted around 5:30 PM thanks to the massive suppression efforts by the fire management teams and the lack of available fuel at the fire's head.

Fire Behavior and Environmental Drivers

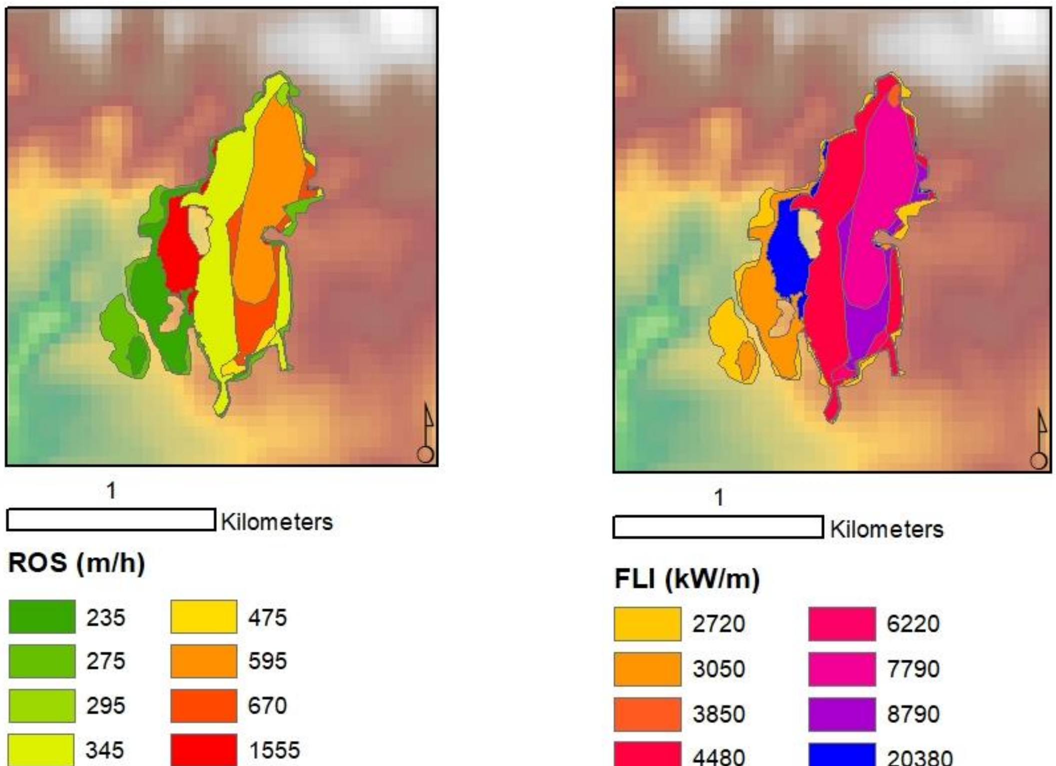
The Alcabideche - Cascais fire exhibited characteristics of a wind-driven fire, influenced predominantly by moderate to strong northerly winds. The fire's behavior varied across **four distinct periods**, with notable increase during periods of strong wind and aligned topography.

Figure 3: Photograph from the helibrigades taken about 20 minutes after the fire ignition (12.20 pm) (courtesy ANEPC).

Period 1 (12:20 pm - 12:40 pm). The first intervention, according to the SADO-ANEPC, took place at 12.26 pm, 6 minutes after the alert (**Figure 3**). Since the ignition point was unknown (but supposedly beyond the road), the rate of spread and the fireline intensity estimated in this period are uncertain. According to the pictures taken by helicopter at 12.40 pm (**Figure 4**), the fire was driven by N-NW winds blowing at almost 30 km/h (**Figure 6**). It is likely that, between ignition and 12:40 pm, the average rate of spread was about 300 m/h, corresponding to a fireline intensity of about 3850 kW/m. This was in line with the Initial Spread Index (ISI) forecast from ANEPC. ISI is a numeric rating that estimates how quickly a fire will spread.

Figure 4: Evolution of the IF Alcabideche – Cascais: picture of the fire smoke column at around 12:40 p.m. Photos taken by helibrigades (courtesy ANEPC).

Period 2 (12:40 pm - 3:45 pm). During P2, the fire moving downslope, driven by the northerly wind, exhibited a significant increase in both rate of spread and fireline intensity, with maximum ROS values close to 670 m/h (from 2.17 pm to 2.38 pm) and a growth rate above 20 ha/h (from 2.17 pm to 2.38 pm and from 2.50 pm to 3.45 pm) (Figure 5). It is likely that the decrease in ROS from 2.38 pm to 2.50 pm was due to the arrival of the fire front to the proximity of the urbanized area (Rua do Outeiro, Murches, Alcabideche), where the suppression efforts were concentrated, and less fuel was available to burn. The fire mostly affected tall Atlantic shrubs, and the intensity was over 7500 kW/m from 12.40 pm to 2.38 pm. The first thermal scan was taken at 3.45 pm.



(a) (b)

Figure 5: (a) Rate of spread (m/h) and (b) fire intensity (kW/m) estimated for the Alcabideche forest fire.

Period 3 (3:45 pm - 4:00 pm). During P3, the head of the fire stopped. Indeed, the presence of the WUI area in the fringe of Alcabideche entailed low fuel continuity and influenced the priority in suppression interventions. On the other hand, the right flank of the fire originated a new frontline very intense and fast, entering a valley area and propagating towards the south driven by a 35 km/h wind. According to Campbell Prediction Systems, all forces were aligned, and the fire spread was supported by an average slope of 6.5% aligned with wind direction and sun exposure. The resulting area burned growth rate was the highest of the whole fire propagation (32 ha/h). The associated fire intensity was extreme (above 20000 kW/m), and generated projections also due to the presence of Pinus stands, with high fuel load (Figure 5 b). In addition, spot fires occurred in P3, positively affected by the abovementioned fuel characteristics and by strong wind speed at high altitude (about 50 km/h). On the other hand, the shallow boundary layer (about 500 m) and the high fuel moisture of dead fuels limited the travelling distance and the number of spot fires.

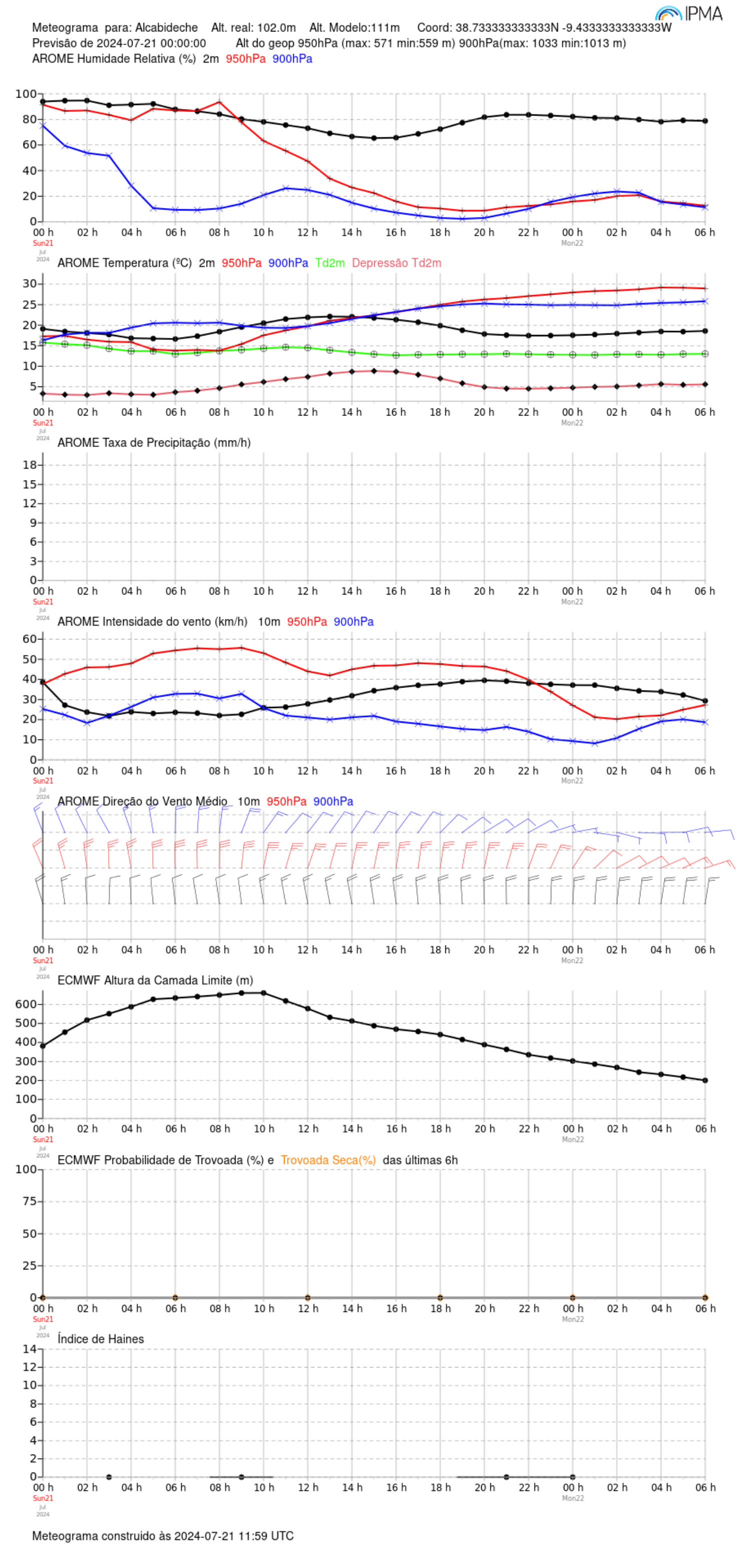


Figure 6: Weather forecast from the AROME model (IPMA) for the IF Alcabideche - Cascais (run 00 UTC of the 21st of July 2024).

Period 4 (4:00 pm - 5:30 pm). The last phase of the fire spread was from 4.00 pm to 5.30 pm. The propagation was mostly on the right flank, and it was less intense (2700-3000 kW/m) and slower (250 m/h) than the previous ones. This type of propagation probably occurred because, once the head of the fire was halted - due to the presence of wildland-urban interfaces (WUIs), reduced fuel availability, and firefighting efforts to protect urban areas - the in-draft of cooler air broke down and fire spread could only continue by flanking, under conditions of lower spread rate and intensity compared to the earlier phase. About 24 more hectares were burned, with an area burned growth rate close to 16 ha/h. The main affected fuels were tall Atlantic shrubs and Pinus stands with litter and understory shrub cover. In this phase, the fire perimeter was further enlarged by some spot fires that created an island beyond the road. The fire was contained in the late afternoon, but the active propagation phase was stopped at around 5.30 pm by the huge suppression effort put in place by the fire management forces.

Impacts

According to the information provided by ANEPC, 62 terrestrial means, 7 aerial means, and 224 operational units were employed to cope with the IF Alcabideche-Cascais.

Lessons Learned

The reconstruction of the Alcabideche-Cascais forest fire provides valuable insights into the interplay of environmental factors, suppression efforts, and fire dynamics. Key lessons learned include:

1) The fire was strongly influenced by northerly winds that directed its spread, especially in alignment with terrain features like the valley. Wind played a significant role in fire spread dynamics, despite elevated fuel moisture content in both live and dead fuels. This highlights the critical role of accurate wind forecasting in fire preparedness.
2) When the head of a wildfire is halted – either through suppression efforts or fuel discontinuities such as those encountered in a wildland-urban interface – it significantly alters fire behavior. The collapse of the in-draft convection pattern reduces activity at the head but activates lateral fire spread along the flanks. This shift must be anticipated during operational planning.
3) The prevalence of tall Atlantic shrubs and pine litter with understory shrubs provided significant fuel loads, leading to very high fire intensity that in some areas was beyond the fire suppression capacities of terrestrial and aerial forces. While fuel moisture levels were moderate, they were low enough to sustain rapid fire propagation under the prevailing conditions.

4) The valley's channeling effect significantly increased the rate of spread and intensity during the third period, highlighting the need to consider topographic features and, in general, alignment of forces in risk assessments and response planning.
5) Spot fires were observed but had restricted travel distances due to a low boundary layer height and relatively high fuel moisture, which helped contain the fire's impact.
6) Finally, and based on the previous conclusions, the reconstruction of the Alcabideche-Cascais forest fire highlights the importance of recognizing that, in certain occasions, strong wind conditions can override fuel moisture constraints, driving intense fire behavior even when fuel conditions appear marginal.

3. Vimioso (Bragança) Fire

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Location	Vimioso, municipality of Bragança, Portugal
Dates	10.08.2024 – 12.08.2024
Duration	33 Hours
Burned Area	2192 ha

Context

The fire started at 18:10 (UTC+1) on August 10, 2024, and was brought under control at 21:30 on August 12 in Vimioso, Bragança region (Portugal), near the Spanish border. The fire was caused by a lightning discharge. This fire occurred in two distinct burn periods. The first burn period began with ignition and lasted until 21:30 on August 10, covering nearly 3 hours of fire activity. The second burn period started with reactivation on August 11 and continued until the fire was extinguished at 03:30 on August 12, lasting approximately 14 hours. The total duration of the fire event was nearly 33 hours, with an active fire period lasting approximately 17 hours. A total of 2192 hectares of land were burned (Fig. 1).

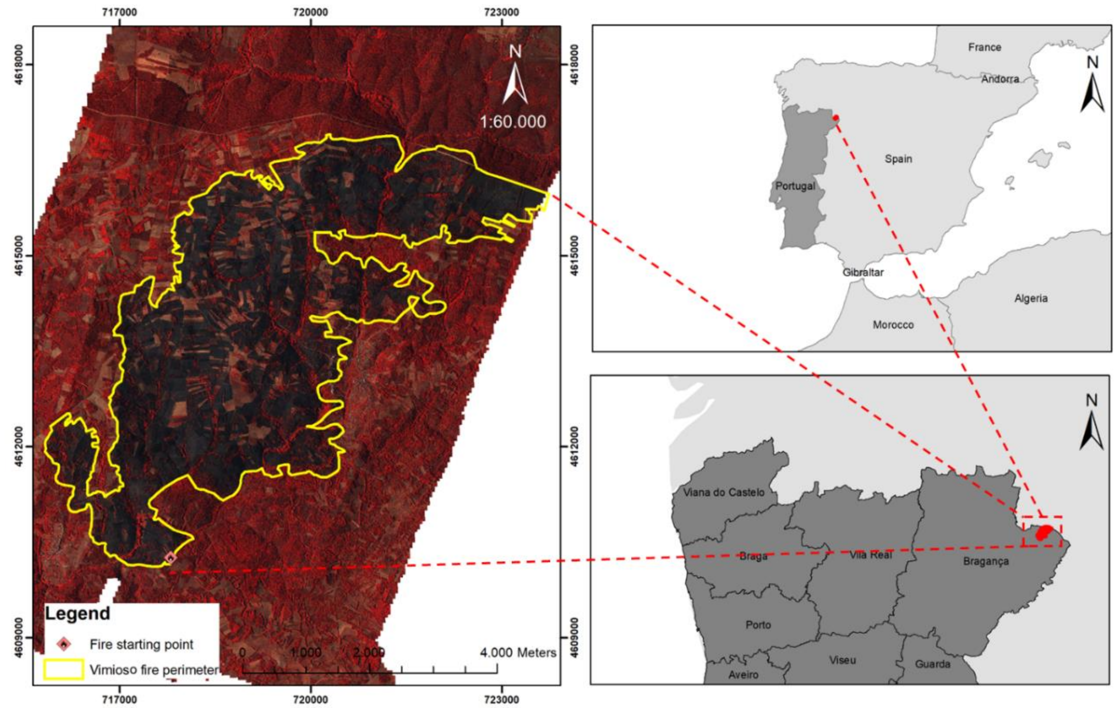


Figure 1. Geographic location of the Vimioso fire in Portugal.

The dominant fuels in the burned area (40%) consisted of tall shrubland (>1 m) with substantial dead and/or fine foliage (12-27 t/ha) (Code: V-MAa), according to Portugal's national fuel map (Sá et al. 2023).

The remaining area was covered by tall grassland (>0.5 m) (2-4 t/ha) (15%) (Code: V-Ha), deciduous litter and a shrub understory, usually with plenty of live fuel (8-17 t/ha) (14%) (Code: M-CAD), tall shrubland (>1 m) poor in dead fuel and/or with relatively coarse foliage (10-19 t/ha) (11%) (Code: V-MMa) and various other fuel types (20%) (Codes: M-EUC, M-PIN and V-Hb) and non-burnable areas (Fig. 2).

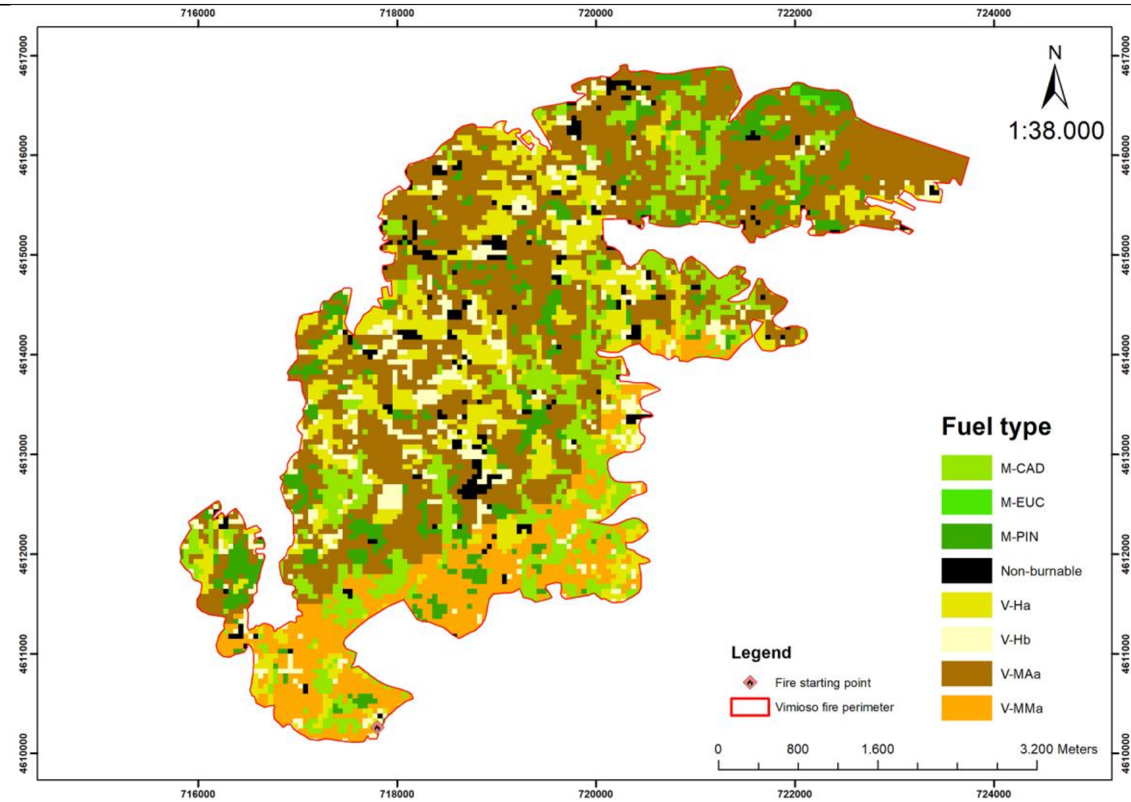


Figure 2. Fuel types in the area affected by the Vimioso fire.

The mean elevation of the burned area was 790 m, with a minimum of 650 m and a maximum of 950 m (Fig. 3a).

The mean slope was 7%, ranging from 0% to 45% (Fig. 3b).

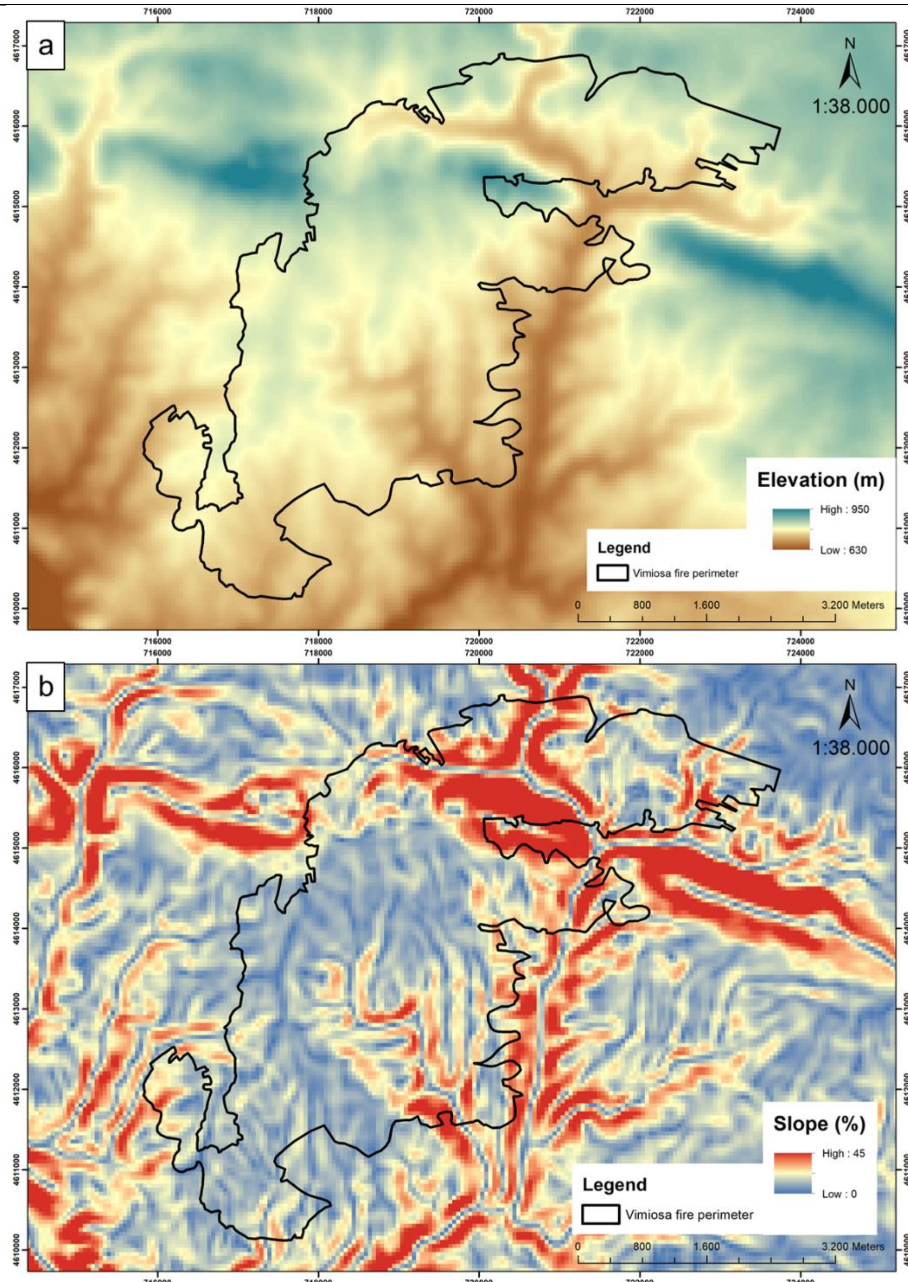


Figure 3. Elevation (a) and slope (b) maps of the Vimioso fire.

Predicted weather conditions during the fire event were obtained from two meteograms provided by the Portuguese Institute for Sea and Atmosphere (IPMA 2024). For the first burn period, predictions in the meteogram indicated that the dead fuel moisture content (DFMC) was approximately 5%, and the wind speed was about 15 km/h, varying between northeast and east directions (Fig. 4b, c).

The predicted wind speed slightly increased at approximately 20 km/h with variations in direction, and the MC increased to approximately 7% as the fire was brought under control at 21:30 (UTC+1) on August 11 (Fig. 4a).

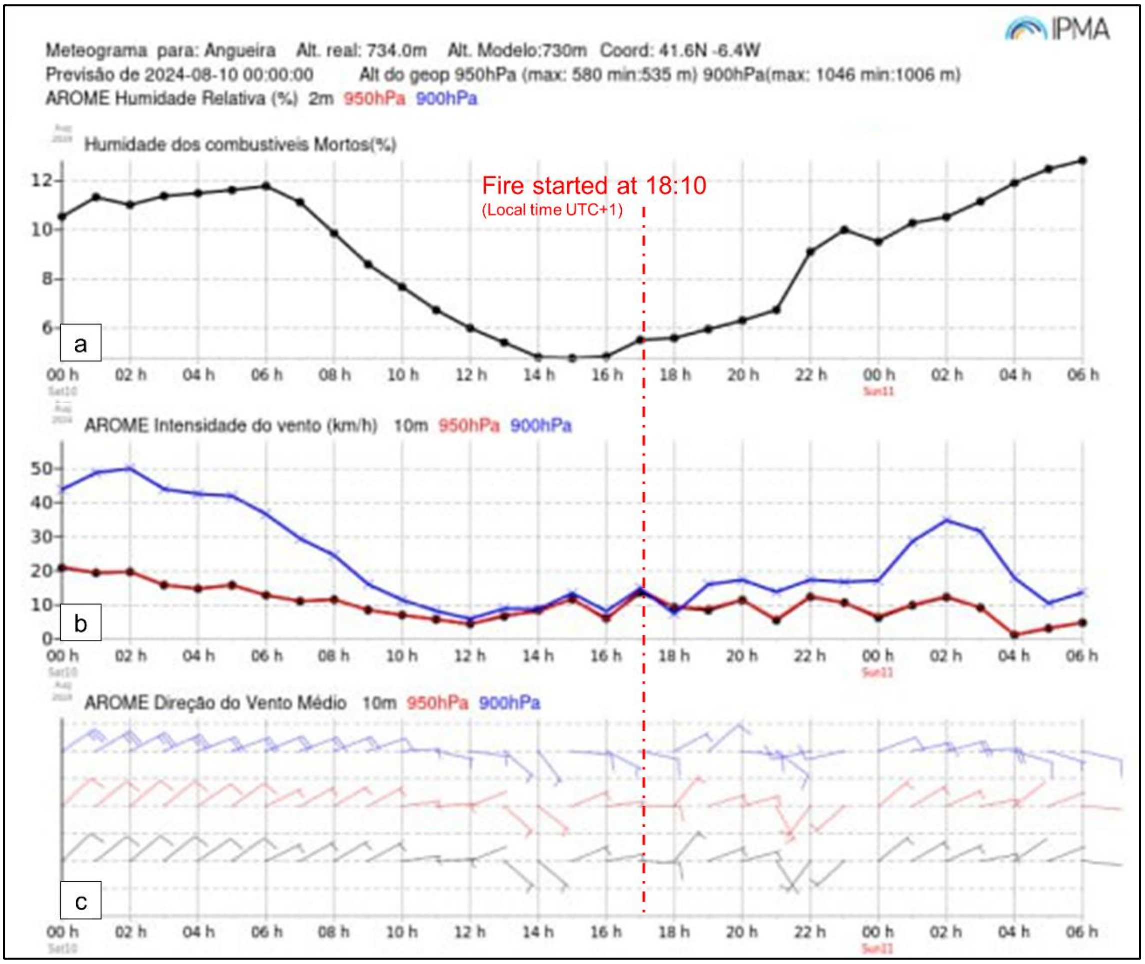


Figure 4. Predictions of dead fuel moisture content (%) (a), wind speed (km/h) (b), and wind direction (c) in the meteogram for the Vimioso fire for the first burn period.

The fire reactivated around 13:30 on August 11. Prior to reactivation, the wind speed increased from 15 to 25 km/h between 9:00 and 13:30. The wind direction was predominantly from the southwest, particularly during the period of highest wind speeds (Fig. 5b, c).

After 22:00, the wind speed decreased to 5 km/h on near midnight, then increased again to 15 km/h, with the wind direction shifting from northwest to west by the end of the fire. The MC was approximately 6% and increased to 14% by the end of the fire at 03:30 on August 12 (Fig. 5a).

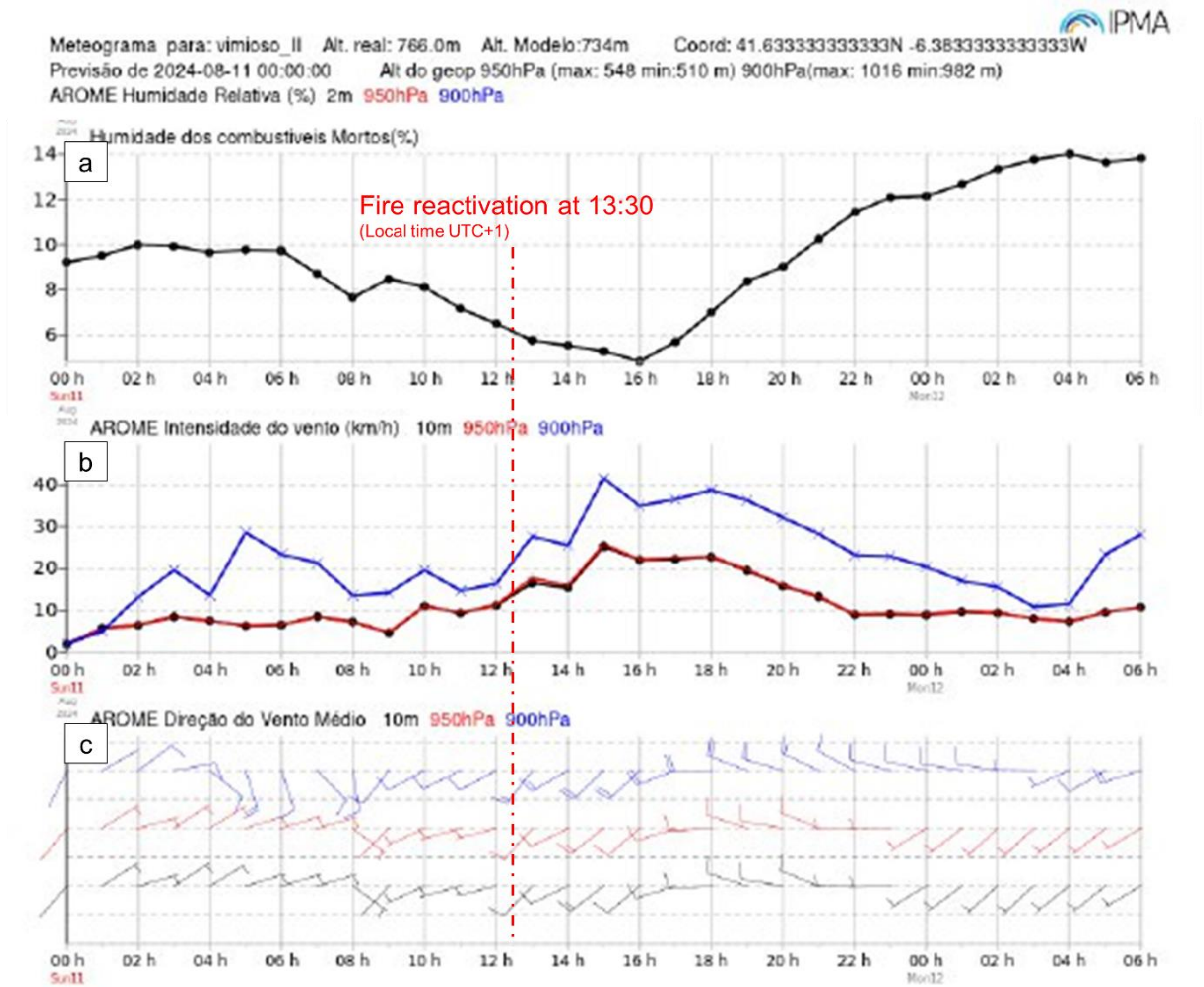


Figure 5. Predictions of dead fuel moisture content (%) (a), wind speed (km/h) (b), and wind direction (c) in the meteogram for the Vimioso fire, covering the reactivation date and time through to the end of the fire.

Fire Progression

The Vimioso fire was analyzed through nine progression phases using data provided by field operatives (fops), airborne thermal and visible imagery (airb), and satellite (sat) sources (Annex Table 1 and Fig. 6).

The fire can be categorized into two distinct burn periods. The first burn period began with ignition and lasted until 21:30 on August 10, covering nearly 3 hours of fire activity. It included three phases of fire progression (1- 3). The second burn period started with reactivation on August 11 and continued until the fire was extinguished at 03:30 on August 12, lasting approximately 14 hours. This period included six phases of fire progression (4-9) (Fig. 6).

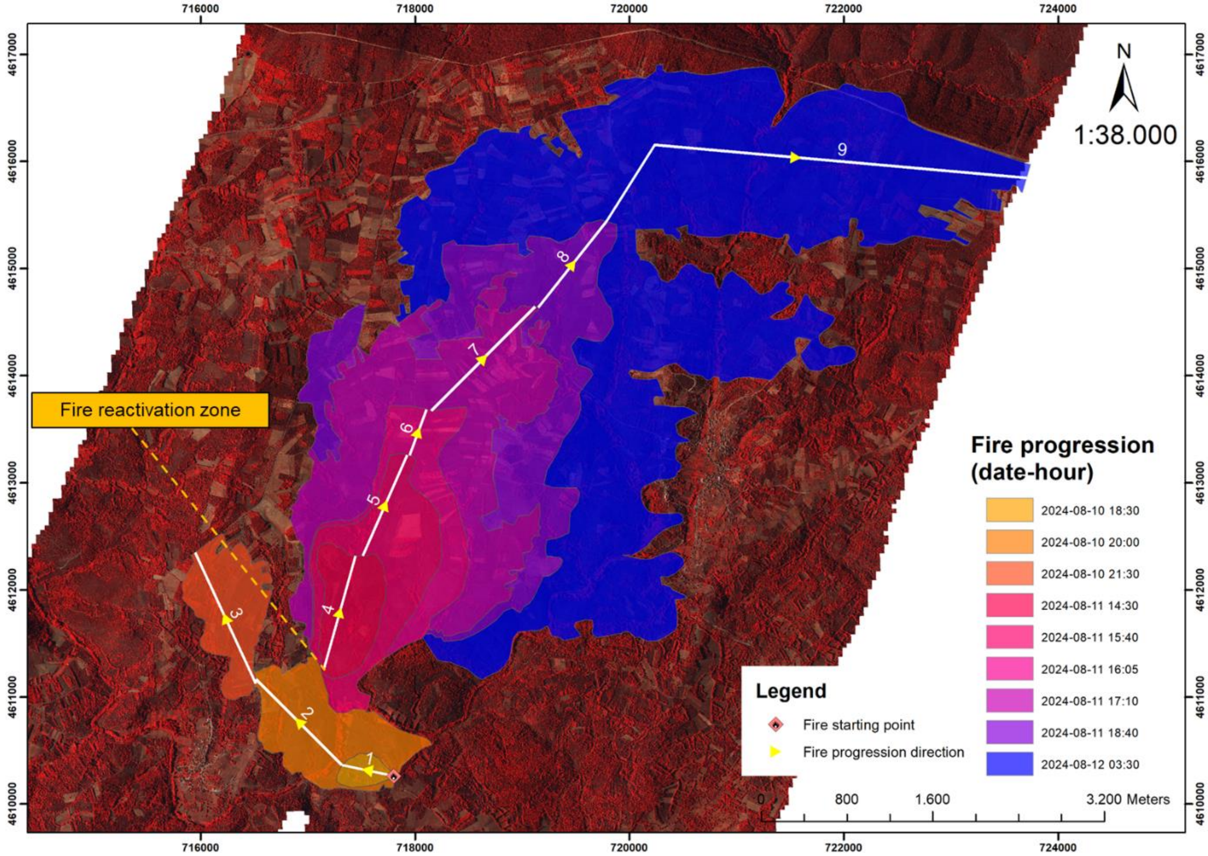


Figure 6. Progression map of the Vimioso fire.

In the first progression period (1) the fire spread to west until 18:30, affecting 11.8 ha, and then continued northwest (2) affecting 100.9 ha until 20:00. The fire continued spreading towards northwest (3) affecting 75.6 ha by 21:30 on August 10 (Table 1, Fig. 6).

The fire reactivated at around 13:30 on August 11, spreading north/northeast (4) affecting 61.1 ha by 14:30. The fire continued spreading in the same direction (5) affecting 110.8 ha by 15:40, and 83.7 ha by 16:05 (6) (Table 1, Fig. 6).

The fire then moved northeast, affecting 323.2 ha (7) and 278.0 ha (8) by 17:00 and 18:40 on August 11, respectively. Finally, the fire changed direction towards the east, burning 1147.0 ha (9) on August 12, reaching its final perimeter to the east on August 12 (Table 1, Fig. 6).

Fire Behavior and Environmental Drivers

The rate of fire spread (ROS) (m/h), fuel consumption (FC) (kg/m²), and Fireline intensity (FI) (kW/m) were calculated using fire progression data and the fuel model of the area (Fig. 7). The results are presented for the two burn periods, along with the fire progression phases associated with each.

The results indicated that the ROS was 1200, 756, and 90 m/h in the 1st, 2nd, and 3rd progression phases of the fire until 21:30 on August, 10, respectively (Fig. 7a) in the first burn period of the fire. FC was 1.56, 1.56, and 1.55 kg/m² in the same phases (Fig. 7b). Corresponding FI values were 10391, 6724, and 8145 kW/m, respectively (Fig. 7c). The ROS and FI patterns were similar in these phases as FC remained nearly constant (Fig. 7a, c).

As a result, mean fire behavior parameters as ROS, FC and FI were 682 m/h, 1.56 kg/m² and 8420 kW/m, respectively in the first burn period (Fig. 7). The first burn period can be classified based on fire behavior and control capacity as a "Normal Fire" (Category 4)" (Tedim et al. 2018), because the mean Fire Intensity (FI) was lower than 10,000 kW/m.

The fire type was surface fire, with crowning likely depending on vegetation type and stand structure. The difficulty of control is extremely high. Moreover, this type of fire was characterized by prolific spotting activity, with distances of 500–1000 meters (Tedim et al. 2018).

The fire was primarily wind-driven, with minimal influence from topography. Furthermore, there were no major changes in fuel type during this phase. By approximately 21:30 on August 10, the fire was brought under control by suppression teams. In conclusion, the fire progression from its beginning until its first control can be described as a "wind-driven fire."

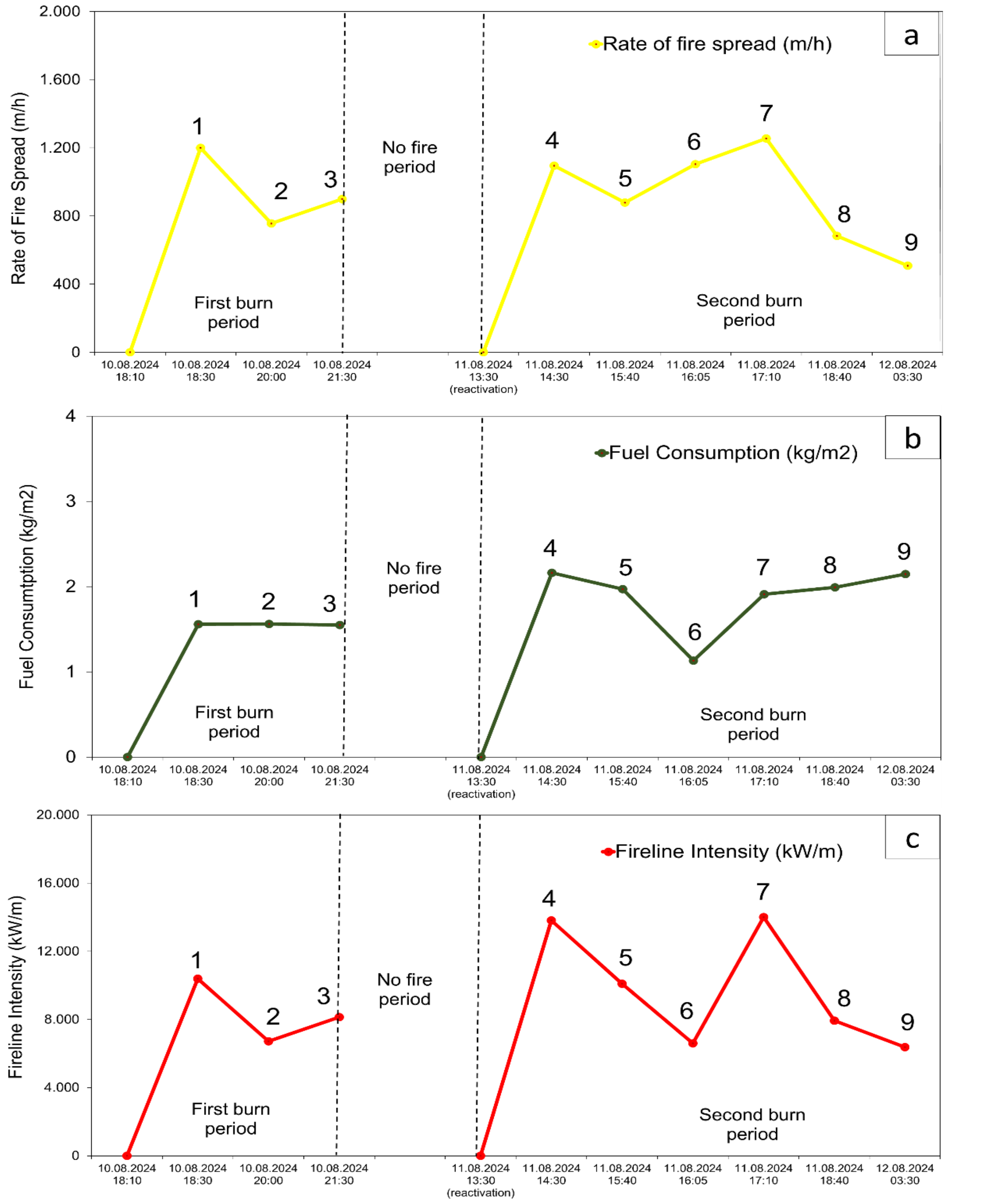


Figure 7. Fire behavior parameters of Vimioso fire (Rate of fire spread (m/h) (a), fuel consumption (kg/m2) (b) and Fireline intensity (kW/m) (c)). Numbers (1 to 9) indicate the phases of fire.

The second burn period began with the re-activation of the fire from an active point remaining in the northern part of the burned area at approximately 13:30 on August 11 (Fig. 7). This reactivation time and location were confirmed by field operators (fops) (APC-Photos) (Fig. 8).

Figure 8. Vimioso fire re-activation point in the northern part of the burned area (APC image) (ANEPC 2024).

The re-activation time was not validated with the Fire Radiative Energy (FRE) data provided by EUMETSAT – Fire Radiative Power Pixel – MSG Product, available at 15-minute intervals (EUMETSAT 2024) due to persistent cloud cover over the burned area prevented the satellite sensor from collecting data.

Following reactivation, the ROS was 1095 m/h, FC was 2.16 kg/m², and FI was 13821 kW/m during the 4th fire progression phase (Fig. 7). This phase was intense (Fig. 12c), with high wind speeds (~25 km/h) driving an increased fire spread and fuel consumption (Fig. 6b) until 14:30. Fire spread slightly upslope after reactivation, making this phase both "topographical and wind-driven."

During the 5th phase, ROS was 878 m/h, FC was 1.97 kg/m², and FI was 10096 kW/m. The extent of the fire at this time was determined by both fire operatives and airborne data. In the 6th phase of fire while the ROS remain high (1104 m/h) (Fig. 7a) the dominant fuel type shifted from V-MAa to V-Ha (Tall grassland) decreasing FC (1.13 kg/m²) (Fig. 7b) and FI (6606 kW/m) (Fig. 7c). This phase demonstrated the significant role of fuel characteristics in influencing fire behavior.

In the 7th phase, ROS was 1255 m/h, FC was 1.91 kg/m², and FI was 14007 kW/m, marking the most intense phase of the Vimioso fire. The extent of the fire at this time was determined using thermal airborne data.

During the 8th phase, ROS decreased to 683 m/h, while FC slightly increased to 1.93 kg/m², and FI decreased to 7939 kW/m (Fig. 7c). From reactivation until the 8th phase, wind speed (30 km/h) and direction remained consistent. Fire behavior during this period was influenced mainly by wind speed and fuel characteristics, as the topography was mostly flat (Fig. 3b).

Finally, the fire's last phase (9h) extended to the northeast and east, and the fire front reached its final perimeter at approximately 03:30 on August 12. The extent of the fire at this time was determined by both fire operatives and NASA FIRMS VIIRS thermal anomalies/hotspots data. ROS was 509 m/h, FC was 2.15 kg/m², and FI was 6377 kW/m. The ROS and FI patterns in the last two progression periods were similar, as FC remained nearly constant (Fig. 7a, c). This final phase was also influenced by changes in wind speed and direction (Fig. 5b, c).

As a result, mean fire behavior parameters as ROS, FC and FI were 920 m/h, 1.88 kg/m², and 9808 kW/m, respectively, during the second burn period. The second burn period was more intense than the first (Fig. 7). The second burn period can be classified as a "Normal Fire" (Category 4)" However, FI values exceeded 10,000 kW/m during some fire progression phases (i.e., phases 4, 5, and 7), with extreme fire behavior observed.

Impacts

There were no fatalities in the Vimioso fire; however, substantial damage occurred to farmlands and orchards. A small house and some depots were also burned by the fire.

Lessons Learned

The analysis of the Vimioso fire highlighted the critical role that weather conditions and fuel type play in influencing fire behavior. Due to the relatively flat topography, wind was the dominant factor driving the fire's progression. The same fire, under very different conditions (first and second burn periods), exhibited significantly different fire behavior, depending on the weather. Increased wind speed resulted in faster and more intense fire behavior during the second burn period. Additionally, variations in dominant fuel types had a significant impact on fireline intensity. While the rate of fire spread increased, fireline intensity decreased due to changes in fuel type (e.g., 6th fire progression phase).

During the second burn period, fire progression primarily occurred in a mosaic cropland area. The mosaic structure might be expected to slow the rate of fire spread and progression, but this was not the case. One possible explanation is that elevated wind speeds enhanced spotting activity and distance, with spotting at the fire front contributing to the increased rate of fire spread during the second burn period. Unburned croplands were visible in the direction of fire progression.

The reactivation was another significant aspect of the Vimioso fire, highlighting the importance of thorough mop-up and monitoring after a fire is deemed as controlled. Images taken by field operators were quite useful for identifying active parts of the fire and potential reactivation zones.

The reconstruction of the Vimioso fire clearly demonstrates the importance of having accurate, timely, easily accessible, and georeferenced information for wildfire monitoring. The availability of high-resolution datasets, both spatially and temporally, increases the potential for understanding fire behavior under changing environmental conditions. Such insights are invaluable for improving preparedness, decision-making, and response efforts in future wildfire events

4. Soutelo (Bragança) fire

Kadir Alperen Coskuner, Karadeniz Technical University (KTU), Turkey

Location	Portugal, NUTS2 regional unit, Terras de Trás-os-Montes, Bragança
Dates	10.08.2024 – 12.08.2024
Duration	35 Hours
Burned Area	445 ha

Context

The fire started at 18:52 (UTC+1) on August 10, 2024, and was brought under control at 00:30 on August 11 in Terras de Trás-os-Montes, Bragança region in Portugal. The fire was caused by a lightning discharge. Although it was initially controlled, reactivation occurred around 19:00 on August 11, and it was finally brought under control at approximately 06:00 on August 12. The total duration of the fire event was nearly 35 hours, with an active fire period of approximately 17 hours. A total of 445 hectares of land were burned (Fig. 1, 2).

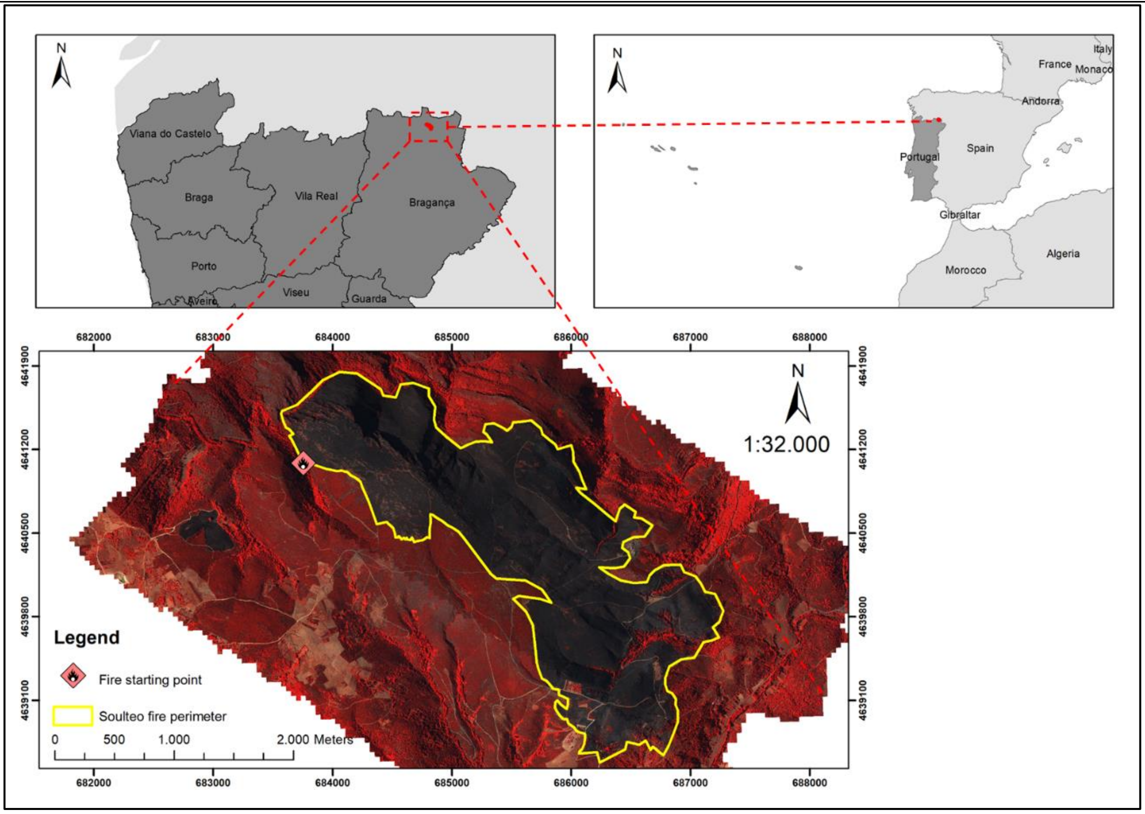


Figure 1. Geographic location of the Soutelo Fire in Portugal.

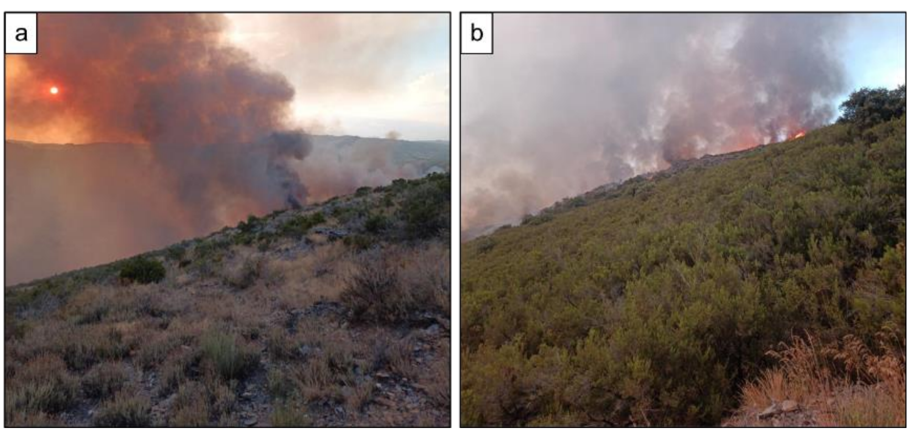


Figure 2. Views of the fire-starting area (a: 10/08/2024, 19:52; b: 10/08/2024, 20:15). These images were taken by APC and obtained from the ANEPC FM system (ANEPC 2024).

The dominant vegetation (77%) in the burned area was tall shrubland (>1 m) with substantial dead and/or fine foliage (12-27 t/ha) (Code: V-MAa), according to Portugal's national fuel map (Sá et al. 2023). The remaining area was covered by low shrubland (<1 m) with substantial dead and/or fine foliage (7-14 t/ha) (12%) (Code: V-MAb) and various other vegetation types (11%) (Codes: M-CAD, M-PIN, NFF4, V-Ha, V-Hb, V-MH) and non-burnable areas (Fig. 3).

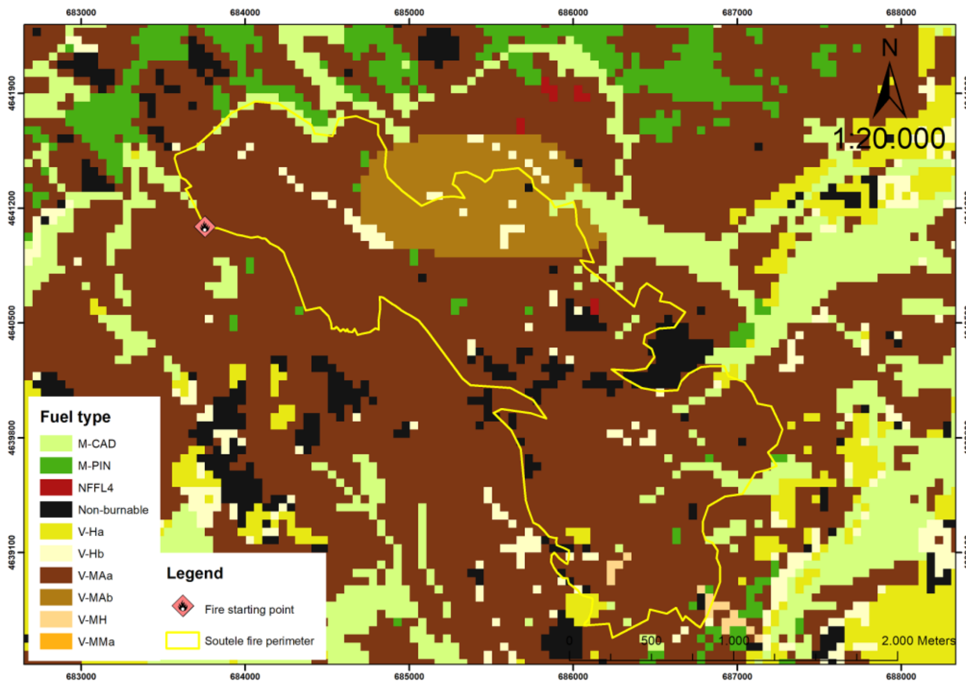


Figure 3. Fuel types in the area affected by the Soutelo fire.

The mean elevation of the burned area is 856m, with a minimum of 692m and a maximum of 1,040m (Figure 4a). The mean slope was 32%, ranging from a minimum of 1% to a maximum of 80% (Figure 4b).

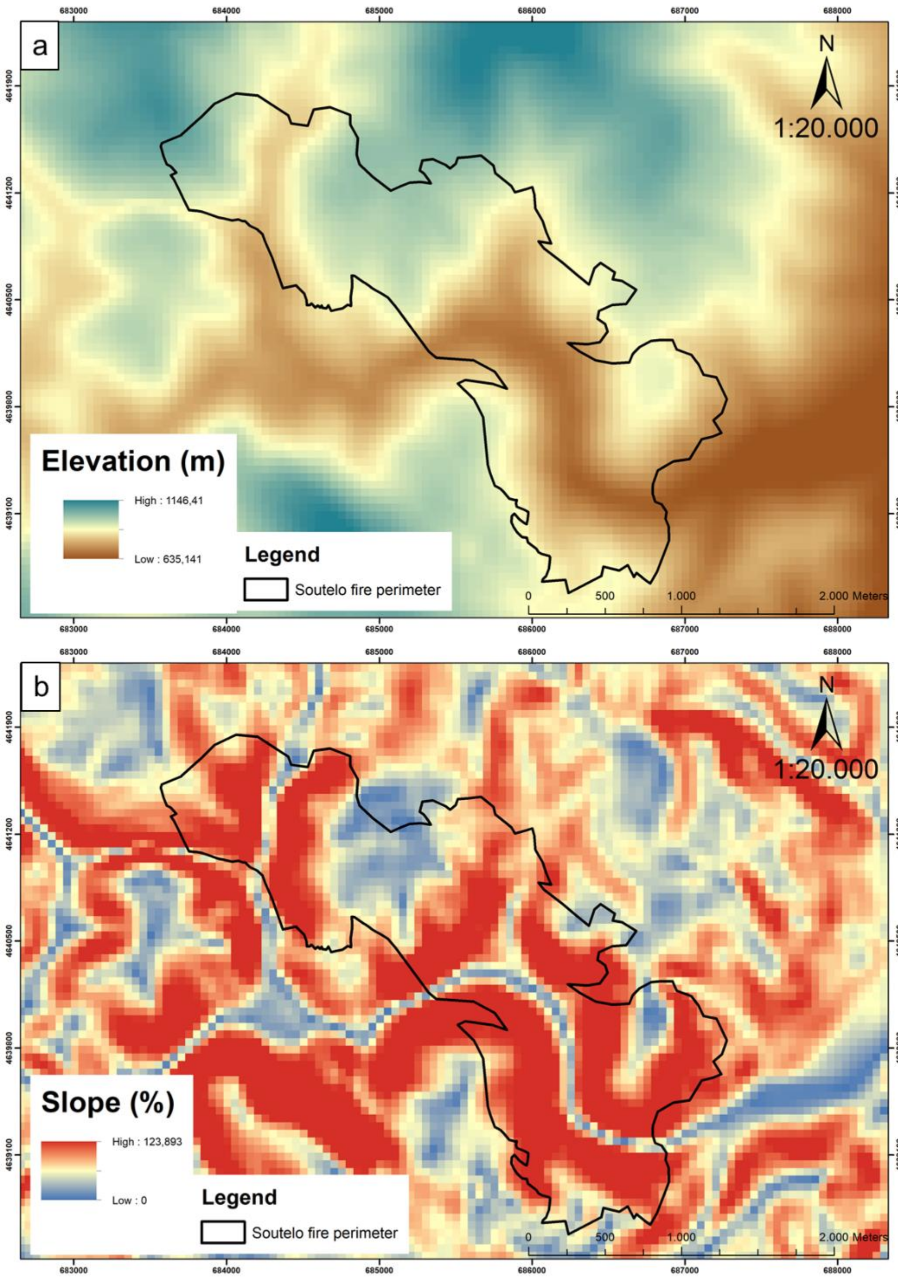


Figure 4. Elevation (a) and slope (b) maps of the Soutelo fire.

Predicted weather conditions during the fire event were obtained from two meteograms provided by the Portuguese Institute for Sea and Atmosphere (IPMA 2024).

Predictions in the meteogram indicated that the dead fuel moisture content (DFMC) was approximately 5%, and the wind speed at the surface was about 10-15 km/h, varying between west and east directions at the beginning of the fire (Fig. 5b, c).

The predicted wind speed remained relatively stable at 15 km/h with variations in direction, and the DFMC increased to approximately 13% by 23:00. The wind speed then decreased to 10 km/h as the fire was brought under control at 00:30 (UTC+1) on August 11 (Fig. 5a).

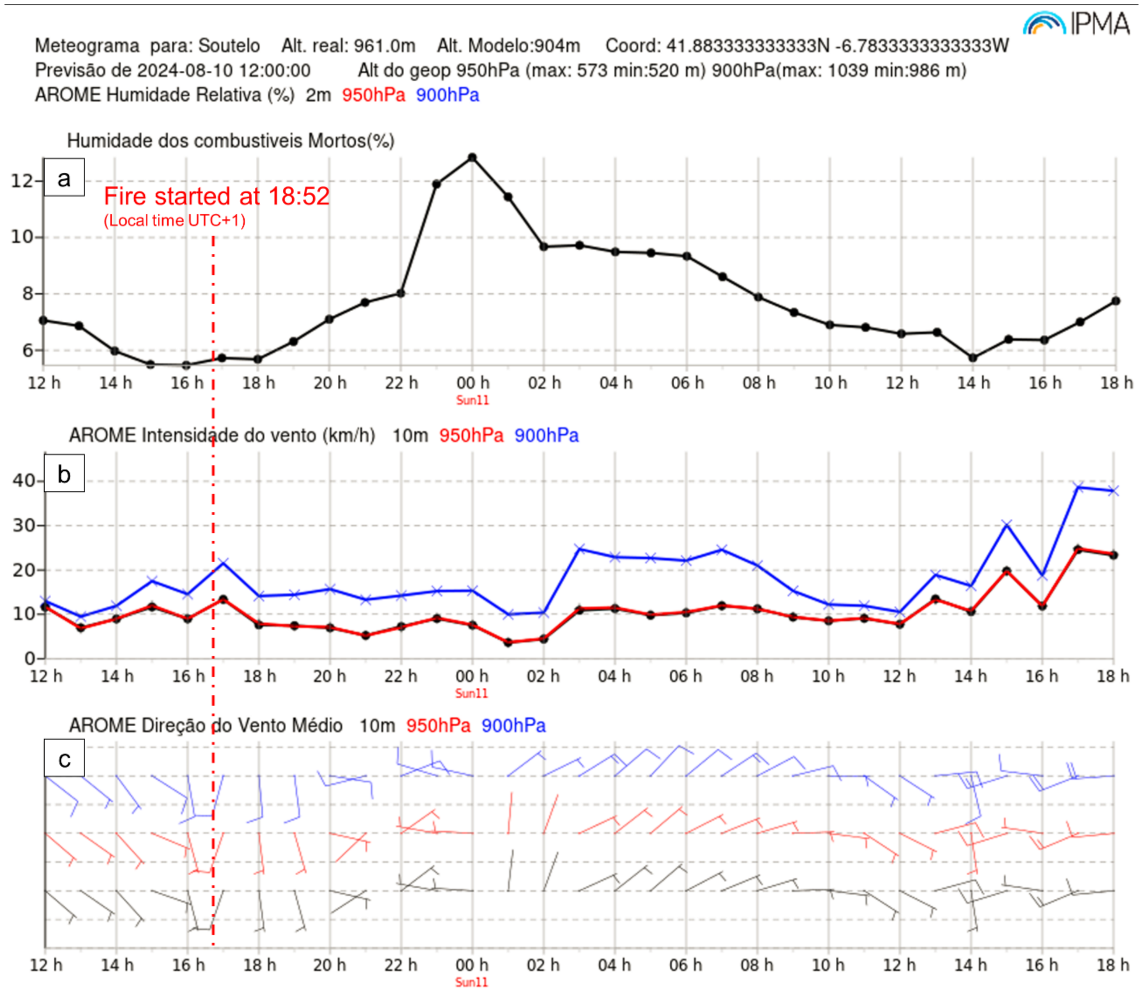


Figure 5. Predictions of dead fuel moisture content (%) (a), wind speed (km/h) (b), and wind direction (c) in the meteogram for the Soutelo fire, covering the starting date and time.

The fire reactivated around 19:00 on August 11. Prior to reactivation, the wind speed increased from 5 to 20 km/h between 11:00 and 19:00. The wind direction was predominantly from the northwest, particularly during the period of highest wind speeds (Fig. 6b, c).

After 19:00, the wind speed decreased to 5 km/h on near midnight, then increased again to 15 km/h, with the wind direction shifting from northwest to west by the end of the fire. The MC was approximately 11% and increased to 15% by the end of the fire (Fig. 6a).

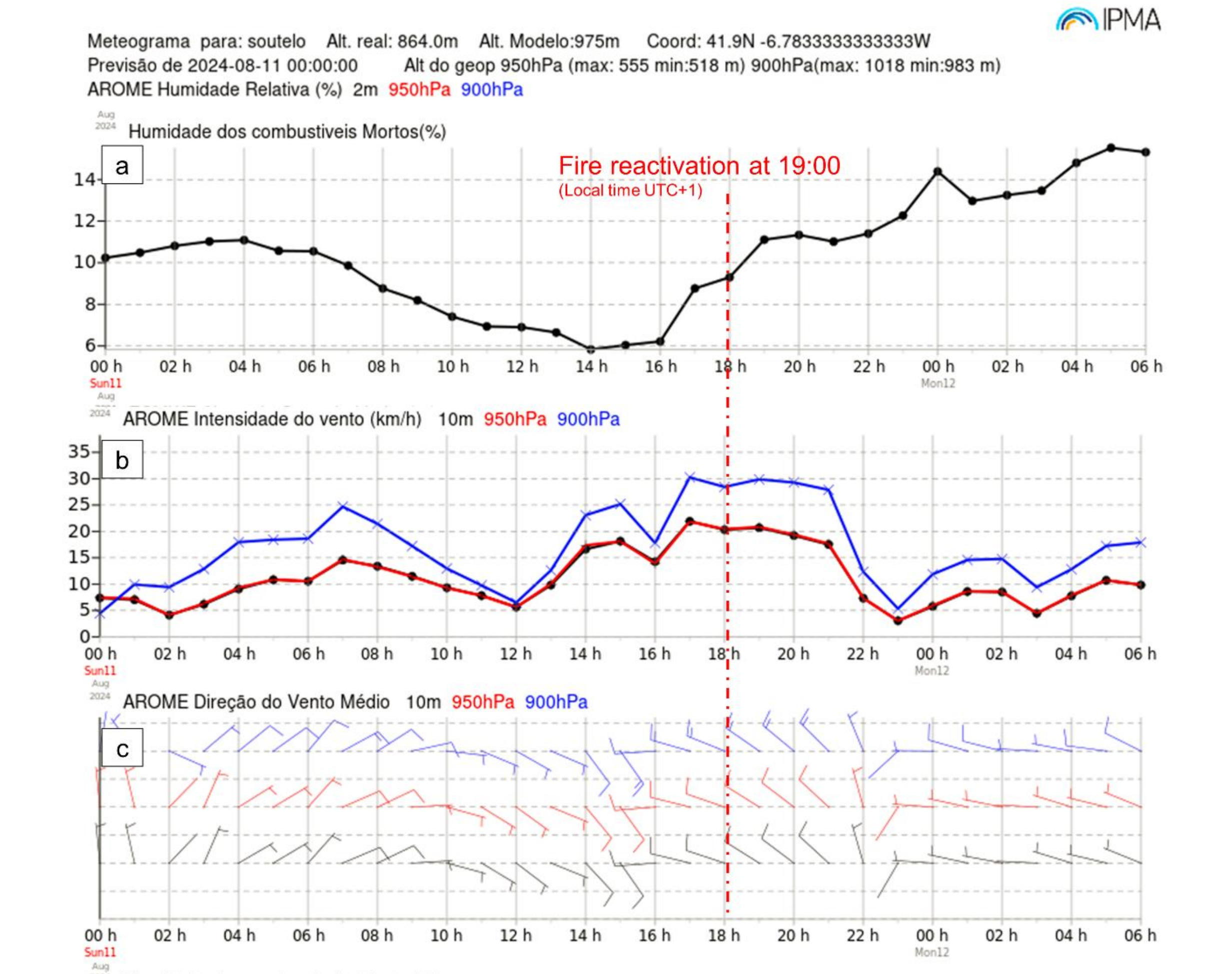


Figure 6. Predictions of dead fuel moisture content (%) (a), wind speed (km/h) (b), and wind direction (c) in the meteogram for the Soutelo fire, covering the reactivation date and time through to the end of the fire.

Fire Progression

The Soutelo fire was analyzed with six progression phases using data provided by field operators (fops), airborne (airb), and satellite (sat) sources (Annex Table 1, Fig. 7).

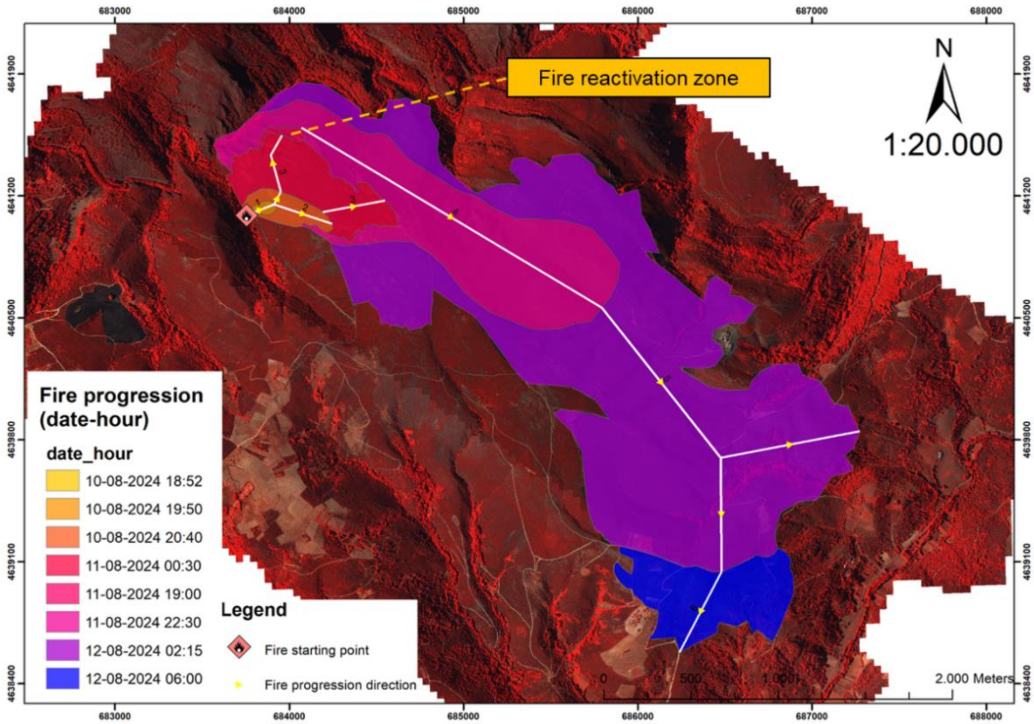


Figure 7. Progression map of the Soutelo fire.

In the first phase (1) the fire spread to northeast until 19:50, affecting 0.9 ha, and then continued towards the east (2) affecting 6,4 ha until 20:40. The fire then spread both east/northeast until 00:30 (3), affecting 27.7 ha on August 11 (Table 1, Fig. 7).

The fire reactivated at around 19:00 on August 11, spreading to the southeast (4) affecting 96.4 ha until 22:30. The fire continued to spread mainly south and southeast until 02:15, affecting 275.7 ha on August 12 (5), and reached the final perimeter in the east. The fire then continued to spread southwest and stopped at 06:00 on August 12, affecting 37.2 ha (Table 1, Fig. 7).

Fire Behavior and Environmental Drivers

The rate of fire spread (ROS) (m/h), fuel consumption (FC) (kg/m^2), and Fireline intensity (FI) (kW/m) were calculated using fire progression data and the fuel model of the area (Fig. 8). The results indicated that ROS values were 186, 420 and 94 m/h in the 1st, 2nd and 3rd phases of fire until 00:30, respectively (Fig 8a).

FC values 2.43, 2.65 and 2.5 kg/m^2 in the 1st, 2nd and 3rd phases of fire, respectively (Fig. 8b). During the same phases, FI values were 2639, 6493 and 1370 kW/m in 1st, 2nd and 3rd, respectively (Fig 8c). The ROS and FI patterns for the three phases of fire were similar because the FC remained nearly the same across the first three progression phases (Fig. 8a, c).

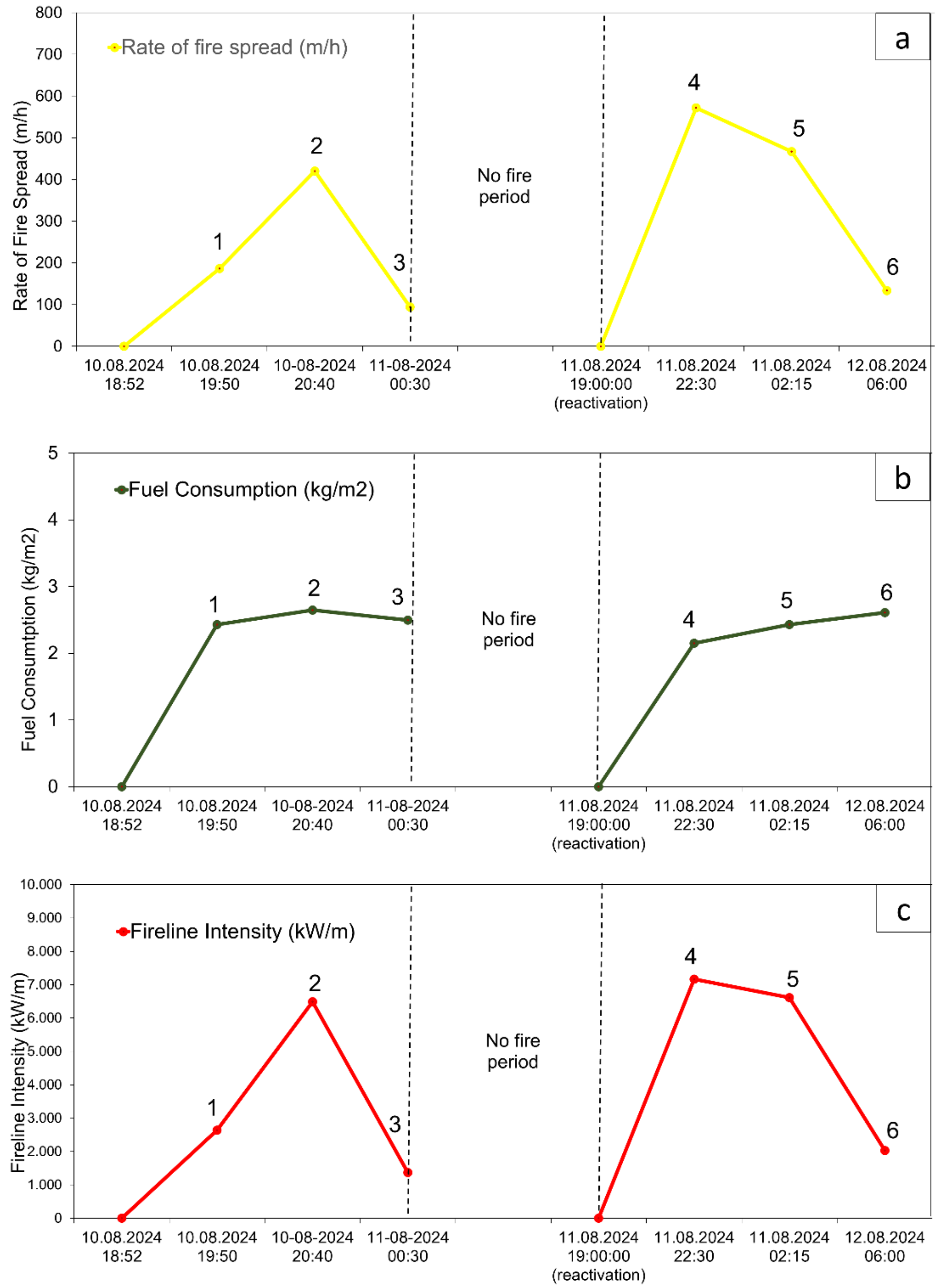


Figure 8. Fire behavior parameters of Soutelo fire (Rate of fire spread (m/h) (a), Fuel consumption (kg/m^2) (b) and Fireline intensity (kW/m) (c)). Numbers (1 to 6) indicate the phases of fire.

During the first three phases, fire spread progressed from downslope to upslope. The fire reached the ridge of the mountain and began moving downslope, resulting in a reduction in the rate of spread. By approximately 00:30 on August 11, the fire was brought under control by the fire suppression teams but without any type of anchoring because most of the area was inaccessible.

The first three phases of the fire behavior in the Soutelo fire were primarily driven by topography, with wind not being a dominant factor in the rate of spread during this time. As a result, the fire progression from its beginning until its first control can be described as a "topographical fire."

However, some active points remained in the northern part of the area, which were difficult for ground crews to access. These active points can be seen in the airborne (AVRAC-GAUF) images (Fig. 9). It is estimated that some active points could not be fully extinguished by aerial suppression due to their location in rocky and sheltered areas (Fig. 9).

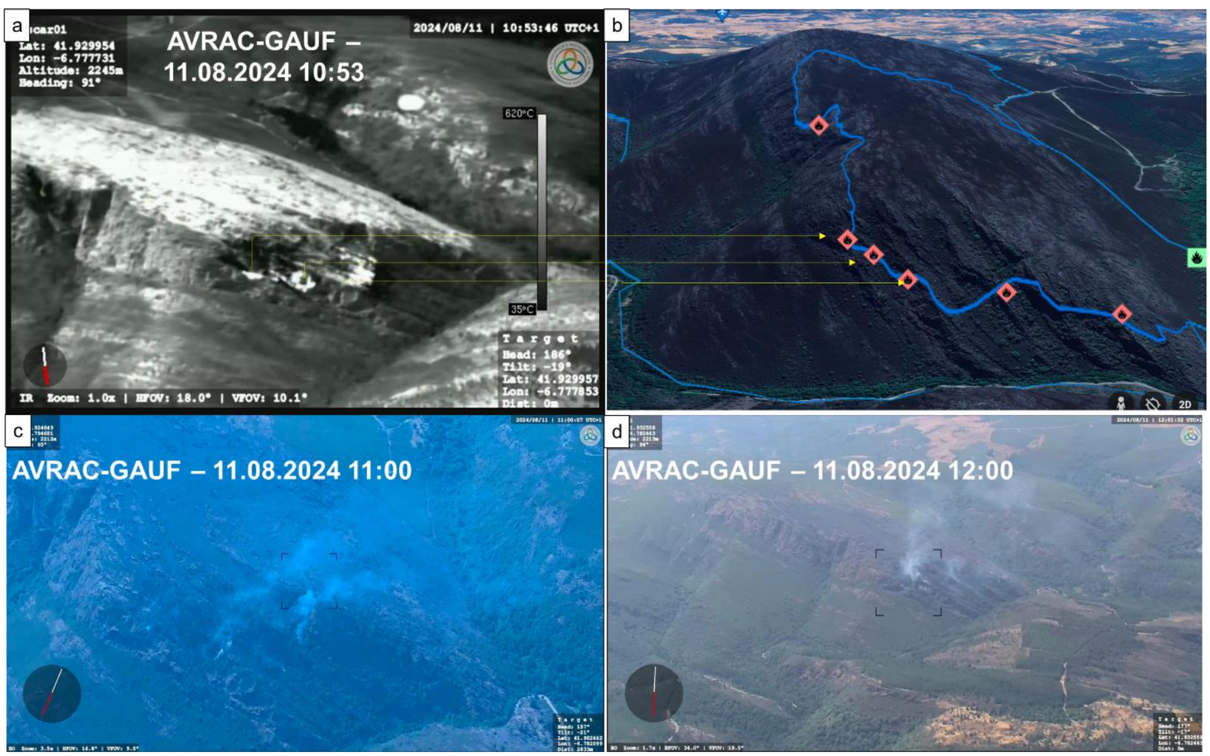


Figure 9. Active points in the northern part of the burned area from AVRAC-GAUF (a, c and d) (ANEPC 2024) and Google Earth (b) satellite images.

The fire reactivated at approximately 19:00 on August 11 within a potential fire activation zone (Fig. 7). The reactivation time was confirmed by the field operatives (fops) and validated with the Fire Radiative Energy (FRE) data provided by EUMETSAT – Fire Radiative Power Pixel – MSG Product, available at 15-minute intervals (Fig. 10) (EUMETSAT 2024).

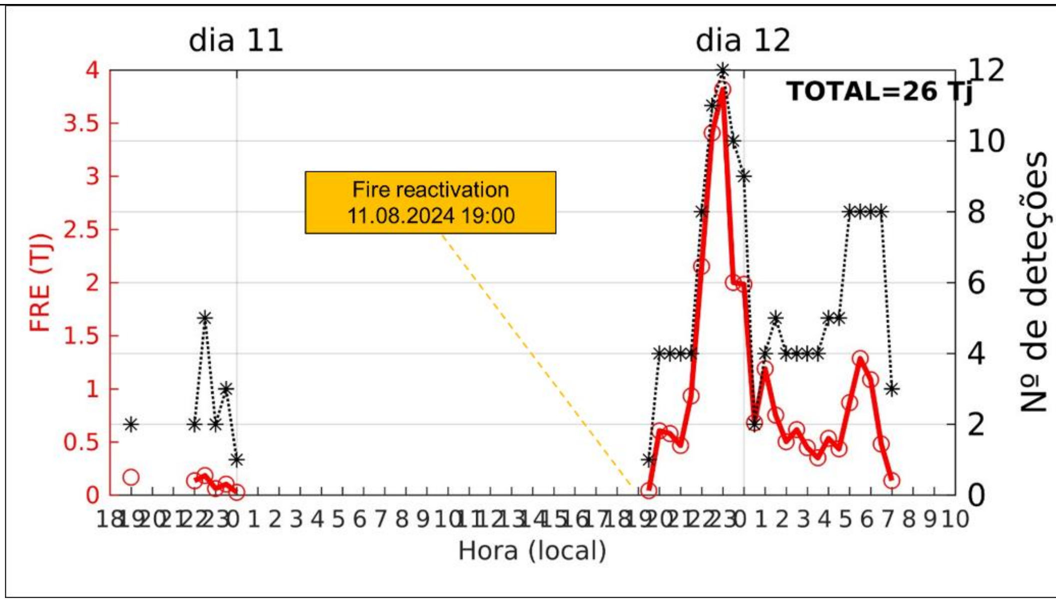


Figure 10. Fire Radiative Energy diagram of the burned area, showing the start and end of the fire, provided by EUMETSAT (2024).

After reactivation, the ROS was 571 m/h, the FC 2.15 kg/m^2 and FI was 7167 kW/m during the 4th period of fire (Fig. 8). This phase was the most intense, with an increased rate of fire spread driven by high wind speed (approximately 20 km/h) (Fig. 6b) until 22:30. The period following the reactivation until 22:30 can be described as a "wind-driven fire."

In the 5th phase of fire, the ROS was 467 m/h, the FC 2.43 kg/m^2 and FI was 6615 kW/m. The extent of the fire at this time was determined by both fops and NASA FIRMS VIIRS thermal anomalies/hotspots data.

Finally, the fire's last phase (6th) extended to the southwest, and the fire front reached its final perimeter at approximately 6:00 am. The ROS was 133 m/h, the FC 2.61 kg/m^2 and FI was 2030 kW/m. This information was confirmed by the FRE data of the area (Fig. 10). The pattern of the ROS and FI was similar because the FC remained nearly same across the last three progression phases (Fig. 8a, c).

The ROS dramatically decreased in the 6th phase of the fire compared to the 5th phase, due to changing slope conditions. In the 5th phase, the fire moved southeast and east under the influence of both wind speed and the upslope effect (Fig. 7). It then continued to move downslope toward the southeast in the 6th phase of the fire. In conclusion, the 5th and 6th phase of fire were influenced by both changing topographical features and variations in wind speed and direction.

When the Soutelo fire was evaluated for classification based on fire behavior and control capacity, it can be classified as a 'Normal Fire (Category 4)'. The mean fire behavior parameters, such as ROS, FC, and FI, were 312 m/h, 2.46 kg/m², and 4386 kW/m, respectively (Fig. 8) in the Soutelo fire. The description of a Category 4 fire is a surface fire, with crowning likely depending on vegetation type and stand structure. The difficulty of control is extremely high. Moreover, this type of fire is characterized by prolific spotting activity, with distances of 500–1000 meters (Tedim et al. 2018).

Impacts

There was no loss of life or damage to infrastructure in the Soutelo fire; however, some small farmlands and orchards were affected. The burned area is also part of the Montesinho Natural Park and is within the Natura 2000 protected areas network.

Lessons Learned

The Soutelo fire was a nighttime fire because the active burning period was almost entirely during the night. Additionally, with a high elevation (≈850 m) and location in a mountainous region, the fire was affected by environmental conditions such as local winds.

A key lesson learned from this fire is the significant impact that changes in slope have on fire behavior. The fire spread much faster uphill than downhill, pre-heating the fuel above and causing it to ignite more quickly. Steeper slopes contributed to a more rapid and intense spread, making it much harder to control.

In contrast, downslope fire spread is typically slower. However, sudden changes in slope, such as ridges or valleys, caused the fire to shift direction unexpectedly, either accelerating or slowing its progress depending on the terrain. Understanding and planning for these variations in slope are crucial for developing effective fire response strategies in mountainous regions.

The reactivation was another significant aspect of the Soutelo fire, highlighting the importance of thorough mop-up and monitoring after a burned area is controlled. Infrared images are quite useful for identifying active parts of the fire and potential reactivation zones.

This reconstruction of the Soutelo fire clearly demonstrates the importance of accurate, timely, easily accessible, and georeferenced information for fire monitoring. The availability of extensive high spatial and temporal resolution datasets during a wildfire event increases the potential for understanding fire behavior under changing environmental conditions. Such an understanding of wildfire behavior is invaluable for future preparedness, decision-making, and fire response efforts.

5. Freixo de Espada a Cinta fire

Franco Casula, Corpo Forestale e di Vigilanza Ambientale of Regione Sardegna , Italy

Location	Freixo de Espada à Cinta, Portugal
Dates	30.08.2024 – 31.08.2024
Duration	10 hours [stabilization after 4 hours]
Burned Area	222 ha

Context

The event started at 13:29 in the NE part of Portugal close to the Spanish border. The main spreading lasted 4h30'; some minor fronts remained active for 13 hours when the event was under control. The fire was declared extinct within 24 hours.

The fire started at 400 m altitude and burned a topographical complex area that is comprised between 200 and 600 m asl (Fig. 1 and 2). It is situated on the right margin of the Douro River that locally flows from N to S with several lateral valleys declining to the river and presenting steep slopes and different aspects. The relief is mainly covered by grasses, shrubs exhibiting different heights and densities with some agroforestry spaces at the base of the slopes and a forested area on the northern border of the burned area. Based on 50 years data, the local return time for the area to be burnt is roughly 10 years. In particular (Fig. 3 and 4) the last three events (2019, 2014 and 2011) covered almost the whole burned area. In 2003, a wildfire risen from a near ignition point, burned the whole area of the present event of 2024 before expanding towards the west after a wind shift that transformed the left flank into the fire head that expanded towards the west pushed by strong and dry winds. The fire spread in a condition of severely dry fuels, relatively high temperatures and low atmospheric humidity with not intense but variable winds (Fig. 5). During the 2003 event, an extraordinary rate of spread acceleration was recorded (blow-up event) and two people lost their life.

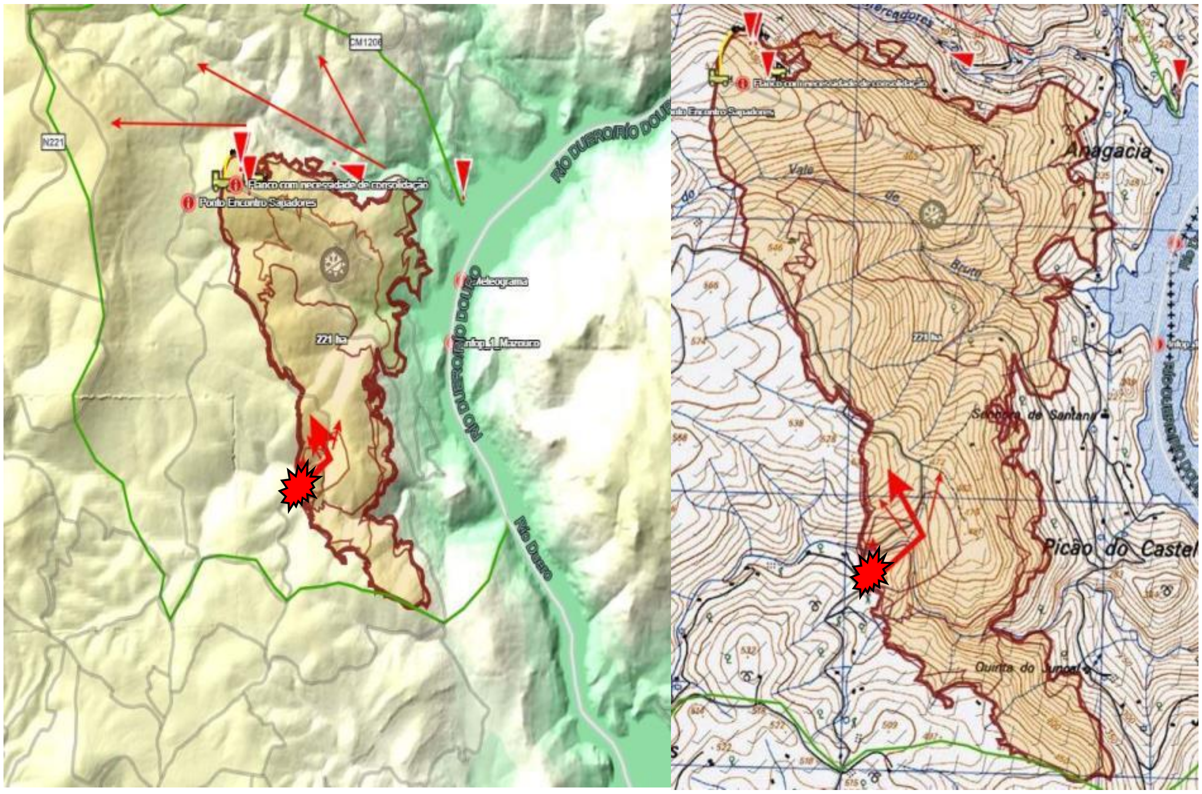


Figure 7, 2. topography of the area where the Freixo de Espada à Cinta fire spread. The red symbol specifies the ignition point, the red arrow shows the first phase of propagation and the change in direction after a first phase.

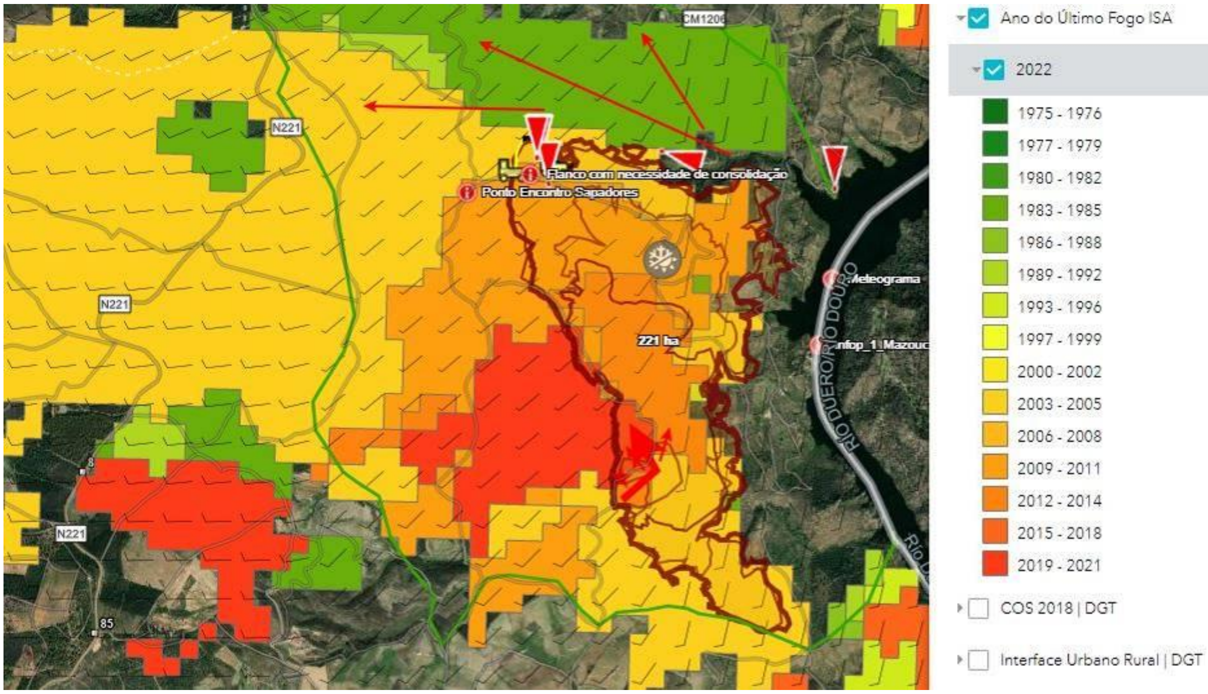


Figure 3. last events that have burned the same area. In legend, the year in in which previous events took place.

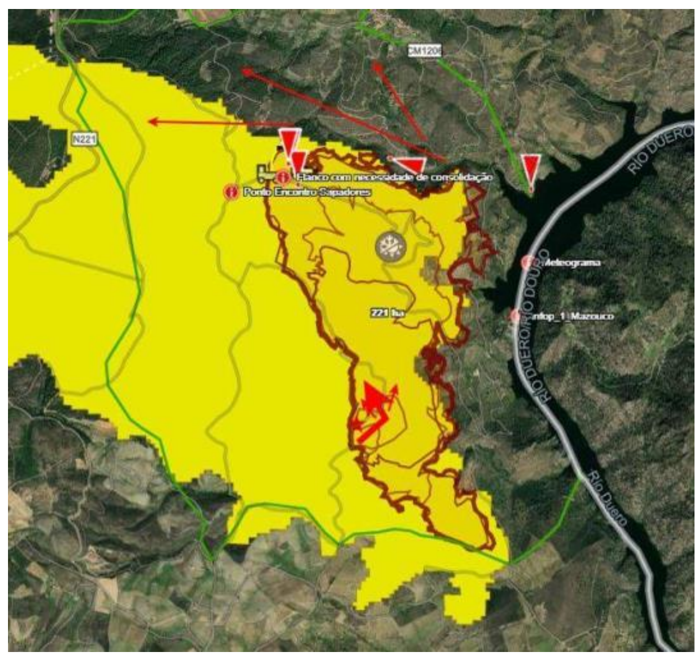


Figure 4. the event of 2003: it shares the ignition point and the initial propagation, burning the same area before expanding westwards due to a change in winds

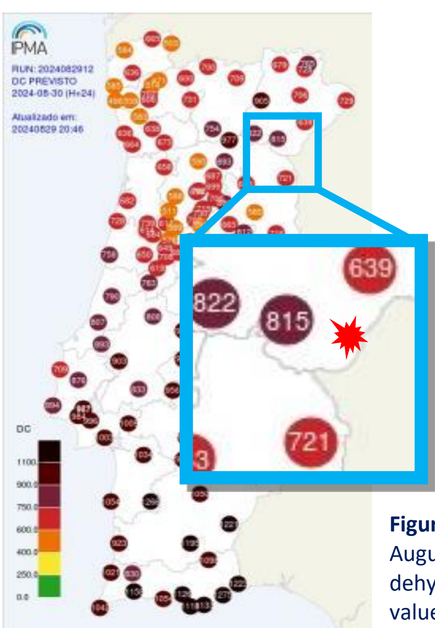


Figure 5. Drought Code (DC) calculated with forecasted meteorological data for August the 30th 2024 by Instituto Portugues do Mar e da Atmosfera (IPMA). The dehydration level of vegetation in the area where the fire happened scored high values of DC although they were not extreme.

Fire Progression

The fire progressions were derived from airborne and field data, provided by ANEPC Fig. 6). The rate-of-spread (m/h) and growth rate (ha/h) were estimated for each progression polygon (Fig. 7 and 8). The fire was divided in 4 propagation phases.

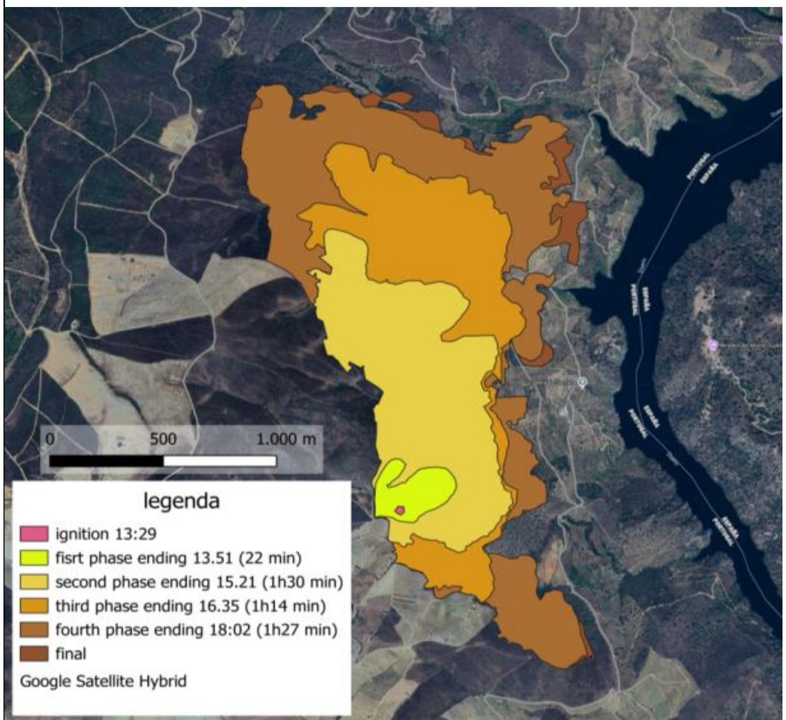


Figure 6. Progressive development of the wildfire. The first phase was drown based on pictures and videos taken by helibrigades while the other perimeters were drown based on the mosaic of IR georeferenced images taken by the AVRAC airplane of the Portuguese Civil Protection.

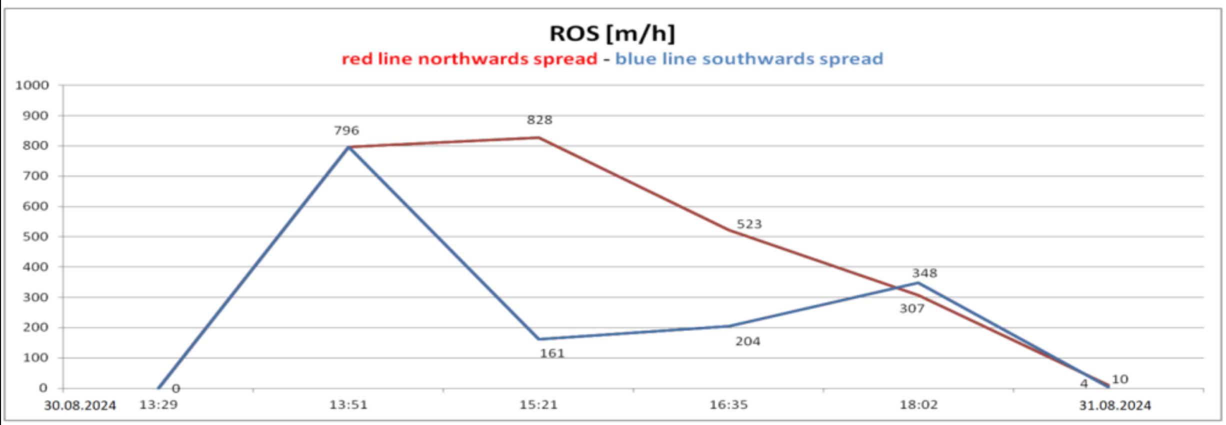


Figure 7. Rate Of Spread (ROS) in meters per hour of the two main directions of propagation. The propagation from ignition at 13h29' to 13h51' is the first phase that is common to both lines.

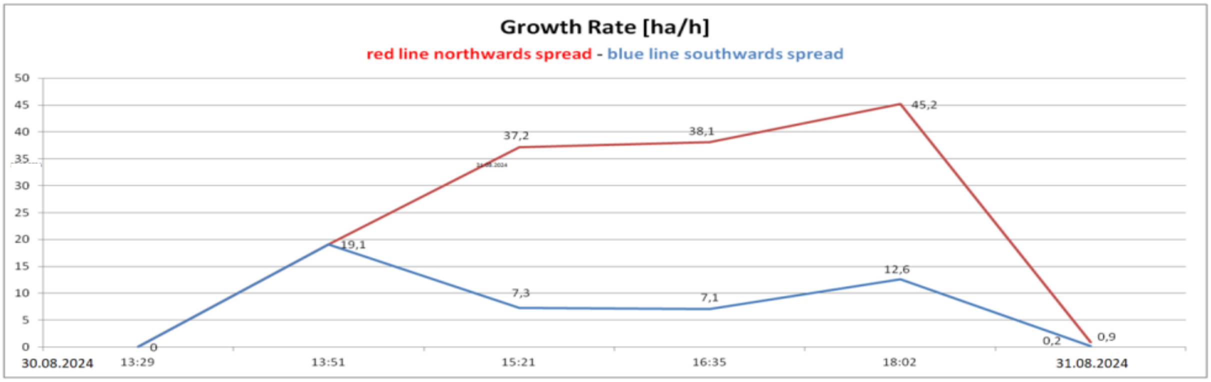


Figure 8. Growth Rate expressed in burned hectares per hour. The image shows the values for the two directions of propagation. The first phase (from ignition at 13h29' to 13h51') is common to both lines.

FIRST PROPAGATION PHASE 13:29-13:51 (22 min): The fire (Fig. 6, 9, 10) started the bottom part of a SSW-NNE oriented little valley spreading upwards to E while opening the propagation on the two sides of the valley: the B front (Fig. 6) propagated towards NE burning the SSE oriented side, while the A front (propagation towards E) burned the W oriented side of the valley with the alignment of west wind and topography. There was also a little SW propagation, but it was not very intense and stopped right away on agricultural fields presenting very low fuel charge. The propagation towards ENE travelled nearly 300 m in 22 minutes (ROS about 800 m/h, estimated FLI 5850 kW/m), passing from 400 to 485 m asl and arriving where the ridge line (that has a N-S direction as the Douro River) presents a saddle shape geomorphology. The two fronts on the two sides of the valley arrived at the saddle on the ridge where they merged.

Figure 9. image of the first phase, taken from the north. Propagation was moving uphill towards the east driven by topography and wind. (30.08.2024 – 13:51).

Figure 10. the first propagation phase seen from the south. It presents two disjointed fronts moving eastwards. The smoke initially flows inclined along the slope and then generates an almost vertical column above the ridgeline. (30.08.2024 – 13:56).

SECOND PROPAGATION PHASE 13:50-15:20 (1h30'): (Fig. 6, 11, 12) Upon reaching the saddle-ridge the two fire fronts did not continue their primary eastward progression toward to the river. Instead, the main fire progression expanded northward, while a secondary fire front advanced southward.

- Northern front: a 500 m width front, oriented E-W, propagated northwards for 1250 m from 13:50 to 15:20 (ROS about 830 m/h, estimated FLI 6100 kW/m) burning the upper part of the east oriented slope of the Douro valley. The burnt area was situated between elevations of 350 and 600 m altitude. Fire propagation occurred along a relatively constant elevation, advancing northward parallel to both the Douro river and the adjacent ridgeline. The fire did not cross the ridgeline and advanced across a series of minor E-W oriented lateral valleys carved on the slope of the Douro River Valley.
- Southern front: the southward propagation was slower and less intense. It descended a SSW oriented slope covering 250 m from 13:50 to 15:20 (ROS 160 m/h, estimated FLI 1200 kW/m).

Figure 11. Second propagation phase seen from the south. The front moving towards the north is faster and more active than the back part that presents a smoke column driven to east by the wind (30.08.2024 – 15:08).

Figure 12. Second propagation phase seen the from south. The front moving towards the north presents some variability in wind direction (here a first inclination of the column towards east) (30.08.2024 – 14:55).

THIRD PROPAGATION PHASE 15:20-16:35 (Fig. 6, 13)

- Northern front: the rate of spread decreased, the fire front reoriented along a NW-SE axis. The fire front expanded laterally, increasing in width. During this phase of progression, the fire crossed multiple valleys, most of which were oriented from WNW to ESE.
  - 15:20-16:35: ROS 520 m/h, estimated FLI 2550 kW/m
- Southern front: the southward progression exhibited a slight increase in ROS as the fire advanced upslope along a north-facing slope of a lateral valley.
  - 15:20-16:35: ROS 200 m/h, estimated FLI 2900 kW/m

FOURTH PROPAGATION PHASE 16:35-18:02 (Fig. 6, 14)

- Northern front: the rate of spread further decreased when the fire advanced downslope along the north-facing forested side of a valley draining ESE toward the Douro River. The fire front reached the maximum width of approximately 1500 m.
  - 16:35-18:02: ROS 310 m/h, estimated FLI 4400 kW/m

- Southern front: the southward progression exhibited an increasing rate of spread and it became faster than the northern one during the last propagation period when the fire was advancing along the right slope of the Douro valley.
    - 16:35-18:02: ROS 350 m/h, estimated FLI 4950 kW/m

After 18:00 the progression of the fire was very slow, and the fire could be considered contained.

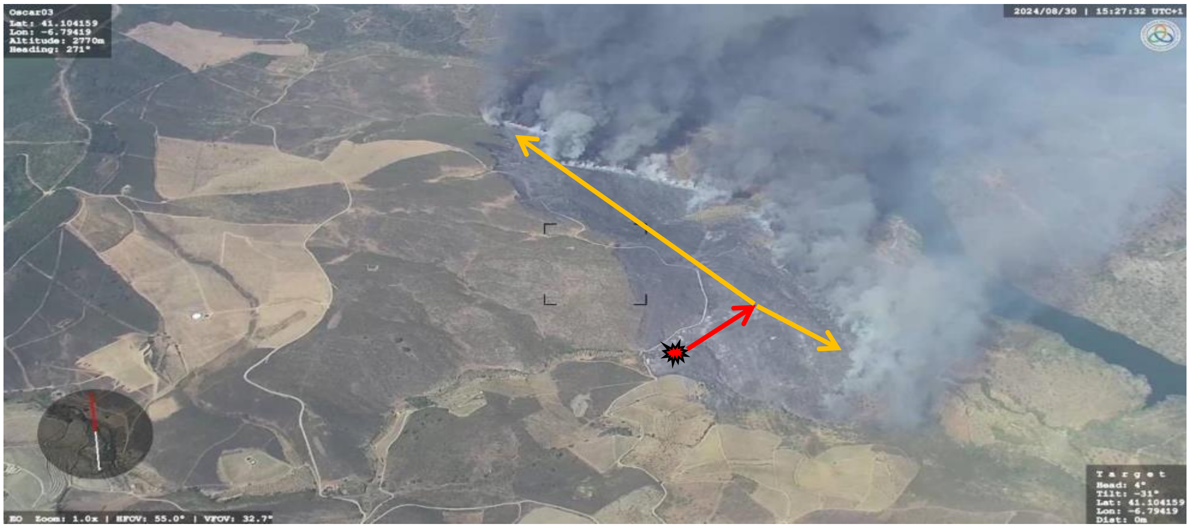


Figure 13. Beginning of the third propagation phase seen from the SSW. The red dot indicates the ignition point, the red arrow the first propagation phase, the orange arrows the second propagation phase. The northern front is still more active. On the back the smoke column is more inclined towards east than in the northern front (30.08.2024 – 15:27).

Figure 14. the beginning of the fourth propagation phase seen from the WNW. The red dot indicates the ignition point, the red arrow the first propagation phase, the orange arrows the second/third propagation phase. The northern front is still more active and moving northwards while on the back the smoke column is more inclined towards east (30.08.2024

Fire Behavior and Environmental Drivers

The fire initially propagated eastward, driven upslope by topographic influence and further accelerated by wind. In particular, the front “B” in Fig. 10 illustrates the critical role of westerly winds during the first propagation phase. The fire did not advance upslope along the south-facing slope, but it spread transversally across the slope, progressing eastward. After 20 min and about 300 m from the ignition (first phase in Fig. 6), the two fronts arrived at the ridge that exhibits a saddle geomorphology. Despite the presence of westerly winds (Fig. 9 and 10) no downslope eastward propagation occured following the first phase: due to complex topography and to the fire generated wind recall from the bottom part of the Douro valley, the light westerly winds arriving to the saddle combined its effect with the uphill winds coming from the east. According to the Campbell prediction system, the eastward progression would be 0/3, and the fire spread changed direction behaving in a not obvious manner:

- due to fuel continuity, it burned with a limited ROS towards the south and east
- the main front advanced fast northward. Although the ascent was finished and the northern front travelled with no differences in altitude, its ROS in the second phase was higher than in the first one.

Figures 11 and 12 show the progression towards north and document, through the smoke column inclination, the variability of wind both in intensity and direction (it varied between south and west). Figures 12 and 13 show that the column of the northern front is slightly inclined towards NE at 15:27 and more inclined to NNE at 16:50 when the wind speed looked higher. The main driver of the second and third phase of the northward propagation was a variable southerly light wind interacting with the easterly upslope winds generated by the propagation itself and combined also with the topographic effect that maintained the left border of burned area in the upper part of the slope, close to the ridge. The spreading was helped by the spatial continuity of fuels that burned with high intensity. The ROS accelerated during uphill propagation and slowed going downwards according to topographic features.

Some IR images documented a rapid increase in fire propagation between 16:22 and 16:30 when two fronts that had burned two belts on the same slope interacted converging quickly and burning the area comprised between them. The slope was SSW oriented and the propagation, according to Campbell classification was proceeding with 3/3. The circular feedback of growing intensity and ROS modified completely fire behavior on the slope up to the ridge where it re-normalized. In Figure 15 a schematic reconstruction of the extreme fire behavior phase is illustrated, based on the IR images. ROS locally reached 2500 m/h since more than 300 m were burnt in less than 8 minutes. This estimate is further supported by IR images between 16:26 and 16:28 (more than 50 m/min).

After 17:30/17:45 northwesterly winds dominated extending into the lateral valleys. This shift reduced the interaction between the prevailing synoptic flow, local slope winds, and fire-induced winds, coinciding with a noticeable decrease in fire intensity (Fig. 16). After burning the entire slope (Fig. 15) and crossing the ridgeline, the north front advanced slowly downslope through a forested north-facing slope. Following the wind shift (Fig. 16), the wind was blowing transversally or slightly upslope, hence the northern front lost its spread potential. On the other hand, the southern front accelerated while it advanced along the right slope of the Douro Valley, driven by the prevailing NW winds. During the fourth propagation phase, the southern front exhibited an average (ROS) of approximately 350 m/h. However, due to a wind shift occurring in the latter part of this phase, the actual ROS was likely higher during this final period. The southern front was put under control when it reached the base of the slope, thanks to the coordinated efforts of both aerial and ground firefighting recources that were deployed and operating in the area.

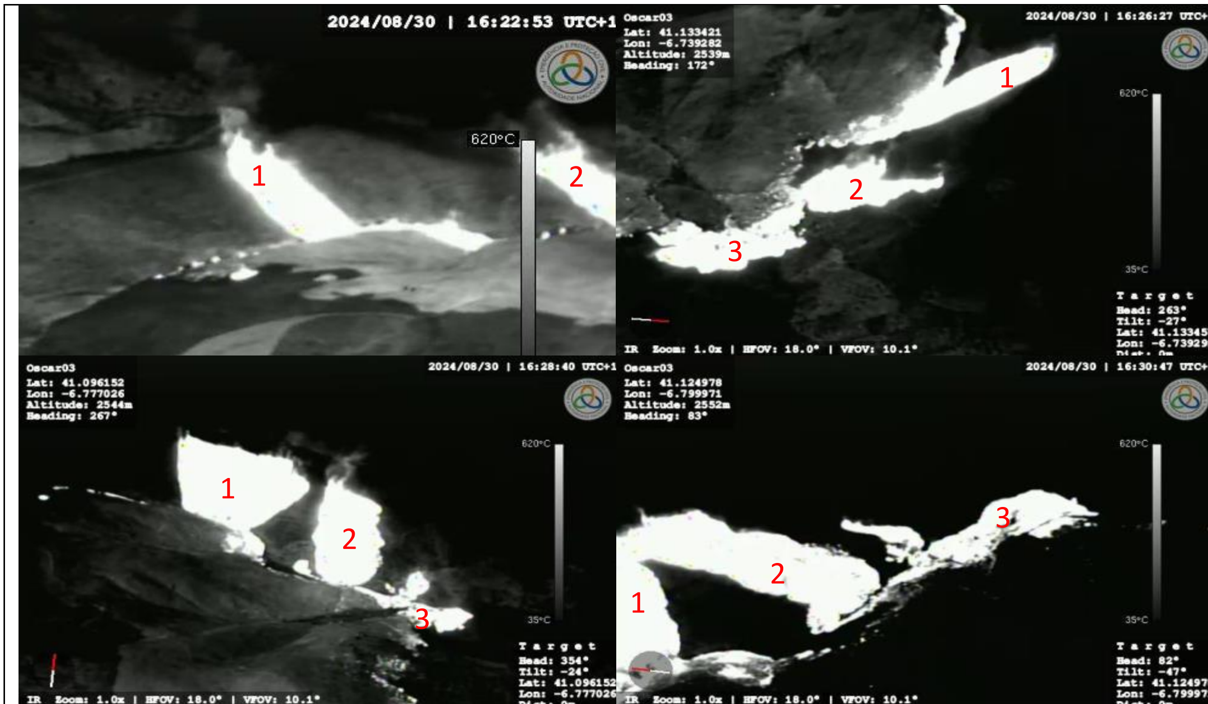


Figure 15. the interaction between the front 1 and 2 that were burning the same slope enhanced ROS and FLI.

The evolution of the fronts using the 4 IR picture above is reconstructed on the app Google Earth using different colors.

Figure 16. the comparison of the picture taken from the helicopter with the image taken by the same perspective in Google Earth shows that, during the fourth propagation phase, the wind changed direction blowing from NW and increased in intensity limiting the complex interaction with local wind. During this period the ROS of the front propagating southward becomes higher than the northwards one (30.08.2024 – 18:16).

The meteorological forecasts available for the day revealed not to be very reliable. According to the ECMWF data that is shown in Figure 17, air temperature would be above 30°C for the whole period with a maximum of 32-33°C, the RH would range from 30% at ignition to 24% at 16:00 to finally rise to 28% at 18:00. Wind speed would grow from 6 km/h up to 9-10 km/h, initially coming from WSW while after 16:30 blowing from W and about at 19:00 from NW. A second output (Fig. 18) was also available, the one by the model AROME, an operational small-scale numerical forecasting model designed to improve short-term forecasts of severe events such as intense Mediterranean precipitation, severe thunderstorms, fog, urban heat during hot weather etc. It downscales and improves the ECMWF data and according to it the meteorological conditions during the fire would be: RH under 20% during the whole period, temperature above 33°C with a T_{max} of 35°C between 16:00 and 17:00, and wind (10 m height) above 6-7 km/h with a maximum of 8-9 km/h at 16:00. Wind direction was initially predicted from SE then at 16:00 from E and at 18:00 from NE. Nor AROME neither ECMWF modelling of wind direction corresponded to the real winds. As documented by the picture available for the event a light and variable wind blew mainly from southerly direction until it changed from NW just before 18:00 hours. The atmospheric conditions forecasted by AROME downscaling model can anyway be considered more accurate than the ECMWF general atmospheric model.

The two models did not predict atmospheric instability conditions in Freixo de Espada à Cinta, but in the western part of Spain, during the 30th of August afternoon, intense and abundant precipitations were taking place due to a meteorological system of cumulonimbus cloud in daily vertical evolution (the closest thunderstorms were at about 130 km East from the fire, close to Salamanca). The Cloud Top Alert monitoring of the area is reported in Figure 19. It shows that, during the fire event, the sky alternated moments in which it was clear with transits from W to E of several cloud systems. The temperature of the upper part of the eastward fast moving clouds on the area ranged between -35°C and -45°C indicating that their top was in the high troposphere (8-9000 m).

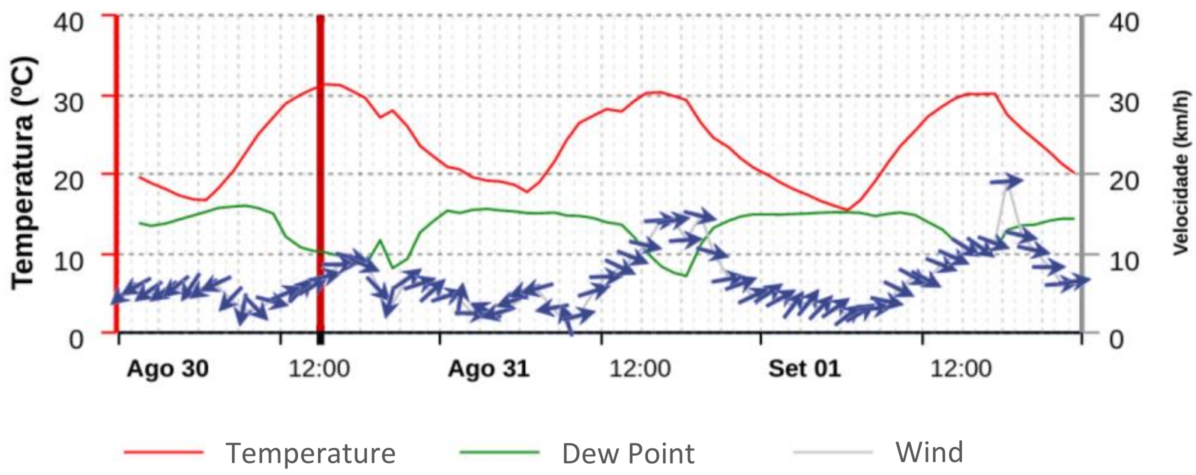


Figure 17. ECMWF forecast - Wind direction and speed [km/h], Air Temperature [°C] and Dew Point [°C].

Although the forecasts predicted a stable atmosphere, the well-organized intense and extensive rains in Spain and the dynamism of the high troposphere above the fire can have had an influence on the variability of winds and on propagation itself. During the period of major fire intensity the release of energy and water vapour by combustion can have activated a local dynamic of convection with upwards vertical movements of air from the low troposphere. The recall of air due to the ascent of the column can create local surface winds especially in inclined valleys that usually have the effect of channelling and increasing the winds. It is probable that some similar effect of environment-fire-atmosphere interaction can have favoured the extreme fire behavior recorded during some periods of the propagation (as in the time frame 16:22-16:30 described in Figure 15).

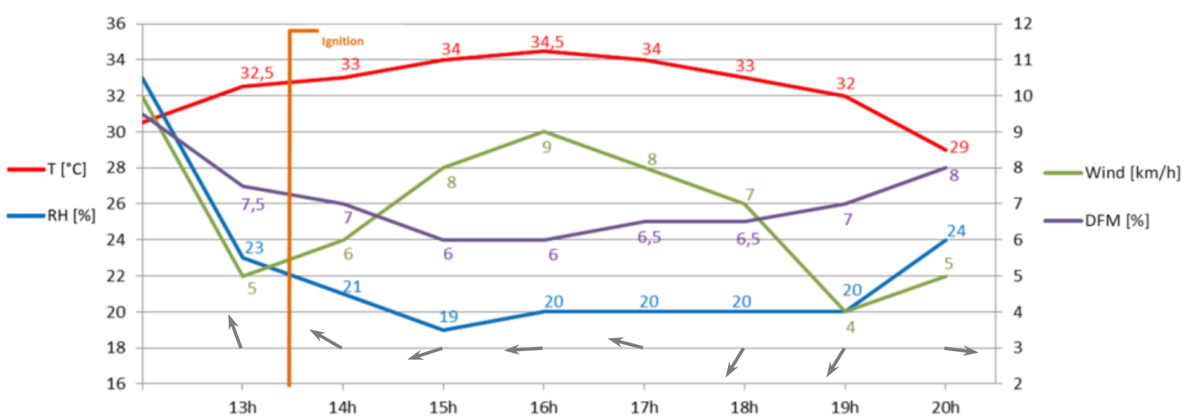
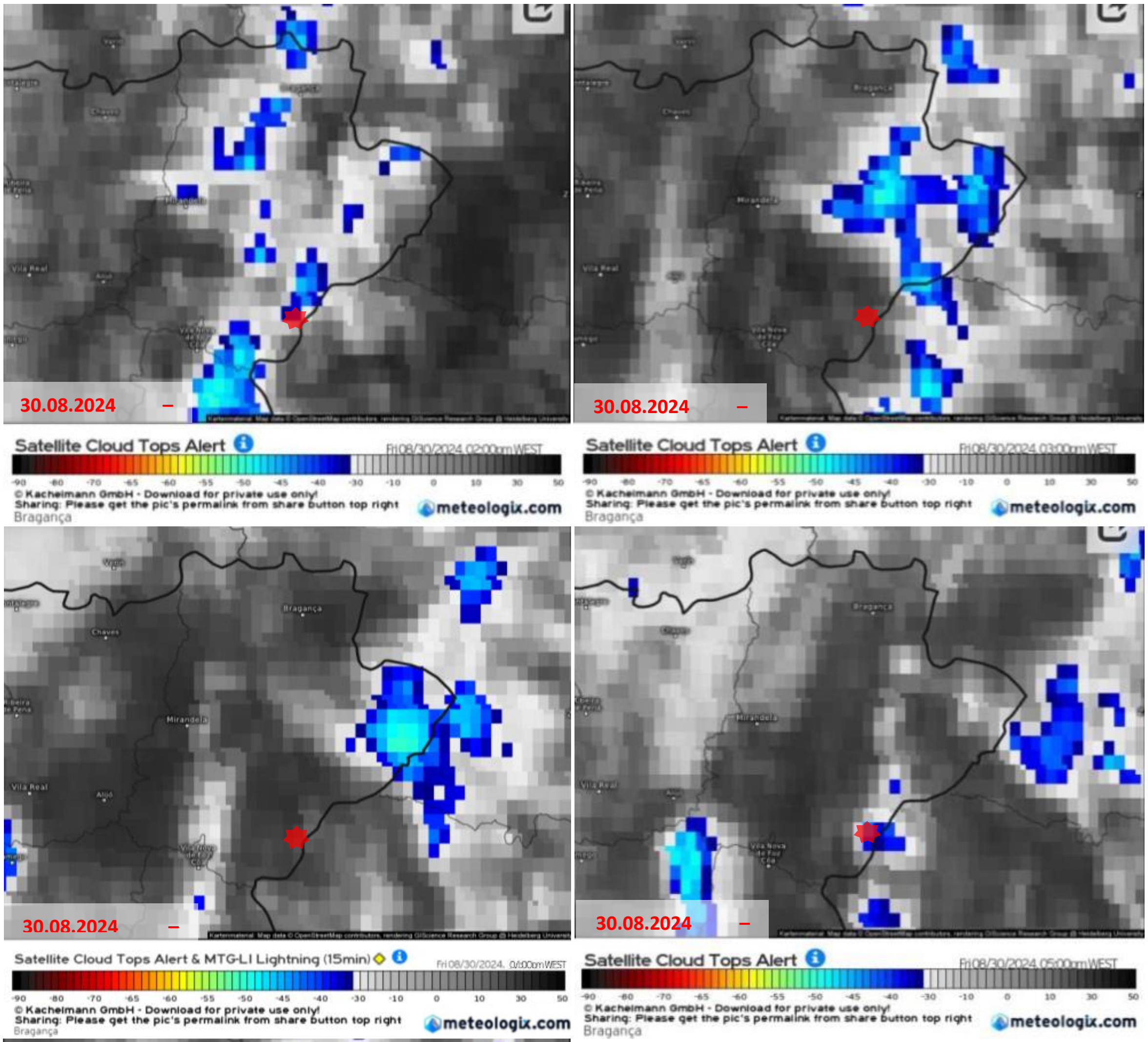


Figure 18. AROME forecast - Wind direction and speed [km/h], Temperature [°C], Relative Humidity [%] and Dead Fuels Moisture [%]. The orange line indicates the ignition time (13h29min).



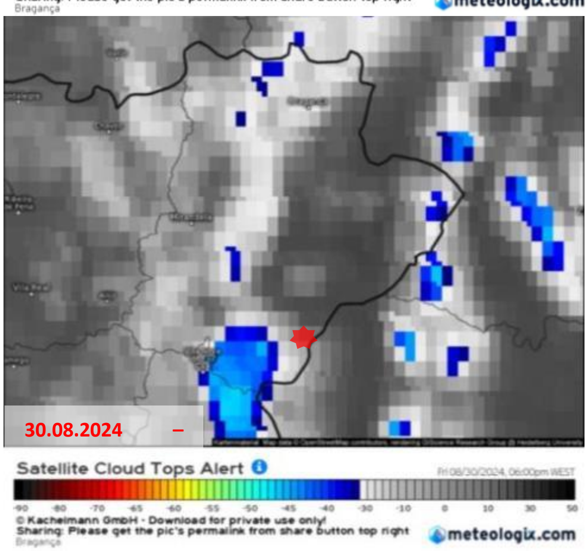


Figure 19. Cloud Top Temperature sequence during the afternoon of August the 30th 2024 above the area of the event (indicated with the red star). A W→E air flow was moving the clouds and their temperature at the top arrived to -45°C, roughly corresponding to 9000 m altitude.

Lessons Learned

Complex topography refers to landscapes with varying slopes, aspects, and geomorphological features like ridges, canyons, and saddles. These elements influence fuel distribution and local wind patterns, often resulting in unpredictable fire behavior and spread patterns that are difficult to simulate. This makes real-time fire behavior prediction challenging, complicating the development of safe suppression strategies and coordination efforts.

Topographically driven wildfires are heavily influenced by terrain-induced effects such as slope angle, sunlight exposure, and the creation of local winds. These variables can intensify fire spread and introduce uncertainty in predictions, especially when spot fires or key events—like a new valley becoming involved—alter the fire's trajectory. In such situations, real-time fire analysis must consider multiple scenarios due to the possibility of drastically different outcomes based on critical but uncertain events during propagation.

The Freixo de Espada à Cinta fire illustrates these dynamics, where two fronts burning parallel uphill created a mutual feedback loop, enhancing both the rate of spread (ROS) and fireline intensity (FLI). With light, variable winds and complex terrain, fire behavior was largely driven by fire-atmosphere interactions rather than external meteorological forces. This highlights the need for dynamic analysis and scenario-based forecasts, while also acknowledging the inherent uncertainty—like weather forecasts—by qualifying the reliability of real-time fire predictions.

6. Padrão (Castelo Branco) fire

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TO BE ADDED

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